

Immingham Green Energy Terminal

Preliminary Environmental Information Report

Appendix 9.B – Underwater Noise

Associated British Ports

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1 Appendix 9B: Underwater Noise

1.1 Introduction

1.1.1 This report presents an assessment of the potential effects of underwater noise and vibration from the Project on marine fauna. The assessment has been undertaken to support the Preliminary Environmental Information Report (PEIR) that has been prepared for the Project. In particular, the assessment has informed the outcomes of the marine ecology assessment (**Chapter 9 Marine Ecology** (PEI Report, Volume II)), which in turn will inform the Habitats Regulations Assessment (HRA) and the Water Framework Directive (WFD) Compliance assessment which will be included in Environmental Statement (ES) and submitted with the Development Consent Order (DCO) application. A detailed description of the Project and construction methodology on which this assessment is based on is included in **Chapter 2 The Project** (PEI Report, Volume II).

1.1.2 This report has been structured as follows:

- **Section 1.1: Introduction** provides a brief introduction to the project and need for this assessment;
- **Section 1.2: Principles of Underwater Acoustics** presents the basic principles which are fundamental to undertaking robust underwater noise assessments;
- **Section 1.3: Underwater Noise Propagation** reviews the key factors influencing the propagation of underwater noise and presents the preferred underwater noise propagation model that has been applied in this underwater noise assessment;
- **Section 1.4: Ambient Noise** presents the baseline acoustic conditions of the study area;
- **Section 1.5: Noise Characteristics of Proposed Development Activities** presents the specific acoustic characteristics of the proposed construction and operational activities;
- **Section 1.6: Hearing Sensitivity and Responses of Marine Fauna** reviews the hearing sensitivity of marine fauna that occur in the study area and the latest available published criteria that have been applied to determine the scale of potential physiological and behavioural effects;
- **Section 1.7: Noise Propagation Modelling Outputs** presents the outputs of the underwater noise modelling;
- **Section 1.8: Potential Effects** reviews the potential effects on local marine fauna; and
- **Section 1.9: Summary and Conclusions** presents an overview of the outcome of the underwater noise assessment and conclusions.

1.2 Principals of Underwater Acoustics

Introduction

1.2.1 Underwater sound is generated by the movement or vibration of any immersed object in water. Sound can be detected: (a) as pressure fluctuations in the medium above and below the local hydrostatic pressure (sound pressure); and (b) by the back and forth motion of the medium, referred to as particle motion (Ref 1-1).

Sound pressure

1.2.2 Sound pressure acts in all directions and is a scalar quantity that can be described in terms of its magnitude and its temporal and frequency characteristics. An important property of sound or 'noise' is its loudness. A loud noise usually has a larger pressure variation and a weak one has a smaller pressure variation.

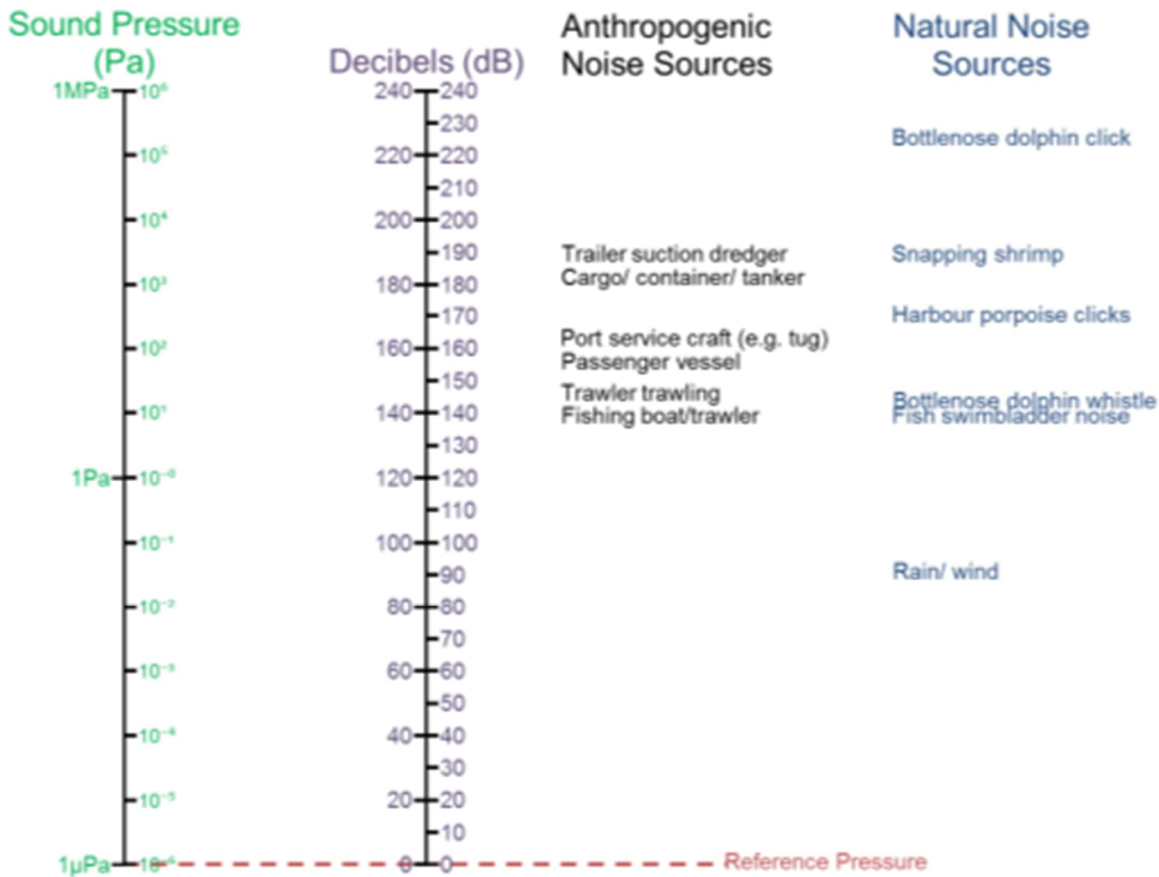
1.2.3 Pressure and pressure variations are expressed in Pascal, abbreviated as Pa, which is defined as Newton per square metre (N/m²). It is not appropriate to express sound or noise in terms of Pa because it would involve dealing with numbers from as small as 0.000001 to as big as 2,000,000. The use of a logarithmic scale, of which the most commonly used is the decibel (dB) scale, compresses the range so that it can be easily described. **Plate 1**-below shows how sounds can be expressed both linearly in Pa and logarithmically in dB.

1.2.4 Confusion arises because sound levels given in dB in water are not the same as sound levels given in dB in air. There are two reasons for this:

- **Reference intensities.** The reference intensities used to compute sound levels in dB are different in water and air. Scientists arbitrarily agreed to use as the reference intensity for underwater sound, the intensity of a sound wave with a pressure of 1 micro Pascal (μPa). However, in the case of sound in air, scientists selected to use 20 μPa as a reference intensity as it is consistent with the minimum threshold of young human adults in their range of best hearing (1,000 -3,000 Hz); and
- **Densities and sound speeds.** The intensity of a sound wave depends not only on the pressure of the wave, but also on the density and sound speed of the medium through which the sound is travelling. Sounds in water and sounds in air that have the same pressures have very different intensities because the density of water is much greater than the density of air and because the speed of sound in water is much greater than the speed of sound in air. For the same pressure, higher density and higher sound speed both give a lower intensity.

1.2.5 The dB levels for sound in water and in air are, therefore, not directly comparable.

Plate 1-1: The sound pressure (Pa) and decibel (dB) scale



Source: Ref 1-2

Particle motion

- 1.2.6 Particle motion is an oscillation back and forth in a particular direction; it is a vector quantity that can only be fully described by specifying both the magnitude and direction of the motion, as well as its magnitude, temporal, and frequency characteristics. The particle motion component of underwater sound comprises both the velocity (m/s) and the acceleration (m/s²) of molecules in the sound wave.
- 1.2.7 Particle motion was previously considered impossible to record (Ref 1-3). However, two approaches have been used in research to estimate particle acceleration (Ref 1-4): 1) accelerometers and 2) the recording of pressure differences between two hydrophones. This was followed closely by the development of a particle motion sensor (Ref 1-5), which has been validated in field studies near an offshore wind farm in the western part of the Baltic Sea.
- 1.2.8 Detection of particle motion requires different types of sensor than those utilized by a conventional hydrophone (Ref 1-6). Such sensors must specify the particle motion in terms of the particle displacement, or its time derivatives (particle velocity or particle acceleration) in three dimensions.

Underwater noise metrics

1.2.9 There are a number of different metrics that may be used as measures of sound pressure (Ref 1-7). The key metrics that are used to characterise noise are as follows:

- **Peak sound pressure (or zero-peak sound pressure).** The maximum sound pressure during a stated time interval. A peak sound pressure may arise from a positive or negative sound pressure, and the unit is Pa. This quantity is typically useful as a metric for a pulsed waveform, though it may also be used to describe a periodic waveform;
- **Peak-peak sound pressure.** The sum of the peak compressional pressure and the peak rarefactional pressure during a stated time interval. This quantity is typically most useful as a metric for a pulsed waveform, though it may also be used to describe a periodic waveform. Peak-peak sound pressure is expressed in Pa;
- **Root mean square (RMS) sound pressure.** The square root of the mean square pressure, where the mean square pressure is the time integral of squared sound pressure over a specified time interval divided by the duration of the time interval. The RMS sound pressure is expressed in Pa;
- **Sound exposure level (SEL).** The integral of the square of the sound pressure over a stated time interval or event (such as an acoustic pulse). Sound exposure is expressed in units of Pa²·s. The quantity is sometimes taken as a proxy for the energy content of the sound wave. Note that SEL is a useful measure of the exposure of a receptor to a sound field, and a frequency weighting is commonly applied; and
- **Frequency weighting.** Frequency-dependent normalised factor(s) by which spectral components are multiplied, resulting in the modification of the amplitude of some components. Frequency weightings are normalised factors and have no units or dimensions but are sometimes expressed as relative factors in decibels (with no reference value). The main motivation for applying a frequency weighting is to account for the frequency-dependent sensitivity of a receptor.

1.2.10 The type of pressure measurement used is an important consideration when comparing noise levels and criteria and the type of pressure measurement should be stated when quoting noise levels.

1.3 Underwater Noise Propagation

1.3.1 The process of noise travelling through a medium is referred to as noise propagation. The factors that influence the propagation of noise in the marine environment and contribute to propagation (or transmission) loss¹ broadly include the following (Ref 1-7):

¹ The reduction in signal as sound propagates from source to receiver.

- The reduction (or attenuation) of sound away from the source due to geometrical spreading;
- Absorption of the sound by the sea-water and the seabed;
- The interaction with the sea-surface (reflection and scattering);
- The interaction with (and transmission through) the seabed;
- The refraction of the sound due to the sound speed gradient;
- The bathymetry (water depth) between source and receiver positions; and
- Source and receiver depth.

1.3.2 The propagation of underwater noise is a very complex process and, therefore, predicting the received sound pressure levels at distance from a source is extremely difficult. Use is generally made of theoretical models or empirical models based on field measurements.

