



Immingham Green Energy Terminal

TR030008

Volume 6

6.4 Environmental Statement Appendices
Appendix 9.B: Underwater Noise Assessment

Planning Act 2008

Regulation 5(2)(a) and 5(2)(l)

Infrastructure Planning (Applications: Prescribed
Forms and Procedure) Regulations 2009 (as
amended)

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Infrastructure Planning

Planning Act 2008

The Infrastructure Planning
(Applications: Prescribed Forms and
Procedure) Regulations 2009 (as amended)

Immingham Green Energy Terminal

Development Consent Order 2023

6.4 Environmental Statement Appendices

Appendix 9.B: Underwater Noise Assessment

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1 Underwater Noise

1.1 Introduction

1.1.1 This report presents an assessment of the potential effects of underwater noise and vibration from the Project on marine fauna. The assessment has been undertaken to support the Environmental Statement (“ES”) that has been prepared for the Project. In particular, the assessment has informed the outcomes of the marine ecology assessment (**Chapter 9: Nature Conservation (Marine Ecology) [TR030008/APP/6.2]**), which in turn will inform the Shadow Habitats Regulations Assessment (“HRA”) and the Water Framework Directive (“WFD”) Compliance assessment which will be included in the ES and submitted with the Development Consent Order (“DCO”) application. A detailed description of the Project and construction methodology on which this assessment is based on is included in **Chapter 2: The Project [TR030008/APP/6.2]**.

1.1.2 This report has been structured as follows:

- a. **Section 1.1: Introduction** provides a brief introduction to the project and need for this assessment.
- b. **Section 1.2: Consultation** presents the feedback that has been received from relevant stakeholders, along with how it has influenced this assessment.
- c. **Section 1.3: Principles of Underwater Acoustics** presents the basic principles which are fundamental to undertaking robust underwater noise assessments.
- d. **Section 1.4: 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.
- e. **Section 1.5: Ambient Noise** presents the baseline acoustic conditions of the study area.
- f. **Section 1.6: Noise Characteristics of Proposed Development Activities** presents the specific acoustic characteristics of the proposed construction and operational activities.
- g. **Section 1.7: 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.
- h. **Section 1.8: Noise Propagation Modelling Outputs** presents the outputs of the underwater noise modelling.
- i. **Section 1.9: Potential Effects** reviews the potential effects on local marine fauna.
- j. **Section 1.10: Summary and Conclusions** presents an overview of the outcome of the underwater noise assessment and conclusions.

1.2 Consultation

- 1.2.1 Consultation on the underwater noise assessment has been undertaken with the Marine Management Organisation (“MMO”) and Cefas (as advisors to the MMO). The outcome of the consultation that has been undertaken to date, along with how it has influenced this underwater noise assessment, is presented in **Table 1**.

Table 1: Consultation summary table

Reference/date	Consultee	Summary of responses	How comments have been addressed
Statutory Consultation January 2023	MMO	The impacts from piling have been assessed as potentially significant for Atlantic salmon (<i>Salmo salar</i>), sea trout (<i>Salmo trutta</i>), European smelt (<i>Osmerus eperlanus</i>), shads (<i>Alosa</i> spp.) and European eel (<i>Anguilla Anguilla</i>). The MMO agree that impacts from piling on migratory fishes should be considered as potentially significant at this stage. However, further assessment and clarification is needed in relation to the underwater noise modelling used to support the conclusions on the significance of effect, and to determine whether additional mitigation is needed.	Noted.
		According to the PEIR, the likely maximum impact piling scenario is for tubular piles to be installed each day using up to four piling rigs. However, it is unclear whether all four rigs will be in operation concurrently. Conversely, Section 1.5.9 of this appendix states that “Piling will be undertaken simultaneously using piling rigs. Adding to identical sources (i.e. doubling the signal)”. It is therefore not clear why concurrent piling using two rigs has been modelled, if four rigs are going to be in operation concurrently. If four piling rigs are to be operating concurrently then this should be modelled as the worst-case scenario. It would also be beneficial if the locations of the rigs used in the modelling were mapped/described to ascertain whether the worst case scenario, in terms of impact range from concurrent piling, has been suitably modelled.	The project methodology has been updated since the PEI Report and there will now be up to two piling rigs driving piles concurrently during construction (Section 1.6). Although it is highly unlikely that the piling hammers will strike in unison to create a cumulative effect, the modelled source level has taken account of two piling sources operating concurrently as a worst case. The locations of the piling rigs have been clarified in the ES to determine whether the worst case in terms of impact range from concurrent piling has been suitably modelled. One of the piling rigs will be located on the jetty approach and one for the jetty head.
		The range of effect for mortal injury, recoverable injury and behavioural effects are presented in Tables 1.6 and 1.8 (Appendix 9B) for percussive and vibro piling respectively, but the range of effect for Temporary Threshold Shift (TTS)	The TTS ranges have been modelled and assessed for both percussive and vibro piling (Section 1.9).

Reference/date	Consultee	Summary of responses	How comments have been addressed
		<p>has not been included. TTS should be modelled and presented in the ES for percussive and vibro piling. Behavioural reactions in fish are predicted to occur across 67% width of the estuary at low water and 46% of the estuary width at high water, and on this basis, the report recognises that there is a risk of a partial acoustic ‘barrier’ to fish movement in the estuary. In order to consider the likelihood and significance of behavioural impacts from piling on migratory species, the dates (i.e., months) when piling will be carried out should be provided. The timing of piling should be discussed in the context of the periods of migration for fish within the Humber Estuary so that appropriate temporal mitigation measures can be more easily determined. The MMO disagree with the estimates of the time fish receptors will be exposed to piling. Firstly, 200 minutes of piling (i.e., 20 minutes of vibro piling and 180 minutes of impact piling) per day would amount to approximately 14% not 13% of a 24-hour day. In addition, piling is disproportionally occurring during daylight hours (7am – 7pm), amounting to approximately 28% of a 12-hour shift. This has the potential to disproportionately affect diurnal migration patterns. Although not necessarily significant this should be considered in the upcoming ES.</p>	<p>The exact timing and programme for the piling has not been confirmed at this stage and, therefore, the assessment has been undertaken on the basis that the works could take place at any time of year as a worst case. Further details of the sensitive seasons for fish species that migrate through the Humber Estuary is provided in Chapter 9: Nature Conservation (Marine Ecology) [TR030008/APP/6.2].</p> <p>The project methodology has been updated since the PEI Report and there will now be approximately 60 minutes of vibro piling and 270 minutes of impact piling per day in a 12 hour shift (Section 1.6). As noted in Section 1.9, the proportion of impact piling is estimated to be at worst around 19 % over a 24 hour period (based on 270 minutes of impact piling each working day). The proportion of vibro piling is estimated to be at worst around 4 % over a 24 hour period (based on 60 minutes of vibro piling each working day). The total estimated time over the period of a day, therefore, that fish receptors will be exposed to any piling (based on 330 minutes of piling each working day) is approximately 23 %.</p> <p>It is noted that piling activity will take place during daylight hours. The potential to disproportionately affect diurnal migration patterns has been considered in Section 1.9.</p>
		<p>For all other fish receptors, impacts from piling have been assessed as not significant. As the area is considered unlikely to be a key foraging, spawning or nursery ground for other marine fish receptors, and given that these species do not exclusively rely on the estuary for migration, the MMO is content that significant impacts to non-migratory, marine fishes are unlikely to occur.</p>	<p>Noted.</p>

Reference/date	Consultee	Summary of responses	How comments have been addressed
		<p>Impacts from underwater noise resulting from capital dredging have been assessed as not significant for all fish receptors. Based on the Popper <i>et al.</i> (Ref 1-1) thresholds for continuous noise (e.g. dredging and vessel movements), Table 1.9 of the underwater noise report shows that the threshold for recoverable injury is reached at 10 m and at 46 m for TTS. Given that dredging is proposed on a 24/7 basis, it is not clear if these impact ranges are an accurate prediction. Furthermore, prolonged periods of dredging have the potential to result in an in-combination impact to fish from increased dredging and vessel noise, coupled with prolonged periods of increased SSC and reduced water quality. Therefore, these conclusions should be revisited.</p>	<p>The assumptions and model input values are set out in Sections 1.4, 1.6 and the thresholds that were applied are set out in Table 3. The consideration of cumulative effects (noise and SSC) has been revisited in the ES (Chapter 9: Nature Conservation (Marine Ecology) and Chapter 25: Cumulative Effects and In-Combination Assessment [TR030008/APP/6.2]).</p>
		<p>In Section 1.5.8 (Appendix 9B), the ‘SEL metric’ should be clarified as it is not clear what this is. For impact piling, this should be the single strike sound exposure level (SELs). Furthermore, it is not clear why the Root Mean Square (RMS) source level is 10 dB higher than the SEL source level. In any case, the RMS metric is generally not appropriate for assessing impulsive sources such as impact piling, therefore this should be removed. The relevant metrics for assessing the impacts of impulsive activities are SEL_{cum} (calculated by the aggregation of SELs) and SPL_{peak}.</p>	<p>The peak, SEL and RMS levels are those that were measured directly in the field and published in the literature that is referenced in Section 1.6. The SEL that is reported is effectively the SELs. The RMS metric has not been used in the modelling of impacts of impact piling on fish but is included as a specific variable in the NOAA user spreadsheet tool that has been used to assess the effects of impact piling on marine mammals (Section 1.9).</p>
		<p>In Section 1.5.9, it is not clear why two identical sources have been added when it is confirmed that a total of four piling rigs may be used. Furthermore, simultaneous piling from the multiple rigs would likely not increase the received peak pressure levels or the single strike SEL, as the individual pulses (and their peaks) originating from distinct</p>	<p>As noted in a previous response, the Project methodology has been updated since the PEI Report and there will now be up to two piling rigs pile driving concurrently during construction (Section 1.6). Although it is highly unlikely that the piling hammers will strike in unison to create a cumulative effect, the modelled source level has taken</p>

Reference/date	Consultee	Summary of responses	How comments have been addressed
		<p>rigs do not generally overlap (due to the distinct timing of the strikes and the propagation paths). Piling from multiple rigs would however increase the total number of strikes and thus the SEL_{cum} over 24 hours.</p>	<p>account of two piling sources as a worst case. The total number of strikes incorporated in the model has taken account of the maximum number of piles (3) that might be installed each day by two piling rigs and is therefore considered to already represent piling from multiple rigs.</p>
		<p>With regard to Table 1.2 Fish response criteria applied in this assessment, it is appropriate that the assessment refers to noise exposure criteria from Popper et al. (Ref 1-1) for fish species. However, TTS is missing from this table for piling and it should be included (in addition to mortality and potential mortal injury, and recoverable injury). Popper et al. provided a TTS threshold (based on the cumulative sound exposure level, SEL_{cum}) of 186 dB re 1 μPa² s for piling, for all fish species.</p>	<p>TTS has been included in this table in the appendix (Table 3). In addition, the TTS ranges have been modelled and assessed for both percussive and vibro piling (Section 1.9).</p>
		<p>For behaviour, the assessment refers to thresholds derived from Hawkins et al. (Ref 1-2). Hawkins et al Ref 1-2 exposed wild sprat and mackerel to short sequences of repeated impulsive playback sounds at different sound pressure levels, simulating the strikes from a percussive pile driver. Observed behaviour responses included the break up of fish schools, and the incidence of responses increased with increasing sound levels. The sound pressure levels to which the fish schools responded on 50% of the presentations were 163.2 and 163 dB re 1 μPa (peak-to-peak) (and estimated single strike sound exposure levels were 135 dB and 142 dB re 1 μPa² s for sprat and mackerel respectively). Such levels correspond to those recorded at tens of kilometres from an operating pile driver. While recognising that the application of simplistic sound level thresholds for behaviour should generally be avoided, these thresholds can be considered</p>	<p>Noted. In the absence of any other known published thresholds for fish behaviour, it was considered that this simple threshold could be used in this assessment to help to provide an indication of potential behavioural effect. It is recognised that it is not entirely appropriate to convert a peak-peak threshold to a zero-peak threshold, however, a metric conversion provided by NOAA Fisheries in their spreadsheet tool and associated user manual has been used. Furthermore, this behavioural threshold has previously been accepted by the MMO for other recent marine licence applications in England.</p>

