Associated British Ports

Immingham Eastern Ro-Ro Terminal

Preliminary Environmental Information:
Appendix 9.2: Preliminary Underwater Noise Assessment

January 2022

Innovative Thinking - Sustainable Solutions

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1 Introduction

1.1 Introduction

1.1.1 This report presents an assessment of the potential effects of underwater noise and vibration from the proposed Immingham Eastern Ro-Ro Terminal on marine fauna. The assessment has been undertaken to support the Preliminary Environmental Information Report (PEIR) that has been prepared for the proposed development. In particular, the assessment has informed the outcomes of the nature conservation and marine ecology assessment (Chapter 9 of the PEIR), which in turn will inform the Habitats Regulations Assessment (HRA) and the Water Framework Direct (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 proposed development and construction methodology on which this assessment is based on is included in Chapters 2 and 3 of the PEIR.

1.1.2 This report has been structured as follows:

- **Section 1: Introduction** provides a brief introduction to the project and need for this assessment;
- **Section 2: Principles of Underwater Acoustics** presents the basic principles which are fundamental to undertaking robust underwater noise assessments;
- **Section 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 4: Ambient Noise** presents the baseline acoustic conditions of the study area;
- **Section 5: Noise Characteristics of Proposed Development Activities** presents the specific acoustic characteristics of the proposed construction and operational activities;
- **Section 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 7: Noise Propagation Modelling Outputs** presents the outputs of the underwater noise modelling;
- **Section 8: Potential Effects** reviews the potential effects on local marine fauna; and
- **Section 9: Summary and Conclusions** presents and overview of the outcome of the underwater noise assessment and conclusions.

2 Principals of Underwater Acoustics

2.1 Introduction

2.1.1 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 (ISO/DIS, 2016).

2.2 Sound pressure

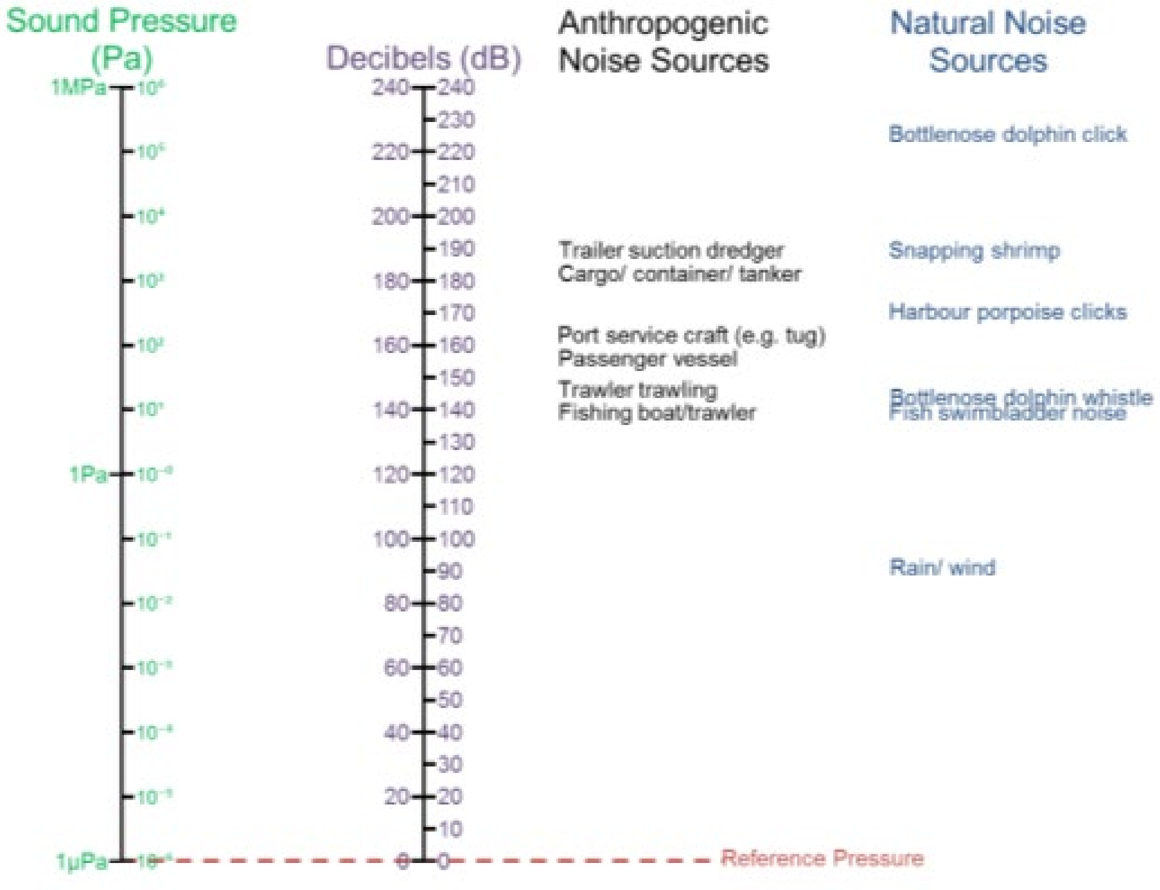
2.2.1 Sound pressure acts in all directions and is a scalar quantity that can be described in terms of its magnitude and its temporal and frequency characteristics. An important property of sound or ‘noise’ is its loudness. A loud noise usually has a larger pressure variation and a weak one has a smaller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

2.2.2 Pressure and pressure variations are expressed in Pascal, abbreviated as Pa, which is defined as Newton per square metre (N/m^2). 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. Figure 1 shows how sounds can be expressed both linearly in Pa and logarithmically in dB.

2.2.3 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 microPascal (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.

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



Source: MMO, 2015

Figure 1. The sound pressure (Pa) and decibel (dB) scale

2.3 Particle motion

2.3.1 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.

2.3.2 Particle motion was previously considered impossible to record (Wysocki and Ladich, 2005). However, two approaches have been used in research to estimate particle acceleration (Radford *et al*., 2012): 1) accelerometers and 2) the recording of pressure differences between two hydrophones. This was followed closely by the development of a particle motion sensor (Sigray and Andersson, 2011), which has been validated in field studies near an offshore wind farm in the western part of the Baltic Sea.

2.3.3 Detection of particle motion requires different types of sensor than those utilized by a conventional hydrophone (Hawkins and Popper, 2017). 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.

2.4 Underwater noise metrics

2.4.1 There are a number of different metrics that may be used as measures of sound pressure (NPL, 2014). 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 $Pa^2 \cdot s$. 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.

2.4.2 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.

3 Underwater Noise Propagation

3.1.1 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) loss[1] broadly include the following (NPL, 2014):

- 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.

3.1.2 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.

3.1.3 In accordance with good practice guidance (NPL, 2014), and in agreement with the MMO and Cefas as their advisor on issues relating to underwater noise, 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 proposed development (MMO, 2021). 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 SPL at distance R from a source (i.e. the received level) and is generally expressed in terms of decibels (dB) for a reference pressure of 1 μPa and a reference range of 1 m (dB re 1 μPa m);
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) also generally expressed as dB re 1 μPa m;
N	is a factor for attenuation due to geometric spreading; and

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

α is a factor for the absorption of sound in water and boundaries (i.e. the sediment or water surface) in dB m^{-1}.

3.1.4 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 (Illinworth and Rodkin, 2007);
- San Rafael Sea Wall in San Francisco Bay, California (Illinworth and Rodkin, 2007);
- Scroby Sands Offshore Wind Farm located off the coast of Great Yarmouth (Nedwell *et al*., 2007a);
- North Hoyle Offshore Wind Farm in Liverpool Bay (Nedwell *et al*., 2007a);
- Kentish Flats Offshore Wind Farm located off the coast of Kent (Nedwell *et* al., 2007a);
- Burbo Bank Offshore Wind Farm in Liverpool Bay (Nedwell *et al*., 2007a);
- Barrow Offshore Wind Farm located south west of Walney Island (Nedwell *et al*., 2007a); and
- Belvedere Energy-from-Waste Plant on Thames Estuary (measurements collected by Subacoustech Ltd on behalf of the Environment Agency and Costain).

3.1.5 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. URS Scott Wilson, 2011; ABPmer, 2015). These values are, therefore, considered to be appropriate to use for the underwater noise assessment in support of the proposed development.