1.3.3 In accordance with good practice guidance (Ref 1-7), a simple logarithmic spreading model has been used to predict the propagation of sound pressure from the sources of construction and operational noise associated with the Project. This model is represented by a logarithmic equation and incorporates factors for noise attenuation and absorption losses. The advantage of this model is that it is simple to use and quick to provide first order calculations of the received (unweighted) sound pressure levels (SPL) with distance from the source due to geometric spreading.

$$L(R) = SL - N \log_{10}(R) - \alpha R$$

Equation 1: Simple logarithmic spreading model

- L(R) is the received level at distance R from a source;
- R is the distance in metres from the source to the receiver;
- SL is the Source Level (i.e. the level of sound generated by the source);
- N is a factor for attenuation due to geometric spreading; and
- α is a factor for the absorption of sound in water and boundaries (i.e. the sediment or water surface) in dB m⁻¹.

1.3.4 The Environment Agency has compiled observed data representing factors for attenuation (N coefficient) and absorption (α coefficient) which were presented at the Institute of Fisheries Management (IFM) Conference on 23 May 2013. These observed data were collected from the following construction projects undertaken in shallow water estuarine and coastal locations:

- Russian River New Bridge in Geyserville, California (Ref 1-8);
- San Rafael Sea Wall in San Francisco Bay, California (Ref 1-8);

- Scroby Sands Offshore Wind Farm located off the coast of Great Yarmouth (Ref 1-9);
- North Hoyle Offshore Wind Farm in Liverpool Bay (Ref 1-9);
- Kentish Flats Offshore Wind Farm located off the coast of Kent (Ref 1-9);
- Burbo Bank Offshore Wind Farm in Liverpool Bay (Ref 1-9);
- Barrow Offshore Wind Farm located south west of Walney Island (Ref 1-9); and
- Belvedere Energy-from-Waste Plant on Thames Estuary (measurements collected by Subacoustech Ltd on behalf of the Environment Agency and Costain).

1.3.5 These provide a mean N coefficient of 17.91 (Standard Deviation (SD) 3.05) and α coefficient of 0.00523 dB m⁻¹ (SD 0.00377 dB m⁻¹) based on 11 and 9 observations respectively. The Environment Agency has recommended the application of these model input values in underwater noise assessments undertaken in shallow water environments (e.g. Ref 1-10; Ref 1-11). These values are, therefore, considered to be appropriate to use for the underwater noise assessment in support of the Project.

1.3.6 Following advice from the MMO and Cefas on another nearby proposed development involving percussive piling on the Humber Estuary (Immingham Eastern Ro-Ro Terminal, IERRT), the received levels associated with the Project activities have been modelled in the SEL metric and then translated to the peak SPL metric using equation (1) in Ref 1-12:

$$SPL_{\text{peak}} = A \text{ SEL} + B$$

Equation 2: Relationship between peak SPL and SEL

A is an empirical constant estimated from measurements with an approximate value of 1.4; and

B is an empirical constant estimated from measurements with an approximate value of – 40.

1.3.7 It is important to recognise that there are a number of limitations associated with the use of simple logarithmic spreading models (Ref 1-7). Such models do not account for changes in bathymetry, and therefore are not able to predict the changes in sound propagation caused by sand banks and complex changes in water depths. In addition, they do not explicitly include frequency dependence, and so cannot predict the increased transmission loss at high frequencies due to increased sound absorption. Ref 1-13 also demonstrated how use of these simple models in complex environments typical of coastal and inland waters can underestimate noise levels close to the source and substantially overestimate noise levels further from the source. In other words, they can underestimate the risk of injury or disturbance to marine fauna close to the source whilst giving the impression that a larger area would be affected.

- 1.3.8 Although this equation generally represents a simplistic model of propagation loss, its use is an established approach in EIAs that has been widely accepted by UK regulators for recent port and waterfront developments.
- 1.3.9 In terms of fish, the National Oceanic and Atmospheric Administration (NOAA) National Marine Fisheries Service (NMFS) in the United States recommends the use of the practical spreading model to developers and has incorporated this model in its pile driving calculation spreadsheet to assess the potential impacts of pile driving on fish (Ref 1-14). This calculator has, therefore, been used to calculate the range at which the peak SPL and cumulative SEL thresholds for pile driving (Ref 1-15) are reached. Further details of the assumptions and input values that have been applied are provided in **Section 1.8**.
- 1.3.10 In terms of marine mammals, NOAA (Ref 1-16) has developed a user spreadsheet tool for assessing the potential effects of different types of noise activities on marine mammals which is based on the simple logarithmic spreading model. This spreadsheet tool has been used to predict the range at which the relevant weighted cumulative SEL and instantaneous peak SPL acoustic thresholds (Ref 1-17) for the onset of temporary threshold shift (TTS) and permanent threshold shift (PTS) are reached during the proposed piling, dredging and vessel activity. Further details, including the input values that have been used are presented in **Section 1.8**.
- 1.3.11 The Project takes place in very shallow water and, therefore, the propagation of noise will be limited. Shallow water acts as a high pass filter that only allows signals to pass with a frequency higher than a certain cut-off frequency and attenuates signals with frequencies lower than this cut-off frequency. The cut-off frequency gets higher as the water gets shallower (Ref 1-18). In this way, the propagation of low frequency underwater noise such as piling will be reduced in very shallow water locations compared to in the deep oceanic waters. At high frequencies (>10 kHz), increasing absorption also prevents high frequency sound propagating over great distances in shallow water.
- 1.3.12 Overall, therefore, a simple logarithmic spreading model is considered proportionate and appropriate to use for this underwater noise assessment.

1.4 Ambient Noise

Introduction

- 1.4.1 Ambient sound is an important consideration in underwater noise assessments as it allows the noise levels caused by a project to be assessed in the context of existing background levels of sound. This section reviews the characteristics of key sources of ambient sound in the study area and considers how these might propagate and vary in space and time.

Definition

- 1.4.2 Ambient sound is commonly defined as background acoustic sound without distinguishable sources (e.g. Ref 1-19; Ref 1-20). This definition, however, has the problem of how to identify distinguishable sources, and how to eliminate them from the measurements.

- 1.4.3 Measurements to characterise the ambient sound in a specific location (i.e. incorporating both natural and anthropogenic sources) are becoming more common as interest grows in the trends in anthropogenic noise in the ocean, for example in response to the Marine Strategy Framework Directive (MSFD) and UK Marine Strategy (Ref 1-21). The EU MSFD Technical Sub-Group (TSG) on Noise defined ambient sound as follows:

“All sound except that resulting from the deployment, operation or recovery of the recording equipment and its associated platform, where ‘all sound’ includes both natural and anthropogenic sounds” (Ref 1-22, p 20).

- 1.4.4 Measurements that characterise the ambient sound at specific locations and include noise from identifiable sources together with non-identifiable sources, are also sometimes referred to as the local ‘soundscape’ (Ref 1-7).

Sources of ambient sound

- 1.4.5 Ambient sound covers the whole acoustic spectrum from below 1 Hz to well over 100 kHz (Ref 1-18). At the lower frequencies shipping noise dominates, while at the higher frequencies noise from waves and precipitation dominates.
- 1.4.6 Natural sources of ambient sound comprise both physical processes and biological activity. Physical processes that are relevant to the study area include wind- and wave-driven turbulence, precipitation and sediment transport processes (Ref 1-23; Ref 1-18). Biological activity includes echo locating marine mammals and fish communication (Ref 1-24; Ref 1-18). These sources of ambient sound vary on a diurnal cycle, a tidal cycle and/or an annual cycle.
- 1.4.7 A range of anthropogenic noise sources contribute to ambient sound. These can be of short duration and impulsive (e.g. seismic surveys, piling, explosions) or long lasting and continuous (e.g. dredging, shipping, trawling, sonar, drilling, small craft and energy installations) (Ref 1-22). Impulsive sounds may, however, be repeated at intervals (duty cycle) and such repetition may become ‘smeared’ with distance and reverberation and become indistinguishable from continuous noise. The key anthropogenic sources contributing to ambient sound in the study area are reviewed below.

Vessel traffic

- 1.4.8 Shipping noise is the dominant contributor to ambient sound in shallow water areas close to shipping lanes and in deeper waters. At longer ranges the sounds of individual ships merge into a background continuum (Ref 1-18). Shipping noise will vary on a diurnal cycle (e.g. ferry and coastal traffic) and an annual cycle (seasonal activity). The source levels (SLs) associated with large ships such as supertankers and container ships are in the range 180 to 190 dB re 1 μ Pa m (Ref 1-2). For smaller shipping vessels and boats the range is 150 to 180 dB re 1 μ Pa m (Ref 1-25; Ref 1-26). Although the exact characteristics depend on vessel type, size and operational mode, the strongest energy occurs below 1,000 Hz.
- 1.4.9 Small motorised craft (e.g. outboard powered inflatables, speed boats and work boats) produce relatively low levels of noise (75 to 159 dB re 1 μ Pa m), and the

output characteristics are highly dependent on speed and other operational characteristics (Ref 1-27). Many of these sources have greater sound energy in higher frequency bands (i.e. above 1,000 Hz) than large ships. Sail powered craft are generally very quiet with the only sound coming from flow noise, wave slap and rigging noise.

- 1.4.10 Vessel traffic in the study area originates from commercial and recreational vessels travelling to and from the Port of Immingham. Further details of the movement of different types of vessels is provided in **Chapter 12 Marine Transport and Navigation** (PEI Report, Volume II).

Dredging

- 1.4.11 Dredging activities emit moderate levels of broadband noise (around 150 to 188 dB re 1 μ Pa m), mainly at lower frequencies (less than 500 Hz) (Ref 1-28; Ref 1-29). Maintenance dredging is carried out in the main navigation channel and berths at the Port of Immingham. The amount of dredging and volume of material removed varies depending on the surveyed levels of the channel and the requirements of the Port. Further details of existing maintenance dredging activities in the study area are included **Chapter 16 Physical Processes** (PEI Report, Volume II).

Frequency dependence of sound propagation

- 1.4.12 Shallow and very shallow water², such as that at the study area, acts as a high pass filter that only allows signals to pass with a frequency higher than a certain cut-off frequency and attenuates signals with frequencies lower than this cut-off frequency. The cut-off frequency gets higher as the water gets shallower (Ref 1-18). In this way, distant shipping makes a reduced contribution to ambient sound in very shallow coastal waters and low frequency sound originates from local sources rather than the great distances found in the deep oceanic waters. At high frequencies (>10 kHz), increasing absorption also prevents high frequency sound propagating over great distances in shallow water so the ambient sound at the study area is dominated by local sound sources.

Spatiotemporal variation

- 1.4.13 Ambient sound levels can show significant variation over space and time (Ref 1-7). The observed temporal and spatial variation in ambient sound level can be tens of decibels (in other words, the amplitude can vary by orders of magnitude). This variation can be in the short-term of minutes and hours, or a medium-term such as a diurnal variation (day to night), variation with tidal flows, or a longer-term seasonal variation. The sound level can also depend on location, an example of one cause of this being proximity to a shipping lane, another being proximity to a biological source such as snapping shrimp.

² The definition of shallow water is somewhat arbitrary. For this underwater noise assessment, shallow water is defined as the depths found on the UK continental shelf i.e. 20 to 200 metres. Very shallow water has depths less than 20 metres.

Measured levels of ambient sound

- 1.4.14 A series of pre-construction and during construction underwater noise monitoring was undertaken in the Humber Estuary at Green Port Hull (GPH) from 17 to 22 October 2014 inclusive, in line with ABP' commitments included in the GPH Environmental Management and Monitoring Plan (EMMP). The purpose of this monitoring was to provide better certainty for the prediction of impacts for future developments (Ref 1-30).
- 1.4.15 RMS SPLs showed a repeating pattern of peaks and troughs, ranging from 107 to 154 dB re 1 μ Pa. Flow speed and broadband SPL were shown to be significantly positively correlated, which suggests that noise levels in the estuary are primarily dependent on tidal flow speed, with levels increasing with higher flow speeds (Ref 1-30).