Reference/date	Consultee	Summary of responses	How comments have been addressed
		<p>to be a conservative indicator for the risk of behavioural responses and potential displacement. Please note that it is not entirely appropriate to convert the peak-to-peak threshold to a zero-to-peak threshold (of 157 dB peak) as has been done.</p>	
		<p>Table 1.6 provides the modelled predictions for fish and impact piling look plausible / reasonable for mortality and recoverable injury. For behaviour, the predicted effect range is 1,554 m. As noted above, the report states “behavioural reactions are anticipated to occur across 67 % width of the Humber Estuary at low water and 46 % of the estuary width at high water, therefore, potentially creating a partial temporary barrier to fish movements”. The simple modelling approach can only provide an order of magnitude of the potential effects, rather than definitive ranges and percentages. Furthermore, using the propagation assumptions detailed in the report (i.e., $TL = 17.91 + \alpha R$), a behavioural threshold of 135 dB SELss and a source level of 203 dB (assuming that this is SELss), effects would be expected to be out to ~ 6 km. The developer should clarify whether there is the risk of a temporary barrier effect across part or all of the estuary. Regarding Table 1.6, the MMO would expect the potential effects of TTS to be considered for fish and impact piling.</p>	<p>The assumptions are set out in Table 6 and the thresholds that were applied are set out in Table 3. As the simple modelling approach is not able to provide exact or definitive ranges, particularly in the near and far-field, this has been clarified in Section 1.4 and the outputs rounded to the nearest order of magnitude.</p> <p>Applying a behavioural threshold of 135dB SELss to the propagation assumptions detailed in Section 1.4 and a SELss source level of 203 dB for 1 piling rig (and 206 dB for two piling rigs) is predicted to result in an effect out to approximately 2km. If the absorption coefficient (α) is omitted from the model, this results in an output of <i>circa</i> 6km (for a SELss source level of 203 dB) and suggest that the omission of this coefficient in the MMO/Cefas’ estimate accounts for this discrepancy.</p> <p>As noted in previous responses, the potential effects of TTS have been included in the ES.</p>
		<p>There appears to be a discrepancy regarding the source level assumptions for vibro piling. Specifically, Table 1.7 states that the SEL and RMS source level values of 183 dB have been used as input values in the NOAA calculator, as per section 1.5 of the report. However, section 1.5 of the report states that “the SL for the vibratory driving of tubular piles as part of the proposed development is assumed</p>	<p>The SEL and RMS source level values of 183 dB quoted in Table 1.7 of the PEI Report are a typographical error and should be 201 dB in line with the values referenced in Section 1.4 for two piling rigs driving piles concurrently “... <i>the unweighted peak SL of concurrent vibro piling by two piling rigs is assumed to be 201 dB re 1 μPa² s (SEL metric), 216 dB re 1 μPa m (peak SPL metric) and 201 dB</i></p>

Reference/date	Consultee	Summary of responses	How comments have been addressed
		<p>based on the loudest near-source (10 m from the source) sound pressure measurements (SEL, peak SPL and RMS) that have been published for the vibratory piling installation of the nearest-sized 1.83 m steel pipe piles in a shallow water environment. Back calculating the sound pressure measurements to 1 m using the simple logarithmic spreading model provides an estimated SL of 198 dB re 1 $\mu\text{Pa}^2 \text{ s}$ (SEL metric), 213 dB re 1 $\mu\text{Pa m}$ (peak SPL metric) and 198 dB re 1 $\mu\text{Pa}^2 \text{ m}$ (RMS metric). This should be clarified in the report. The MMO also presume that the Popper <i>et al.</i> threshold for impulsive noise have been used in the assessment of vibro piling for fish.</p>	<p>re 1 $\mu\text{Pa m}$ (RMS metric)". This has been clarified and corrected in this appendix (see Table 10).</p> <p>The Popper <i>et al.</i> cumulative SEL thresholds for pile driving have indeed been used in the assessment of vibro piling for fish as indicated on Table 3.</p>
		<p>The report states that dredging operations will be undertaken for 24 hours and therefore, the cumulative sound exposure (over 24 hours) should be considered, although the MMO appreciate that there are no defined SEL_{cum} thresholds at present for continuous sources and fish. Given that pulse sounds such as percussive piling noise are likely to have a greater effect on fish than continuous sources at the same level (Ref 1-3), the Popper <i>et al</i> (Ref 1-1) thresholds for this impact piling could be applied in the assessment of cumulative sound exposure from continuous sources as a precautionary approach (as has presumably been done within this assessment for vibro piling). The MMO agree that 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. Nevertheless, given the 24-hour dredging operations, we would expect larger effects than what has been presented.</p>	<p>Noted. Although, the Popper <i>et al.</i> SEL_{cum} thresholds for piling are not considered appropriate for continuous noise generating activities such as dredging and vessel movements, the modelling has been revisited and these thresholds have been applied to the assessment of dredging noise, in addition to the RMS guideline thresholds (see Table 3 and Section 1.9).</p> <p>As noted in a previous response, the Popper <i>et al.</i> thresholds for pile driving have been used in the assessment of vibro piling for fish (see Table 3).</p>

Reference/date	Consultee	Summary of responses	How comments have been addressed
		<p>The MMO have no major concerns with the predictions for marine mammals for percussive and vibro piling. In general, they appear to be relatively conservative in most cases. However, the predictions in Table 1.15 for dredging and vessel movements look smaller than expected and it is recommended to check whether the SEL_{cum} over 24 hours has been appropriately assessed. Even if we assume a fleeing receptor, then we would still expect larger TTS effect ranges (over part of the estuary) for harbour porpoise, based on 24-hour exposure.</p>	<p>The assumptions and model input values are set out in Sections 1.4 and 1.6 and the thresholds that were applied are set out in Table 4. As explained in Section 1.9, NOAA's user spreadsheet tool (Ref 1-4), has been used in accordance with the guidance provided in NOAA's user manual to predict the range which the weighted NOAA SEL_{cum} acoustic thresholds for PTS and TTS are reached during the proposed dredging and vessel movements associated with the construction and operation of the proposed development. The assumptions and input values to this spreadsheet are clearly set out in Table 19. These have been revisited and checked and the outputs remain unchanged in the appendix, apart from the rounding of distances to the nearest order of magnitude in response to an earlier comment.</p>

1.3 Principals of Underwater Acoustics

Introduction

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

Sound pressure

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

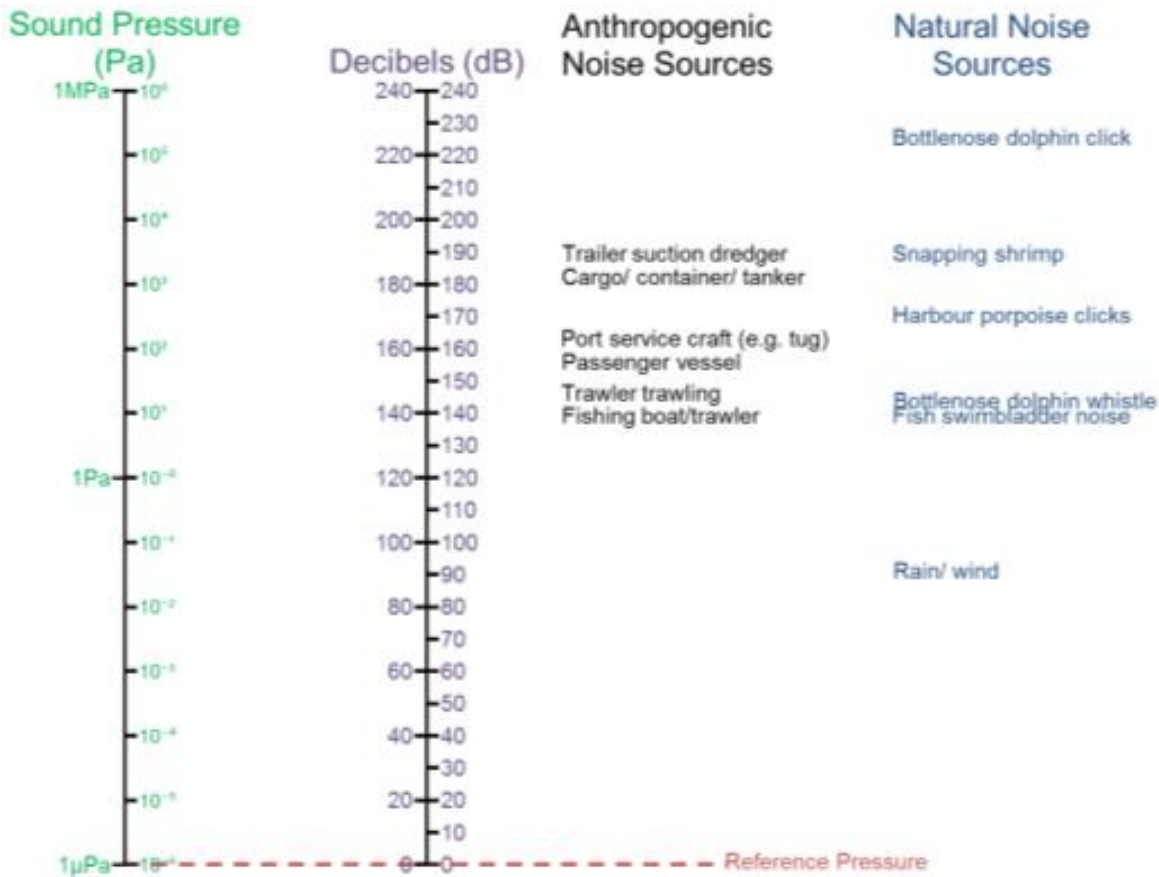
1.3.3 Pressure and pressure variations are expressed in Pascal, abbreviated as Pa, which is defined as Newton per square metre (N/m²). It is not appropriate to express sound or noise in terms of Pa because it would involve dealing with numbers from as small as 0.000001 to as big as 2,000,000. The use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

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

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

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

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



Source: Ref 1-5

Particle motion

- 1.3.6 Particle motion is an oscillation back and forth in a particular direction; it is a vector quantity that can only be fully described by specifying both the magnitude and direction of the motion, as well as its magnitude, temporal, and frequency characteristics. The particle motion component of underwater sound comprises both the velocity (m/s) and the acceleration (m/s²) of molecules in the sound wave.
- 1.3.7 Particle motion was previously considered impossible to record (Ref 1-6). However, two approaches have been used in research to estimate particle acceleration (Ref 1-7): 1) accelerometers and 2) the recording of pressure differences between two hydrophones. This was followed closely by the development of a particle motion sensor (Ref 1-8), which has been validated in field studies near an offshore wind farm in the western part of the Baltic Sea.
- 1.3.8 Detection of particle motion requires different types of sensors than those utilised by a conventional hydrophone (Ref 1-9). Such sensors must specify the particle motion in terms of the particle displacement, or its time derivatives (particle velocity or particle acceleration) in three dimensions.

Underwater noise metrics

- 1.3.9 There are a number of different metrics that may be used as measures of sound pressure (Ref 1-10). The key metrics that are used to characterise noise are as follows:
- a. **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.
 - b. **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.
 - c. **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.
 - d. **Sound exposure level (“SEL”).** The integral of the square of the sound pressure over a stated time interval or event (such as an acoustic pulse). Sound exposure is expressed in units of Pa²-s. The quantity is sometimes taken as a proxy for the energy content of the sound wave. Note that SEL is a useful measure of the exposure of a receptor to a sound field, and a frequency weighting is commonly applied.
 - e. **Frequency weighting.** Frequency-dependent normalised factor(s) by which spectral components are multiplied, resulting in the modification of the amplitude of some components. Frequency weightings are normalised factors and have no units or dimensions but are sometimes expressed as relative factors in decibels (with no reference value). The main motivation for applying a frequency weighting is to account for the frequency-dependent sensitivity of a receptor.
- 1.3.10 The type of pressure measurement used is an important consideration when comparing noise levels and criteria and the type of pressure measurement should be stated when quoting noise levels.

1.4 Underwater Noise Propagation

- 1.4.1 The process of noise travelling through a medium is referred to as noise propagation. The factors that influence the propagation of noise in the marine environment and contribute to propagation (or transmission) loss¹ broadly include the following (Ref 1-10):
- a. The reduction (or attenuation) of sound away from the source due to geometrical spreading.
 - b. Absorption of the sound by the sea-water and the seabed.
 - c. The interaction with the sea-surface (reflection and scattering).
 - d. The interaction with (and transmission through) the seabed.
 - e. The refraction of the sound due to the sound speed gradient.
 - f. The bathymetry (water depth) between source and receiver positions.
 - g. Source and receiver depth.
- 1.4.2 The propagation of underwater noise is a very complex process and, therefore, predicting the received sound pressure levels at distance from a source is extremely difficult. Use is generally made of theoretical models or empirical models based on field measurements.
- 1.4.3 In accordance with good practice guidance (Ref 1-10), a simple logarithmic spreading model has been used to predict the propagation of sound pressure from the sources of construction and operational noise associated with the Project. This model is represented by a logarithmic equation and incorporates factors for noise attenuation and absorption losses. The advantage of this model is that it is simple to use and quick to provide first order calculations of the received (unweighted) sound pressure levels (“SPL”) with distance from the source due to geometric spreading.