3.1.6 It is important to recognise that there are a number of limitations associated with the use of simple logarithmic spreading models (NPL, 2014). 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. Farcas *et al*. (2016) 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.

3.1.7 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.

3.1.8 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 (NMFS, 2021). This calculator has, therefore, been used to calculate the range at which the peak SPL and cumulative SEL thresholds for pile driving (Popper *et al.*, 2014) are reached. Further details of the assumptions and input values that have been applied are provided in Section 8.1.

3.1.9 In terms of marine mammals, NOAA (2021) 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 (NOAA, 2018) 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 8.2.

3.1.10 The proposed development 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 (Harland *et al.*, 2005). 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.

3.1.11 Overall, therefore, a simple logarithmic spreading model is considered proportionate and appropriate to use for this underwater noise assessment. The MMO and Cefas as their advisor agree that a simple modelling approach in this instance is appropriate (MMO, 2021).

4 Ambient Noise

4.1 Introduction

4.1.1 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.

4.2 Definition

4.2.1 Ambient sound is commonly defined as background acoustic sound without distinguishable sources (e.g. Wenz, 1962; Urick, 1983). This definition, however, has the problem of how to identify distinguishable sources, and how to eliminate them from the measurements.

4.2.2 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 (Defra, 2019). 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" (Dekeling et al., 2014, p 20).*

4.2.3 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' (NPL, 2014).

4.3 Sources of ambient sound

4.3.1 Ambient sound covers the whole acoustic spectrum from below 1 Hz to well over 100 kHz (Harland *et al*., 2005). At the lower frequencies shipping noise dominates, while at the higher frequencies noise from waves and precipitation dominates.

4.3.2 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 (Malme *et al.*, 1989; Harland *et al*., 2005). Biological activity includes echo locating marine mammals and fish communication (Battele, 2004; Harland *et al*., 2005). These sources of ambient sound vary on a diurnal cycle, a tidal cycle and/or an annual cycle.

4.3.3 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) (Dekeling *et al*., 2014). 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

4.3.4 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 (Harland *et al*., 2005). 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 1μPa m (MMO, 2015). For smaller shipping vessels and boats the range is 150 to 180 dB re 1μPa m (UKMMAS, 2010; CEDA, 2011). Although the exact characteristics depend on vessel type, size and operational mode, the strongest energy occurs below 1,000 Hz.

4.3.5 Small motorised craft (e.g. outboard powered inflatables, speed boats and work boats) produce relatively low levels of noise (75 to 159 dB re 1μPa m), and the output characteristics are highly dependent on speed and other operational characteristics (Richardson *et al*., 1995). 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.

4.3.6 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 the commercial and recreational navigation chapter (Chapter 10 of the PEIR).

Dredging

4.3.7 Dredging activities emit moderate levels of broadband noise (around 150 to 188 dB re 1μPa m), mainly at lower frequencies (less than 500 Hz) (Thomsen *et al*., 2009; Jones and Marten, 2016). 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 in the physical processes chapter (Chapter 7 of the PEIR).

4.4 Frequency dependence of sound propagation

4.4.1 Shallow and very shallow water[2], 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 (Harland *et al*., 2005). 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.

4.5 Spatiotemporal variation

4.5.1 Ambient sound levels can show significant variation over space and time (NPL, 2014). 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.

4.6 Measured levels of ambient sound

4.6.1 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 (ABPmer, 2017).

4.6.2 RMS SPLs showed a repeating pattern of peaks and troughs, ranging from 107 to 154 dB re 1 μPa. 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 (ABPmer, 2017).

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[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.

5 Noise Characteristics of Proposed Development Activities

5.1 Introduction

5.1.1 During the construction and operation of the proposed development 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.

5.2 Piling

5.2.1 The proposed development will involve the installation of approximately 162 steel tubular piles, which will range in size from 965 mm to a maximum of 1,321 mm diameter. The majority of the piling will be from a crane barge 50 m x 30 m or jack up *circa* 500T 30 m x 20 m utilising a *circa* 350T crawler crane, a vibratory hammer (PVE 38M) and percussive piling hammer (BSP CG300). The piles will be transported to the jetty area by flat top barge and pitched from this barge to the piling gates. The vibro hammer will then be installed and the pile will be vibrated to refusal. This hammer will then be put down and the percussive hammer will be placed on top of the pile and driven to its final level.

5.2.2 The approach trestle will be built from land with the same piling equipment (minus the barges) but will be built out sequentially from the shore allowing the crane to track over the newly installed structure with the possible aid of some intermediate temporary support piles. In other words, piling will be undertaken simultaneously using two piling rigs on two fronts (i.e. the land and water) and may result in cumulative piling noise.

5.2.3 Each tubular pile will require approximately 5 minutes of vibro piling and 45 minutes of impact piling. The maximum impact piling scenario is for 4 tubular piles to be installed each day using two piling rigs, one on each front, involving around 20 minutes of vibro piling and 180 minutes of impact piling per day in a 12 hour shift.

5.2.4 The piling works will be undertaken six days per week (Monday to Saturday). Working hours will be from 7 am to 7 pm (Monday to Friday) and 7am to 1pm (Saturday).

Impact piling

5.2.5 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.

5.2.6 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 (Brekhovskikh, 1960). 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.

5.2.7 Impulsive sources such as pile driving should have SLs expressed for a single pulse as either SEL with units of dB re 1 µPa² s, or as a peak-peak or zero-peak SPL, with units of dB re 1 µPa (Farcas *et al*., 2016). 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 (DPTI, 2012). 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.

5.2.8 The Environment Agency has developed a model of observed SL of percussive piling of tubular piles versus pile diameter which was presented at the Institute of Fisheries Management Conference on 23 May 2013.

$$SL = 10.973\,Ln(PD) + 231.74$$

Equation 2. Observed source level versus pile diameter

SL is provided as unweighted peak-to-peak SL in dB re 1 µPa m[3]; and
PD is the pile diameter in metres.

5.2.9 This model was derived from 21 observations of publicly available percussive piling noise data, primarily from Subacoustech studies but also the California Department of Transportation (Caltrans) compendium of pile driving sound

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[3] Peak SL dB re 1 µPa m is calculated by subtracting 6 dB from peak-to-peak SL.

data (Illingworth & Rodkin, 2007) and Institute for Technical and Applied Physics (ITAP) (Matuschek and Betke, 2009).

5.2.10 This model indicates that the worst case noise will be generated by the largest diameter piles. Based on this model (Equation 2), the impact piling of 1,321 mm tubular piles is predicted to have an unweighted peak SL of 229 dB re 1 μPa m.

5.2.11 Piling will be undertaken simultaneously using two 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 can be assumed to be 232 dB re 1 μPa m.

5.2.12 It should be noted that piling SLs estimated through field measurements during impact piling involved in the construction of GPH showed a good level of agreement with the prediction in the ES for that project (225 to 240 dB re 1 μPa (peak) observed versus 230 dB re 1 μPa (peak) predicted) (ABPmer, 2017). A similar approach to estimating the SL of impact piling has been taken for the proposed Immingham Eastern Ro-Ro Terminal as was done for the ES of GPH. The results of the underwater noise monitoring undertaken at GPH indicates that there is a reasonable degree of confidence in these SL estimates (ABPmer, 2017).

Vibro piling

5.2.13 Vibratory hammers use oscillatory hammers that vibrate the pile, causing the sediment surrounding the pile to liquefy and allow pile penetration (ICF Jones & Stokes and Illingworth & Rodkin, 2009). 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.

5.2.14 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 for the vibratory piling installation of the nearest-sized 1.8 m steel pipe piles in a shallow water environment (Illinworth & Rodkin, 2007; ICF Jones & Stokes and Illingworth and Rodkin, 2009). Back-calculating to 1 m using the simple logarithmic spreading model (equation 1) provides an estimated SL of 198 dB re 1 μPa m (RMS sound pressure and SEL for 1 second of continuous driving) and 213 dB re 1 μPa m (zero-peak sound pressure).

5.2.15 Piling will be undertaken simultaneously using two 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 can be assumed to be 216 dB re 1 μPa m.

5.3 Dredging

5.3.1 The dredging requirements for the proposed development will 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 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).

