Fair Isle Harbour Improvement Works

A.15 Underwater Noise Report

On behalf of **Shetland Isle Council (SIC)**

Shetland Islands Council

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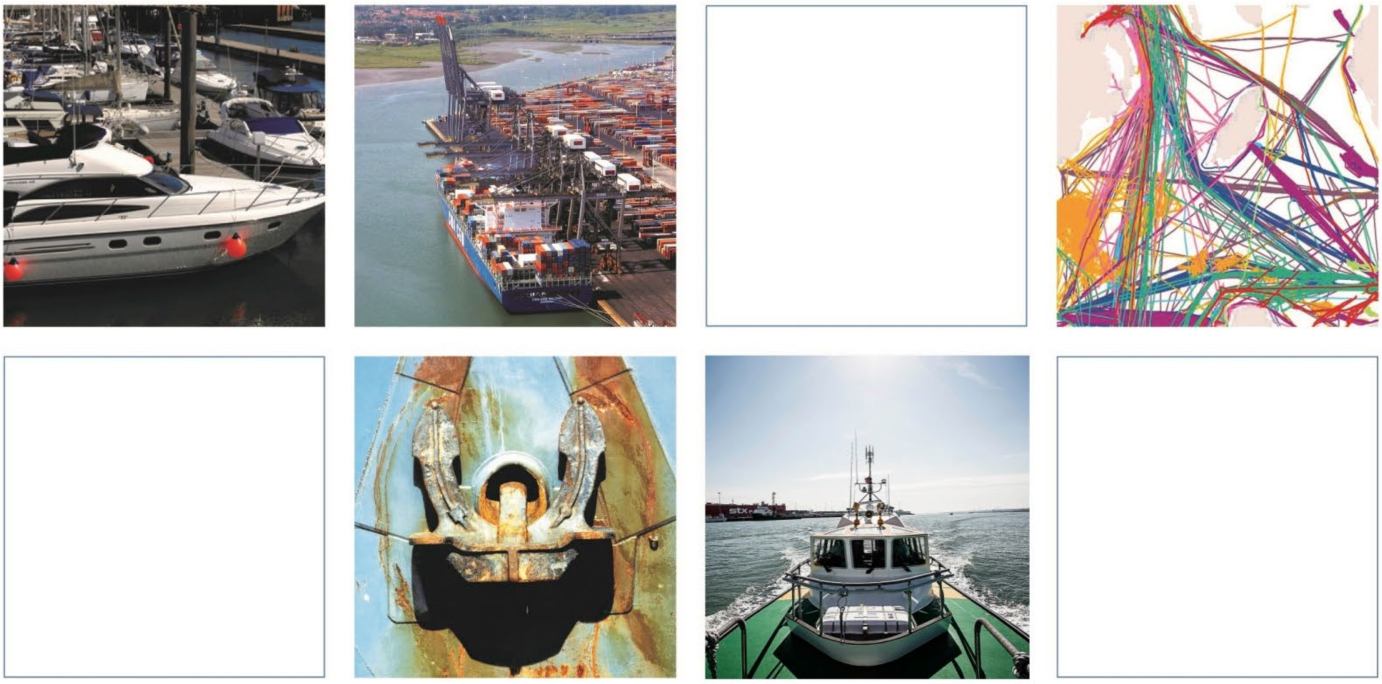
Stantec

Fair Isle Ferry Upgrade

Underwater Noise Assessment

March 2023



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1 Introduction

This report presents an assessment of the potential effects of underwater noise and vibration from the proposed Fair Isle Ferry Upgrade Project on marine fauna present at North Haven (Fair Isle) and Grutness (Shetland). This assessment has been undertaken to support the environmental assessments that have been prepared for the proposed works.

This report has been structured as follows:

Section 1:	**Introduction** provides a brief introduction to the project and need for this assessment;
Section 2:	**Underwater Noise Propagation** reviews the key factors influencing the propagation of underwater noise and presents the preferred underwater noise propagation model that has been applied in this underwater noise assessment;
Section 3:	**Ambient Noise** presents the baseline acoustic conditions of the study area;
Section 4:	**Noise Characteristics of Proposed Works Activities** presents the specific acoustic characteristics of the proposed construction and operational activities;
Section 5:	**Hearing Sensitivity and Responses of Marine Fauna** reviews the hearing sensitivity of marine fauna that occur in the study area and the latest available published criteria that have been applied to determine the scale of potential physiological and behavioural effects;
Section 6:	**Noise Propagation Modelling Outputs** presents the outputs of the underwater noise modelling;
Section 7:	**Potential Effects** reviews the potential effects on local marine fauna; and
Section 8:	**Summary and Conclusions** presents an overview of the outcome of the underwater noise assessment and proposed mitigation measures.