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

Equation 1: Simple logarithmic spreading model

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

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

- 1.4.4 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 at Sheffield on 23 May 2013 (Ref 1-11). These observed data were collected from the following construction projects undertaken in shallow water estuarine and coastal locations:
- a. Russian River New Bridge in Geyserville, California (Ref 1-12).
 - b. San Rafael Sea Wall in San Francisco Bay, California (Ref 1-12)
 - c. Scroby Sands Offshore Wind Farm located off the coast of Great Yarmouth (Ref 1-13).
 - d. North Hoyle Offshore Wind Farm in Liverpool Bay (Ref 1-13).
 - e. Kentish Flats Offshore Wind Farm located off the coast of Kent (Ref 1-13)
 - f. Burbo Bank Offshore Wind Farm in Liverpool Bay (Ref 1-13).
 - g. Barrow Offshore Wind Farm located south west of Walney Island (Ref 1-13).
 - h. Belvedere Energy-from-Waste Plant on Thames Estuary (measurements collected by Subacoustech Ltd on behalf of the Environment Agency and Costain).
- 1.4.5 These provide a mean N coefficient of 17.91 (Standard Deviation (“SD”) 3.05) and α coefficient of 0.00523 dB m⁻¹ (SD 0.00377 dB m⁻¹) based on 11 and 9 observations respectively. The Environment Agency has recommended the application of these model input values in underwater noise assessments undertaken in shallow water environments (e.g. Ref 1-14; Ref 1-15). These values are, therefore, considered to be appropriate to use for the underwater noise assessment in support of the Project.
- 1.4.6 Following advice from the MMO and Cefas on another nearby proposed development involving percussive piling on the Humber Estuary (Immingham Eastern Ro-Ro Terminal (“IERRT”)), the received levels associated with the Project activities have been modelled in the SEL metric and then translated to the peak SPL metric using equation (1) in Ref 1-16:

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

Equation 2: Relationship between peak SPL and SEL

- A* is an empirical constant estimated from measurements with an approximate value of 1.4
- B* is an empirical constant estimated from measurements with an approximate value of – 40

- 1.4.7 It is important to recognise that there are a number of limitations associated with the use of simple logarithmic spreading models (Ref 1-10). Such models do not account for changes in bathymetry, and therefore are not able to predict the changes in sound propagation caused by sand banks and complex changes in water depths. In addition, they do not explicitly include frequency dependence, and so cannot predict the increased transmission loss at high frequencies due to increased sound absorption. Ref 1-17 also demonstrated how use of these simple models in complex environments typical of coastal and inland waters can underestimate noise levels close to the source and substantially overestimate noise levels further from the source. In other words, they can underestimate the risk of injury or disturbance to marine fauna close to the source whilst giving the impression that a larger area would be affected.
- 1.4.8 Although this equation generally represents a simplistic model of propagation loss, its use is an established approach in EIAs that has been widely accepted by UK regulators for recent port and waterfront developments. As advised by the MMO and Cefas in their response to the PEI Report, the modelling outputs presented in this appendix have been rounded to the nearest order of magnitude to account for the fact that the simple modelling approach is not able to provide exact or definitive ranges and percentages.
- 1.4.9 In terms of fish, the National Oceanic and Atmospheric Administration (“NOAA”) National Marine Fisheries Service (“NMFS”) in the United States recommends the use of the practical spreading model to developers and has incorporated this model in its pile driving calculation spreadsheet to assess the potential impacts of pile driving on fish (Ref 1-18). This calculator has, therefore, been used to calculate the range at which the peak SPL and SEL_{cum} thresholds for pile driving (Ref 1-1) are reached. Further details of the assumptions and input values that have been applied are provided in **Section 1.9**.
- 1.4.10 In terms of marine mammals, NOAA (Ref 1-4) 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 SEL_{cum} and instantaneous peak SPL acoustic thresholds (Ref 1-19) for the onset of temporary threshold shift (“TTS”) and permanent threshold shift (“PTS”) are reached during the proposed piling, dredging and vessel activity. Further details, including the input values that have been used are presented in **Section 1.9**.
- 1.4.11 The Project takes place in very shallow water and, therefore, the propagation of noise will be limited. Shallow water acts as a high pass filter that only allows signals to pass with a frequency higher than a certain cut-off frequency and attenuates signals with frequencies lower than this cut-off frequency. The cut-off frequency gets higher as the water gets shallower (Ref 1-20). In this way, the propagation of low frequency underwater noise such as piling will be reduced in very shallow water locations compared to in the deep oceanic waters. At high frequencies (>10 kHz), increasing absorption also prevents high frequency sound propagating over great distances in shallow water.

1.4.12 Overall, therefore, a simple logarithmic spreading model is considered proportionate and appropriate to use for this underwater noise assessment.

1.5 Ambient Noise

Introduction

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

Definition

1.5.2 Ambient sound is commonly defined as background acoustic sound without distinguishable sources (e.g. Ref 1-21; Ref 1-22). This definition, however, has the problem of how to identify distinguishable sources, and how to eliminate them from the measurements.

1.5.3 Measurements to characterise the ambient sound in a specific location (i.e. incorporating both natural and anthropogenic sources) are becoming more common as interest grows in the trends in anthropogenic noise in the ocean, for example in response to the Marine Strategy Framework Directive (“MSFD”) and UK Marine Strategy (Ref 1-23). The EU MSFD Technical Sub-Group (“TSG”) on Noise defined ambient sound as follows:

“All sound except that resulting from the deployment, operation or recovery of the recording equipment and its associated platform, where ‘all sound’ includes both natural and anthropogenic sounds” (Ref 1-24, p 20).

1.5.4 Measurements that characterise the ambient sound at specific locations and include noise from identifiable sources together with non-identifiable sources, are also sometimes referred to as the local ‘soundscape’ (Ref 1-10).

Sources of ambient sound

1.5.5 Ambient sound covers the whole acoustic spectrum from below 1 Hz to well over 100 kHz (Ref 1-20). At the lower frequencies shipping noise dominates, while at the higher frequencies noise from waves and precipitation dominates.

1.5.6 Natural sources of ambient sound comprise both physical processes and biological activity. Physical processes that are relevant to the study area include wind- and wave-driven turbulence, precipitation and sediment transport processes (Ref 1-25; Ref 1-20). Biological activity includes echo locating marine mammals and fish communication (Ref 1-26; Ref 1-20). These sources of ambient sound vary on a diurnal cycle, a tidal cycle and/or an annual cycle.

- 1.5.7 A range of anthropogenic noise sources contribute to ambient sound. These can be of short duration and impulsive (e.g. seismic surveys, piling, explosions) or long lasting and continuous (e.g. dredging, shipping, trawling, sonar, drilling, small craft and energy installations) (Ref 1-24). Impulsive sounds may, however, be repeated at intervals (duty cycle) and such repetition may become ‘smeared’ with distance and reverberation and become indistinguishable from continuous noise. The key anthropogenic sources contributing to ambient sound in the study area are reviewed below.

Vessel traffic

- 1.5.8 Shipping noise is the dominant contributor to ambient sound in shallow water areas close to shipping lanes and in deeper waters. At longer ranges the sounds of individual ships merge into a background continuum (Ref 1-20). Shipping noise will vary on a diurnal cycle (e.g. ferry and coastal traffic) and an annual cycle (seasonal activity). The source levels (“SLs”) associated with large ships such as supertankers and container ships are in the range 180 to 190 dB re 1 μ Pa m (Ref 1-5). For smaller shipping vessels and boats the range is 150 to 180 dB re 1 μ Pa m (Ref 1-27; Ref 1-28). Although the exact characteristics depend on vessel type, size and operational mode, the strongest energy occurs below 1,000 Hz.
- 1.5.9 Small, motorised craft (e.g. outboard powered inflatables, speed boats and work boats) produce relatively low levels of noise (75 to 159 dB re 1 μ Pa m), and the output characteristics are highly dependent on speed and other operational characteristics (Ref 1-29). Many of these sources have greater sound energy in higher frequency bands (i.e. above 1,000 Hz) than large ships. Sail powered craft are generally very quiet with the only sound coming from flow noise, wave slap and rigging noise.
- 1.5.10 Vessel traffic in the study area originates from commercial and recreational vessels travelling to and from the Port. Further details of the movement of different types of vessels is provided in **Chapter 12: Marine Transport and Navigation [TR030008/APP/6.2]**.

Dredging

- 1.5.11 Dredging activities emit moderate levels of broadband noise (around 150 to 188 dB re 1 μ Pa m), mainly at lower frequencies (less than 500 Hz) (Ref 1-30; Ref 1-31). Maintenance dredging is carried out in the main navigation channel and berths at the Port. The amount of dredging and volume of material removed varies depending on the surveyed levels of the channel and the requirements of the Port. Further details of existing maintenance dredging activities in the study area are included **Chapter 16: Physical Processes [TR030008/APP/6.2]**.

Frequency dependence of sound propagation

- 1.5.12 Shallow and very shallow water², such as that at the study area, acts as a high pass filter that only allows signals to pass with a frequency higher than a certain cut-off frequency and attenuates signals with frequencies lower than this cut-off frequency. The cut-off frequency gets higher as the water gets shallower (Ref 1-20). In this way, distant shipping makes a reduced contribution to ambient sound in very shallow coastal waters and low frequency sound originates from local sources rather than the great distances found in the deep oceanic waters. At high frequencies (>10 kHz), increasing absorption also prevents high frequency sound propagating over great distances in shallow water so the ambient sound at the study area is dominated by local sound sources.

Spatiotemporal variation

- 1.5.13 Ambient sound levels can show significant variation over space and time (Ref 1-10). 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.

Measured levels of ambient sound

- 1.5.14 A series of pre-construction and during construction underwater noise monitoring was undertaken in the Humber Estuary at Green Port Hull (“GPH”) from 17 to 22 October 2014 inclusive, in line with ABP’ commitments included in the GPH Environmental Management and Monitoring Plan (“EMMP”). The purpose of this monitoring was to provide better certainty for the prediction of impacts for future developments (Ref 1-32).
- 1.5.15 RMS SPLs showed a repeating pattern of peaks and troughs, ranging from 107 to 154 dB re 1 μ Pa. Flow speed and broadband SPL were shown to be significantly positively correlated, which suggests that noise levels in the estuary are primarily dependent on tidal flow speed, with levels increasing with higher flow speeds (Ref 1-32).

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.

1.6 Noise Characteristics of Project Activities

Introduction

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

Piling

1.6.2 The Project will involve the installation of up to approximately 393 steel tubular piles of varying sizes to support the approach jetty and jetty head. Further details are provided in **Chapter 2: The Project [TR030008/APP/6.2]** but are summarised here:

- a. The approach jetty will consist of up to 215 piles of up to 1.2m diameter and up to 55m in length.
- b. The jetty head and breasting dolphins will consist of up to 104 piles of up to 1.5m diameter and up to 55m in length.
- c. The mooring dolphins will consist of up to 72 piles of up to 1.5m diameter and up to 67m in length.
- d. Two additional monopile fenders may be required of up to 2.3m diameter and up to 45m in length.

1.6.3 Every pile will involve a different duration of installation based on the specific ground conditions that the pile is being driven through. The assessment is, therefore, based on the likely timeframes that are estimated to be required. Each tubular pile is anticipated to require approximately 20 minutes of vibro piling and approximately 90 minutes of impact piling. The duration of impact piling per pile will vary depending on the length of the pile. The longer piles (of up to 67m in length) will involve less impact piling as they require an initial section of pile to be driven followed by an additional length of pile welded on to the top before driving the final section of the pile to the required design depth. These longer piles will take longer than one day to be fully driven to the design depths. The absolute maximum impact piling scenario is for up to three tubular piles to be installed each day using up to two piling rigs pile driving at any one time, one on the jetty approach and one for the jetty head/platform. Taking account of the different length and type of piles that will be driven by the two piling rigs, the maximum pile driving scenario will involve approximately 60 minutes of vibro piling and 270 minutes of impact piling per day. In reality, less than three piles are likely to be driven per day and, therefore, the assumptions on pile driving periods are considered to represent a worst case.

1.6.4 The piling works will be undertaken seven days per week. Intended working hours will be from 07:00 to 19:00 in winter months (1 September to 31 March inclusive) and sunrise to sunset in the summer months.

Impact piling

- 1.6.5 The highest peak underwater noise levels generated during the proposed marine works will arise from impact piling. Impact piling involves a large weight or “ram” being dropped or driven onto the top of the pile, driving it into the seabed. Noise is created in air by the hammer, as a direct result of the impact of the hammer with the pile. Some of this airborne noise is transmitted into the water. Of more significance to the underwater noise, however, is the direct radiation of noise from the surface of the pile into the water as a consequence of the compressional, flexural or other complex structural waves that travel down the pile following the impact of the hammer on its head. As water is of similar density to steel and, in addition, due to its high sound speed, waves in the submerged section of the pile couple sound efficiently into the surrounding water. These waterborne waves will radiate outwards, usually providing the greatest contribution to the underwater noise.
- 1.6.6 At the end of the pile, force is exerted on the substrate not only by the force transmitted from the hammer by the pile, but also by the structural waves travelling down the pile which induce lateral waves in the seabed. These may travel as both compressional waves, in a similar manner to the sound in the water, or as a seismic wave, where the displacement travels as Rayleigh waves (Ref 1-33). The waves can travel outwards through the seabed or by reflection from deeper sediments. As they propagate, sound will tend to “leak” upwards into the water, contributing to the waterborne soundwaves. Since the speed of sound is generally greater in consolidated sediments than in water, these waves usually arrive first as a precursor to the waterborne wave. Generally, the level of the seismic wave is typically 10 to 20 dB below the waterborne arrival, and hence it is the latter that dominates the noise.
- 1.6.7 Impulsive sources such as pile driving should have SLs expressed for a single pulse as either SEL with units of dB re 1 $\mu\text{Pa}^2 \text{ s}$, or as a peak-peak or zero-peak SPL, with units of dB re 1 μPa (Ref 1-17). Impact piling is impulsive in character with multiple pulses occurring at blow rates in the order of 30 to 60 impacts per minute. Typical SLs range from peak SPL of 190 to 245 dB re 1 μPa (Ref 1-34). Most of the sound energy usually occurs at lower frequencies between 100 Hz and 1 kHz. Factors that influence the SL include the size, shape, length and material of the pile, the weight and drop height of the hammer, and the seabed material and depth.
- 1.6.8 As discussed above, the Project will involve the installation of piles of varying sizes. The highest peak noise levels are generally associated with larger-sized piles given the larger surface area of the pile in contact with the water and the larger hammer energy and/or pile driving time involved in driving them. On this project, the largest piles are up to 2.3m in diameter. However, given that only a total of two of these piles will be driven for the Project, they only represent a very small proportion of all the piles (< 1%). In addition to modelling the propagation of noise associated with these larger 2.3m diameter piles as a worst case, therefore, the propagation of noise associated with the second largest 1.5m diameter piles, which comprises a more significant proportion of all the piles (45%), has also been modelled.