5.3.2 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 (CEDA, 2011; WODA, 2013; Jones and Marten, 2016). For most dredging activities, the main source of sound relates to the vessel engine noise. Dredging activities produce broadband and continuous sound[4], mainly at lower frequencies of less than 500 Hz and moderate RMS SLs from around 150 to 188 dB re 1 µPa m (Thomsen *et al*., 2009; CEDA, 2011; Robinson *et al*., 2011; WODA, 2013; MMO, 2015; Jones and Marten, 2016).

5.3.3 Backhoe dredgers generate RMS SLs in the range of 154 to 179 dB re 1 µPa m (Reine *et al*., 2012; Nedwell *et al*., 2008). 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 (CEDA, 2011).

5.3.4 SLs of TSHDs are variable but generally range from 160 to above 180 dB re 1 µPa m for large TSHDs (Robinson *et al*., 2011). The most intense sound emissions from the TSHDs are in the low frequencies, up to and including 1,000 Hz in most cases (Robinson *et al*., 2011; De Jong *et al*., 2010). 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 (Robinson *et al*., 2011).

5.3.5 Overall, the dredgers involved in the proposed development during construction and operation are anticipated to generate a worst case unweighted RMS SL of up to 188 dB re 1 µPa m.

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[4] 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.

5.4 Vessel movements

5.4.1 Vessels involved during the construction of the proposed development will primarily be the crane barge, flat top barge, backhoe dredger with associated attendant barges and TSHD. During operation, the new berths are designed to service the embarkation and disembarkation of principally commercial and automotive traffic, possibly with provision for a small element of passenger use during quiet periods.

5.4.2 The dredgers and barges are anticipated to generate SLs of up to 188 dB re 1 µPa m (UKMMAS, 2010; CEDA, 2011). The cargo ships and vehicle carrier vessels involved during the operation will produce RMS SLs in the region of 178 to 184 dB re 1µPa m (McKenna *et al*., 2012; MMO, 2015).

5.4.3 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 µPa m. Continuous (24/7) noise generation from vessel activities has been assumed and as such, provides a precautionary assessment.

6 Hearing Sensitivity and Responses of Marine Fauna

6.1 Introduction

6.1.1 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.

6.2 Benthic invertebrates

6.2.1 Benthic invertebrates lack a gas-filled bladder and are, therefore, unable to detect the pressure changes associated with sound waves (Carrol *et al*., 2017). 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 (Carrol *et al*., 2017). 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 (Carrol *et al*., 2017).

6.2.2 Scientific understanding of the potential effects of underwater noise on invertebrates is relatively underdeveloped (Hawkins *et al*., 2015). There is limited research to suggest that exposure to near-field low-frequency sound may cause anatomical damage (Carrol *et al*., 2017). Anecdotal evidence indicates there was pronounced statocyst and organ damage in seven stranded giant squid after nearby seismic surveys (Guerra *et al*., 2004). Day *et al.* (2016) found airgun exposure caused damaged statocysts in rock lobsters up to a year later. No such effects, however, were detected in other studies (Christian *et al*., 2003; Lee-Dadswell, 2009). 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 (Carrol *et al*., 2017).

6.2.3 There is increasing evidence to suggest that benthic invertebrates respond to particle motion[5] (Roberts *et al*., 2016). For example, blue mussels *Mytilus edulis* vary valve gape, oxygen demand and clearance rates (Spiga *et al*., 2016; Roberts *et al*., 2016) and hermit crabs *Paganus bernhardus* shift their shell and at very high amplitudes, leave their shell, examine it and then return (Roberts *et al*., 2016). 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) (Roberts *et al*., 2016). 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 (Tidau and Briffa, 2016). Population level and mortality effects, however, are considered unlikely. Effects on benthic invertebrates are, therefore, not considered further in the assessment.

6.3 Fish

6.3.1 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).

6.3.2 There is a wide diversity in hearing structures in fish which leads to different auditory capabilities across species (Webb *et al*., 2008). All fish can sense the particle motion component of an acoustic field via the inner ear as a result of whole-body accelerations (Radford *et al*., 2012), 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 (Popper *et al*., 2014; Hawkins *et al*., 2015; Nedelec *et al*., 2016). Although many fish are also likely to detect sound pressure[6], particle motion is considered equally or potentially more important (Hawkins and Popper, 2017).

6.3.3 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 (Hawkins and Popper, 2017). 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 (Popper *et al*., 2014).

6.3.4 The nature conservation and marine ecology chapter (Chapter 9) provides a detailed review of the fish receptors that occur in the study area. Categories

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[5] 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.

[6] 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.

proposed by Popper *et al.* (2014) for each of the key fish species are included in Table 1.

Table 1. Categorisation of key fish species in the study area according to Popper *et al*. (2014) criteria

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

6.3.5 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 (Hawkins and Popper, 2017). They have a wider frequency range, extending to several kHz and generally show higher sensitivity to sound pressure than fishes in the other categories.

6.3.6 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) (Hawkins and Popper, 2016). 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 (Popper and Coombs, 1982; Popper and Fay, 2011; Hawkins and Popper, 2017).

6.3.7 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 (Mueler-Blenkle *et al*., 2010). 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 (Martin *et al*., 2016). Direct measurements of particle motion have also been hampered by the lack of guidance on data analysis methods.

6.3.8 Particle velocity can be calculated indirectly from sound pressure measurements using relatively simple models (MacGillivray *et al*., 2004). 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 (Nedelec *et al*., 2016).

6.3.9 Steps that are required to improve knowledge of the effects of particle motion on marine fauna have recently been set out (Popper and Hawkins, 2018). 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 (Faulkner *et al*., 2018). The underwater noise assessment has, therefore, been based on the latest available evidence and focused on the effects of sound pressure.

6.3.10 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 (Hastings and Popper, 2005). 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 (Hawkins and Myrberg Jr, 1983). 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.

6.3.11 The published noise exposure criteria for fish that have been used in this underwater noise assessment are presented in Table 2.

Table 2. Fish response criteria applied in this assessment

Fish Hearing Category*	Piling		Dredging and Vessel Movements			All Activities
	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 SEL$_{\text{cum}}$ >207 dB peak	203 dB SEL$_{\text{cum}}$ >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 SEL$_{\text{cum}}$ >207 dB peak	203 dB SEL$_{\text{cum}}$ >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 SEL$_{\text{cum}}$ >213 dB peak	>216 dB SEL$_{\text{cum}}$ >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 SEL$_{\text{cum}}$ >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

* Popper *et al.* (2014).
** Hawkins *et al.* (2014).
Peak and RMS SPL is in dB re 1 µPa and cumulative SEL (SEL$_{\text{cum}}$) is in dB re 1 µPa^{2}s.
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).

6.3.12 The Popper *et al.* (2014) quantitative instantaneous peak SPL and cumulative SEL criteria for different marine activities involved in the proposed development (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). These guidelines are based on an understanding that fish will respond to sounds and their hearing sensitivity.

6.3.13 While the Popper *et al.* (2014) 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 (Popper *et al*., 2014; Hawkins and Popper, 2017; Faulkner *et al*., 2018). 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 (Hawkins and Popper, 2014; Hawkins *et al*., 2015; Faulkner *et al*., 2018). 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 (Ellison *et al*., 2012; Pena *et al*., 2013). For example, a startle or reflex response to the onset of a noise source does not necessarily lead to displacement from the ensonified area.

6.3.14 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 (Hastings and Popper, 2005; Kastelein *et al*., 2008; Popper and Hastings, 2009). As a consequence, only hearing data based on behavioural experiments is acceptable for assessing the ability of fish to detect sound (Sisneros *et al*., 2016).

6.3.15 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 (Dunlop *et al*., 2017). An empirical behavioural threshold could also be adopted using *in situ* observed responses of fish to similar sound sources (Faulkner *et al*., 2018). 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 µPa RMS (McCauley *et al*., 2000). At levels of around 161-168 dB re 1 µPa RMS active avoidance of the air gun source would be expected to occur (Pearson *et al*., 1992; McCauley *et al*., 2000). These responses may, however, differ from those of unconfined fish.

6.3.16 More recent work has been undertaken by Hawkins *et al.* (2014) 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 µPa (equivalent to peak SPL of 157 dB re 1 µPa), 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 2).