1.5 Noise Characteristics of Proposed Development Activities

Introduction

- 1.5.1 During the construction and operation of the Project there are a number of activities that are expected to generate underwater noise levels which may affect marine fauna. This section reviews the underwater noise characteristics of these activities and the associated noise levels that have been applied in the assessment. The worst case potential scenario is considered in order to define the project envelope.

Piling

- 1.5.2 The Project will involve the installation of approximately 380 steel tubular piles, which are estimated to be approximately up to 1,372 mm diameter in size and 50 m in length. Further details are provided in **Chapter 2 The Project** (PEI Report, Volume II).
- 1.5.3 Every pile will involve a different duration of installation based on the specific ground conditions that the pile is being driven through. The assessment is, therefore, based on the likely timeframes that are estimated to be required. Each tubular pile is anticipated to require approximately 5 minutes of vibro piling and approximately 45 minutes of impact piling. The likely maximum impact piling scenario is for 4 tubular piles to be installed each day using up to four piling rigs across both fronts. The maximum impact pile driving scenario will involve approximately 20 minutes of vibro piling and 180 minutes of impact piling per day in a 12 hour shift. In reality, less than 4 piles are likely to be driven per day and, therefore, the assessment is considered to represent a worst case.
- 1.5.4 The piling works will be undertaken seven days per week. Intended working hours will be from 7 am to 7 pm.

Impact piling

- 1.5.5 The highest peak underwater noise levels generated during the proposed marine works will arise from impact piling. Impact piling involves a large weight or "ram" being dropped or driven onto the top of the pile, driving it into the seabed. Noise

is created in air by the hammer, as a direct result of the impact of the hammer with the pile. Some of this airborne noise is transmitted into the water. Of more significance to the underwater noise, however, is the direct radiation of noise from the surface of the pile into the water as a consequence of the compressional, flexural or other complex structural waves that travel down the pile following the impact of the hammer on its head. As water is of similar density to steel and, in addition, due to its high sound speed, waves in the submerged section of the pile couple sound efficiently into the surrounding water. These waterborne waves will radiate outwards, usually providing the greatest contribution to the underwater noise.

- 1.5.6 At the end of the pile, force is exerted on the substrate not only by the force transmitted from the hammer by the pile, but also by the structural waves travelling down the pile which induce lateral waves in the seabed. These may travel as both compressional waves, in a similar manner to the sound in the water, or as a seismic wave, where the displacement travels as Rayleigh waves (Ref 1-31). The waves can travel outwards through the seabed or by reflection from deeper sediments. As they propagate, sound will tend to “leak” upwards into the water, contributing to the waterborne soundwaves. Since the speed of sound is generally greater in consolidated sediments than in water, these waves usually arrive first as a precursor to the waterborne wave. Generally, the level of the seismic wave is typically 10 to 20 dB below the waterborne arrival, and hence it is the latter that dominates the noise.
- 1.5.7 Impulsive sources such as pile driving should have SLs expressed for a single pulse as either SEL with units of dB re 1 $\mu\text{Pa}^2 \text{ s}$, or as a peak-peak or zero-peak SPL, with units of dB re 1 μPa (Ref 1-13). Impact piling is impulsive in character with multiple pulses occurring at blow rates in the order of 30 to 60 impacts per minute. Typical SLs range from peak SPL of 190 to 245 dB re 1 μPa (Ref 1-32). Most of the sound energy usually occurs at lower frequencies between 100 Hz and 1 kHz. Factors that influence the SL include the size, shape, length and material of the pile, the weight and drop height of the hammer, and the seabed material and depth.
- 1.5.8 The SL for the impact driving of tubular piles as part of the Project is assumed based on the loudest near-source (10 m from the source) sound pressure measurements (SEL, peak SPL and RMS) that have been published for the percussive piling installation of the nearest-sized 1.52 m Cast-in-Steel-Shell (CISS) steel pipe piles in a shallow water environment (Ref 1-8; Ref 1-33; Ref 1-34). Back-calculating the sound pressure measurements to 1 m using the simple logarithmic spreading model (equation 1) provides an estimated SL of 203 dB re 1 $\mu\text{Pa}^2 \text{ s}$ (SEL metric), 228 dB re 1 $\mu\text{Pa m}$ (peak SPL metric) and 213 dB re 1 $\mu\text{Pa m}$ (RMS metric).
- 1.5.9 Piling will be undertaken simultaneously using piling rigs. Adding two identical sources (i.e. doubling the signal) will increase the received level by 3 dB. In other words, the unweighted peak SL of concurrent impact piling by more than one piling rig is assumed to be 206 dB re 1 $\mu\text{Pa}^2 \text{ s}$ (SEL metric), 231 dB re 1 $\mu\text{Pa m}$ (peak SPL metric) and 216 dB re 1 $\mu\text{Pa m}$ (RMS metric).

Vibro piling

- 1.5.10 Vibratory hammers use oscillatory hammers that vibrate the pile, causing the sediment surrounding the pile to liquefy and allow pile penetration (Ref 1-33). Peak SPLs for vibratory hammers can exceed 180 dB; however, the sound from these hammers rises relatively slowly. The vibratory hammer produces sound energy that is spread out over time and is generally 10 to 20 dB lower than impact pile driving. Although peak sound levels can be substantially less than those produced by impact hammers, the total energy imparted can be comparable to impact driving because the vibratory hammer operates continuously and requires more time to install the pile.
- 1.5.11 The SL for the vibratory driving of tubular piles as part of the proposed development is assumed based on the loudest near-source (10 m from the source) sound pressure measurements (SEL, peak SPL and RMS) that have been published for the vibratory piling installation of the nearest-sized 1.83 m steel pipe piles in a shallow water environment (Ref 1-8; Ref 1-33; Ref 1-34). Back-calculating the sound pressure measurements to 1 m using the simple logarithmic spreading model (equation 1) provides an estimated SL of 198 dB re 1 $\mu\text{Pa}^2 \text{ s}$ (SEL metric), 213 dB re 1 $\mu\text{Pa m}$ (peak SPL metric) and 198 dB re 1 $\mu\text{Pa m}$ (RMS metric).
- 1.5.12 Piling will be undertaken simultaneously using piling rigs. Adding two identical sources (i.e. doubling the signal) will increase the received level by 3 dB. In other words, the unweighted peak SL of concurrent vibro piling by more than one piling rig is assumed to be 201 dB re 1 $\mu\text{Pa}^2 \text{ s}$ (SEL metric), 216 dB re 1 $\mu\text{Pa m}$ (peak SPL metric) and 201 dB re 1 $\mu\text{Pa m}$ (RMS metric).

Dredging

- 1.5.13 The dredging requirements for the Project is anticipated to involve the use of a backhoe dredger (e.g. Mannu Pekka or similar) and trailing suction hopper dredger (TSHD) (e.g. Cork Sand and Long Sand or similar). The backhoe dredging will involve the excavated material being loaded directly to attendant split barges for disposal. TSHD is the method that is predominantly used for existing maintenance dredge activities within the Port of Immingham and its approaches and will continue to be used in the future. Dredge operations will be continuous (24/7).
- 1.5.14 Dredging involves a variety of sound generating activities which can be broadly divided into sediment excavation, transport and placement of the dredged material at the disposal site (Ref 1-26; Ref 1-35; Ref 1-29). For most dredging activities, the main source of sound relates to the vessel engine noise. Dredging activities produce broadband and continuous sound³, mainly at lower frequencies of less than 500 Hz and moderate RMS SLs from around 150 to 188 dB re 1 $\mu\text{Pa m}$ (Ref 1-28; Ref 1-26; Ref 1-36; Ref 1-35; Ref 1-2; Ref 1-29).

³ Continuous sound is defined here as a sound wave with a continuous waveform, as opposed to transient/pulsed sounds such as pile driving that start and end in a relatively short amount of time.

- 1.5.15 Backhoe dredgers generate RMS SLs in the range of 154 to 179 dB re 1 μ Pa m (Ref 1-37; Ref 1-38). Measurements of underwater sound from backhoe dredging operations indicate that the highest levels of underwater sound occur when the excavator is in contact with the seabed. This type of dredging is generally considered to be quieter compared to other types of dredging, with recorded sound levels just above the background sound at approximately 1 km from the source (Ref 1-26).
- 1.5.16 SLs of TSHDs are variable but generally range from 160 to above 180 dB re 1 μ Pa m for large TSHDs (Ref 1-36). The most intense sound emissions from the TSHDs are in the low frequencies, up to and including 1,000 Hz in most cases (Ref 1-36; Ref 1-39). Differences in sound levels are mainly a result of the difference in size between the dredging vessels observed rather than the materials dredged. High frequency components of the broadband sound are generated by sand and gravel movement through the suction pipes, the movement of the draghead on the seabed, splashing from the spillways, cavitation and use of positioning thrusters. Also, gravelly sand extraction resulted in higher levels of this sound than sandy gravel when comparing the same dredging vessel (Ref 1-36).
- 1.5.17 Overall, the dredgers involved in the Project during construction and operation are anticipated to generate a worst case unweighted RMS SL of up to 188 dB re 1 μ Pa m.

Vessel movements

- 1.5.18 Vessels involved during the construction of the Project will primarily be the jack up barge, floating crane barges, flat top barges, backhoe dredger with associated attendant barges and TSHD. During operation, the new jetty is designed to service a range of vessels transporting liquid bulk products including ammonia (to produce green hydrogen) to help decarbonise the United Kingdom's (UK) transport sector and support carbon dioxide (CO₂) imports and exports to facilitate carbon capture and storage.
- 1.5.19 The dredgers and barge are anticipated to generate SLs of up to 188 dB re 1 μ Pa m (Ref 1-25; Ref 1-26). The cargo ships involved during the operation are anticipated to produce RMS SLs in the region of 180 dB re 1 μ Pa m (Ref 1-40; Ref 1-2).
- 1.5.20 Overall, the vessels movements involved in the construction and operation of the proposed development are anticipated to generate worst case unweighted RMS SLs of up to 188 dB re 1 μ Pa m. Continuous (24/7) noise generation from vessel activities has been assumed and as such, provides a precautionary assessment.

1.6 Hearing Sensitivity and Responses of Marine Fauna

Introduction

- 1.6.1 The impact of underwater noise upon wildlife is primarily dependent on the sensitivity of the species likely to be affected. The following sections describe the hearing sensitivity of marine fauna that occur in the study area and the latest available published criteria that have been applied in the underwater noise

assessment to determine the scale of potential physiological and behavioural effects.