2 Underwater Noise Propagation

In accordance with good practice guidance (NPL, 2014), a simple logarithmic spreading model has been used to predict the propagation of sound levels from the key sources of underwater noise associated with the proposed works. 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) levels with distance from the source due to geometric spreading.

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

Equation 1 Simple logarithmic spreading model

Where:

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

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

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

These provide a mean N coefficient of 17.91 (Standard Deviation (SD) 3.05) and α coefficient of 0.00523 dB m^{-1} (SD 0.00377 dB m^{-1}) based on 11 and 9 observations respectively. The Environment Agency has recommended the application of these model input values in underwater noise assessments undertaken in shallow water environments (e.g. URS Scott Wilson, 2011; ABPmer, 2015) and this semi-empirical approach has also been accepted by the MMO and their advisor Cefas for developments in England. These values are, therefore, considered to be appropriate to use for the underwater noise assessment in support of the proposed works.

Following advice from the MMO and Cefas on another recent project on the Humber Estuary (MMO, pers. comm., 5 May 2022), the received levels associated with the proposed works activities have been modelled in the Sound Exposure Level (SEL) metric, where there is considered to be a better understanding of both SLs and propagation loss, and then translated to the peak Sound Pressure Level (SPL) metric using equation (1) in Lippert *et al.* (2015):

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

Equation 2 Relationship between peak SPL and SEL

Where:

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

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

There are a number of limitations associated with the use of simple logarithmic spreading models (NPL, 2014). Such models do not account for changes in bathymetry and, therefore, are not able to predict the changes in sound propagation caused by sand banks and changes in water depths. It is, therefore, important for underwater noise assessments in such environments to take account of varying bathymetry. It is also important for any solid physical structures that have the potential to redirect or constrain noise transmission (e.g. breakwaters, harbour quay walls, headlands) to be considered. An element of expert judgement and qualitative review of the implications of the site specific environment on noise propagation is, therefore, also required for underwater noise assessments that employ simple logarithmic spreading models.

Another limitation of simple logarithmic spreading models is that they do not explicitly include frequency dependence, and so cannot predict the increased transmission loss at high frequencies due to increased sound absorption. Farcas *et al*. (2016) also demonstrated how use of these simple models in complex environments typical of coastal and inland waters can underestimate noise levels close to the source and substantially overestimate noise levels further from the source. In other words, they can underestimate the risk of injury or disturbance to marine fauna close to the source whilst giving the impression that a larger area would be affected than would actually be the case.

Although more complex models are available, these tend to be computationally demanding, take longer to run and require the assessment of multiple scenarios (e.g. different tidal states/water depths), which generate more complex outputs that are challenging to interpret. They also often require a large number of model input parameters (e.g. hammer energy, pile penetration depth) that can only be appropriately defined and developed once the final design and methodology for the proposed development has been confirmed.

Despite the simple logarithmic spreading model (equation 1 above) representing a basic 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 in shallow water marine environments (ABPmer, 2020; 2021a; 2021b; ABPmer, 2022a; ABPmer, 2022b; RPS, 2018).

In terms of fish, the National Oceanic and Atmospheric Administration (NOAA) National Marine Fisheries Service (NMFS) in the United States recommends the use of the practical spreading model to developers and has incorporated this model in its pile driving calculation spreadsheet to assess the potential impacts of pile driving on fish (NMFS, 2022). This calculator has, therefore, been used to calculate the range at which the peak SPL and cumulative SEL thresholds for pile driving (Popper *et al*., 2014) are reached. Further details of the assumptions and input values that have been applied are provided in Section 7.

In terms of marine mammals, NOAA (2022) has developed a user spreadsheet tool for assessing the potential effects of different types of noise activities on marine mammals which is based on the simple logarithmic spreading model. This spreadsheet tool has been used to predict the range at which the relevant weighted cumulative SEL and instantaneous peak SPL acoustic thresholds (NOAA, 2018) for the onset of temporary threshold shift (TTS) and permanent threshold shift (PTS) are reached during the proposed project activities. Further details, including the input values that have been used are presented in Section 7.