6.3.17 Auditory and non-auditory injuries in fish have not been observed or documented to occur in association with dredging (Thomsen *et al*., 2009). 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 (McQueen *et al*., 2019), as well increased stress-related cortisol levels in fish species (Wenger *et al*., 2017). 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.

6.3.18 Potential behavioural effects in the past have also been inferred by comparing the received sound level with the auditory threshold of marine fauna. Richardson *et al*. (1995) and Thomsen *et al*. (2006), 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 Nedwell *et al*. (2007b), 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.

6.3.19 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. ABPmer, 2015; URS Scott Wilson, 2011). 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 (Hawkins and Popper, 2017). Furthermore, the dB_{ht} criteria are based on measures of inner ear responses and should rather be based on behavioural threshold determinations (Popper *et al*., 2014; Hawkins and Popper, 2017). The use of dB_{ht} criteria is, therefore, not advisable and has not been applied to this assessment (Hawkins and Popper, 2017).

6.4 Marine mammals

6.4.1 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.

6.4.2 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.

6.4.3 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 Clark *et al.,* 2009). 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.

6.4.4 NOAA (2018) 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 Southall *et al.* (2007) for preventing auditory/physiological injuries in marine mammals. Further recommendations have recently been published regarding marine mammal noise exposure by Southall *et al.* (2019) which complement the NOAA (2018) 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.

6.4.5 The NOAA (2018) and Southall *et al.* (2019) thresholds are categorised according to marine mammal hearing groups. The nature conservation and marine ecology chapter (Chapter 9) 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 NOAA (2018), 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”).

6.4.6 NOAA (2018) and Southall *et al.* (2019) 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 3.

Table 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	TTS	TTS	PTS
High-frequency (HF) cetaceans (harbour porpoise)	140 dB SEL$_{cum}$ 196 dB peak	140 dB SEL$_{cum}$ 196 dB peak	153 dB SEL$_{cum}$	173 dB SEL$_{cum}$
Phocid pinnipeds in water (PW) (true seals)	170 dB SEL$_{cum}$ 212 dB peak	170 dB SEL$_{cum}$ 212 dB peak	181 dB SEL$_{cum}$	201 dB SEL$_{cum}$
Peak SPL has a reference value of 1 µPa and weighted cumulative SEL has a reference value of 1 µPa^{2}s.				

6.4.7 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 Hawkins and Popper (2017).

6.4.8 There are no equivalent SPL behavioural response criteria that would represent the sources of underwater noise associated with the proposed development. 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 (Southall *et al*., 2007).

6.4.9 Field studies have demonstrated behavioural responses of harbour porpoises to anthropogenic noise (Cefas, 2020). A number of studies have shown avoidance of pile driving activities during offshore wind farm construction (Brandt *et al*., 2011; Carstensen *et al*., 2006; Dähne *et al*., 2013), with the range of measurable responses extending to at least 21 km in some cases (Tougaard *et al*., 2009). Seismic surveys have also elicited avoidance behaviour in harbour porpoises, albeit short-term (Thompson *et al*., 2013), and monitoring of echolocation activity suggests possible negative effects on foraging activity in the vicinity of seismic operations (Pirotta *et al*., 2014). There is a scarcity of studies quantifying behavioural impacts from dredging (Thomsen *et al*., 2011). An investigation by Diederichs *et al.* (2011) showed that harbour porpoises temporarily avoided an area of sand extraction off the Island of Sylt in Germany. Diederichs *et al*. (2011) 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.

6.4.10 Few studies have documented responses of seals to underwater noise in the field (Cefas, 2020). Koschinski *et al*. (2003) 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: Harris *et al*., (2001) reported animals swimming away and avoidance within ~150 m of a seismic survey, while Moulton *et al*., (2003) found no discernible difference in seal densities in response to construction and drilling for an oil pipeline.

6.4.11 A number of field observations of harbour porpoise and pinnipeds to multiple pulse sounds have been made and are reviewed by Southall *et al.* (2007). 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. Further information on the dB_{ht} metric and its limitations is provided in Section 6.3 and is, therefore, not repeated here.

6.4.12 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.

7 Noise Propagation Modelling Outputs

7.1.1 The simple logarithmic spreading model (equation 1) described in Section 3 was applied to the worst case (highest) unweighted peak SLs associated with the proposed development 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 NPL (2014). Table 4 shows the results of this analysis at various distances from the sources of noise associated with the proposed development.

Table 4. Maximum predicted unweighted received levels in dB re 1 μPa during piling and dredging

Range (m)	Impact Piling	Vibro Piling	Dredging and Vessel Movements
1	232	216	188
10	214	198	170
100	196	180	152
200	190	174	146
500	181	165	137
1,000	173	157	129
2,300*	160	144	116
3,400**	151	135	107
5,000	140	124	96
10,000	108	92	64

* Approximate distance from the most seaward point of the proposed development and opposite shore at low water.

** Approximate distance from the most seaward point of the proposed development and opposite shore at high water.

7.1.2 The instantaneous peak levels of underwater noise generated during impact piling for the proposed development are predicted to reduce to around 173 dB re 1 μPa within 1 km of the source of piling which is comparable to the SL generated by a large ferry or freighter (MMO, 2015). The peak levels of underwater noise that reach the opposite shore of the estuary are predicted to range from approximately 151 to 160 dB re 1 μPa depending on the tidal state. These levels are comparable to the SLs generated by passenger or recreational vessels (MMO, 2015).

7.1.3 The instantaneous peak levels of underwater noise generated during vibro piling are predicted to reduce to around 157 dB re 1 μPa within 1 km of the source of piling which is comparable to the SL generated by a passenger vessel or a recreational boat (MMO, 2015) and within the existing background levels of noise previously measured in the Humber Estuary (Section 4.6).

7.1.4 The levels of underwater noise generated by dredging and vessel movements are predicted to reach existing background levels within around 100 m from the source. It should be noted that the proposed development 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.

8 Potential Effects

8.1 Fish

Impact piling

8.1.1 The calculator developed by NMFS (2021) 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 (Popper *et al*., 2014) are reached. The model input values and associated assumptions for impact piling are included in Table 5.

Table 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 (NMFS, 2021) 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 5.2).
Peak SPL SL	232	The peak SL was based on the use of the Environment Agency model of observed level versus pile diameter (Equation 2) and the assumption that two piling rigs with impact hammers will be used concurrently (see Section 5.2).
SEL SL	207	As no direct measurements were available, the SEL SL was estimated by subtracting 25 dB from the peak SL as per the NMFS pile driving calculator instructions (NMFS, 2021).
RMS SL	217	As no direct measurements were available, the RMS SL was estimated by subtracting 15 dB from the peak SL as per the NMFS pile driving calculator instructions (NMFS, 2021).
Distance from source (m)	1	The peak SL was based on values at 1 m from the source (see Section 5.2).
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 3).

8.1.2 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 proposed development are included in Table 6.

Table 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)	25	82	25	138	2,629
Swim bladder is not involved in hearing (particle motion detection)	25	56	25	138	2,629
No swim bladder (particle motion detection)	12	18	12	26	2,629
Eggs and larvae	25	56	(N) Moderate (I) Low (F) Low		2,629

8.1.3 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.

8.1.4 Behavioural reactions are anticipated to occur across the entire width of the estuary at low water and the majority of the estuary width (77 %) 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.

8.1.5 The scale of the behavioural effect is also dependent on the size of fish (which affects maximum swimming speed). The physical processes chapter (Chapter 7, Volume 1 of PEIR) notes that peak flows above 1.8 m/s are recorded in the area of the Humber Estuary fronting the Port of Immingham. Assuming that fish are not swimming actively but instead moving only passively with tidal flows, they would take around 49 minutes to travel up or down estuary through the zone of behavioural disturbance during impact piling. 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, are able to move out of the behavioural effects zone in less time.

8.1.6 The effects of piling noise on fish also need to be considered in terms of the duration of exposure. Piling noise will take place over a period of approximately 20 weeks. Piling will not take place continuously as there will be periods of downtime, pile positioning and set up.

8.1.7 The piling works will be undertaken 7 am to 7 pm (Monday to Friday) and 7am to 1 pm (Saturday). 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 around 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 11 % (based on a worst case 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 11 % of the time. Furthermore, piling during daytime hours will benefit migratory species that tend to move at night, such as the European eel.