Benthic invertebrates

- 1.6.2 Benthic invertebrates lack a gas-filled bladder and are, therefore, unable to detect the pressure changes associated with sound waves (Ref 1-41). All cephalopods as well as some bivalves, echinoderms, and crustaceans, however, have a sac-like structure called a statocyst which includes a mineralised mass (statolith) and associated sensory hairs. Statocysts develop during the larval stage and may allow an organism to detect the particle motion associated with soundwaves in water to orient itself (Ref 1-41). In addition to statocysts, cephalopods have epidermal hair cells which help them to detect particle motion in their immediate vicinity, comparable to lateral lines in fish. Similarly, decapods have sensory setae on their body, including on their antennae which may be used to detect low-frequency vibrations. Whole body vibrations due to particle motion have been detected in cuttlefish and scallops, although species names and details of associated behavioural responses are not specified (Ref 1-41).
- 1.6.3 Scientific understanding of the potential effects of underwater noise on invertebrates is relatively underdeveloped (Ref 1-42). There is limited research to suggest that exposure to near-field low-frequency sound may cause anatomical damage (Ref 1-41). Anecdotal evidence indicates there was pronounced statocyst and organ damage in seven stranded giant squid after nearby seismic surveys (Ref 1-43). Ref 1-44 found airgun exposure caused damaged statocysts in rock lobsters up to a year later. No such effects, however, were detected in other studies (Ref 1-45; Ref 1-46). The disparate results between studies seem to be due to differences in SELs and duration, in some cases due to tank interference, although taxa-specific differences in physical vulnerability to acoustic stress cannot be discounted (Ref 1-41).
- 1.6.4 There is increasing evidence to suggest that benthic invertebrates respond to particle motion⁴ (Ref 1-47). For example, blue mussels *Mytilus edulis* vary valve gape, oxygen demand and clearance rates (Ref 1-48; Ref 1-47) and hermit crabs *Paganus bernhardus* shift their shell and at very high amplitudes, leave their shell, examine it and then return (Ref 1-47). The vibration levels at which these responses were observed generally correspond to levels measured near anthropogenic operations such as pile driving and up to 300 m from explosives testing (blasting) (Ref 1-47). A range of behavioural effects have also been recorded in decapod crustaceans, including a change in locomotion activity, reduction in antipredator behaviour and change in foraging habits (Ref 1-49). Population level and mortality effects, however, are considered unlikely. Effects on benthic invertebrates are, therefore, not considered further in the assessment.

⁴ Particle motion is a back and forth motion of the medium in a particular direction; it is a vector quantity that can only be fully described by specifying both the magnitude and direction of the motion, as well as its magnitude, temporal, and frequency characteristics.

Fish

- 1.6.5 In comparison to marine mammals, fish are more sensitive to noise at lower frequencies and generally have a reduced range of hearing than marine mammals (i.e. their hearing ability spans a restricted range of frequencies).
- 1.6.6 There is a wide diversity in hearing structures in fish which leads to different auditory capabilities across species (Ref 1-50). All fish can sense the particle motion component of an acoustic field via the inner ear as a result of whole-body accelerations (Ref 1-4), and noise detection ('hearing') becomes more specialised with the addition of further hearing structures. Particle motion is especially important for locating sound sources through directional hearing (Ref 1-15; Ref 1-42; Ref 1-9). Although many fish are also likely to detect sound pressure⁵, particle motion is considered equally or potentially more important (Ref 1-6).
- 1.6.7 From the few studies of hearing capabilities in fishes that have been conducted, it is evident that there are potentially substantial differences in auditory capabilities from one fish species to another (Ref 1-6). Since it is not feasible to determine hearing sensitivity for all fish species, one approach to understand hearing has been to distinguish fish groups on the basis of differences in their anatomy and what is known about hearing in other species with comparable anatomy (Ref 1-15).
- 1.6.8 **Chapter 9 Marine Ecology** (PEI Report, Volume II) provides a detailed review of the fish receptors that occur in the study area. Categories proposed by Ref 1-15 for each of the key fish species are included in **Table 1.1**.

Table 1.1: Categorisation of key fish species in the study area according to Ref 1-15 criteria

Swim Bladder or Air Cavities Aid Hearing	Swim Bladder Does Not Aid Hearing	No Swim Bladder
Allis shad (<i>Alosa alosa</i>)	Atlantic cod (<i>Gadus morhua</i>)	Dab (<i>Limanda limanda</i>)
Herring (<i>Clupea harengus</i>)	European eel (<i>Anguilla anguilla</i>)	Dover sole (<i>Solea solea</i>)
Sprat (<i>Spratus spratus</i>)	Atlantic salmon (<i>Salmo salar</i>)	European plaice (<i>Pleuronectes platessa</i>),
Twaite shad (<i>Alosa fallax</i>)	European seabass (<i>Dicentrarchus labrax</i>)	Flounder (<i>Platichthys flesus</i>)
	European smelt (<i>Osmerus eperlanus</i>)	River lamprey (<i>Lampetra fluviatilis</i>)
	Sea trout (<i>Salmo trutta</i>)	Sea lamprey (<i>Petromyzon marinus</i>)

⁵ Pressure fluctuations in the medium above and below the local hydrostatic pressure; it acts in all directions and is a scalar quantity that can be described in terms of its magnitude and its temporal and frequency characteristics.

Swim Bladder or Air Cavities Aid Hearing	Swim Bladder Does Not Aid Hearing	No Swim Bladder
	Whiting (<i>Merlangius merlangus</i>)	

- 1.6.9 The first category comprises fish that have special structures mechanically linking the swim bladder to the ear. These fish are sensitive primarily to sound pressure, although they also detect particle motion (Ref 1-6). They have a wider frequency range, extending to several kHz and generally show higher sensitivity to sound pressure than fishes in the other categories.
- 1.6.10 The second category comprises fish with a swim bladder where the organ does not appear to play a role in hearing. Some of the fish in this category are considered to be more sensitive to particle motion than sound pressure (see below) and show sensitivity to only a narrow band of frequencies, namely the salmonids (Salmonidae) (Ref 1-51). This second category also comprises fishes with swim bladders that are close, but not intimately connected, to the ear, such as codfishes (Gadidae) and eels (Anguillidae). These fish are sensitive to both particle motion and sound pressure, and show a more extended frequency range, extending up to about 500 Hz (Ref 1-52; Ref 1-53; Ref 1-6).
- 1.6.11 The third category comprises fish which lack swim bladders that are sensitive only to sound particle motion and show sensitivity to only a narrow band of frequencies (e.g. flatfishes, sharks, skates and rays). Particle motion rather than sound pressure is considered to be potentially more important to fish without swim bladders. Acoustic particle motion in the water and seabed, for example, has been shown to induce behavioural reactions in sole (Ref 1-54). However, there is no published literature on the levels of particle motion generated during construction activities (e.g. pile-driving) and the distance at which they can be detected. This may be due to the fact that there are far fewer devices (and less skill in their use) for detection and analysis of particle motion compared to hydrophone devices for detection of sound pressure (Ref 1-55). Direct measurements of particle motion have also been hampered by the lack of guidance on data analysis methods.
- 1.6.12 Particle velocity can be calculated indirectly from sound pressure measurements using relatively simple models (Ref 1-56). However, such estimates of sound particle velocity are only valid in environments that are distant from reflecting boundaries and other acoustic discontinuities. These conditions are rarely met in the shelf-sea and shallow-water habitats that most aquatic organisms inhabit and that are applicable to the study area (Ref 1-9).
- 1.6.13 Steps that are required to improve knowledge of the effects of particle motion on marine fauna have recently been set out (Ref 1-57). However, at present there continues to be a lack of particle motion measurement standards, lack of easy to use and reasonably priced instrumentation to measure particle motion, and lack of sound exposure criteria for particle motion. As such, the scope for considering particle motion in underwater noise assessments is currently limited (Ref 1-58). The underwater noise assessment has, therefore, been based on the latest available evidence and focused on the effects of sound pressure.

- 1.6.14 The extent to which intense underwater sound might cause an adverse environmental impact in a particular fish species is dependent upon the level of sound pressure or particle motion, its frequency, duration and/or repetition (Ref 1-59). The range of potential effects from intense sound sources, such as pile driving, includes immediate death, permanent or temporary tissue damage and hearing loss, behavioural changes and masking effects. Tissue damage can result in eventual death or may make the fish less fit until healing occurs, resulting in lower survival rates. Hearing loss can also lower fitness until hearing recovers. Behavioural changes can potentially result in animals avoiding migratory routes or leaving feeding or reproduction grounds with potential population level consequences. Biologically important sounds can also be masked where the received levels are marginally above existing background levels (Ref 1-60). The ability to detect and localise the source of a sound is of considerable biological importance to many fish species and is often used to assess the suitability of a potential mate or during territorial displays and during predator prey interactions.
- 1.6.15 The published noise exposure criteria for fish that have been used in this underwater noise assessment are presented in **Table 1.2**.

Table 1.2: Fish response criteria applied in this assessment

Fish Hearing Category*	Piling		Dredging and Vessel Movements			Piling
	Mortality and Potential Mortal Injury*	Recoverable Injury*	Mortality and Potential Mortal Injury*	Recoverable Injury*	TTS*	Behaviour**
Swim bladder involved in hearing (primarily pressure detection)	207 dB SELcum >207 dB peak	203 dB SELcum >207 dB peak	(N) Low (I) Low (F) Low	170 dB RMS for 48 h	158 dB RMS for 12 h	> 157 dB peak
Swim bladder is not involved in hearing (particle motion detection)	210 dB SELcum >207 dB peak	203 dB SELcum >207 dB peak	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	> 157 dB peak
No swim bladder (particle motion detection)	>219 dB SELcum >213 dB peak	>216 dB SELcum >213 dB peak	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	> 157 dB peak
Eggs and larvae	210 dB SELcum >207 dB peak	(N) Moderate (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	> 157 dB peak

* Ref 1-15

** Ref 1-61.

Peak and RMS SPL is in dB re 1 µPa and cumulative SEL (SELcum) is in dB re 1 µPa2s.

All criteria are presented as sound pressure even for fish without swim bladders since no data for particle motion exist.

Relative risk (high, moderate, low) is given for animals at three distances from the source defined in relative terms as near (N), intermediate (I), and far (F).

- 1.6.16 The Ref 1-15 quantitative instantaneous peak SPL and cumulative SEL criteria for different marine activities involved in the Project (i.e. piling, dredging and vessel movements) have been used to determine the mortality/potential mortal injury and recoverable injury for all the fish hearing categories representing the key fish species that occur in the study area (**Table 1.1**). These guidelines are based on an understanding that fish will respond to sounds and their hearing sensitivity.
- 1.6.17 While the Ref 1-15 noise exposure criteria provide thresholds for auditory impairment, there are many data gaps that preclude the setting of specific noise exposure criteria for behavioural responses in fish (Ref 1-15; Ref 1-6; Ref 1-58). The onset of behavioural responses is much more difficult to quantify as reactions are likely to be strongly influenced by behavioural or ecological context and the effect of a particular response is often unclear and may not necessarily scale with received sound level (Ref 1-51; Ref 1-42 Ref 1-58). In other words, behaviour may be more strongly related to the particular circumstances of the animal, the activities in which it is engaged, and the context in which it is exposed to sounds (Ref 1-62; Ref 1-63). For example, a startle or reflex response to the onset of a noise source does not necessarily lead to displacement from the ensonified area.
- 1.6.18 This uncertainty is further compounded by the limitations of observing fish behavioural responses in a natural context. Few studies have conducted behavioural field experiments with wild fish and laboratory experiments may not give a realistic measure of how fish will respond in their natural environment (Ref 1-59; Ref 1-64; Ref 1-65). As a consequence, only hearing data based on behavioural experiments is acceptable for assessing the ability of fish to detect sound (Ref 1-66).
- 1.6.19 Recent studies have considered approaches to quantify the risk of behavioural responses, for example through dual criteria based on dose-response curves for proximity to the sound source and received sound level (Ref 1-67). An empirical behavioural threshold could also be adopted using *in situ* observed responses of fish to similar sound sources (Ref 1-58). A study observing the responses of caged fish to nearby air gun operations found that initial increases in swimming behaviour may occur at a level of 156 dB re 1 μ Pa RMS (Ref 1-68). At levels of around 161-168 dB re 1 μ Pa RMS active avoidance of the air gun source would be expected to occur (Ref 1-69; Ref 1-68). These responses may, however, differ from those of unconfined fish.
- 1.6.20 More recent work has been undertaken by Ref 1-61 reporting behavioural responses of schools of wild sprat and mackerel to playbacks of pile driving. At a single-pulse peak-to-peak SPL of 163 dB re 1 μ Pa (equivalent to peak SPL of 157 dB re 1 μ Pa using the metric conversion provided by NOAA Fisheries in their spreadsheet tool and associated user manual; Ref 1-16), schools of sprat and mackerel were observed to disperse or change depth on 50 % of presentations. In the absence of similar data for other species, this threshold has been applied for all fish species (**Table 1.2**).
- 1.6.21 Auditory and non-auditory injuries in fish have not been observed or documented to occur in association with dredging (Ref 1-28). The literature suggests that