- 1.6.9 The SL for the impact driving of 2.3m diameter piles as part of the Project is assumed based on the loudest near-source (10m from the source) sound pressure measurements (SEL, peak SPL and RMS) that have been published for the percussive piling installation of the nearest-sized 2.4m Cast-in-Steel-Shell (“CISS”) steel pipe piles in a shallow water environment (Ref 1-12; Ref 1-35; Ref 1-36). Back-calculating the sound pressure measurements to 1m using the simple logarithmic spreading model (equation 1) provides an estimated SL of 213 dB re 1 $\mu\text{Pa}^2\text{s}$ (SEL metric) and 238 dB re 1 $\mu\text{Pa m}$ (peak SPL metric) and 223 dB re 1 $\mu\text{Pa m}$ (RMS metric).
- 1.6.10 The SL for the impact driving of 1.5m diameter piles as part of the Project is assumed based on the loudest near-source (10m from the source) sound pressure measurements (SEL, peak SPL and RMS) that have been published for the percussive piling installation of the nearest-sized 1.52m CISS steel pipe piles in a shallow water environment (Ref 1-12; Ref 1-35; Ref 1-36). Back-calculating the sound pressure measurements to 1m using the simple logarithmic spreading model (equation 1) provides an estimated SL of 203 dB re 1 $\mu\text{Pa}^2\text{s}$ (SEL metric) and 228 dB re 1 $\mu\text{Pa m}$ (peak SPL metric) and 213 dB re 1 $\mu\text{Pa m}$ (RMS metric).
- 1.6.11 The 2.3m diameter monopiles that will be driven by the piling rig for the jetty head/platform have the potential to be driven at the same time as the other piling activities using the other rig on the jetty approach. In order to determine the resultant total SPL of multiple sources, the SPLs are added logarithmically, and can be calculated using the following formula:

$$\text{SPL}_{\text{Total}} = 10 \times \text{LOG}_{10}[10^{\text{SPL}_1/10} + 10^{\text{SPL}_2/10}]$$

Equation 3: Logarithmic Addition of Sound Levels

- 1.6.12 Applying this equation to the unweighted peak SL of concurrent impact piling of 2.3m diameter and 1.5m diameter piles (as a worst case) by two piling rigs is estimated to be 213 dB re 1 $\mu\text{Pa}^2\text{s}$ (SEL metric), 238 dB re 1 $\mu\text{Pa m}$ (peak SPL metric) and 223 dB re 1 $\mu\text{Pa m}$ (RMS metric).
- 1.6.13 The worst case scenario for the other piles that make up a more significant proportion of all the piles is for 1.5m diameter piles to be driven concurrently 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 of 1.5m diameter piles (as a worst case) by two piling rigs is assumed to be 206 dB re 1 $\mu\text{Pa}^2\text{s}$ (SEL metric), 231 dB re 1 $\mu\text{Pa m}$ (peak SPL metric) and 216 dB re 1 $\mu\text{Pa m}$ (RMS metric).

Vibro piling

- 1.6.14 Vibratory hammers use oscillatory hammers that vibrate the pile, causing the sediment surrounding the pile to liquefy and allow pile penetration (Ref 1-35). Peak SPLs for vibratory hammers can exceed 180 dB; however, the sound from these hammers rises relatively slowly. The vibratory hammer produces sound energy that is spread out over time and is generally 10 to 20 dB lower than impact pile driving. Although peak sound levels can be substantially less than those produced by impact hammers, the total energy imparted can be

comparable to impact driving because the vibratory hammer operates continuously and requires more time to install the pile.

- 1.6.15 The SL for the vibratory driving of either 2.3m or 1.5m diameter tubular piles as part of the proposed development is assumed based on the loudest near-source (10m from the source) sound pressure measurements (SEL, peak SPL and RMS) that have been published for the vibratory piling installation of the nearest-sized 1.83m steel pipe piles in a shallow water environment (Ref 1-12; Ref 1-35; Ref 1-36). Back-calculating the sound pressure measurements to 1m using the simple logarithmic spreading model (**Equation 1**) provides an estimated SL of 198 dB re 1 $\mu\text{Pa}^2 \text{ s}$ (SEL metric), 213 dB re 1 $\mu\text{Pa m}$ (peak SPL metric) and 198 dB re 1 $\mu\text{Pa m}$ (RMS metric).
- 1.6.16 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 by two piling rigs is assumed to be 201 dB re 1 $\mu\text{Pa}^2 \text{ s}$ (SEL metric), 216 dB re 1 $\mu\text{Pa m}$ (peak SPL metric) and 201 dB re 1 $\mu\text{Pa m}$ (RMS metric).

Dredging

- 1.6.17 The dredging requirements for the Project is anticipated to involve the use of a backhoe dredger (e.g. Mannu Pekka or similar) and trailing suction hopper dredger (“TSHD”) (e.g. Cork Sand and Long Sand or similar). The backhoe dredging will involve the excavated material being loaded directly to attendant split barges for disposal. TSHD is the method that is predominantly used for existing maintenance dredge activities within the Port and its approaches and will continue to be used in the future. Dredge operations will be continuous (24/7).
- 1.6.18 Dredging involves a variety of sound generating activities which can be broadly divided into sediment excavation, transport and placement of the dredged material at the disposal site (Ref 1-28; Ref 1-37; Ref 1-31). For most dredging activities, the main source of sound relates to the vessel engine noise. Dredging activities produce broadband and continuous sound³, mainly at lower frequencies of less than 500 Hz and moderate RMS SLs from around 150 to 188 dB re 1 $\mu\text{Pa m}$ (Ref 1-30; Ref 1-28; Ref 1-38; Ref 1-37; Ref 1-5; Ref 1-31).
- 1.6.19 Backhoe dredgers generate RMS SLs in the range of 154 to 179 dB re 1 $\mu\text{Pa m}$ (Ref 1-39; Ref 1-40). Measurements of underwater sound from backhoe dredging operations indicate that the highest levels of underwater sound occur when the excavator is in contact with the seabed. This type of dredging is generally considered to be quieter compared to other types of dredging, with recorded sound levels just above the background sound at approximately 1 km from the source (Ref 1-28).

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

- 1.6.20 SLs of TSHDs are variable but generally range from 160 to above 180 dB re 1 μ Pa m for large TSHDs (Ref 1-38). The most intense sound emissions from the TSHDs are in the low frequencies, up to and including 1,000 Hz in most cases (Ref 1-38; Ref 1-41). Differences in sound levels are mainly a result of the difference in size between the dredging vessels observed rather than the materials dredged. High frequency components of the broadband sound are generated by sand and gravel movement through the suction pipes, the movement of the draghead on the seabed, splashing from the spillways, cavitation and use of positioning thrusters. Also, gravelly sand extraction resulted in higher levels of this sound than sandy gravel when comparing the same dredging vessel (Ref 1-38).
- 1.6.21 Overall, the dredgers involved in the Project during construction and operation are anticipated to generate a worst case unweighted RMS SL of up to 188 dB re 1 μ Pa m.

Vessel movements

- 1.6.22 Vessels involved during the construction of the Project will primarily be the jack up barge, floating crane barge, flat top barges, backhoe dredger with associated attendant barges, multicats, tugs and safety boat. During operation, the new jetty is designed to support the import and export of a range of liquid bulk energy products including (i) ammonia (NH₃) (to produce green hydrogen) to help the decarbonisation of industrial activities and in particular the heavy transport sector and (ii) carbon dioxide (CO₂), to facilitate carbon capture and storage, both of which will assist the UK's transition towards net zero. Maintenance dredging of the new berth will be undertaken by a TSHD.
- 1.6.23 The dredger and barges are anticipated to generate SLs of up to 188 dB re 1 μ Pa m (Ref 1-27; Ref 1-28). The cargo ships involved during the operation are anticipated to produce RMS SLs in the region of 180 dB re 1 μ Pa m (Ref 1-42; Ref 1-5).
- 1.6.24 Overall, the vessels movements involved in the construction and operation of the proposed development are anticipated to generate worst case unweighted RMS SLs of up to 188 dB re 1 μ Pa m. Continuous (24/7) noise generation from vessel activities has been assumed and as such, provides a precautionary assessment.

1.7 Hearing Sensitivity and Responses of Marine Fauna

Introduction

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

Benthic invertebrates

- 1.7.2 Benthic invertebrates lack a gas-filled bladder and are, therefore, unable to detect the pressure changes associated with sound waves (Ref 1-43). All cephalopods as well as some bivalves, echinoderms, and crustaceans, however, have a sac-like structure called a statocyst which includes a mineralised mass (statolith) and associated sensory hairs. Statocysts develop during the larval stage and may allow an organism to detect the particle motion associated with soundwaves in water to orient itself (Ref 1-43). In addition to statocysts, cephalopods have epidermal hair cells which help them to detect particle motion in their immediate vicinity, comparable to lateral lines in fish. Similarly, decapods have sensory setae on their body, including on their antennae which may be used to detect low-frequency vibrations. Whole body vibrations due to particle motion have been detected in cuttlefish and scallops, although species names and details of associated behavioural responses are not specified (Ref 1-43).
- 1.7.3 Scientific understanding of the potential effects of underwater noise on invertebrates is relatively underdeveloped (Ref 1-44). There is limited research to suggest that exposure to near-field low-frequency sound may cause anatomical damage (Ref 1-43). Anecdotal evidence indicates there was pronounced statocyst and organ damage in seven stranded giant squid after nearby seismic surveys (Ref 1-45). Ref 1-46 found airgun exposure caused damaged statocysts in rock lobsters up to a year later. No such effects, however, were detected in other studies (Ref 1-47; Ref 1-48). The disparate results between studies seem to be due to differences in SELs and duration, in some cases due to tank interference, although taxa-specific differences in physical vulnerability to acoustic stress cannot be discounted (Ref 1-43).
- 1.7.4 There is increasing evidence to suggest that benthic invertebrates respond to particle motion⁴ (Ref 1-49). For example, blue mussels *Mytilus edulis* vary valve gape, oxygen demand and clearance rates (Ref 1-50; Ref 1-49) and hermit crabs *Pagurus bernhardus* shift their shell and at very high amplitudes, leave their shell, examine it and then return (Ref 1-49). The vibration levels at which these responses were observed generally correspond to levels measured near anthropogenic operations such as pile driving and up to 300m from explosives testing (blasting) (Ref 1-49). A range of behavioural effects have also been recorded in decapod crustaceans, including a change in locomotion activity, reduction in antipredator behaviour and change in foraging habits (Ref 1-51). Population level and mortality effects, however, are considered unlikely. Effects on benthic invertebrates are, therefore, not considered further in the assessment.

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

Fish

- 1.7.5 In comparison to marine mammals, fish are more sensitive to noise at lower frequencies and generally have a reduced range of hearing than marine mammals (i.e. their hearing ability spans a restricted range of frequencies).
- 1.7.6 There is a wide diversity in hearing structures in fish which leads to different auditory capabilities across species (Ref 1-52). All fish can sense the particle motion component of an acoustic field via the inner ear as a result of whole-body accelerations (Ref 1-7), and noise detection ('hearing') becomes more specialised with the addition of further hearing structures. Particle motion is especially important for locating sound sources through directional hearing (Ref 1-1; Ref 1-44; Ref 1-13). Although many fish are also likely to detect sound pressure⁵, particle motion is considered equally or potentially more important (Ref 1-9).
- 1.7.7 From the few studies of hearing capabilities in fishes that have been conducted, it is evident that there are potentially substantial differences in auditory capabilities from one fish species to another (Ref 1-9). Since it is not feasible to determine hearing sensitivity for all fish species, one approach to understand hearing has been to distinguish fish groups on the basis of differences in their anatomy and what is known about hearing in other species with comparable anatomy (Ref 1-1).
- 1.7.8 **Chapter 9: Nature Conservation (Marine Ecology) [TR030008/APP/6.2]** provides a detailed review of the fish receptors that occur in the study area. Categories proposed by Ref 1-1 for each of the key fish species are included in **Table 2**.