8.1.8 It is also important to consider the noise from piling against existing background or ambient noise conditions (Section 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

8.1.9 The calculator developed by NMFS (2021) has been used to calculate the range at which the instantaneous peak and cumulative SEL thresholds for vibro driving (Popper *et al*., 2014) are reached. The model input values and associated assumptions for vibro piling are included in Table 7.

8.1.10 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 8.

8.1.11 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.

8.1.12 Behavioural reactions are anticipated to occur across the 44 % of the width of the estuary at low water and 30 % 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 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 (NMFS, 2021) 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 5.2).
Peak SPL SL	198	Loudest near-source (10 m from the source) sound pressure measurements for the vibratory piling installation of 1.8 m steel pipe piles in a shallow water environment (Illinworth & Rodkin, 2007; ICF Jones & Stokes and Illingworth and Rodkin, 2009) and the assumption that two piling rigs with vibro hammers will be used concurrently (see Section 5.2).
SEL SL	183	As above.
RMS SL	183	As above.
Distance from source (m)	10	Distance from the source at which the sound levels were measured for the vibratory piling installation of 1.8 m steel pipe piles in a shallow water environment (Illinworth & Rodkin, 2007; ICF Jones & Stokes and Illingworth and Rodkin, 2009) (see Section 5.2).
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 3).

Table 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	63	1,003
Swim bladder is not involved in hearing (particle motion detection)	3	26	3	63	1,003
No swim bladder (particle motion detection)	1	8	1	12	1,003
Eggs and larvae	25	56	(N) Moderate (I) Low (F) Low		1,003

8.1.13 The scale of the behavioural effect is also dependent on the size of fish (which affects maximum swimming speed). The physical processes chapter (Chapter 7) notes that peak flows above 1.8 m/s are recorded in the area of the Humber Estuary fronting the Port of Immingham. Assuming that fish are not swimming actively but instead moving only passively with tidal flows, they would take around 19 minutes to travel up or down estuary through the zone of behavioural disturbance during impact piling. 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, are able to move out of the behavioural effects zone in less time.

8.1.14 The effects of piling noise on fish also need to be considered in terms of the duration of exposure. Piling noise will take place over a period of approximately 7 weeks. Piling will not take place continuously as there will be periods of downtime, pile positioning and set up.

8.1.15 The piling works will be undertaken 7 am to 7 pm (Monday to Friday) and 7am to 1 pm (Saturday). 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 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.

8.1.16 It is also important to consider the noise from piling against existing background or ambient noise conditions (Section 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

8.1.17 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 proposed development are included on Table 9.

8.1.18 The worst case SL generated by dredging and vessels is below the Popper *et al.* (2014) 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 Popper *et al.* (2014) 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 9).

8.1.19 According to Popper *et al*. (2014), 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 9).

8.1.20 Popper *et al*. (2014) 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 9).

8.1.21 Popper *et al.* (2014) 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 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.

8.1.22 The range at which the Hawkins *et al.* (2014) quantitative instantaneous peak SPL behavioural threshold is reached is within around 52 m from dredging, noting that this will be a moderate behavioural response in fish with a swim bladder or air cavities that aid hearing and a minor behavioural response in fish with a swim bladder that does not aid hearing and fish without a swim bladder. This broadly correlates with the Popper *et al*. (2014) qualitative behavioural guidelines discussed above.

8.1.23 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 short term (approximately 100 days (14 weeks) in total).

Table 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	Behaviour
Swim bladder involved in hearing (primarily pressure detection)	(N) Low (I) Low (F) Low	10	46	(N) High (I) Moderate (F) Low	52
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	52
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	52
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	52

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).

8.2 Marine mammals

Impact piling

8.2.1 NOAA's user spreadsheet tool (NOAA, 2021) has been used to predict the range at which the weighted cumulative SEL and instantaneous peak SPL acoustic thresholds (NOAA, 2018) for the onset of PTS and TTS are reached during the proposed impact piling activity.

8.2.2 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 10.

Table 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 (NOAA, 2021).
Sound Pressure Level (L_{rms}), specified at "x" metres (dB re 1 μPa)	217	The peak SL was based on the use of the Environment Agency model of observed level versus pile diameter (Equation 2) and the assumption that two piling rigs with impact hammers will be used concurrently (see Section 5.2). As no direct measurements were available, the RMS SL was estimated by subtracting 15 dB from the peak SL as per the NMFS pile driving calculator instructions (NMFS, 2021).
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 5.2).
Strike (pulse) duration (seconds)	0.1	Default value provided in the NOAA instructions (NOAA, 2021).
Number of strikes per pile	675	Maximum value provided for existing field data in the NMFS pile driving calculator (NMFS, 2021) and, therefore, considered a reasonable worst case.
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 3).
Distance of sound pressure level measurement (m)	1	The peak SL was based on values at 1 m from the source (see Section 5.2).

8.2.3 The distances at which PTS and TTS in marine mammals are predicted to occur during impact piling activities associated with the construction of the proposed development are included in Table 11.

8.2.4 There is predicted to be a risk of instantaneous PTS and TTS in harbour porpoise within 47 m and 102 m respectively from the source of the percussive piling noise. The risk of instantaneous PTS and TTS in seals is within 6 m and 13 m respectively.

8.2.5 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 2.1 km and 14.3 km respectively. The maximum distance for PTS and TTS in seals is 1.1 km and 7.3 km respectively.

8.2.6 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 23 minutes and 2.7 hours respectively. This is less than 11 % 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 12 minutes and 1.4 hours respectively. This is less than 6 % 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.

Table 11. Approximate distances (metres) marine mammal response criteria are reached during impact piling

Marine Mammal Hearing Group	PTS		TTS	
	SEL_{cum}	Peak	SEL_{cum}	Peak
Harbour porpoise	2,085	47	14,341	102
Common seal and grey seal	1,067	6	7,337	13

8.2.7 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.

8.2.8 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.

8.2.9 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 (Southall *et al*., 2007). Mild to moderate behavioural responses of any individuals within these zones could include movement away from a sound source and/or visible startle response (Southall *et al*., 2007).

8.2.10 The effects of piling noise on marine mammals also need to be considered in terms of the duration of exposure. Piling noise will take place over a period of approximately 20 weeks. Piling will not take place continuously as there will be periods of downtime, pile positioning and set up.

8.2.11 The piling works will be undertaken 7 am to 7 pm (Monday to Friday) and 7am to 1 pm (Saturday). 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 around 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 11 % (based on a worst case 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 11 % of the time.

8.2.12 It is also important to consider the noise from piling against existing background or ambient noise conditions (Section 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

8.2.13 NOAA's user spreadsheet tool (NOAA, 2021) has been used to predict the range at which the weighted cumulative SEL acoustic thresholds (NOAA, 2018) for the onset of PTS and TTS are reached during the proposed vibro piling activity.

8.2.14 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 12.

Table 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 (NOAA, 2021).
Sound Pressure Level (L_{rms}), specified at "x" metres (dB re 1 μPa)	183	Loudest near-source (10 m from the source) sound pressure measurements for the vibratory piling installation of 1.8 m steel pipe piles in a shallow water environment (Illinworth & Rodkin, 2007; ICF Jones & Stokes and Illingworth and Rodkin, 2009) and the assumption that two piling rigs with vibro hammers will be used concurrently (see Section 5.2).
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 5.2).
Duration to drive a single pile (minutes)	5	Each tubular pile will require 5 minutes of vibro piling (see Section 5.2).
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 3).
Distance of sound pressure level measurement (m)	10	Distance from the source at which the sound levels were measured for the vibratory piling installation of 1.8 m steel pipe piles in a shallow water environment (Illinworth & Rodkin, 2007; ICF Jones & Stokes and Illingworth and Rodkin, 2009) (see Section 5.2).

8.2.15 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 13.

Table 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)	92	1,209
Phocid pinniped (PW) (true seals)	44	574

8.2.16 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 92 m and 1.2 km respectively. The maximum distance for PTS and TTS in seals is 44 m and 574 m respectively.

8.2.17 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 13 minutes respectively. This is less than 0.9 % 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.

8.2.18 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.

8.2.19 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 (Southall *et al*., 2007). Mild to moderate behavioural responses of any individuals within these zones could include movement away from a sound source and/or visible startle response (Southall *et al*., 2007).