dredging noise is unlikely to cause direct mortality or instantaneous injury. However, the (predominantly) low-frequency sounds produced by dredging overlap with the hearing range of many fish species, which may pose a risk in TTS, auditory masking, and behavioural effects (Ref 1-70), as well increased stress-related cortisol levels in fish species (Ref 1-71). A TTS involves a temporary reduction of hearing capability caused by exposure to underwater noise. An intense short exposure can produce the same scale of TTS as a long-term, repeated exposure to lower sound levels. The significance of the TTS varies among species depending on their dependence on sound as a sensory cue for ecologically relevant functions. Furthermore, it is important to note that the biological significance of such responses is largely unknown.

- 1.6.22 Potential behavioural effects in the past have also been inferred by comparing the received sound level with the auditory threshold of marine fauna. Ref 1-27 and Ref 1-72, for example, have used received levels of noise in comparison with the corresponding hearing thresholds of marine fauna in order to estimate the range of audibility and zones of influence from underwater sound sources. This form of analysis has been taken a stage further by Ref 1-73, where the underwater noise is compared with receptor hearing threshold across the entire receptor auditory bandwidth in the same manner that the dB(A) is used to assess noise sources in air for humans. These include behavioural thresholds, where received sound levels around 90 dB above hearing threshold (dB_{ht}) are considered to cause a strong behavioural avoidance, levels around 75 dB_{ht} a moderate behavioural response and levels around 50 dB_{ht} a minor response.
- 1.6.23 The dB_{ht} criteria have been applied in a number of offshore renewables EIAs and the Environment Agency has previously recommended it to be used in impact assessments in coastal/estuarine environments (e.g. Ref 1-11; Ref 1-10). However, it is worth noting that the dB_{ht} criteria have not been validated by experimental study and have not been published in an independent peer-reviewed paper. The dB_{ht} approach does not take into account potential for sound sensitivity to changes with that of the life stage of the organism, time of year, animal motivation, or other factors that might affect hearing and behavioural responses to sound (Ref 1-6). Furthermore, the dB_{ht} criteria are based on measures of inner ear responses and should rather be based on behavioural threshold determinations (Ref 1-15, Ref 1-6). The use of dB_{ht} criteria is, therefore, not advisable and has not been applied to this assessment (Ref 1-6).

Marine mammals

- 1.6.24 Marine mammals are particularly sensitive to underwater noise at higher frequencies and generally have a wider range of hearing than other marine fauna, namely fish (i.e. their hearing ability spans a larger range of frequencies). The hearing sensitivity and frequency range of marine mammals varies between different species and is dependent on their physiology.
- 1.6.25 The impacts of underwater noise on marine mammals can broadly be split into lethal and physical injury, auditory injury and behavioural response. The possibility exists for lethality and physical damage to occur at very high exposure levels, such as those typically close to underwater explosive operations or offshore impact piling operations. A PTS is permanent hearing damage caused

by very intensive noise or by prolonged exposure to noise. As explained above, a TTS involves a temporary reduction of hearing capability caused by exposure to underwater noise. Both PTS and TTS are considered to be auditory/physiological injuries.

- 1.6.26 At lower SPLs, it is more likely that behavioural responses to underwater sound will be observed. These reactions may include the animals leaving the area for a period of time, or a brief startle reaction. Masking effects may also occur at lower levels of noise. Masking is the interference with the detection of biologically relevant communication signals such as echolocation clicks or social signals. Masking has been shown in acoustic signals used for communication among marine mammals (see Ref 1-74). Masking may in some cases hinder echolocation of prey or detection of predators. If the signal-to-noise ratio prevents detection of subtle or even prominent pieces of information, inappropriate or ineffective responses may be shown by the receiving organism.
- 1.6.27 Ref 1-17 provides technical guidance for assessing the effects of underwater anthropogenic (human-made) sound on the hearing of marine mammal species. Specifically, the received levels, or acoustic thresholds, at which individual marine mammals are predicted to experience changes in their hearing sensitivity (either temporary or permanent) for acute, incidental exposure to underwater anthropogenic sound sources are provided. These thresholds update and replace the previously proposed criteria in Ref 1-75 for preventing auditory/physiological injuries in marine mammals. Further recommendations have recently been published regarding marine mammal noise exposure by Ref 1-76 which complement the Ref 1-17 thresholds and also look at a wider range of marine mammals species, as well as the hearing sensitivity of amphibious mammals (e.g. seals, sea otters) to airborne noise.
- 1.6.28 The Ref 1-17 and Ref 1-76 thresholds are categorised according to marine mammal hearing groups. **Chapter 9 Marine Ecology** (PEI Report, Volume II) provides a detailed review of the marine mammal receptors that occur in the study area. The key marine mammal species comprise harbour porpoise, common seal and grey seal. According to Ref 1-17, harbour porpoise is categorised as a high-frequency (HF) cetacean and common and grey seals are categorised as pinniped phocids in water (PW) (earless seals or “true seals”).
- 1.6.29 Ref 1-17 and Ref 1-76 provide weighted cumulative SEL acoustic thresholds for non-impulsive sources (e.g. vibro piling) and unweighted peak SPL and weighted cumulative SEL acoustic thresholds for impulsive sources (e.g. impact piling) which are categorised according to marine mammal hearing groups. The relevant acoustic thresholds for the onset of TTS and PTS due to non-impulsive and impulsive sound sources for the relevant marine mammal groups are presented in **Table 1.3**.

Table 1.3: Marine mammal response criteria applied in this assessment

Marine Mammal Hearing Group	Impulsive (Impact Piling)		Non-Impulsive (Vibro Piling, Dredging and Vessel Movements)	
	TTS	PTS	TTS	PTS
High-frequency (HF) cetaceans (harbour porpoise)	140 dB SEL _{cum} 196 dB peak	155 dB SEL _{cum} 202 dB peak	153 dB SEL _{cum}	173 dB SEL _{cum}
Phocid pinnipeds in water (PW) (true seals)	170 dB SEL _{cum} 212 dB peak	185 dB SEL _{cum} 218 dB peak	181 dB SEL _{cum}	201 dB SEL _{cum}

Peak SPL has a reference value of 1 μ Pa and weighted cumulative SEL has a reference value of 1 μ Pa²s.

- 1.6.30 Peak SPL acoustic thresholds for impulsive sound sources provide an estimate of the instantaneous worst-case potential effects on marine mammals. Cumulative SEL is calculated from the energy in a representative single pile strike and the number of strikes over a 24 hour period. This measure assumes that all strikes have the same received single strike SEL value, which is rarely the case since the animal (or source) is likely to be moving relative to each other. It also assumes that the animal is stationary within the zone of potential effect for a 24 hour period which is highly unlikely. Furthermore, it does not take potential physiological or physical recovery from any effects of a single signal exposure into account. As such, this averaging metric has the potential to result in false conclusions on the effects of sound exposure and needs to be treated with more caution as noted by Ref 1-6.
- 1.6.31 There are no equivalent SPL behavioural response criteria that would represent the sources of underwater noise associated with the Project. Behavioural reactions to acoustic exposure are less predictable and difficult to quantify than effects of noise exposure on hearing or physiology as reactions are highly variable and context specific (Ref 1-75).
- 1.6.32 Field studies have demonstrated behavioural responses of harbour porpoises to anthropogenic noise (Ref 1-77). A number of studies have shown avoidance of pile driving activities during offshore wind farm construction (Ref 1-78; Ref 1-79; Ref 1-80), with the range of measurable responses extending to at least 21 km in some cases (Ref 1-81). Seismic surveys have also elicited avoidance behaviour in harbour porpoises, albeit short-term (Ref 1-82), and monitoring of echolocation activity suggests possible negative effects on foraging activity in the vicinity of seismic operations (Ref 1-83). There is a scarcity of studies quantifying behavioural impacts from dredging (Ref 1-84). An investigation by Ref 1-86 showed that harbour porpoises temporarily avoided an area of sand extraction off the Island of Sylt in Germany. Ref 1-86 found that, when the dredging vessel was closer than 600 m to the porpoise detector location, it took three times longer before a porpoise was again recorded than during times without sand extraction. However, after the ship left the area, the clicks resumed to the baseline rate.

- 1.6.33 Few studies have documented responses of seals to underwater noise in the field (Ref 1-77). Tracking studies found reactions of the grey seals to pile driving during the construction of windfarms were diverse (Ref 1-85). These included altered surfacing or diving behaviour, and changes in swim direction including swimming away from the source, heading into shore or travelling perpendicular to the incoming sound, or coming to a halt. Also, in some cases no apparent changes in their diving behaviour or movement was observed. Of the different behavioural changes observed a decline in descent speed occurred most frequent, which suggests a transition from foraging (diving to the bottom), to more horizontal movement. These changes in behaviour were on average larger and occurred more frequent at smaller distances from the pile driving events, and such changes were statistically significantly different at least up to 36 km. In addition to changes in dive behaviour, also changes in movement were recorded. There was evidence that on average grey seals within 33 km were more likely to swim away from the pile driving. In some cases, seals exposed to pile-driving at close range, returned to the same area on subsequent trips. This suggests that some seals had an incentive to go to these areas, which was stronger than the potential deterring effect of the pile-driving.
- 1.6.34 A telemetry study found no overall significant displacement of common seal during construction of a wind farm in The Wash, south-east England (Ref 1-87). However, during piling, seal usage (abundance) was significantly reduced up to 25 km from the piling activity; within 25 km of the centre of the wind farm, there was a 19 to 83 % (95 % confidence intervals) decrease in usage compared to during breaks in piling, equating to a mean estimated displacement of 440 individuals. This amounts to significant displacement starting from predicted received levels of between 166 and 178 dB re 1 μ Pa (peak-peak). Displacement was limited to piling activity; within 2 hours of cessation of pile driving, seals were distributed as per the non-piling scenario.
- 1.6.35 Ref 1-88 conducted a playback experiment on harbour seals in which the recorded sound of an operational wind turbine was projected via a loudspeaker, resulting in modest displacement of seals from the source (median distance was 284 vs 239 m during control trials). Two further studies of ringed seals (*Phoca hispida*), which are closely related to both harbour and grey seals, have observed behaviour in response to anthropogenic noise: Ref 1-89 reported animals swimming away and avoidance within ~150 m of a seismic survey, while Ref 1-90 found no discernible difference in seal densities in response to construction and drilling for an oil pipeline.
- 1.6.36 A number of field observations of harbour porpoise and pinnipeds to multiple pulse sounds have been made and are reviewed by Ref 1-75. The results of these studies are considered too variable and context-specific to allow single disturbance criteria for broad categories of taxa and of sounds to be developed. Another way to evaluate the responses of marine mammals and the likelihood of behavioural responses is by comparing the received sound level against species specific hearing threshold levels. The dB_{ht} metric and its limitations has already been discussed earlier in this section and is, therefore, not repeated here.