Table 2: Categorisation of key fish species in the study area according to Ref 1-1 criteria

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

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

Swim Bladder or Air Cavities Aid Hearing	Swim Bladder Does Not Aid Hearing	No Swim Bladder
	Sea trout (<i>Salmo trutta</i>) Whiting (<i>Merlangius merlangus</i>)	Sea lamprey (<i>Petromyzon marinus</i>)

- 1.7.9 The first category comprises fish that have special structures mechanically linking the swim bladder to the ear. These fish are sensitive primarily to sound pressure, although they also detect particle motion (Ref 1-9). They have a wider frequency range, extending to several kHz and generally show higher sensitivity to sound pressure than fishes in the other categories.
- 1.7.10 The second category comprises fish with a swim bladder where the organ does not appear to play a role in hearing. Some of the fish in this category are considered to be more sensitive to particle motion than sound pressure (see below) and show sensitivity to only a narrow band of frequencies, namely the salmonids (Salmonidae) (Ref 1-53). This second category also comprises fishes with swim bladders that are close, but not intimately connected, to the ear, such as codfishes (Gadidae) and eels (Anguillidae). These fish are sensitive to both particle motion and sound pressure, and show a more extended frequency range, extending up to about 500 Hz (Ref 1-54; Ref 1-55; Ref 1-9).
- 1.7.11 The third category comprises fish which lack swim bladders that are sensitive only to sound particle motion and show sensitivity to only a narrow band of frequencies (e.g. flatfishes, sharks, skates and rays). Particle motion rather than sound pressure is considered to be potentially more important to fish without swim bladders. Acoustic particle motion in the water and seabed, for example, has been shown to induce behavioural reactions in sole (Ref 1-56). However, there is no published literature on the levels of particle motion generated during construction activities (e.g. pile-driving) and the distance at which they can be detected. This may be due to the fact that there are far fewer devices (and less skill in their use) for detection and analysis of particle motion compared to hydrophone devices for detection of sound pressure (Ref 1-57). Direct measurements of particle motion have also been hampered by the lack of guidance on data analysis methods.
- 1.7.12 Particle velocity can be calculated indirectly from sound pressure measurements using relatively simple models (Ref 1-58). However, such estimates of sound particle velocity are only valid in environments that are distant from reflecting boundaries and other acoustic discontinuities. These conditions are rarely met in the shelf-sea and shallow-water habitats that most aquatic organisms inhabit and that are applicable to the study area (Ref 1-13).
- 1.7.13 Steps that are required to improve knowledge of the effects of particle motion on marine fauna have recently been set out (Ref 1-59). However, at present there continues to be a lack of particle motion measurement standards, lack of easy to use and reasonably priced instrumentation to measure particle motion, and lack of sound exposure criteria for particle motion. As such, the scope for considering particle motion in underwater noise assessments is currently limited (Ref 1-60).

The underwater noise assessment has, therefore, been based on the latest available evidence and focused on the effects of sound pressure.

- 1.7.14 The extent to which intense underwater sound might cause an adverse environmental impact in a particular fish species is dependent upon the level of sound pressure or particle motion, its frequency, duration and/or repetition (Ref 1-61). The range of potential effects from intense sound sources, such as pile driving, includes immediate death, permanent or temporary tissue damage and hearing loss, behavioural changes and masking effects. Tissue damage can result in eventual death or may make the fish less fit until healing occurs, resulting in lower survival rates. Hearing loss can also lower fitness until hearing recovers. Behavioural changes can potentially result in animals avoiding migratory routes or leaving feeding or reproduction grounds with potential population level consequences. Biologically important sounds can also be masked where the received levels are marginally above existing background levels (Ref 1-62). The ability to detect and localise the source of a sound is of considerable biological importance to many fish species and is often used to assess the suitability of a potential mate or during territorial displays and during predator prey interactions.
- 1.7.15 The published noise exposure criteria for fish that have been used in this underwater noise assessment are presented in **Table 3**.

Table 3: Fish response criteria applied in this assessment

Fish Hearing Category*	Piling [^]			Dredging and Vessel Movements			All Activities
	Mortality and Potential Mortal Injury*	Recoverable Injury*	TTS*	Mortality and Potential Mortal Injury*	Recoverable Injury*	TTS*	Behaviour**
Swim bladder involved in hearing (primarily pressure detection)	207 dB SEL _{cum} >207 dB peak	203 dB SEL _{cum} >207 dB peak	186 dB SEL _{cum}	207 dB SEL _{cum} (N) Low (I) Low (F) Low	203 dB SEL _{cum} 170 dB RMS for 48 h	186 dB SEL _{cum} 158 dB RMS for 12 h	> 157 dB peak
Swim bladder is not involved in hearing (particle motion detection)	210 dB SEL _{cum} >207 dB peak	203 dB SEL _{cum} >207 dB peak	> 186 dB SEL _{cum}	210 dB SEL _{cum} (N) Low (I) Low (F) Low	203 dB SEL _{cum} (N) Low (I) Low (F) Low	> 186 dB SEL _{cum} (N) Moderate (I) Low (F) Low	> 157 dB peak
No swim bladder (particle motion detection)	>219 dB SEL _{cum} >213 dB peak	>216 dB SEL _{cum} >213 dB peak	>> 186 dB SEL _{cum}	>219 dB SEL _{cum} (N) Low (I) Low (F) Low	>216 dB SEL _{cum} (N) Low (I) Low (F) Low	>> 186 dB SEL _{cum} (N) Moderate (I) Low (F) Low	> 157 dB peak
Eggs and larvae	210 dB SEL _{cum} >207 dB peak	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low	210 dB SEL _{cum} (N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	> 157 dB peak

Fish Hearing Category*	Piling [^]			Dredging and Vessel Movements			All Activities
	Mortality and Potential Mortal Injury*	Recoverable Injury*	TTS*	Mortality and Potential Mortal Injury*	Recoverable Injury*	TTS*	Behaviour**
[^] Peak SPL and cumulative SEL (SEL _{cum}) thresholds are relevant for impact piling whereas cumulative SEL thresholds are more relevant for vibro piling given its continuous nature. * Ref 1-1 ** Ref 1-2. Peak and RMS SPL is in dB re 1 µPa and cumulative SEL 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).							

- 1.7.16 The quantitative instantaneous peak SPL and SEL_{cum} criteria (Ref 1-1) for different marine activities involved in the Project (i.e. piling, dredging and vessel movements) have been used to determine the mortality/potential mortal injury, recoverable injury and TTS for all the fish hearing categories representing the key fish species that occur in the study area (**Table 2**). These guidelines are based on an understanding that fish will respond to sounds and their hearing sensitivity.
- 1.7.17 While the noise exposure criteria (Ref 1-1) provide thresholds for auditory impairment, there are many data gaps that preclude the setting of specific noise exposure criteria for behavioural responses in fish (Ref 1-1; Ref 1-9; Ref 1-60). The onset of behavioural responses is much more difficult to quantify as reactions are likely to be strongly influenced by behavioural or ecological context and the effect of a particular response is often unclear and may not necessarily scale with received sound level (Ref 1-53; Ref 1-44 Ref 1-60). In other words, behaviour may be more strongly related to the particular circumstances of the animal, the activities in which it is engaged, and the context in which it is exposed to sounds (Ref 1-63; Ref 1-64). For example, a startle or reflex response to the onset of a noise source does not necessarily lead to displacement from the ensonified area.
- 1.7.18 This uncertainty is further compounded by the limitations of observing fish behavioural responses in a natural context. Few studies have conducted behavioural field experiments with wild fish and laboratory experiments may not give a realistic measure of how fish will respond in their natural environment (Ref 1-61; Ref 1-65; Ref 1-66). As a consequence, only hearing data based on behavioural experiments is acceptable for assessing the ability of fish to detect sound (Ref 1-67).
- 1.7.19 Recent studies have considered approaches to quantify the risk of behavioural responses, for example, through dual criteria based on dose-response curves for proximity to the sound source and received sound level (Ref 1-68). An empirical behavioural threshold could also be adopted using *in situ* observed responses of fish to similar sound sources (Ref 1-60). 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 (Ref 1-69). At levels of around 161-168 dB re 1 µPa RMS active avoidance of the air gun source would be expected to occur (Ref 1-70; Ref 1-69). These responses may, however, differ from those of unconfined fish.
- 1.7.20 More recent work has been undertaken by Ref 1-2 reporting behavioural responses of schools of wild sprat and mackerel to playbacks of pile driving. At a single-pulse peak-peak SPL of 163 dB re 1 µPa (equivalent to peak SPL of 157 dB re 1 µPa using the metric conversion provided by NOAA Fisheries in their spreadsheet tool and associated user manual; Ref 1-4), 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 3**).

- 1.7.21 Auditory and non-auditory injuries in fish have not been observed or documented to occur in association with dredging (Ref 1-30). The literature suggests that dredging noise is unlikely to cause direct mortality or instantaneous injury. However, the (predominantly) low-frequency sounds produced by dredging overlap with the hearing range of many fish species, which may pose a risk in TTS, auditory masking, and behavioural effects (Ref 1-71), as well increased stress-related cortisol levels in fish species (Ref 1-72). A TTS involves a temporary reduction of hearing capability caused by exposure to underwater noise. An intense short exposure can produce the same scale of TTS as a long-term, repeated exposure to lower sound levels. The significance of the TTS varies among species depending on their dependence on sound as a sensory cue for ecologically relevant functions. Furthermore, it is important to note that the biological significance of such responses is largely unknown.
- 1.7.22 Potential behavioural effects in the past have also been inferred by comparing the received sound level with the auditory threshold of marine fauna. Ref 1-29 and Ref 1-73, for example, have used received levels of noise in comparison with the corresponding hearing thresholds of marine fauna in order to estimate the range of audibility and zones of influence from underwater sound sources. This form of analysis has been taken a stage further by Ref 1-74, where the underwater noise is compared with receptor hearing threshold across the entire receptor auditory bandwidth in the same manner that the dB(A) is used to assess noise sources in air for humans. These include behavioural thresholds, where received sound levels around 90 dB above hearing threshold (dB_{ht}) are considered to cause a strong behavioural avoidance, levels around 75 dB_{ht} a moderate behavioural response and levels around 50 dB_{ht} a minor response.
- 1.7.23 The dB_{ht} criteria have been applied in a number of offshore renewables EIAs and the Environment Agency has previously recommended it to be used in impact assessments in coastal/estuarine environments (e.g. Ref 1-15; Ref 1-14). However, it is worth noting that the dB_{ht} criteria have not been validated by experimental study and have not been published in an independent peer-reviewed paper. The dB_{ht} approach does not take into account potential for sound sensitivity to changes with that of the life stage of the organism, time of year, animal motivation, or other factors that might affect hearing and behavioural responses to sound (Ref 1-9). Furthermore, the dB_{ht} criteria are based on measures of inner ear responses and should rather be based on behavioural threshold determinations (Ref 1-1, Ref 1-9). The use of dB_{ht} criteria is, therefore, not advisable and has not been applied to this assessment (Ref 1-9).

Marine mammals

- 1.7.24 Marine mammals are particularly sensitive to underwater noise at higher frequencies and generally have a wider range of hearing than other marine fauna, namely fish (i.e. their hearing ability spans a larger range of frequencies). The hearing sensitivity and frequency range of marine mammals varies between different species and is dependent on their physiology.

- 1.7.25 The impacts of underwater noise on marine mammals can broadly be split into lethal and physical injury, auditory injury and behavioural response. The possibility exists for lethality and physical damage to occur at very high exposure levels, such as those typically close to underwater explosive operations or offshore impact piling operations. A PTS is permanent hearing damage caused by very intensive noise or by prolonged exposure to noise. As explained above, a TTS involves a temporary reduction of hearing capability caused by exposure to underwater noise. Both PTS and TTS are considered to be auditory/physiological injuries.
- 1.7.26 At lower SPLs, it is more likely that behavioural responses to underwater sound will be observed. These reactions may include the animals leaving the area for a period of time, or a brief startle reaction. Masking effects may also occur at lower levels of noise. Masking is the interference with the detection of biologically relevant communication signals such as echolocation clicks or social signals. Masking has been shown in acoustic signals used for communication among marine mammals (see Ref 1-75). Masking may in some cases hinder echolocation of prey or detection of predators. If the signal-to-noise ratio prevents detection of subtle or even prominent pieces of information, inappropriate or ineffective responses may be shown by the receiving organism.
- 1.7.27 Ref 1-19 provides technical guidance for assessing the effects of underwater anthropogenic (human-made) sound on the hearing of marine mammal species. Specifically, the received levels, or acoustic thresholds, at which individual marine mammals are predicted to experience changes in their hearing sensitivity (either temporary or permanent) for acute, incidental exposure to underwater anthropogenic sound sources are provided. These thresholds update and replace the previously proposed criteria in Ref 1-76 for preventing auditory/physiological injuries in marine mammals. Further recommendations have recently been published regarding marine mammal noise exposure by Ref 1-77 which complement the Ref 1-19 thresholds and also look at a wider range of marine mammal species, as well as the hearing sensitivity of amphibious mammals (e.g. seals, sea otters) to airborne noise.
- 1.7.28 The Ref 1-19 and Ref 1-77 thresholds are categorised according to marine mammal hearing groups. **Chapter 9: Nature Conservation (Marine Ecology) [TR030008/APP/6.2]** provides a detailed review of the marine mammal receptors that occur in the study area. The key marine mammal species comprise harbour porpoise, common seal and grey seal. According to Ref 1-19, harbour porpoise is categorised as a high-frequency (“HF”) cetacean and common and grey seals are categorised as pinniped phocids in water (“PW”) (earless seals or “true seals”).
- 1.7.29 Ref 1-19 and Ref 1-77 provide weighted SEL_{cum} acoustic thresholds for non-impulsive sources (e.g. vibro piling) and unweighted peak SPL and weighted SEL_{cum} 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 4**.