8.2.20 The effects of piling noise on marine mammals also need to be considered in terms of the duration of exposure. Piling noise will take place over a period of approximately 7 weeks. Piling will not take place continuously as there will be periods of downtime, pile positioning and set up.

8.2.21 The piling works will be undertaken 7 am to 7 pm (Monday to Friday) and 7am to 1 pm (Saturday). 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.

8.2.22 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

8.2.23 NOAA's user spreadsheet tool (NOAA, 2021) has been used to predict the range at which the weighted cumulative SEL acoustic thresholds (NOAA, 2018) for PTS and TTS are reached during the proposed dredging and vessel movements associated with the construction and operation of the proposed development.

8.2.24 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 14.

Table 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 (NOAA, 2021) that leads to the greatest predicted ranges for PTS and TTS and is, therefore, considered a worst case.
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 5.3 and Section 5.4).
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.

8.2.25 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 15.

Table 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

8.2.26 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 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.

8.2.27 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 Port of Immingham even if the dredging and vessel movements were to take place continuously 24/7.

9 Summary and Conclusions

9.1.1 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 Immingham Eastern Ro-Ro Terminal.

9.1.2 In accordance with available guidance (NPL, 2014; Farcas *et al*., 2016; Faulkner *et al*., 2018), and as agreed by the MMO and Cefas, 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 (Hawkins *et al*., 2014; Popper *et al*., 2014; NOAA, 2018; Southall *et al*., 2019).

9.1.3 A number of mitigation measures are proposed to reduce or minimise potential adverse effects during construction:

- **Vibro piling**: Vibro piling is proposed to be used as much as possible (which produces lower source noise levels than impact piling). However, in order to drive the piles to the required design level impact piling is likely to be required;
- **Soft start**: The gradual increase of piling power, incrementally, until full operational power is achieved will be used as part of the piling methodology. This will give fish and marine mammals the opportunity to move away from the area before the onset of full impact strikes. The duration of the soft start is proposed to be 20 minutes in line with the JNCC “Statutory nature conservation agency protocol for minimising the risk of injury to marine mammals during piling” (JNCC, 2010); and
- **Impact piling protocol**: A Marine Mammal Observer will follow the JNCC “Statutory nature conservation agency protocol for minimising the risk of injury to marine mammals during piling” (JNCC, 2010) during percussive piling.

10 References

ABPmer. (2015). Royal Pier Waterfront EIA: Marine and Estuarine Ecology. Report for RPW (Southampton) Ltd. ABPmer Report No. R.2438.

ABPmer. (2017). Underwater Noise Monitoring at Green Port Hull, Rationale for completion of monitoring and a summary of findings to date, ABPmer Report No. R.2823. A report produced by ABPmer for Associated British Ports, June 2017.

Battele. (2004). Pinniped Assessment for the Cape Wind Project. Nantucket Sound. Prepared for the US Army Corps of Engineers.

Brandt, M., Diederichs, A., Betke, K. and Nehls, G. (2011). Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea. Marine Ecology Progress Series, 421, pp.205–216.

Brekhovskikh, L.M. (1960). Propagation of surface Rayleigh waves along the uneven boundary of an elastic body. Soviet Physics-Acoustics, 5, pp.288-295.

Carrol., A.G., Przeslawski, R., Duncan, A., Gunning, M. and Bruce B. (2017). A critical review of the potential impacts of marine seismic surveys on fish & invertebrates. Marine Pollution Bulletin, 114, pp.9-24.

Carstensen, J., Henriksen, O.D. and Teilmann, J. (2006). Impacts of offshore wind farm construction on harbour porpoises: Acoustic monitoring of echolocation activity using porpoise detectors (T-PODs). Marine Ecology Progress Series, 321, pp.295–308.

Centre for Environmental Data Analysis (CEDA). (2011). Underwater sound in relation to dredging. CEDA Position Paper - 7 November 2011.

Centre for Environment, Fisheries and Aquaculture Science (Cefas). (2020). The Sizewell C Project: Volume 2 Main Development Site Chapter 22 Marine Ecology and Fisheries Appendix 22L – Underwater noise effects assessment for Sizewell C: Edition 2. Revision 1.0. May 2020.

Christian, J.R., Mathieu, A., Thompson, D.H., White, D. and Buchanan, R.A. (2003). Effect of Seismic Energy on SnowCrab (Chionoecetes opilio). Environmental Funds Project No. 144. Fisheries and Oceans Canada. Calgary (106p).

Clark, C.W., Ellison, W.T., Southall, B.L., Hatch, L., Van Parijs, S.M., Frankel, A. and Ponirakis, D. (2009). Acoustic masking in marine ecosystems: intuitions, analysis, and implication. Marine Ecology Progress Series, 395, pp.201-222.

Dähne, M., Gilles, A., Lucke, K., Peschko, V., Adler, S., Krügel, K. and Sundermeyer, J. (2013). Effects of pile-driving on harbour porpoises (Phocoena phocoena) at the first offshore wind farm in Germany. Environmental Research Letters, 8(2), 0.025002.

Day, R.D., McCauley, R., Fitzgibbon, Q.P. and Semmens, J.M. (2016). Assessing the Impact of Marine Seismic Surveys on Southeast Australian Scallop and Lobster Fisheries. (FRDC Report 2012/008) University of Tasmania, Hobart.

De Jong, C.A.F., Ainslie, M.A., Dreschler, J., Jansen, E., Heemskerk, E. and Groen, W. (2010). Underwater noise of Trailing Suction Hopper Dredgers at Maasvlakte 2: Analysis of source levels and background noise. Commissioned by Port of Rotterdam. TNO report TNO-DV, p.C335.

Dekeling, R.P.A., Tasker, M.L., Van der Graaf, A.J., Ainslie, M.A., Andersson, M.H., André, M., Borsani, J.F., Brensing, K., Castellote, M., Cronin, D. and Dalen, J. (2014). Monitoring Guidance for Underwater Noise in European Seas, Part II: Monitoring Guidance Specifications. A guidance document within the Common Implementation Strategy for the Marine Strategy Framework Directive by MSFD Technical Subgroup on Underwater Noise.

Department for Environment, Food and Rural Affairs (Defra). (2019). Marine strategy part one: UK updated assessment and Good Environmental Status. [Online] Available at: https://www.gov.uk/government/publications/marine-strategy-part-one-uk-updated-assessment-and-good-environmental-status.

Department for Infrastructure and Transport (DPTI). (2012). Underwater Piling Noise Guidelines. Government of South Australia, Department of Planning, Transport and Infrastructure. First published: November 2012. Version 1.

Diederichs, A., Brandt, M.J., Betke, K. and Nehls G. (2011). Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea. Marine Ecological Progress Series, 421, pp.205-216.

Dunlop, R.A., Noad, M.J., McCauley, R.D., Scott-Hayward, L., Kniest, E., Slade, R. and Cato, D.H. (2017). Determining the behavioural dose response relationship of marine mammals to air gun noise and source proximity. Journal of Experimental Biology, 220, pp.2878–2886.

Ellison, W.T., Southall B.L., Clark C.W. and Frankel A.S. (2012). A new context-based approach to assess marine mammal behavioural responses to anthropogenic sounds. Conservation Biology, 26(1), pp.21-28.

Farcas, A., Thompson, P.M. and Merchant, N.D. (2016). Underwater noise modelling for environmental impact assessment. Environmental Impact Assessment Review, 57, pp.114-122.

Faulkner, R.C., Farcas, A. and Merchant, N.D. (2018). Guiding principles for assessing the impact of underwater noise. Journal of Applied Ecology, 55(6), pp.2531-2536.

Guerra, Á., González, Á.F. and Rocha, F. (2004). A review of the records of giant squid in the north-eastern Atlantic and severe injuries in Architeuthis dux stranded after acoustic explorations. ICES CM 200, 29.

Harland, E.J., Jones, S.A.S. and Clarke, T. (2005). SEA 6 Technical report: Underwater ambient noise. QINETIQ/S&E/MAC/CR050575.

Harris, R.E., Miller, G.W. and Richardson, W.J. (2001). Seal responses to airgun sounds during summer seismic surveys in the Alaskan Beaufort Sea. Marine Mammal Science, 17, pp.795–812.