1.6.37 Masking effects may also occur at lower levels of noise. Masking is the interference with the detection of biologically relevant communication signals such as echolocation clicks or social signals. Masking has been shown in acoustic signals used for communication among marine mammals. Masking may in some cases hinder echolocation of prey or detection of predators. If the signal-to-noise ratio prevents detection of subtle or even prominent pieces of information, inappropriate or ineffective responses may be shown by the receiving organism.

1.7 Noise Propagation Modelling Outputs

1.7.1 The simple logarithmic spreading model (equation 1) described in **Section 1.3** was applied to the worst case (highest) unweighted SLs associated with the Project activities (i.e. impact piling with two rigs, vibro piling with two rigs, dredging and vessel movements) to determine the unweighted received levels with range. These received levels represent unweighted metrics as recommended in Ref 1-7. **Table 1.4** shows the results of this analysis at various distances from the sources of noise associated with the Project.

Table 1.4: Maximum predicted unweighted received levels during proposed development activities

Range (m)	Impact Piling (SEL in dB 1 $\mu\text{Pa}^2\cdot\text{s}$)	Vibro Piling (SEL in dB 1 $\mu\text{Pa}^2\cdot\text{s}$)	Dredging and Vessel Movements (RMS in dB re 1 μPa)
1	206	201	188
10	188	183	170
100	170	165	152
200	164	159	146
500	155	150	137
1,000	147	142	129
2,300*	134	129	116
3,400**	125	120	107
5,000	114	109	96
10,000	82	77	64
<p>* Approximate distance from the most seaward point of the proposed development and opposite shore at low water.</p> <p>** Approximate distance from the most seaward point of the proposed development and opposite shore at high water.</p>			

- 1.7.2 The SEL received levels of underwater noise generated during impact piling for the proposed development are predicted to reduce to around 147 dB 1 $\mu\text{Pa}^2\cdot\text{s}$ within 1 km of the source of piling which is equivalent to peak SPL of 166 dB re 1 μPa using equation 2 (**Section 1.3**) and comparable to the SL generated by a tug and barge (Ref 1-2). The peak levels of underwater noise that reach the opposite shore of the estuary are predicted to range from approximately 125 to 134 dB 1 $\mu\text{Pa}^2\cdot\text{s}$ (equivalent to 135 to 147 dB re 1 μPa) depending on the tidal state. These levels are comparable to the SLs generated by recreational boats (Ref 1-2).
- 1.7.3 The instantaneous peak levels of underwater noise generated during vibro piling are predicted to reduce to around 142 dB 1 $\mu\text{Pa}^2\cdot\text{s}$ within 1 km of the source of piling which is equivalent to peak SPL of 159 dB re 1 μPa and comparable to the SL generated by a passenger vessel or a recreational boat (Ref 1-55).
- 1.7.4 The levels of underwater noise generated by dredging and vessel movements are predicted to reach existing background levels previously measured in the Humber Estuary (**Section 1.4**) within around 100 m from the source. It should be noted that the Project is located at the Port of Immingham which already experiences intermittent elevated levels of underwater noise of a similar scale to that which is predicted due to the range of vessels that already operate in this area and ongoing maintenance dredging.

1.8 Potential Effects

Fish

Impact piling

- 1.8.1 The calculator developed by Ref 1-14 as a tool for assessing the potential effects to fish exposed to elevated levels of underwater sound produced during pile driving has been used to calculate the range at which the instantaneous peak and cumulative SEL thresholds for impact pile driving (Ref 1-15) are reached. The model input values and associated assumptions for impact piling are included in **Table 1.5**.

Table 1.5: NMFS piling calculator input values for impact piling

Model Inputs	Value	Assumptions
Number of strikes per pile	675	Maximum value provided for existing field data in the NMFS pile driving calculator (Ref 1-14 and, therefore, considered a reasonable worst case.
Number of piles per day	4	The maximum impact piling scenario is for the marine works to comprise up to 4 tubular piles to be installed each day (see Section 1.5).
Peak SPL SL	231	Loudest near-source (10 m from the source) sound pressure measurements for the percussive piling installation of 1.52 m CISS steel pipe piles in a shallow water environment (Ref 1-8; Ref 1-33; Ref 1-34) back-calculated to 1 m and the assumption

Model Inputs	Value	Assumptions
		that more than one piling rig with impact hammers will be used concurrently (see Section 1.5).
SEL SL	206	As above.
Distance from source (m)	1	The sound levels that were measured for the percussive piling installation of 1.52 m CISS steel pipe piles in a shallow water environment (Ref 1-8; Ref 1-33; Ref 1-34) have been back-calculated to 1 m from the source (see Section 1.5).
Noise reduction due to abatement (dB)	NA	Not applicable.
Transmission loss coefficient	17.91	Derived from 11 observations of transmission loss coefficient collected from a number of construction projects undertaken in shallow water estuarine and coastal locations (see Section 1.3).

1.8.2 The distances at which potential mortality/injury and behavioural effects in fish are predicted to occur during impact piling activities associated with the construction of the Project are included in **Table 1.6**.

Table 1.6: Approximate distances (metres) fish response criteria are reached during concurrent impact piling

Fish Hearing Category	Mortality/ Potential Mortal Injury		Recoverable Injury		Behaviour
	Peak	SEL _{cum}	Peak	SEL _{cum}	Peak
Swim bladder involved in hearing (primarily pressure detection)	22	72	22	121	1,554
Swim bladder is not involved in hearing (particle motion detection)	22	49	22	121	1,554
No swim bladder (particle motion detection)	10	15	10	23	1,554
Eggs and larvae	22	49	(N) Moderate (I) Low (F) Low		1,554

1.8.3 Given the mobility of fish, any individuals that might be present within the localised areas associated with potential mortality/injury during pile driving activities would be expected to easily move away and avoid harm.

1.8.4 Behavioural reactions are anticipated to occur across 67 % width of the Humber Estuary at low water and 46 % of the estuary width at high water, therefore, potentially creating a partial temporary barrier to fish movements. The scale of the behavioural response is partly dependent on the hearing sensitivity of the

species. Fish with a swim bladder involved in hearing (e.g. herring) may exhibit a moderate behavioural reaction within distance in which a behavioural response is predicted (e.g. a sudden change in swimming direction, speed or depth). Fish with a swim bladder that is not involved in hearing (e.g. European eel) are likely to display a milder behavioural reaction. Fish without a swim bladder (e.g. river lamprey) are anticipated to only show very subtle changes in behaviour in this zone.

- 1.8.5 The scale of the behavioural effect is also dependent on the size of fish (which affects maximum swimming speed). Smaller fish, juveniles and fish larvae swim at slower speeds and are likely to move passively with the prevailing current. Larger fish are more likely to actively swim and, therefore, may be able to move out of the behavioural effects zone in less time, although it is recognised that the movement of fish is very complex and not possible to define with a high degree of certainty.
- 1.8.6 The effects of piling noise on fish also need to be considered in terms of the duration of exposure. Information on duration of piling activities will be available at the next stage of the Project and will inform the environmental assessments that support the DCO application. Although the total duration of piling activities is still to be defined it is recognised that piling will not take place continuously as there will be periods of downtime, pile positioning and set up.
- 1.8.7 The construction of the proposed development may be completed in a single stage, or it may be sequenced such that the construction of the second berth takes place at the same time as operation of the first berth (see **Chapter 2 The Project** (PEI Report, Volume II)). In the case of a sequenced construction, the overall duration of piling will take place over a longer period. However, there will be no change in the overall peak levels of underwater noise generated by the construction of both berths at once versus a sequenced construction (i.e. the magnitude of change). Therefore, the underwater noise assessment is considered the worst case and will not be altered by a sequenced construction period.
- 1.8.8 The piling works will be undertaken 7 am to 7 pm (Monday to Sunday). The maximum impact piling scenario is for 4 tubular piles to be installed each day from either front (i.e. the land and water), involving approximately 180 minutes of impact piling per day in a 12 hour shift. There will, therefore, be significant periods over a 24-hour period when fish will not be disturbed by any impact piling noise. The actual proportion of impact piling is estimated to be at worst around 13 % (based on 180 minutes of impact piling each working day) over any given construction week. In other words, any fish that remain within the predicted behavioural effects zone at the time of percussive piling will be exposed a maximum of up to 13 % of the time.
- 1.8.9 It is also important to consider the noise from piling against existing background or ambient noise conditions (**Section 1.4**). The area in which the construction will take place already experiences regular vessel operations and ongoing maintenance dredging, and, therefore, fish are likely to be habituated to a certain level of anthropogenic background noise.

Vibro piling

- 1.8.10 The calculator developed by Ref 1-14 has been used to calculate the range at which the instantaneous peak and cumulative SEL thresholds for vibro driving (Ref 1-15) are reached. The model input values and associated assumptions for vibro piling are included in **Table 1.7**.
- 1.8.11 The distances at which potential mortality/injury and behavioural effects in fish are predicted to occur during vibro piling activities associated with the construction of the proposed development are included in **Table 1.8**.
- 1.8.12 Given the mobility of fish, any individuals that might be present within the localised areas associated with potential mortality/injury during pile driving activities would be expected to easily move away and avoid harm.
- 1.8.13 Behavioural reactions are anticipated to occur across 48 % of the width of the Humber Estuary at low water and 33 % of the estuary width at high water. The scale of the behavioural response is partly dependent on the hearing sensitivity of the species. Fish with a swim bladder involved in hearing (e.g. herring) may exhibit a moderate behavioural reaction within distance in which a behavioural response is predicted (e.g. a sudden change in swimming direction, speed or depth). Fish with a swim bladder that is not involved in hearing (e.g. European eel) are likely to display a milder behavioural reaction. Fish without a swim bladder (e.g. river lamprey) are anticipated to only show very subtle changes in behaviour in this zone.

Table 1.7: NMFS piling calculator input values for vibro piling

Model Inputs	Value	Assumptions
Number of strikes per pile	675	Maximum value provided for existing field data in the NMFS pile driving calculator (Ref 1-14 and, therefore, considered a reasonable worst case).
Number of piles per day	4	The maximum vibro piling scenario is for the marine works to comprise up to 4 tubular piles to be installed each day (see Section 1.5).
Peak SPL SL	216	Loudest near-source (10 m from the source) sound pressure measurements for the vibratory piling installation of 1.83 m steel pipe piles in a shallow water environment (Ref 1-8; Ref 1-33; Ref 1-34) back-calculated to 1 m and the assumption that more than one piling rig with vibro hammers will be used concurrently (see Section 1.5).
SEL SL	183	As above.
RMS SL	183	As above.
Distance from source (m)	1	The sound levels that were measured for the vibratory piling installation of 1.83 m steel pipe piles in a shallow water environment (Ref 1-8; Ref 1-33; Ref 1-34) have been back-calculated to 1 m from the source (see Section 1.5).