The proposed works at North Haven and Grutness take place in very shallow water and, therefore, the propagation of noise will be limited. Shallow water acts as a high pass filter that only allows signals to pass with a frequency higher than a certain cut-off frequency and attenuates signals with frequencies lower than this cut-off frequency. The cut-off frequency gets higher as the water gets shallower (Harland *et al*., 2005). In this way, the propagation of low frequency underwater noise such as piling will be reduced in very shallow water locations compared to in the deep oceanic waters. At high frequencies (>10 kHz), increasing absorption also prevents high frequency sound propagating over great distances in shallow water.

Overall, therefore, a simple logarithmic spreading model based on conservative assumptions is considered proportionate and sufficiently precautionary to use for this underwater noise assessment.

3 Ambient Noise

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.

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

Measurements to characterise the ambient sound in a specific location (i.e. incorporating both natural and anthropogenic sources) are becoming more common as interest grows in the trends in anthropogenic noise in the ocean, for example in response to the Marine Strategy Framework Directive (MSFD) and UK Marine Strategy (Defra, 2019).

Measurements that characterise the ambient sound at specific locations and include noise from identifiable sources together with non-identifiable sources, are also sometimes referred to as the local ‘soundscape’ (NPL, 2014).

3.1 Sources of ambient sound

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

Natural sources of ambient sound comprise both physical processes and biological activity. Physical processes that are relevant to the study area include wind- and wave-driven turbulence, precipitation and sediment transport processes (Malme *et al.*, 1989; Harland *et al.*, 2005). Biological activity includes echo locating marine mammals and fish communication (Battele, 2004; Harland *et al.*, 2005). These sources of ambient sound vary on a diurnal cycle, a tidal cycle and/or an annual cycle.

A range of anthropogenic noise sources contribute to ambient sound. These can be of short duration and impulsive (e.g. seismic surveys, piling, explosions) or long lasting and continuous (e.g. dredging, shipping, trawling, sonar, drilling, small craft and energy installations) (Dekeling *et al.*, 2014). Impulsive sounds may, however, be repeated at intervals (duty cycle) and such repetition may become ‘smeared’ with distance and reverberation and become indistinguishable from continuous noise. The key anthropogenic sources contributing to ambient sound in the study area are reviewed below.

3.1.1 Vessel traffic

Shipping noise is the dominant contributor to ambient sound in shallow water areas close to shipping lanes and in deeper waters. At longer ranges the sounds of individual ships merge into a background continuum (Harland *et al.*, 2005). Shipping noise will vary on a diurnal cycle (e.g. ferry and coastal traffic) and an annual cycle (seasonal activity). The SLs associated with large ships such as supertankers and container ships are in the range 180 to 190 dB re 1µPa m (MMO, 2015). For smaller shipping vessels and boats the range is 150 to 180 dB re 1µPa m (UKMMAS, 2010; CEDA, 2011). Although the exact characteristics depend on vessel type, size and operational mode, the strongest energy occurs below 1,000 Hz.

There is a busy shipping lane less than 3 km to the west of Fair Isle which is likely to be contributing to the ambient sound at North Haven. The nearest shipping lane to Grutness is around 1 to 2 km west, involving a number of tanker transits each week, around 5 km offshore. AIS shipping traffic data covering the period 2012-2017 indicates that at Grutness, the bay and surrounding area have on average 208 vessel transits a year. These generally involve around 5-20 weekly transits. About a 1 km east of the bay, AIS data shows vessel traffic to increase notably, with more than 600 transits a year.

Small motorised craft (e.g. outboard powered inflatables, speed boats and work boats) produce relatively low levels of noise (75 to 159 dB re 1µPa m), and the output characteristics are highly dependent on speed and other operational characteristics (Richardson *et al.*, 1995). Many of these sources have greater sound energy in higher frequency bands (i.e. above 1,000 Hz) than large ships. Sail powered craft are generally very quiet with the only sound coming from flow noise, wave slap and rigging noise. North Haven, in particular, regularly receives recreational boat traffic in the summer, including tender craft from cruise ships. To the north of the airport, is a small marina just over 1 km from the proposal.

Vessel traffic in the immediate study area of the proposed ferry terminal upgrades at North Haven and Grutness originates from ferry vessels travelling between the terminals. The existing ferry service runs regularly during the spring and summer months predominantly, due to weather constraints.