Hastings, M.C. and Popper, A.N. (2005). Effects of sound on fish. California Department of Transportation. Division of Research and Innovation Office Materials and Infrastructure.

Hawkins, A.D. and Myrberg Jr, A.A. (1983). Hearing and sound communication under water. In: Bioacoustics: A Comparative Approach (Ed. by B. Lewis), pp. 347-405: Academic Press.

Hawkins, A.D., Roberts, L. and Cheesman, S. (2014). Responses of free-living coastal pelagic fish to impulsive sounds. The Journal of the Acoustical Society of America, 135, pp.3101-3116.

Hawkins, A.D., Pembroke, A. and Popper, A. (2015). Information gaps in understanding the effects of noise on fishes and invertebrates. Reviews in Fish Biology and Fisheries, 25, pp.39–64.

Hawkins, A. and Popper, A.N. eds. (2016). The effects of noise on aquatic life II. Springer.

Hawkins A. D. and Popper, A. N. (2017). A sound approach to assessing the impact of underwater noise on marine fishes and invertebrates. ICES Journal of Marine Science, 74(3), pp.635–651.

ICF Jones and Stokes and Illingworth and Rodkin. (2009). Technical Guidance for Assessment and Mitigation of the Hydroacoustic Effects of Pile Driving on Fish. Prepared for: California Department of Transportation. [Online] Available at: http://www.dot.ca.gov/hq/env/bio/files/Guidance_Manual_2_09.pdf.

Illingworth, R. and Rodkin, R. (2007). Compendium of Pile Driving Sound Data. Prepared for: The California Department of Transportation, Sacramento, CA.

Joint Nature Conservation Committee (JNCC). (2010). Statutory nature conservation agency protocol for minimising the risk of injury to marine mammals from piling noise.

Jones, D. and Marten, K. (2016). Dredging sound levels, numerical modelling and EIA. Terra et Aqua, 144, pp.21-29.

Kastelein, R.A., Verboom, W.C., Jennings, N., de Haan, D. and van der Heul, S. (2008). The influence of 70 and 120 kHz tonal signals on the behaviour of harbor porpoises (Phocoena phocoena) in a floating pen. Marine Environmental Research, 66(3), pp.319-326.

Koschinski, S., Culik, B.M., Henriksen, O.D., Tregenza, N., Ellis, G., Jansen, C. and Käthe, G. (2003). Behavioural reactions of free-ranging porpoises and seals to the noise of a simulated 2 MW windpower generator. Marine Ecology Progress Series, 265, pp.263–273.

Lee-Dadswell, G.R. (2009). Theoretical Examination of the Absorption of Energy by Snow Crabs Exposed to Seismic Air-gun Pulses: Stage 2-Improvements to Model and Examination of Resonances. Technical Report, OEER Association.

MacGillivray, A., Austin, M. and Hannay, D. (2004). Underwater sound level and velocity measurements from study of airgun noise impacts on Mackenzie River fish species. JASCO Research Pvt. Ltd., Japan.

Malme, C.I., Miles, P.R., Miller, G.W., Richardson, W.J., Roseneau, D.G., Thomson, D.H. and Greene, C.R. (1989). Analysis and ranking of the acoustic disturbance potential of petroleum industry activities and other sources of noise in the environment of marine mammals in Alaska. Final Report No. 6945 to the US Minerals Management Service, Anchorage, AK. BBN Systems and Technologies Corp.

Marine Management Organisation (MMO). (2015). Modelled Mapping of Continuous Underwater Noise Generated by Activities. A report produced for the Marine Management Organisation, pp 50. MMO Project No: 1097. ISBN: 978-1-909452-87-9.

Marine Management Organisation (MMO). (2021). MMO scoping consultation response on the application by Associated British Ports (the Applicant) for an Order granting Development Consent for the Immingham Eastern Ro-Ro Terminal (the Proposed Development). Letter dated 12 October 2021 (Ref: DCO/2021/00004).

Martin, B., Zeddies, D.G., Gaudet, B. and Richard, J. (2016). Evaluation of three sensor types for particle motion measurement. In: The Effects of Noise on Aquatic Life II, pp.679–686. Ed. by A. N. Popper, and A. D. Hawkins. Springer, New York.

Matuschek, R. and Betke, K. (2009). Measurements of Construction Noise During Pile Driving of Offshore Research Platforms and Wind Farms. NAG/DAGA 2009, Rotterdam.

McCauley, R.D., Fewtrell, J., Duncan, A.J., Jenner, C., Jenner, M-N., Penrose, J.D., Prince, R.I.T., Adhitya, A., Murdoch, J. and McCabe, K. (2000). Marine seismic surveys – A study of environmental implications. Appea Journal, pp.692-707.

McKenna, M.F., Ros, D., Wiggins, S.M. and Hildebrand, J.A. (2012). Underwater radiated noise from modern commercial ships. Journal of the Acoustical Society America, 131(1), pp.92-103.

McQueen, A.D., Suedel, B.C. and Wilkens, J.L. (2019). Review of the Adverse Biological Effects of Dredging-induced Underwater Sounds. WEDA Journal of Dredging, 17(1).

Moulton, V.D., Richardson, W.J., Williams, M.T. and Blackwell, S.B. (2003). Ringed seal densities and noise near an icebound artificial island with construction and drilling. Acoustics Research Letters Online, 4, p.112.

Mueller-Blenkle, C., McGregor, P.K., Gill, A.B., Andersson, M.H., Metcalfe, J., Bendall, V., Sigray, P., Wood, D. and Thomsen, F. (2010). Effects of pile-driving noise on the behaviour of marine fish. COWRIE Ref: Fish 06-08, Technical Report 31 March 2010.

National Marine Fisheries Service (NMFS). (2021). Section 7 Consultation Guidance: Pile Driving Noise Calculator (Excel spreadsheet download). [Online] Available at: https://www.fisheries.noaa.gov/southeast/consultations/section-7-consultation-guidance (accessed October 2021).

National Oceanic and Atmospheric Administration (NOAA). (2018). 2018 Revisions to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0): Underwater Thresholds for Onset of Permanent and Temporary Threshold Shifts. U.S. Dept. of Commer., NOAA. NOAA Technical Memorandum NMFS-OPR-59, 167p.

National Oceanic and Atmospheric Administration (NOAA). (2021). User Manual and User Spreadsheet Tool - 2018 Acoustic Technical Guidance. [Online] Available at: https://www.fisheries.noaa.gov/action/user-manual-optional-spreadsheet-tool-2018-acoustic-technical-guidance (accessed August 2021).

National Physical Laboratory (NPL). (2014). Good Practice Guide for Underwater Noise Measurement, National Measurement Office, Marine Scotland, The Crown Estate, Robinson, S.P., Lepper, P. A. and Hazelwood, R.A., NPL Good Practice Guide No. 133, ISSN: 1368-6550.

Nedelec, S.L., Campbell, J., Radford, A.N., Simpson, S.D. and Mercant, N.D. (2016). Particle motion: the missing link in underwater acoustic ecology. Methods in Ecology and Evolution, 7, pp.836-842.

Nedwell, J.R., Turnpenny, A.W.H., Lovell, J., Parvin, S.J., Workman, R., Spinks, J.A.L. and Howell, D. (2007a). A validation of the dBht as a measure of the behavioural and auditory effects of underwater noise. Subacoustech Report No. 534R1231.

Nedwell, J.R., Parvin, S.J., Edwards, B., Workman, R., Brooker, A.G. and Kynoch, J.E. (2007b). Measurement and interpretation of underwater noise during construction and operation of offshore wind farms in UK waters. Subacoustech Report No. 544R0738 to COWRIE Ltd. ISBN: 978-0-9554279-5-4.

Nedwell, J.R., Parvin, S.J., Brooker, A.G. and Lambert, D.R. (2008). Subacoustech Report No. 805R0444.

Pearson, W.H., Skalski, J.R. and Malme, C.I. (1992). Effects of sounds from a geophysical survey device on behaviour of captive rockfish (Sebastes spp.). Canadian Journal of Fisheries and Aquatic Sciences, 49(7), pp.1343-1355.

Pena, H., Handegard, N.O. and Ona, E. (2013). Feeding herring schools do not react to seismic air gun surveys. ICES Journal of Marine Science, 70, pp.1174–1180.