Model Inputs	Value	Assumptions
Noise reduction due to abatement (dB)	NA	Not applicable.
Transmission loss coefficient	17.91	Derived from 11 observations of transmission loss coefficient collected from a number of construction projects undertaken in shallow water estuarine and coastal locations (see Section 1.3).

Table 1.8: Approximate distances (metres) fish response criteria are reached during concurrent vibro piling

Fish Hearing Category	Mortality/ Potential Mortal Injury		Recoverable Injury		Behaviour
	Peak	SEL _{cum}	Peak	SEL _{cum}	Peak
Swim bladder involved in hearing (primarily pressure detection)	3	38	3	64	1,105
Swim bladder is not involved in hearing (particle motion detection)	3	26	3	64	1,105
No swim bladder (particle motion detection)	1	8	1	12	1,105
Eggs and larvae	3	26	(N) Moderate (I) Low (F) Low		1,105

- 1.8.14 The scale of the behavioural effect is also dependent on the size of fish (which affects maximum swimming speed). Smaller fish, juveniles and fish larvae swim at slower speeds and are likely to move passively with the prevailing current. Larger fish are more likely to actively swim and, therefore, may be able to move out of the behavioural effects zone in less time.
- 1.8.15 The effects of piling noise on fish also need to be considered in terms of the duration of exposure. Information on duration of piling activities will be available at the next stage of the Project and will inform the environmental assessments that support the DCO application. Although the total duration of piling activities is still to be defined it is recognised that piling will not take place continuously as there will be periods of downtime, pile positioning and set up.
- 1.8.16 The construction of the proposed development may be completed in a single stage, or it may be sequenced such that the construction of the second berth takes place at the same time as operation of the first berth (see **Chapter 2 The Project** (PEI Report, Volume II)). In the case of a sequenced construction, the overall duration of piling will take place over a longer period. However, there will be no change in the overall peak levels of underwater noise generated by the construction of both berths at once versus a sequenced construction (i.e. the

magnitude of change). Therefore, the underwater noise assessment is considered the worst case and will not be altered by a sequenced construction period.

- 1.8.17 The piling works will be undertaken 7 am to 7 pm (Monday to Sunday). The maximum vibro piling scenario is for 4 tubular piles to be installed each day from either front (i.e. the land and water), involving around 20 minutes of vibro piling per day in a 12 hour shift. There will, therefore, be significant periods over a 24-hour period when fish will not be disturbed by any vibro driving noise. The actual proportion of vibro piling is estimated to be at worst around 1 % (based on an estimated 20 minutes of vibro piling each working day) over any given construction week. In other words, any fish that remain within the predicted behavioural effects zone at the time of vibro piling will be exposed a maximum of up to 1 % of the time.
- 1.8.18 It is also important to consider the noise from piling against existing background or ambient noise conditions (**Section 1.4**). The area in which the construction will take place already experiences regular vessel operations and ongoing maintenance dredging, and, therefore, fish are likely to be habituated to a certain level of anthropogenic background noise.

Dredging and vessel movements

- 1.8.19 The relative risk and distances at which potential mortality/injury and behavioural effects in fish are predicted to occur as a result of the dredging and vessel movements associated with the construction and operation of the Project are included in **Table 1.9**.
- 1.8.20 The worst case SL generated by dredging and vessels is below the Ref 1-15 quantitative instantaneous peak SPL and cumulative SEL thresholds for pile driving, which indicates that there is no risk of mortality, potential mortal injury or recoverable injury in all categories of fish even at the very source of the dredger or vessel noise. This appears to correlate with the Ref 1-15 recommended qualitative guidelines for continuous noise sources which consider that the risk of mortality and potential mortal injury in all fish is low in the near, intermediate and far-field (**Table 1.9**).
- 1.8.21 According to Ref 1-15, the risk of recoverable injury is also considered low for fish with no swim bladder and fish with a swim bladder that is not involved in hearing. There is a greater risk of recoverable injury in fish where the swim bladder is involved in hearing (e.g. herring) whereby a cumulative noise exposure threshold is recommended (170 dB rms for 48 h). The distance at which recoverable injury is predicted in these fish as a result of the dredging and vessel movements is 10 m (**Table 1.9**).
- 1.8.22 Ref 1-15 advise that there is a moderate risk of TTS occurring in the nearfield (i.e. tens of metres from the source) in fish with no swim bladder and fish with a swim bladder that is not involved in hearing and a low risk in the intermediate and far-field. There is a greater risk of TTS in fish where the swim bladder is involved in hearing (e.g. herring) whereby a cumulative noise exposure threshold is recommended (158 dB rms for 12 h). The distance at which TTS is predicted in these fish as a result of the dredging and vessel movements is 46 m (**Table 1.9**).

1.8.23 Ref 1-15 guidelines suggest that there is considered to be a high risk of potential behavioural responses occurring in the nearfield (i.e. tens of metres from the source) for fish species with a swim bladder involved in hearing and a moderate risk in other fish species (**Table 1.9**). At intermediate distances (i.e. hundreds of metres from the source) there is considered to be a moderate risk of potential behavioural responses in all fish and in the farfield (i.e. thousands of metres from the source) there is considered to be a low risk of a response in all fish.

Table 1.9: Relative risk and distances (metres) fish response criteria are reached during dredging and vessel movements

Fish Hearing Category	Mortality/ Potential Mortal Injury/ Recoverable Injury	Recoverable injury	TTS	Behaviour
Swim bladder involved in hearing (primarily pressure detection)	(N) Low (I) Low (F) Low	10	46	(N) High (I) Moderate (F) Low
Swim bladder is not involved in hearing (particle motion detection)	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Moderate (F) Low
No swim bladder (particle motion detection)	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Moderate (F) Low
Eggs and larvae	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Moderate (F) Low

Distances are in metres (m).
 Relative risk (high, moderate, low) is given for animals at three distances from the source defined in relative terms as near (N), intermediate (I), and far (F).

1.8.24 Overall, there is considered to be a low risk of any injury in fish as a result of the underwater noise generated by dredging and vessel movements. The level of exposure will depend on the position of the fish with respect to the source, the propagation conditions, and the individual's behaviour over time. However, it is unlikely that a fish would remain in the vicinity of a dredger for extended periods. Behavioural responses are anticipated to be spatially negligible in scale and fish will be able to move away and avoid the source of the noise as required. Furthermore, the period of dredging will be relatively short term.

Marine mammals

Impact piling

- 1.8.25 NOAA’s user spreadsheet tool (Ref 1-16) has been used to predict the range at which the weighted cumulative SEL and instantaneous peak SPL acoustic thresholds (Ref 1-17) for the onset of PTS and TTS are reached during the proposed impact piling activity.
- 1.8.26 In accordance with the guidance provided in NOAA’s user manual and the instructions included within the user spreadsheet, ‘Tab E.1: Impact pile driving (stationary source: impulsive, intermittent)’ and ‘E1.2: Method to calculate peak and SEL_{cum} using rms SPL source level’ was selected as the most appropriate method to apply for the percussive piling activity. The model input values, and associated assumptions are included in **Table 1.10**.

Table 1.10: NOAA user spreadsheet tool input values for ‘Tab E.1: Impact pile driving (stationary source: impulsive, intermittent)’

Model Inputs	Value	Assumptions
Weighting factor adjustment (kHz)	2	Default value for impact pile driving hammers provided in the NOAA instructions (Ref 1-16).
L _{p,0-pk} specified at “x” meters (dB re 1 μPa)	231	Loudest near-source (10 m from the source) sound pressure measurements for the percussive piling installation of 1.52 m CISS steel pipe piles in a shallow water environment (Ref 1-8; Ref 1-33; Ref 1-34) back-calculated to 1 m and the assumption that more than one piling rig with impact hammers will be used concurrently (see Section 1.5).
Sound Pressure Level (L _{rms}), specified at “x” metres (dB re 1 μPa)	216	Loudest near-source (10 m from the source) sound pressure measurements for the percussive piling installation of 1.52 m CISS steel pipe piles in a shallow water environment (Ref 1-8; Ref 1-33; Ref 1-34) back-calculated to 1 m and the assumption that more than one piling rig with impact hammers will be used concurrently (see Section 1.5).
Number of piles per day	4	The maximum impact piling scenario is for the marine works to comprise up to 4 tubular piles to be installed each day (see Section 1.5).
Strike (pulse) duration (seconds)	0.1	Default value provided in the NOAA instructions (Ref 1-16).
Number of strikes per pile	675	Maximum value provided for existing field data in the NMFS pile driving calculator (Ref 1-14) and, therefore, considered a reasonable worst case.

Model Inputs	Value	Assumptions
Transmission loss coefficient	17.91	Derived from 11 observations of transmission loss coefficient collected from a number of construction projects undertaken in shallow water estuarine and coastal locations (see Section 1.3).
Distance of sound pressure level measurement (m)	1	The sound levels that were measured for the percussive piling installation of 1.52 m CISS steel pipe piles in a shallow water environment (Ref 1-8; Ref 1-33; Ref 1-34) have been back-calculated to 1 m from the source (see Section 1.5).

1.8.27 The distances at which PTS and TTS in marine mammals are predicted to occur during impact piling activities associated with the construction of the Project are included in **Table 1.11**.

Table 1.11: Approximate distances (metres) marine mammal response criteria are reached during impact piling

Marine Mammal Hearing Group	PTS		TTS	
	SELcum	Peak	SELcum	Peak
Harbour porpoise	1,833	42	12,611	90
Common seal and grey seal	938	5	6,452	12

1.8.28 There is predicted to be a risk of instantaneous PTS and TTS in harbour porpoise within 42 m and 90 m respectively from the source of the percussive piling noise. The risk of instantaneous PTS and TTS in seals is within 5 m and 12 m respectively.

1.8.29 If the propagation of underwater noise from impact piling were unconstrained by any boundaries, the maximum theoretical distance at which the predicted cumulative SEL weighted levels of underwater noise during impact piling is within the limits of PTS and TTS in harbour porpoise is 1.8 km and 12.6 km respectively. The maximum distance for PTS and TTS in seals is 0.9 km and 6.5 km respectively.

1.8.30 Assuming a lower worst case swimming speed of 1.5 m/s for all marine mammal species (including both adults and juveniles), the maximum time that would take harbour porpoise to leave the centre of the cumulative SEL weighted PTS and TTS injury zones during impact piling is estimated to be 20 minutes and 2.3 hours respectively. This is less than 10 % of the time that would be required for an injury to occur and, therefore, assuming harbour porpoise evade the injury effects zone, they are not considered to be at risk of any permanent or temporary injury during impact piling. The maximum time that would take seals to leave the PTS and TTS zones is estimated to be 10 minutes and 1.2 hours respectively. This is less than 5 % of the time that would be required for an injury to occur and, therefore, assuming seals evade the injury effects zone, they are not considered to be at risk of any permanent or temporary injury during impact piling.