3.2 Frequency dependence of sound propagation

Shallow and very shallow water[1], such as that at the study area, acts as a high pass filter that only allows signals to pass with a frequency higher than a certain cut-off frequency and attenuates signals with frequencies lower than this cut-off frequency. The cut-off frequency gets higher as the water gets shallower (Harland *et al.*, 2005). In this way, distant shipping makes a reduced contribution to ambient sound in very shallow coastal waters and low frequency sound originates from local sources rather than the great distances found in the deep oceanic waters. At high frequencies (>10 kHz), increasing absorption also prevents high frequency sound propagating over great distances in shallow water so the ambient sound at the study area is dominated by local sound sources.

3.3 Spatiotemporal variation

Ambient sound levels can show significant variation over space and time (NPL, 2014). The observed temporal and spatial variation in ambient sound level can be tens of decibels (in other words, the amplitude can vary by orders of magnitude). This variation can be in the short-term of minutes and hours, or a medium-term such as a diurnal variation (day to night), variation with tidal flows, or a longer-term seasonal variation. The sound level can also depend on location, an example of one cause of this being proximity to a shipping lane (Section 3.1.1), another being proximity to a biological source such as snapping shrimp.

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[1] 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.

4 Noise Characteristics of Proposed Works Activities

There are a number of activities associated with the proposed works 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.

4.1 Fair Isle (North Haven)

4.1.1 Dredging

The Fair Isle Harbour Improvement Works at North Haven is anticipated to involve the dredging of rock (rock breaking) and the dredging of soft material(sand/silts). It is assumed that there will be up to 10 hours of dredging per day. Dredging will take place over approximately 7 months acknowledging that this would not be continuous dredging operations. The dredging activities are likely to involve the use of a large barge-mounted excavator.

Dredging involves a variety of sound generating activities which can be broadly divided into sediment excavation, transport and placement of the dredged material at the disposal site (CEDA, 2011; WODA, 2013; Jones and Marten, 2016). For most dredging activities, the main source of sound relates to the vessel engine noise. In terms of the proposed works at North Haven, the dredger will be almost stationary when it is dredging or travelling at very slow speeds of around 3 knots and, therefore, the levels of engine propeller noise will be very low.

Dredging activities produce broadband and continuous sound[2], mainly at lower frequencies of less than 500 Hz and moderate root mean squared (RMS) SLs from around 150 to 188 dB re 1 µPa m (Thomsen *et al.*, 2009; CEDA, 2011; Robinson *et al.*, 2011; WODA, 2013; MMO, 2015; Jones and Marten, 2016). Backhoe dredgers generate RMS SLs in the range of 154 to 179 dB re 1 µPa m (Reine *et al.*, 2012; Nedwell *et al.*, 2008). Measurements of underwater sound from backhoe dredging operations indicate that the highest levels of underwater sound occur when the excavator is in contact with the seabed. Cutter suction dredgers generate RMS SLs in the range of 172 to 185 dB re 1 µPa m (Reine *et al.*, 2012; MMO, 2015). SLs of Trailing Suction Hopper Dredgers (TSHDs) are variable but generally range from 160 to above 180 dB re 1 µPa m for large TSHDs (Robinson *et al.*, 2011). The most intense sound emissions from the TSHDs are in the low frequencies, up to and including 1,000 Hz in most cases (Robinson *et al.*, 2011; De Jong *et al.*, 2010).

Sound recordings of dredging operations involving rock fracturing by a hydraulic cutterhead dredge and six distinct sources associated with a mechanical backhoe dredging operation during rock excavation indicate that the rock fracturing produced an RMS SL of 175 dB re 1 µPa m, whereas six distinct sources associated with rock excavation had RMS SLs ranging from 164.2 to 179.4 dB re 1 µPa m (Reine *et al.*, 2014).

Overall, the dredger involved in removing the rock and soft material during the proposed works is anticipated to generate a worst case unweighted RMS SL of up to 188 dB re 1 µPa m.

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[2] 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.

4.1.2 Rock armour placement

The proposed works at North Haven will involve the placement of rock armour on the existing breakwater.

Underwater noise generated by rock dumping activities is mainly as a result of the splash, tumble and grinding of rocks during the placement process (SLR Consulting, 2019). Generally, noise from one rock placement event has a slow signal rise time and then reaches its peak level, then followed by a slow drop in levels. Placement activities can be regarded as a sporadic occurrence.