Pirotta, E., Brookes, K. L., Graham, I. M., and Thompson, P. M. 2014. Variation in harbour porpoise activity in response to seismic survey noise. Biology Letters, 10: 5.

Popper A.N. and Coombs S. (1982). The morphology and evolution of the ear in Actinopterygian fishes. American Zoologist, 22, pp.311–328.

Popper, A.N. and Hastings, M.C. (2009). The effects of anthropogenic sources of sound on fishes. Journal of Fish Biology, 75, pp.455-489.

Popper A.N. and Fay R.R. (2011). Rethinking sound detection by fishes. Hearing Research, 273(1-2), pp.25–36.

Popper A.N., Hawkins A.D., Fay R.R., Mann D.A., Bartol S., Carlson T.J., Coombs S., Ellison W.T., Gentry R.L., Halvorsen M.B., Løkkeborg S., Rogers P.H., Southall B.L., Zeddies D.G. and Tavolga W.N. (2014). Sound exposure guidelines for fishes and sea turtles: a technical report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI. ASA S3/SC1.4 TR-2014. Springer and ASA Press, Cham, Switzerland.

Popper, A.N. and Hawkins, A.D. (2018). The importance of particle motion to fishes and invertebrates. Journal of the Acoustical Society of America, 143(1), pp.470-488.

Radford, C.A., Montgomery, J.C., Caiger, P. and Higgs, D.M. (2012). Pressure and particle motion detection thresholds in fish: a re-examination of salient auditory cues in teleosts. Journal of Experimental Biology, 215(19), pp.3429-3435.

Reine, K.J., Clarke, D.G. and Dickerson, C. (2012). Characterization of underwater sounds produced by a hydraulic cutterhead dredge fracturing limestone rock.

Richardson, W.J., Green Jr, C.R., Malme, C.I. and Thomson, D.H. (1995). Marine Mammals and Noise. Academic Press, New York.

Roberts, L., Hardig, H.R., Voellmy, I., Bruintjes, R., Simpson, S.D., Radford, A.N., Breithaupt, T. and Elliott M. (2016). Exposure of benthic invertebrates to sediment vibration: From laboratory experiments to outdoor simulated pile-driving. Proc. Mtgs. Acoust. 27. [Online] Available at: https://doi.org/10.1121/2.0000324.

Robinson, S.P., Theobald, P.D., Hayman, G., Wang, L.S., Lepper, P.A., Humphrey, V. and Mumford, S. (2011). Measurement of noise arising from marine aggregate dredging operations. Marine Aggregate Levy Sustainability Fund (MALSF). MEPF Ref no. 09/P108.

Sigray, R. and Andersson, M.H. (2011). Particle motion measured at an operational wind turbine in relation to hearing sensitivity in fish. Journal of the Acoustical Society of America, 130, pp.200–207.

Sisneros, J.A., Popper, A.N., Hawkins, A.D. and Fay, R.R. (2016). Auditory Evoked Potential audiograms compared to behavioural audiograms in aquatic animals. In: The Effects of Noise on Aquatic Life, II, pp. 1049–1056. Ed. by A. N. Popper, and A. D. Hawkins. Springer Science Business Media, New York.

Southall, B.L., Bowles, A.E., Ellison, W.T., Finneran, J.J., Gentry, R.L., Greene Jr, C.R., Kastak, D., Miller, J.H., Nachigall, P.E., Richardson, W.J., Thomas, J.A. and Tyack, P.L. (2007). Marine mammal noise exposure criteria: initial scientific recommendations. Aquatic Mammals, 33, pp.411–521.

Southall, B.L., Finneran, J.J., Reichmuth, C., Nachtigall, P.E., Ketten, D.R., Bowles, A.E., Ellison, W.T., Nowacek, D.P. and Tyack, P.L. (2019). Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects. Aquatic Mammals, 45(2), p.125.

Spiga, I., Caldwell, G.S. and Bruintjes, R. (2016). Influence of Pile Driving on the Clearance Rate of the Blue Mussel, Mytilus edulis (L.). In Proceedings of Meetings on Acoustics 4ENAL (Vol.27, No.1, p.040005). Acoustical Society of America. [Online] Available at: https://doi.org/10.1121/2.0000277.

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

Thomsen, F., McCully, S., Wood, D., Pace, F. and White, P. (2009). A generic investigation into Noise Profiles of Marine Dredging in Relation to the Acoustic Sensitivity of the Marine Fauna in UK Waters with Particular Emphasis on Aggregate Dredging: PHASE 1 Scoping and Review of Key Issues. MEPF Ref No. MEPF/08/P21.

Thomsen, F., McCully, S.R., Weiss, L.R., Wood, D.T., Warr, K.J., Barry, J. and Law, R.J. (2011). Cetacean stock assessments in relation to exploration and production industry activity and other human pressures: review and data needs. Aquatic Mammals, 37(1), pp.1-93.

Tidau, S. and Briffa, M. (2016). Review on behavioural impacts of aquatic noise on crustaceans. In Proceedings of Meetings on Acoustics 4ENAL, (Vol.27, No.1, p.010028). Acoustical Society of America. [Online] Available at: http://dx.doi.org/10.1121/2.0000302.

Tougaard, J., Carstensen, J., Teilmann, J., Skov, H., and Rasmussen, P. (2009). Pile driving zone of responsiveness extends beyond 20 km for harbor porpoises (Phocoena (L.)). The Journal of the Acoustical Society of America, 126, pp.11–14.

UK Marine Monitoring Assessment Strategy (UKMMAS). (2010). Charting Progress 2 Feeder report: Clean and Safe Seas. (Eds. Law, R. and Maes, T.). Published by Department for Environment Food and Rural Affairs on behalf of UKMMAS. p.366.

Urick, R.J. (1983). Principles of Underwater Sound for Engineers. Urick, R. New York: McGraw-Hill, 1984.

URS Scott Wilson. (2011). Green Port Hull Environmental Statement.

Webb, J.F., Montgomery, J.C. and Mogdans, J. (2008). Bioacoustics and the lateral line system of fishes. In Fish Bioacoustics (pp. 145-182). Springer, New York, NY.

Wenger, A.S., Harvey, E., Wilson, S., Rawson, C., Newman, S.J., Clarke, D., Saunders, B.J., Browne, N., Travers, M.J., Mcilwain, J.L. and Erftemeijer, P.L. (2017). A critical analysis of the direct effects of dredging on fish. Fish and Fisheries, 18(5), pp.967-985.

Wenz, G.M.J. (1962). Acoustic ambient noise in the ocean: Spectra and sources. Journal of Acoustical Society of America, 34, pp.1936–1956.

World Organisation of Dredging Associations (WODA). (2013). Technical Guidance on: Underwater Sound in Relation to Dredging.

Wysocki, L.E. and Ladich, F. (2005). Hearing in fishes under noise conditions. Journal of the Association of Research in Otolaryngology, 6, pp.28–36.

11 Abbreviations/Acronyms

ABP	Associated British Ports
CEDA	Centre for Environmental Data Analysis
Cefas	Centre for Environment, Fisheries and Aquaculture Science
dB	Decibel
DCO	Development Consent Order
Defra	Department for Environment, Food and Rural Affairs
DPTI	Department for Infrastructure and Transport
EMMP	Environmental Management and Monitoring Plan
ES	Environmental Statement
EU	European Union
GPH	Green Port Hull
HF	High Frequency
HRA	Habitats Regulations Assessment
IFM	Institute of Fisheries Management
JNCC	Joint Nature Conservation Committee
MMO	Marine Management Organisation
MSFD	Marine Strategy Framework Directive
µPa	microPascal
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NPL	National Physical Laboratory
Pa	Pascal
PEIR	Preliminary Environmental Information Report
RMS	Root Mean Square
SD	Standard Deviation
SEL	Sound Exposure Level
SL	Source Level
SPL	Sound Pressure Level
TSG	Technical Sub-Group
TSHD	Trailing Suction Hopper Dredger
TTS	Temporary Threshold Shift
UKMMAS	UK Marine Monitoring Assessment Strategy
WFD	Water Framework Directive
WODA	World Organisation of Dredging Associations

Cardinal points/directions are used unless otherwise stated.

SI units are used unless otherwise stated.

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