- 1.8.31 Impact piling is predicted to cause instantaneous injury effects within close proximity to the activity and strong behavioural responses over a wider area although this will be constrained to within the outer section of the Humber Estuary between Hull and Cleethorpes.
- 1.8.32 The results indicate that if any marine mammals present in the estuary were to remain stationary within the cumulative SEL distances from the source of piling over a 24 hour period, it could result in temporary and/or permanent hearing injury. However, it is considered highly unlikely that any individual marine mammal will stay within this “injury zone” during the piling operations.
- 1.8.33 Any marine mammals present are likely to evade the area. Behavioural responses could include movement away from a sound source, aggressive behaviour related to noise exposure (e.g. tail/flipper slapping, fluke display, abrupt directed movement), visible startle response and brief cessation of reproductive behaviour (Ref 1-75). Mild to moderate behavioural responses of any individuals within these zones could include movement away from a sound source and/or visible startle response (Ref 1-75).
- 1.8.34 The effects of piling noise on marine mammals also need to be considered in terms of the duration of exposure. Information on duration of piling activities will be available at the next stage of the Project and will inform the environmental assessments that support the DCO application. Although the total duration of piling activities is still to be defined it is recognised that piling will not take place continuously as there will be periods of downtime, pile positioning and set up.
- 1.8.35 The construction of the proposed development may be completed in a single stage, or it may be sequenced such that the construction of the second berth takes place at the same time as operation of the first berth (see **Chapter 2 The Project** (PEI Report, Volume II)). In the case of a sequenced construction, the overall duration of piling will take place over a longer period. However, there will be no change in the overall peak levels of underwater noise generated by the construction of both berths at once versus a sequenced construction (i.e. the magnitude of change). Therefore, the underwater noise assessment is considered the worst case and will not be altered by a sequenced construction period.
- 1.8.36 The piling works will be undertaken 7 am to 7 pm (Monday to Sunday). The maximum impact piling scenario is for 4 tubular piles to be installed each day from either front (i.e. the land and water), involving approximately 180 minutes of impact piling per day in a 12 hour shift. There will, therefore, be significant periods over a 24-hour period when marine mammals will not be disturbed by any impact piling noise. The actual proportion of impact piling is estimated to be at worst around 13 % (based on 180 minutes of impact piling each working day) over any given construction week. In other words, any fish that remain within the predicted behavioural effects zone at the time of percussive piling will be exposed a maximum of up to 13 % of the time.
- 1.8.37 It is also important to consider the noise from piling against existing background or ambient noise conditions (**Section 1.4**). The area in which the construction will take place already experiences regular vessel operations and ongoing

maintenance dredging, and, therefore, marine mammals are likely to be habituated to a certain level of anthropogenic background noise.

Vibro piling

- 1.8.38 NOAA’s user spreadsheet tool (Ref 1-16) has been used to predict the range at which the weighted cumulative SEL acoustic thresholds (Ref 1-17) for the onset of PTS and TTS are reached during the proposed vibro piling activity.
- 1.8.39 In accordance with the guidance provided in NOAA’s user manual and the instructions included within the user spreadsheet, ‘Tab A.1: Vibratory pile driving (stationary source: non-impulsive, continuous)’ was selected as the most appropriate method to apply for the vibro piling activity. The model input values and associated assumptions are included in **Table 1.12**.

Table 1.12: NOAA user spreadsheet tool input values for ‘Tab A.1: Vibratory pile driving (stationary source: non-impulsive, continuous)’

Model Inputs	Value	Assumptions
Weighting factor adjustment (kHz)	2.5	Default value for vibratory pile driving hammers provided in the NOAA instructions (Ref 1-16).
Sound Pressure Level (L_{rms}), specified at "x" metres (dB re 1 μ Pa)	201	Loudest near-source (10 m from the source) sound pressure measurements for the vibratory piling installation of 1.83 m steel pipe piles in a shallow water environment (Ref 1-8; Ref 1-33; Ref 1-34) and the assumption that more than one piling rig with vibro hammers will be used concurrently (see Section 1.5).
Number of piles within 24 hr period	4	The maximum vibro piling scenario is for the marine works to comprise up to 4 tubular piles to be installed each day (see Section 1.5).
Duration to drive a single pile (minutes)	5	Each tubular pile will require 5 minutes of vibro piling (see Section 1.5).
Transmission loss coefficient	17.91	Derived from 11 observations of transmission loss coefficient collected from a number of construction projects undertaken in shallow water estuarine and coastal locations (see Section 1.3).
Distance of sound pressure level measurement (m)	1	The sound levels that were measured for the vibratory piling installation of 1.83 m steel pipe piles in a shallow water environment (Ref 1-8; Ref 1-33; Ref 1-34) have been back-calculated to 1 m from the source (see Section 1.5).

- 1.8.40 The distances at which PTS and TTS in marine mammals are predicted to occur during vibro piling activities associated with the construction of the proposed development are included in **Table 1.13**.

Table 1.13: Approximate distances (metres) marine mammal response criteria are reached during vibro piling

Marine Mammal Hearing Group	PTS	TTS
High-frequency (HF) cetaceans (porpoises, river dolphins)	94	1,223
Phocid pinniped (PW) (true seals)	44	581

- 1.8.41 If the propagation of underwater noise from vibro piling were unconstrained by any boundaries, the maximum theoretical distance at which the predicted cumulative SEL weighted levels of underwater noise during vibro piling is within the limits of PTS and TTS in harbour porpoise is 94 m and 1.2 km respectively. The maximum distance for PTS and TTS in seals is 44 m and 581 m respectively.
- 1.8.42 Assuming a lower worst case swimming speed of 1.5 m/s for all marine mammal species (including both adults and juveniles), the maximum time that would take harbour porpoise to leave the centre of the cumulative SEL weighted PTS and TTS injury zones during vibro piling is estimated to be 1 minute and 14 minutes respectively. This is less than 1 % of the time that would be required for an injury to occur and, therefore, assuming harbour porpoise evade the injury effects zone, they are not considered to be at risk of any permanent or temporary injury during vibro piling. The maximum time that would take seals to leave the PTS and TTS zones is estimated to be 29 seconds and 6 minutes respectively. This is less than 0.4 % of the time that would be required for an injury to occur and, therefore, assuming seals evade the injury effects zone, they are not considered to be at risk of any permanent or temporary injury during vibro piling.
- 1.8.43 The results indicate that if any marine mammals present in the estuary were to remain stationary within the cumulative SEL distances from the source of piling over a 24 hour period, it could result in temporary and/or permanent hearing injury. However, it is considered highly unlikely that any individual marine mammal will stay within this “injury zone” during the piling operations.
- 1.8.44 Any marine mammals are likely to evade the area. Behavioural responses could include movement away from a sound source, aggressive behaviour related to noise exposure (e.g. tail/flipper slapping, fluke display, abrupt directed movement), visible startle response and brief cessation of reproductive behaviour (Ref 1-75). Mild to moderate behavioural responses of any individuals within these zones could include movement away from a sound source and/or visible startle response (Ref 1-75).
- 1.8.45 The effects of piling noise on marine mammals also need to be considered in terms of the duration of exposure. Information on duration of piling activities will be available at the next stage of the Project and will inform the environmental assessments that support the DCO application. Although the total duration of piling activities is still to be defined it is recognised that piling will not take place continuously as there will be periods of downtime, pile positioning and set up.

- 1.8.46 The construction of the Project may be completed in a single stage, or it may be sequenced such that the construction of the second berth takes place at the same time as operation of the first berth (see **Chapter 2 The Project** (PEI Report, Volume II)). In the case of a sequenced construction, the overall duration of piling will take place over a longer period. However, there will be no change in the overall peak levels of underwater noise generated by the construction of both berths at once versus a sequenced construction (i.e. the magnitude of change). Therefore, the underwater noise assessment is considered the worst case and will not be altered by a sequenced construction period.
- 1.8.47 The piling works will be undertaken 7 am to 7 pm (Monday to Sunday). The maximum vibro piling scenario is for 4 tubular piles to be installed each day from either front (i.e. the land and water), involving around 20 minutes of impact piling per day in a 12 hour shift. There will, therefore, be significant periods over a 24-hour period when marine mammals will not be disturbed by any vibro driving noise. The actual proportion of vibro piling is estimated to be at worst around 1 % (based on an estimated 20 minutes of vibro piling each working day) over any given construction week. In other words, any marine mammals that remain within the predicted behavioural effects zone at the time of vibro piling will be exposed a maximum of up to 1 % of the time.
- 1.8.48 It is also important to consider the noise from piling against existing background or ambient noise conditions. The area in which the construction will take place already experiences regular vessel operations, and, therefore, marine mammals are likely to be habituated to a certain level of anthropogenic background noise disturbance.

Dredging and vessel movements

- 1.8.49 NOAA’s user spreadsheet tool (Ref 1-16) has been used to predict the range at which the weighted cumulative SEL acoustic thresholds (Ref 1-17) for PTS and TTS are reached during the proposed dredging and vessel movements associated with the construction and operation of the proposed development.
- 1.8.50 In accordance with the guidance provided in NOAA’s user manual and the instructions included within the user spreadsheet, ‘Tab C: Mobile source, non-impulsive, continuous (“safe distance” methodology)’ was selected as the most appropriate method to apply for the dredging and vessel activity. The model input values, and associated assumptions are included in **Table 1.14**.

Table 1.14: NOAA user spreadsheet tool input values for ‘Tab C: Mobile source, non-impulsive, continuous (“safe distance” methodology)’

Model Inputs	Value	Assumptions
Weighting factor adjustment (kHz)	2.5	The maximum recommended default value provided in the user spreadsheet (Ref 1-16) that leads to the greatest predicted ranges for PTS and TTS and is, therefore, considered a worst case.

Model Inputs	Value	Assumptions
Source Level (L_{rms})	188	The maximum estimated RMS SL for all forms of dredging and vessels that will be involved in construction and operation of the proposed development (see Section 1.5).
Source velocity (m/s)	1	Value is based on the minimum sailing speed of a dredging vessel as it removes material from the seabed. A lower source velocity value predicts greater ranges at which PTS and TTS are reached and, therefore, the lowest reasonable source velocity associated with the dredging and vessel activity has been applied as a worst case.

1.8.51 The distances at which PTS and TTS in marine mammals are predicted to occur during dredging and vessel movements associated with the construction and operation of the proposed development are included in **Table 1.15**.

Table 1.15: Approximate distances (metres) marine mammal response criteria are reached during dredging and vessel movements

Marine Mammal Hearing Group	PTS	TTS
High-frequency (HF) cetacean (harbour porpoise)	<1	44
Phocid pinniped (PW) (grey seal and common seal)	<1	12

1.8.52 There is predicted to be no risk of PTS in harbour porpoise and the risk of TTS is limited to within less than 44 m from the dredging or vessel activity (**Table 1.15**). There is predicted to be no risk of PTS in seals and the risk of TTS is limited to within 12 m from the source.

1.8.53 Overall, there is not considered to be any risk of injury or significant disturbance to marine mammals from the proposed dredging and vessel activities that are proposed at the Project even if the dredging and vessel movements were to take place continuously 24/7.

1.9 Summary and Conclusions

1.9.1 This report presents the underwater noise modelling that has been undertaken to determine the potential impacts of underwater noise on key marine receptors as a result of the construction and operation of the Project.

1.9.2 In accordance with available guidance (Ref 1-7; Ref 1-13; Ref 1-58), a simple logarithmic spreading model has been selected to predict the propagation of sound pressure from the key sources of underwater noise, taking account of its limitations and constraints. The predicted levels of underwater noise have been compared against peer-reviewed noise exposure criteria to determine the potential risk of impact on marine fauna (Ref 1-61; Ref 1-15; Ref 1-17; Ref 1-76).

1.9.3 In order to reduce the level of potential impact associated with underwater noise and vibration on fish and marine mammals during construction (piling), a number of mitigation measures are being considered including the use of soft start procedures, the use of vibro piling where possible with seasonal/night time piling restrictions specifically for migratory fish species and JNCC piling protocols for marine mammals (Ref 1-91).

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