Table 4: Marine mammal response criteria applied in this assessment

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

Peak SPL has a reference value of 1 µPa and weighted SEL_{cum} has a reference value of 1 µPa²s.

- 1.7.30 Peak SPL acoustic thresholds for impulsive sound sources provide an estimate of the instantaneous worst-case potential effects on marine mammals. SEL_{cum} is calculated from the energy in a representative single pile strike and the number of strikes over a 24 hour period. This measure assumes that all strikes have the same received single strike SEL value, which is rarely the case since the animal (or source) is likely to be moving relative to each other. It also assumes that the animal is stationary within the zone of potential effect for a 24 hour period which is highly unlikely. Furthermore, it does not take potential physiological or physical recovery from any effects of a single signal exposure into account. As such, this averaging metric has the potential to result in false conclusions on the effects of sound exposure and needs to be treated with more caution as noted by Ref 1-9.
- 1.7.31 There are no equivalent SPL behavioural response criteria that would represent the sources of underwater noise associated with the Project. Behavioural reactions to acoustic exposure are less predictable and difficult to quantify than effects of noise exposure on hearing or physiology as reactions are highly variable and context specific (Ref 1-76).
- 1.7.32 Field studies have demonstrated behavioural responses of harbour porpoises to anthropogenic noise (Ref 1-78). A number of studies have shown avoidance of pile driving activities during offshore wind farm construction (Ref 1-79; Ref 1-80; Ref 1-81), with the range of measurable responses extending to at least 21km in some cases (Ref 1-82). Seismic surveys have also elicited avoidance behaviour in harbour porpoises, albeit short-term (Ref 1-83), and monitoring of echolocation activity suggests possible negative effects on foraging activity in the vicinity of seismic operations (Ref 1-84). There is a scarcity of studies quantifying behavioural impacts from dredging (Ref 1-85). An investigation by Ref 1-86 showed that harbour porpoises temporarily avoided an area of sand extraction off the Island of Sylt in Germany. Ref 1-86 found that, when the dredging vessel was closer than 600m to the porpoise detector location, it took three times longer before a porpoise was again recorded than during times without sand extraction. However, after the ship left the area, the clicks resumed to the baseline rate.

- 1.7.33 Few studies have documented responses of seals to underwater noise in the field (Ref 1-78). Tracking studies found reactions of the grey seals to pile driving during the construction of windfarms were diverse (Ref 1-87). These included altered surfacing or diving behaviour, and changes in swim direction including swimming away from the source, heading into shore or travelling perpendicular to the incoming sound, or coming to a halt. In addition, in some cases no apparent changes in their diving behaviour or movement was observed. Of the different behavioural changes observed a decline in descent speed occurred most frequent, which suggests a transition from foraging (diving to the bottom), to more horizontal movement. These changes in behaviour were on average larger and occurred more frequent at smaller distances from the pile driving events, and such changes were statistically significantly different at least up to 36km. In addition to changes in dive behaviour, also changes in movement were recorded. There was evidence that on average grey seals within 33km were more likely to swim away from the pile driving. In some cases, seals exposed to pile-driving at close range, returned to the same area on subsequent trips. This suggests that some seals had an incentive to go to these areas, which was stronger than the potential deterring effect of the pile-driving.
- 1.7.34 A telemetry study found no overall significant displacement of common seal during construction of a wind farm in The Wash, south-east England (Ref 1-88). However, during piling, seal usage (abundance) was significantly reduced up to 25km from the piling activity; within 25km of the centre of the wind farm, there was a 19 to 83% (95% confidence intervals) decrease in usage compared to during breaks in piling, equating to a mean estimated displacement of 440 individuals. This amounts to significant displacement starting from predicted received levels of between 166 and 178 dB re 1 μ Pa (peak-peak). Displacement was limited to piling activity; within 2 hours of cessation of pile driving, seals were distributed as per the non-piling scenario.
- 1.7.35 Ref 1-89 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 239m during control trials). Two further studies of ringed seals (*Phoca hispida*), which are closely related to both harbour and grey seals, have observed behaviour in response to anthropogenic noise: Ref 1-90 reported animals swimming away and avoidance within ~150m of a seismic survey, while Ref 1-91 found no discernible difference in seal densities in response to construction and drilling for an oil pipeline.
- 1.7.36 A number of field observations of harbour porpoise and pinnipeds to multiple pulse sounds have been made and are reviewed by Ref 1-76. The results of these studies are considered too variable and context-specific to allow single disturbance criteria for broad categories of taxa and of sounds to be developed. Another way to evaluate the responses of marine mammals and the likelihood of behavioural responses is by comparing the received sound level against species specific hearing threshold levels. The dB_{ht} metric and its limitations has already been discussed earlier in this section and is, therefore, not repeated here.

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

1.8 Noise Propagation Modelling Outputs

1.8.1 The simple logarithmic spreading model (Equation 1) described in **Section 1.4** was applied to the worst case (highest) unweighted SLs associated with the Project activities (i.e. impact piling with two rigs, vibro piling with two rigs, dredging and vessel movements) to determine the unweighted received levels with range. These received levels represent unweighted metrics as recommended in Ref 1-10. **Table 5** shows the results of this analysis at various distances from the sources of noise associated with the Project.

Table 5: Maximum predicted unweighted received levels during proposed development activities

Range (m)	Impact Piling 1.5m piles (SEL in dB 1 $\mu\text{Pa}^2\cdot\text{s}$)	Impact Piling 2.3m piles (SEL in dB 1 $\mu\text{Pa}^2\cdot\text{s}$)	Vibro Piling 1.5m and 2.3 piles (SEL in dB 1 $\mu\text{Pa}^2\cdot\text{s}$)	Dredging and Vessel Movements (RMS in dB re 1 μPa)
1	206	213	201	188
10	188	195	183	170
100	170	177	165	152
200	164	171	159	146
500	155	162	150	137
1,000	147	154	142	129
2,300*	134	141	129	116
3,400**	125	132	120	107
5,000	114	121	109	96
10,000	82	89	77	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.				

- 1.8.2 The levels of underwater noise generated by impact piling are predicted to reach existing background levels previously measured in the Humber Estuary (**Section 1.5**) within around 2 to 3km from the source. The SEL received levels of underwater noise generated during impact piling for the proposed development are predicted to reduce to around 147 to 154 dB 1 $\mu\text{Pa}^2\cdot\text{s}$ within 1km of the source of piling which is equivalent to peak SPL of 166 dB re 1 μPa using **Equation 2 (Section 1.4)** and comparable to the SL generated by a tug and barge (Ref 1-5). The peak levels of underwater noise that reach the opposite shore of the estuary are predicted to range from approximately 125 to 141 dB 1 $\mu\text{Pa}^2\cdot\text{s}$ (equivalent to 135 to 157 dB re 1 μPa) depending on the tidal state. These levels are comparable to the SLs generated by recreational boats (Ref 1-5).
- 1.8.3 The levels of underwater noise generated by vibro piling are predicted to reach existing background levels in the estuary (**Section 1.5**) within around 1km from the source. The instantaneous peak levels of underwater noise generated during vibro piling are predicted to reduce to around 142 dB 1 $\mu\text{Pa}^2\cdot\text{s}$ within 1km of the source of piling which is equivalent to peak SPL of 159 dB re 1 μPa and comparable to the SL generated by a passenger vessel or a recreational boat (Ref 1-57).
- 1.8.4 The levels of underwater noise generated by dredging and vessel movements are predicted to reach existing background levels previously measured in the Humber Estuary (**Section 1.5**) within around 100m from the source. It should be noted that the Project is located at the Port which already experiences intermittent elevated levels of underwater noise of a similar scale to that which is predicted due to the range of vessels that already operate in this area and ongoing maintenance dredging.

1.9 Potential Effects

Fish

Impact piling

- 1.9.1 The calculator developed by Ref 1-18 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 SEL_{cum} thresholds for impact pile driving (Ref 1-1) are reached. The model input values and associated assumptions for impact piling of 2.3m and 1.5m diameter piles are included in **Table 6** and **Table 7** respectively.

Table 6: NMFS piling calculator input values for impact piling 2.3m diameter piles

Model Inputs	Value	Assumptions
Peak SPL SL	238	Loudest near-source (10m from the source) sound pressure measurements for the percussive piling installation of 2.4 CISS steel pipe piles in a shallow water environment (Ref 1-12; Ref 1-35; Ref 1-36) back-calculated to 1m and the assumption that two piling rigs with impact hammers will be used concurrently (see Section 1.6).

Model Inputs	Value	Assumptions
SEL SL	213	As above.
Distance from source (m)	1	The sound levels that were measured for the percussive piling installation of 2.4m CISS steel pipe piles in a shallow water environment (Ref 1-12; Ref 1-35; Ref 1-36) have been back-calculated to 1m from the source (see Section 1.6).
Transmission loss coefficient	17.91	Derived from 11 observations of transmission loss coefficient collected from a number of construction projects undertaken in shallow water estuarine and coastal locations (see Section 1.4).
Number of piles per day	2	A total of up to two 2.3m diameter monopiles may require to be installed and, therefore, the maximum impact piling scenario is for two of these types of piles to be piled in a day.
Number of strikes per pile	675	Maximum value provided for existing field data in the NMFS pile driving calculator (Ref 1-18) and, therefore, considered a reasonable worst case.
Attenuation (dB)	NA	Not applicable.

Table 7: NMFS piling calculator input values for impact piling 1.5m diameter piles

Model Inputs	Value	Assumptions
Peak SPL SL	231	Loudest near-source (10m from the source) sound pressure measurements for the percussive piling installation of 1.52m CISS steel pipe piles in a shallow water environment (Ref 1-12; Ref 1-35; Ref 1-36) back-calculated to 1m and the assumption that two piling rigs with impact hammers will be used concurrently (see Section 1.6).
SEL SL	206	As above.
Distance from source (m)	1	The sound levels that were measured for the percussive piling installation of 1.52m CISS steel pipe piles in a shallow water environment (Ref 1-12; Ref 1-35; Ref 1-36) have been back-calculated to 1m from the source (see Section 1.6).
Transmission loss coefficient	17.91	Derived from 11 observations of transmission loss coefficient collected from a number of construction projects undertaken in shallow water estuarine and coastal locations (see Section 1.4).
Number of piles per day	3	The maximum impact piling scenario is for the marine works to comprise up to 3 tubular piles to be installed each day (see Section 1.6).
Number of strikes per pile	675	Maximum value provided for existing field data in the NMFS pile driving calculator (Ref 1-18) and, therefore, considered a reasonable worst case.

Model Inputs	Value	Assumptions
Attenuation (dB)	NA	Not applicable.

1.9.2 The distances at which mortality and potential mortal injury, recoverable injury, TTS, and behavioural effects in fish are predicted to occur during impact piling of 2.3m and 1.5m diameter piles are included in **Table 8** and **Table 9** respectively.

Table 8: Approximate distances (metres) fish response criteria are reached during concurrent impact piling 2.3m diameter piles

Fish Hearing Category	Mortality/Potential Mortal Injury		Recoverable Injury		TTS	Behaviour
	Peak	SEL _{cum}	Peak	SEL _{cum}	SEL _{cum}	Peak
Swim bladder involved in hearing (primarily pressure detection)	80	200	80	300	3,000	2,000
Swim bladder is not involved in hearing (particle motion detection)	80	100	80	300	3,000	2,000
No swim bladder (particle motion detection)	40	40	40	60	3,000	2,000
Eggs and larvae	80	100	(N) Moderate (I) Low (F) Low		(N) Moderate (I) Low (F) Low	2,000

Table 9: Approximate distances (metres) fish response criteria are reached during concurrent impact piling 1.5m diameter piles

Fish Hearing Category	Mortality/Potential Mortal Injury		Recoverable Injury		TTS	Behaviour
	Peak	SEL _{cum}	Peak	SEL _{cum}	SEL _{cum}	Peak
Swim bladder involved in hearing (primarily pressure detection)	20	60	20	100	900	2,000
Swim bladder is not involved in hearing (particle motion detection)	20	40	20	100	900	2,000
No swim bladder (particle motion detection)	10	10	10	20	900	2,000
Eggs and larvae	20	40	(N) Moderate (I) Low (F) Low		(N) Moderate (I) Low (F) Low	2,000

- 1.9.3 Given the mobility of fish and the unconstrained area at the site of the proposed piling works for the Project, any individuals that might be present within the localised areas associated with mortality and potential mortal injury and recoverable injury during pile driving activities would be expected to easily move away and avoid harm.
- 1.9.4 TTS and behavioural responses are predicted to occur approximately 2 to 3km from the source of impact piling for 2.3m monopiles and 1 to 2km from the source of impact piling 1.5m diameter piles. For the 2.3m monopiles, TTS and behavioural reactions are anticipated to occur across 87% to 100% width of the Humber Estuary at low water and 59% to 88% of the width of the estuary at high water. For the 1.5m diameter piles, TTS and behavioural reactions are anticipated to occur across 43% to 87% width at low water and 29% to 59% width at high water. Impact piling, therefore, has the potential to create a partial temporary barrier to fish movements.
- 1.9.5 The scale of the behavioural response is partly dependent on the hearing sensitivity of the species. Fish with a swim bladder involved in hearing (e.g. herring) may exhibit a moderate behavioural reaction within distance in which a behavioural response is predicted (e.g. a sudden change in swimming direction, speed or depth). Fish with a swim bladder that is not involved in hearing (e.g. European eel) are likely to display a milder behavioural reaction. Fish without a swim bladder (e.g. river lamprey) are anticipated to only show very subtle changes in behaviour in this zone.
- 1.9.6 The scale of the behavioural effect is also dependent on the size of fish (which affects maximum swimming speed). Smaller fish, juveniles and fish larvae swim at slower speeds and are likely to move passively with the prevailing current. Larger fish are more likely to actively swim and, therefore, may be able to move out of the behavioural effects zone in less time, although it is recognised that the movement of fish is very complex and not possible to define with a high degree of certainty.
- 1.9.7 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 343 days. However, piling will not take place continuously as there will be periods of downtime, pile positioning and set up.
- 1.9.8 The piling works will be undertaken seven days per week. Intended working hours will be from 07:00 to 19:00 in March, September October and sunrise to sunset in June and August. The maximum impact piling scenario is for three tubular piles to be installed each day using up to two piling rigs pile driving at any one time, involving approximately 270 minutes of impact piling per day. 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 19% over a 24 hour period (based on 270 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 19% over the period of a day.

1.9.9 The piling will occur between 07:00 and 19:00 in March, September and October and sunrise to sunset in June and August, which has the potential to disproportionately affect fish that migrate during daylight hours, whilst reducing the potential exposure of fish that predominantly migrate during night time hours (e.g. river lamprey and glass eel).

1.9.10 It is also important to consider the noise from piling against existing background or ambient noise conditions (**Section 1.5**). The levels of underwater noise generated by impact piling are predicted to reach existing background levels previously measured in the Humber Estuary within around 2 to 3km from the source (**Section 1.8**). Furthermore, the area in which the construction will take place already experiences regular vessel operations and ongoing maintenance dredging, and, therefore, fish are likely to be habituated to a certain level of anthropogenic background noise.

Vibro piling

1.9.11 The calculator developed by Ref 1-18 has been used to calculate the range at which the instantaneous peak and SEL_{cum} thresholds for vibro driving (Ref 1-1) of either 2.3m diameter or 1.5m diameter piles are reached. The model input values and associated assumptions for vibro piling are included in **Table 10**.

Table 10: NMFS piling calculator input values for vibro piling

Model Inputs	Value	Assumptions
Peak SPL SL	216	Loudest near-source (10m from the source) sound pressure measurements for the vibratory piling installation of 1.83m steel pipe piles in a shallow water environment (Ref 1-12; Ref 1-35; Ref 1-36) back-calculated to 1m and the assumption that two piling rigs with vibro hammers will be used concurrently (see Section 1.6).
SEL SL	201	As above.
RMS SL	201	As above.
Distance from source (m)	1	The sound levels that were measured for the vibratory piling installation of 1.83m steel pipe piles in a shallow water environment (Ref 1-12; Ref 1-35; Ref 1-36) have been back-calculated to 1m from the source (see Section 1.6).
Transmission loss coefficient	17.91	Derived from 11 observations of transmission loss coefficient collected from a number of construction projects undertaken in shallow water estuarine and coastal locations (see Section 1.4).
Number of piles per day	3	The maximum vibro piling scenario is for the marine works to comprise up to three tubular piles to be installed each day (see Section 1.6).
Duration to drive a single pile (minutes)	20	Each tubular pile is anticipated to require approximately 20 minutes of vibro piling (see Section 1.6).

Model Inputs	Value	Assumptions
Attenuation (dB)	NA	Not applicable.

1.9.12 The distances at which mortality and potential mortal injury, recoverable injury, TTS, 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 11**.

Table 11: Approximate distances (metres) fish response criteria are reached during concurrent vibro piling

Fish Hearing Category	Mortality/ Potential Mortal Injury	Recoverable Injury	TTS	Behaviour
	SEL _{cum}	SEL _{cum}	SEL _{cum}	Peak
Swim bladder involved in hearing (primarily pressure detection)	50	80	700	1,000
Swim bladder is not involved in hearing (particle motion detection)	30	80	700	1,000
No swim bladder (particle motion detection)	10	10	700	1,000
Eggs and larvae	30	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low	1,000

1.9.13 Given the mobility of fish and the unconstrained area at the site of the proposed piling works for the Project, any individuals that might be present within the localised areas associated with mortality and potential mortal injury and recoverable injury during pile driving activities would be expected to easily move away and avoid harm.

1.9.14 TTS and behavioural responses are predicted to occur around 1km from the source of vibro piling. TTS and behavioural reactions are anticipated to occur across 30% and 43% of the width of the Humber Estuary at low water respectively and 21% and 29% of the estuary width at high water.

1.9.15 The scale of the behavioural response is partly dependent on the hearing sensitivity of the species. Fish with a swim bladder involved in hearing (e.g. herring) may exhibit a moderate behavioural reaction within distance in which a behavioural response is predicted (e.g. a sudden change in swimming direction,

speed or depth). Fish with a swim bladder that is not involved in hearing (e.g. European eel) are likely to display a milder behavioural reaction. Fish without a swim bladder (e.g. river lamprey) are anticipated to only show very subtle changes in behaviour in this zone.

- 1.9.16 The scale of the behavioural effect is also dependent on the size of fish (which affects maximum swimming speed). Smaller fish, juveniles and fish larvae swim at slower speeds and are likely to move passively with the prevailing current. Larger fish are more likely to actively swim and, therefore, may be able to move out of the behavioural effects zone in less time.
- 1.9.17 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 343 days. However, piling will not take place continuously as there will be periods of downtime, pile positioning and set up.
- 1.9.18 The piling works will be undertaken seven days per week. Intended working hours will be from 07:00 to 19:00 in winter months (1 September to 31 March inclusive) and sunrise to sunset in the summer months. The maximum vibro piling scenario is for three tubular piles to be installed each day using up to two piling rigs pile driving at any one time, involving approximately 60 minutes of vibro piling per day. 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 4% over a 24 hour period (based on an estimated 60 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 4% over the period of a day.
- 1.9.19 The piling will occur between 07:00 and 19:00 in winter months (1 September to 31 March inclusive) and sunrise to sunset in the summer months, which has the potential to disproportionately affect fish that migrate during daylight hours, whilst reducing the potential exposure of fish that migrate during night time hours (e.g. river lamprey and glass eel).
- 1.9.20 It is also important to consider the noise from piling against existing background or ambient noise conditions (**Section 1.5**). The levels of underwater noise generated by vibro piling are predicted to reach existing background levels previously measured in the Humber Estuary within around 1km from the source (**Section 1.8**). Furthermore, the area in which the construction will take place already experiences regular vessel operations and ongoing maintenance dredging, and, therefore, fish are likely to be habituated to a certain level of anthropogenic background noise.

Dredging and vessel movements

- 1.9.21 The relative risk and distances at which mortality and potential mortal injury, recoverable injury, TTS and behavioural effects in fish are predicted to occur as a result of the dredging and vessel movements associated with the construction and operation of the Project are included in **Table 12**.

- 1.9.22 The qualitative guidelines for continuous noise sources (Ref 1-1) consider that the relative risk of mortality and potential mortal injury in all fish is low in the near, intermediate and far-field (**Table 12**). Applying the SEL_{cum} thresholds for piling (Ref 1-1) on a precautionary basis, indicate that there is a risk of mortality/potential mortal injury within 50m in fish with a swim bladder involved in hearing, within 30m in fish with a swim bladder that is not involved in hearing and 10m for fish with no swim bladder.
- 1.9.23 According to Ref 1-1, the relative 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 guideline quantitative 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 using the model and assumptions presented in **Section 1.4** is 10m (**Table 12**). Applying the SEL_{cum} thresholds for piling (Ref 1-1) on a precautionary basis, indicate that there is a risk of recoverable injury within 80m in fish with a swim bladder and 20m for fish with no swim bladder.
- 1.9.24 Ref 1-1 advises that there is a moderate risk of a 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 guideline quantitative 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 using the model and assumptions presented in **Section 1.4** is 50m (**Table 12**). Applying the SEL_{cum} thresholds for piling (Ref 1-1) on a precautionary basis, indicate that there is a risk of TTS occurring within 700m in all fish.
- 1.9.25 Ref 1-1 guidelines suggest that there is considered to be a high risk of potential behavioural responses occurring in the near-field (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 12**). 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 far-field (i.e. thousands of metres from the source) there is considered to be a low risk of a response in all fish.

Table 12: Relative risk and distances (metres) fish response criteria are reached during dredging and vessel movements

Fish Hearing Category	Mortality/ Potential Mortal Injury		Recoverable injury			TTS			Behaviour
	Relative Risk	SEL _{cum}	Relative Risk	SEL _{cum}	RMS	Relative Risk	SEL _{cum}	RMS	Relative Risk
Swim bladder involved in hearing (primarily pressure detection)	(N) Low (I) Low (F) Low	50	-	80	10	-	700	50	(N) High (I) Moderate (F) Low
Swim bladder is not involved in hearing (particle motion detection)	(N) Low (I) Low (F) Low	30	(N) Low (I) Low (F) Low	80	-	(N) Moderate (I) Low (F) Low	700	-	(N) Moderate (I) Moderate (F) Low
No swim bladder (particle motion detection)	(N) Low (I) Low (F) Low	10	(N) Low (I) Low (F) Low	20	-	(N) Moderate (I) Low (F) Low	700	-	(N) Moderate (I) Moderate (F) Low
Eggs and larvae	(N) Low (I) Low (F) Low	30	(N) Low (I) Low (F) Low	-	-	(N) Low (I) Low (F) Low	-	-	(N) Moderate (I) Moderate (F) Low

Distances are in metres (m).

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

1.9.26 Overall, there is generally 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. TTS and behavioural responses are anticipated to be relatively localised in scale and, in the context of the estuary width and the unconstrained nature of the location, fish will be able to move away and avoid the source of the noise as required. Furthermore, the period of capital dredging during construction will be very short term and temporary, lasting a period of around 12 days.

1.9.27 It is also important to consider the existing background or ambient noise conditions (**Section 1.5**). The levels of underwater noise generated by dredging and vessel movements are predicted to reach existing background levels previously measured in the Humber Estuary within around 100m from the source (**Section 1.8**). Furthermore, the estuary and location of the proposed works already experiences regular vessel operations and ongoing maintenance dredging, and, therefore, fish are already habituated to a similar level of anthropogenic background noise.

Marine mammals

Impact piling

- 1.9.28 NOAA’s user spreadsheet tool (Ref 1-4) has been used to predict the range at which the weighted SEL_{cum} and instantaneous peak SPL acoustic thresholds (Ref 1-19) for the onset of PTS and TTS are reached during the proposed impact piling activity.
- 1.9.29 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 ‘E1.1: Method to calculate peak and SEL_{cum} single strike equivalent’ was selected as the most appropriate method to apply for the percussive piling activity. The model input values, and associated assumptions for impact piling of 2.3m and 1.5m diameter piles are included in **Table 13** and **Table 14** respectively.

Table 13: NOAA user spreadsheet tool input values for ‘Tab E.1: Impact pile driving (stationary source: impulsive, intermittent)’ of 2.3m diameter piles

Model Inputs	Value	Assumptions
Weighting factor adjustment (kHz)	2	Default value for impact pile driving hammers provided in the NOAA instructions (Ref 1-4).
Lp,0-pk specified at “x” meters (dB re 1 µPa)	238	Loudest near-source (10m from the source) sound pressure measurements for the percussive piling installation of 2m CISS steel pipe piles in a shallow water environment (Ref 1-12; Ref 1-35; Ref 1-36) back-calculated to 1 m and the assumption that two piling rigs with impact hammers will be used concurrently (see Section 1.6).
Single Strike SEL _{ss} (LE,p, single strike), specified at “x” metres (dB re 1 µPa ² s)	213	As above.
Number of strikes per pile	675	Maximum value provided for existing field data in the NMFS pile driving calculator (Ref 1-18) and, therefore, considered a reasonable worst case.

Model Inputs	Value	Assumptions
Number of piles per day	2	A total of two 2.3m diameter monopiles require to be installed and, therefore, the maximum impact piling scenario is for two of these types of piles to be piled in a day.
Transmission loss coefficient	17.91	Derived from 11 observations of transmission loss coefficient collected from a number of construction projects undertaken in shallow water estuarine and coastal locations (see Section 1.4).
Distance of sound pressure level measurement (m)	1	The sound levels that were measured for the percussive piling installation of 2.4m CISS steel pipe piles in a shallow water environment (Ref 1-12; Ref 1-35; Ref 1-36) have been back-calculated to 1 m from the source (see Section 1.6).

Table 14: NOAA user spreadsheet tool input values for ‘Tab E.1: Impact pile driving (stationary source: impulsive, intermittent)’ of 1.5m diameter piles

Model Inputs	Value	Assumptions
Weighting factor adjustment (kHz)	2	Default value for impact pile driving hammers provided in the NOAA instructions (Ref 1-4).
Lp,0-pk specified at “x” meters (dB re 1 μ Pa)	231	Loudest near-source (10m from the source) sound pressure measurements for the percussive piling installation of 1.52m CISS steel pipe piles in a shallow water environment (Ref 1-12; Ref 1-35; Ref 1-36) back-calculated to 1m and the assumption that two piling rigs with impact hammers will be used concurrently (see Section 1.6).
Single Strike SEL _{ss} (LE,p, single strike), specified at “x” metres (dB re 1 μ Pa ² s)	206	As above.
Number of strikes per pile	675	Maximum value provided for existing field data in the NMFS pile driving calculator (Ref 1-18) and, therefore, considered a reasonable worst case.
Number of piles per day	3	The maximum impact piling scenario is for the marine works to comprise up to three tubular piles to be installed each day (see Section 1.6).
Transmission loss coefficient	17.91	Derived from 11 observations of transmission loss coefficient collected from a number of construction projects undertaken in shallow water estuarine and coastal locations (see Section 1.4).

Model Inputs	Value	Assumptions
Distance of sound pressure level measurement (m)	1	The sound levels that were measured for the percussive piling installation of 1.52m CISS steel pipe piles in a shallow water environment (Ref 1-12; Ref 1-35; Ref 1-36) have been back-calculated to 1m from the source (see Section 1.6).

1.9.30 The distances at which PTS and TTS in marine mammals are predicted to occur during impact piling of 2.3m and 1.5m diameter piles are included in **Table 15** and **Table 16**.

Table 15: Approximate distances (metres) marine mammal response criteria are reached during impact piling 2.3m diameter piles

Marine Mammal Hearing Group	PTS		TTS	
	SEL _{cum}	Peak	SEL _{cum}	Peak
Harbour porpoise	3,000	100	20,000	200
Common seal and grey seal	2,000	10	10,000	30

Table 16: Approximate distances (metres) marine mammal response criteria are reached during impact piling 1.5m diameter piles

Marine Mammal Hearing Group	PTS		TTS	
	SEL _{cum}	Peak	SEL _{cum}	Peak
Harbour porpoise	2,000	40	10,000	90
Common seal and grey seal	800	5	5,000	10

1.9.31 There is predicted to be a risk of instantaneous PTS and TTS in harbour porpoise within approximately 100m and 200m respectively from the source of the percussive piling noise of 2.3m diameter piles, and within approximately 40m and 90m respectively from the source of the percussive piling noise of 1.5m diameter piles. The risk of instantaneous PTS and TTS in seals is within approximately 10 and 30m respectively from the source for the 2.3m diameter piles and within approximately 5m and 10m respectively for the 1.5m diameter piles.

1.9.32 If the propagation of underwater noise from impact piling were unconstrained by any boundaries, the maximum theoretical distance at which the predicted SEL_{cum} weighted levels of underwater noise during impact piling is within the limits of PTS and TTS in harbour porpoise is approximately 3km and 20km respectively for 2.3m diameter piles and approximately 2km and 10km respectively for 1.5m diameter piles. The maximum distance for PTS and TTS in seals is

approximately 2km and 10km respectively for 2.3m diameter piles, and approximately 800m and 5km respectively for 1.5m diameter piles.

- 1.9.33 Assuming a lower worst case swimming speed of 1.5m/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 SEL_{cum} weighted PTS and TTS injury zones during impact piling is estimated to be around 30 minutes and 4 hours respectively for 2.3m diameter piles and around 20 minutes and 2 hours respectively for 1.5m diameter piles. This is less than 17% 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 around 20 minutes and two hours respectively for 2.3m diameter piles and around nine minutes and one hour respectively for 1.5m diameter piles. This is less than 9% of the time that would be required for an injury to occur and, therefore, assuming seals evade the injury effects zone, they are not considered to be at risk of any permanent or temporary injury during impact piling.
- 1.9.34 Impact piling is predicted to cause instantaneous injury effects within close proximity to the activity and strong behavioural responses over a wider area although this will be constrained to within the outer section of the Humber Estuary between Hull and Cleethorpes.
- 1.9.35 The results indicate that if any marine mammals present in the estuary were to remain stationary within the SEL_{cum} distances from the source of piling over a 24 hour period, it could result in temporary and/or permanent hearing injury. However, it is considered highly unlikely that any individual marine mammal will stay within this “injury zone” during the piling operations.
- 1.9.36 Any marine mammals present are likely to evade the area. Behavioural responses could include movement away from a sound source, aggressive behaviour related to noise exposure (e.g. tail/flipper slapping, fluke display, abrupt directed movement), visible startle response and brief cessation of reproductive behaviour (Ref 1-76). Mild to moderate behavioural responses of any individuals within these zones could include movement away from a sound source and/or visible startle response (Ref 1-76).
- 1.9.37 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 343 days. However, piling will not take place continuously as there will be periods of downtime, pile positioning and set up.
- 1.9.38 The piling works will be undertaken seven days per week. Intended working hours will be from 07:00 to 19:00 in winter months (1 September to 31 March inclusive) and sunrise to sunset in the summer months. The maximum impact piling scenario is for three tubular piles to be installed each day using up to two piling rigs pile driving at any one time, involving approximately 270 minutes of impact piling per day. There will, therefore, be significant periods over a 24-hour period when marine mammals will not be disturbed by any impact piling noise. The actual proportion of impact piling is estimated to be at worst around 19% over a 24 hour period (based on 270 minutes of impact 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 percussive piling will be exposed a maximum of up to 19% over the period of a day.

- 1.9.39 It is also important to consider the noise from piling against existing background or ambient noise conditions (**Section 1.5**). The levels of underwater noise generated by impact piling are predicted to reach existing background levels previously measured in the Humber Estuary within around 2 to 3km from the source (**Section 1.8**). Furthermore, the area in which the construction will take place already experiences regular vessel operations and ongoing maintenance dredging, and, therefore, marine mammals are likely to be habituated to a certain level of anthropogenic background noise.

Vibro piling

- 1.9.40 NOAA’s user spreadsheet tool (Ref 1-4) has been used to predict the range at which the weighted SEL_{cum} acoustic thresholds (Ref 1-19) for the onset of PTS and TTS for either 2.3m diameter or 1.5m diameter piles are reached during the proposed vibro piling activity.
- 1.9.41 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 17**.
- 1.9.42 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 18**.

Table 17: NOAA user spreadsheet tool input values for ‘Tab A.1: Vibratory pile driving (stationary source: non-impulsive, continuous)’

Model Inputs	Value	Assumptions
Weighting factor adjustment (kHz)	2.5	Default value for vibratory pile driving hammers provided in the NOAA instructions (Ref 1-4).
Sound Pressure Level (L _{rms}), specified at "x" metres (dB re 1 µPa)	201	Loudest near-source (10m from the source) sound pressure measurements for the vibratory piling installation of 1.83m steel pipe piles in a shallow water environment (Ref 1-12; Ref 1-35; Ref 1-36) and the assumption that two piling rigs with vibro hammers will be used concurrently (see Section 1.6).
Number of piles within 24 hr period	3	The maximum vibro piling scenario is for the marine works to comprise up to three tubular piles to be installed each day (see Section 1.6).
Duration to drive a single pile (minutes)	20	Each tubular pile is anticipated to require approximately 20 minutes of vibro piling (see Section 1.6).

Model Inputs	Value	Assumptions
Transmission loss coefficient	17.91	Derived from 11 observations of transmission loss coefficient collected from a number of construction projects undertaken in shallow water estuarine and coastal locations (see Section 1.4).
Distance of sound pressure level measurement (m)	1	The sound levels that were measured for the vibratory piling installation of 1.83m steel pipe piles in a shallow water environment (Ref 1-12; Ref 1-35; Ref 1-36) have been back-calculated to 1m from the source (see Section 1.6).

Table 18: 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)	200	2,000
Phocid pinniped (PW) (true seals)	80	1,000

- 1.9.43 If the propagation of underwater noise from vibro piling were unconstrained by any boundaries, the maximum theoretical distance at which the predicted SEL_{cum} weighted levels of underwater noise during vibro piling is within the limits of PTS and TTS in harbour porpoise is 200m and 2km respectively. The maximum distance for PTS and TTS in seals is 80m and 1km respectively.
- 1.9.44 Assuming a lower worst case swimming speed of 1.5m/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 SEL_{cum} weighted PTS and TTS injury zones during vibro piling is estimated to be around 2 minutes and 30 minutes respectively. This is less than 3% 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 around 1 minute and 10 minutes respectively. This is less than 1% of the time that would be required for an injury to occur and, therefore, assuming seals evade the injury effects zone, they are not considered to be at risk of any permanent or temporary injury during vibro piling.
- 1.9.45 The results indicate that if any marine mammals present in the estuary were to remain stationary within the SEL_{cum} distances from the source of piling over a 24 hour period, it could result in temporary and/or permanent hearing injury. However, it is considered highly unlikely that any individual marine mammal will stay within this “injury zone” during the piling operations.
- 1.9.46 Any marine mammals are likely to evade the area. Behavioural responses could include movement away from a sound source, aggressive behaviour related to noise exposure (e.g. tail/flipper slapping, fluke display, abrupt directed movement), visible startle response and brief cessation of reproductive behaviour (Ref 1-76). Mild to moderate behavioural responses of any individuals within

these zones could include movement away from a sound source and/or visible startle response (Ref 1-76).

- 1.9.47 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 343 days. However, piling will not take place continuously as there will be periods of downtime, pile positioning and set up.
- 1.9.48 The piling works will be undertaken seven days per week. Intended working hours will be from 07:00 to 19:00 in winter months (1 September to 31 March inclusive) and sunrise to sunset in the summer months. The maximum vibro piling scenario is for three tubular piles to be installed each day using up to two piling rigs pile driving at any one time, involving approximately 60 minutes of vibro piling per day. 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 4% over a 24 hour period (based on an estimated 60 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 4% over the period of a day.
- 1.9.49 It is also important to consider the noise from piling against existing background or ambient noise conditions (**Section 1.5**). The levels of underwater noise generated by vibro piling are predicted to reach existing background levels previously measured in the Humber Estuary within around 1km from the source (**Section 1.8**). Furthermore, the area in which the construction will take place already experiences regular vessel operations, and, therefore, marine mammals are likely to be habituated to a certain level of anthropogenic background noise disturbance.

Dredging and vessel movements

- 1.9.50 NOAA's user spreadsheet tool (Ref 1-4) has been used to predict the range at which the weighted SEL_{cum} acoustic thresholds (Ref 1-19) for PTS and TTS are reached during the proposed dredging and vessel movements associated with the construction and operation of the proposed development.
- 1.9.51 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 19**.

Table 19: NOAA user spreadsheet tool input values for ‘Tab C: Mobile source, non-impulsive, continuous (“safe distance” methodology)’

Model Inputs	Value	Assumptions
Weighting factor adjustment (kHz)	2.5	The maximum recommended default value provided in the user spreadsheet (Ref 1-4) 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 1.6).
Source velocity (m/s)	1	Value is based on a very low sailing speed for a dredger or vessel. A lower source velocity value predicts greater ranges at which PTS and TTS are reached and, therefore, the lowest reasonable source velocity associated with the dredging and vessel activity has been applied as a worst case.

1.9.52 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 20**.

Table 20: 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	40
Phocid pinniped (PW) (grey seal and common seal)	<1	10

1.9.53 There is predicted to be no risk of PTS in harbour porpoise and the risk of TTS is limited to within around 40m from the dredging or vessel activity (**Table 20**). There is predicted to be no risk of PTS in seals and the risk of TTS is limited to within approximately 10m from the source.

1.9.54 Overall, there is not considered to be any risk of injury or significant disturbance to marine mammals from the proposed dredging and vessel activities that are proposed at the Project even if the dredging and vessel movements were to take place continuously 24/7. Furthermore, the period of capital dredging during construction will be very short term and temporary, lasting a period of around 12 days.

1.9.55 It is also important to consider the existing background or ambient noise conditions (**Section 1.5**). The estuary and location of the proposed works already experiences regular vessel operations and ongoing maintenance dredging, and, therefore, marine mammals are already habituated to a similar level of anthropogenic background noise.

1.10 Summary and Conclusions

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

1.10.2 In accordance with available guidance (Ref 1-10; Ref 1-17; Ref 1-60), a simple logarithmic spreading model has been selected to predict the propagation of sound pressure from the key sources of underwater noise, taking account of its limitations and constraints. The predicted levels of underwater noise have been compared against peer-reviewed noise exposure criteria to determine the potential risk of impact on marine fauna (Ref 1-2; Ref 1-1; Ref 1-19; Ref 1-77).

1.10.3 In order to reduce the level of potential impact associated with underwater noise and vibration on fish and marine mammals during construction (piling), a number of mitigation measures are proposed including the use of soft start procedures, the use of vibro piling where possible with seasonal/night time piling restrictions specifically for migratory fish species, and JNCC piling protocols for marine mammals (Ref 1-92). Further details are provided in the marine ecology assessment (**Chapter 9: Nature Conservation (Marine Ecology) [TR030008/APP/6.2]**).

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