There is little available information on noise emissions from rock placement in marine environments. However, the underwater noise emissions for rock dumping activities during marine cable laying operations are low compared to vessel propulsion noise and pile driving (Nedwell and Howell, 2004; Wyatt, 2008; Nedwell *et al.,* 2012).

The rock placement operations required as part of the proposed works at North Haven will take place primarily onshore and, therefore, there will be limited direct coupling between the activity and the water environment. The noise from rock placement activities will, therefore, be considerably reduced due to the absorption of the sound by the air and by the solid breakwater structure, the interaction with the ground surface (reflection and scattering) and the interaction with and transmission through the seabed. Overall, given that any rock placement operations would generate relatively low levels of sound and would take place largely outside the water environment, they are unlikely to be measurable in the water environment. The potential effects on marine fauna are, therefore, considered to be negligible and these effects are, therefore, not considered further in this underwater noise assessment.

4.1.3 Vessel movements

There will be vessels involved during the construction phase of the project, including the presence of the dredger (Section 4.1.1) and the anticipated delivery of material by sea, as well as disposal of the dredged material at a licensed disposal site.

The new Roll-on/Roll-off (Ro-Ro) ferry vessel involved during the operation of the upgraded ferry terminal at North Haven will be a maximum of 24 m in length and the draught is likely to be similar to the existing (GSIV service draught 2.7m) with the aim of limiting dredging through vessel design.

Vessels that are 20-30 m in length generate SLs in the region of 150 to 166 dB re 1µPa m (MMO, 2015). Overall, the vessels movements involved in the construction and operational phase of the project are anticipated to generate worst case unweighted RMS SLs of up to 166 dB re 1 µPa m. Continuous (24/7) noise generation from vessel activities during construction and operation has been assumed and as such, provides a precautionary assessment.

4.1.4 Other noise sources

Other potential sources of underwater noise during construction of the upgraded ferry facility at North Haven include the following:

- Installing various steel dowels into the rockhead: base plinth for quay wall, linkspan lifting dolphins, new slipway foundations;
- Placing precast concrete units underwater to form the quay wall;
- Back filling quayside with granular fill;
- Removing sections of the existing slipway;
- Drilling; and

- ‘Silent’ non-explosive methods of rock breaking using either a ‘Cardox’ CO_2 rock breaking system, expanding concrete or similar.

These activities generate considerably lower levels of noise than dredging or piling and are not anticipated to result in any significant effects on marine fauna. They have, therefore, not been considered further in this assessment.

4.2 Shetland (Grutness)

4.2.1 Piling

It is expected that up to 328 no. AZ 40-700 sheet piles will be installed in the subtidal marine environment to construct the extension to the pier at Grutness. While piling will likely involve a combination of impact (percussive) and vibratory installation methods, as a worst-case it is assumed that impact piling will be required throughout. Piling activities will be intermittent involving 4 days to pile each sheet pile cell, followed by 12 days of non-piling activities to complete that cell (3 days to install waling beams, 2 days to install tie rods, 3 days to backfill, 4 days to set up temporary works for next cell), before another 4 days of piling to create the next sheet pile cell and so on. Piling activity will be carried out for a maximum of 10 hours per day (between 07:00 and 19:00) for 4 days, followed by 12 days of non-piling activities, repeated for 10 cells. The likely anticipated maximum impact piling scenario is for 8 piles to be installed per day.

The proposed methodology is to install piles “end over” using land-based piling plant sitting on the end of the existing pier. As each cell is completed and backfilled, the plant can move onto the cell and construct the next. It is estimated that piling activities will take a maximum of 6 months, between April and September. While it is assumed that piling would be carried out from the land side (on pier), if the contractor prefers to use a barge mounted piling rig, the total duration of piling will be approximately 3 months with piling undertaken 5.5 days per week (with similar working hour patterns as above).

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.

At the end of the pile, force is exerted on the substrate not only by the force transmitted from the hammer by the pile, but also by the structural waves travelling down the pile which induce lateral waves in the seabed. These may travel as both compressional waves, in a similar manner to the sound in the water, or as a seismic wave, where the displacement travels as Rayleigh waves (Brekhovskikh, 1960). The waves can travel outwards through the seabed or by reflection from deeper sediments. As they propagate, sound will tend to “leak” upwards into the water, contributing to the waterborne soundwaves.

Since the speed of sound is generally greater in consolidated sediments than in water, these waves usually arrive first as a precursor to the waterborne wave. Generally, the level of the seismic wave is typically 10 to 20 dB below the waterborne arrival, and hence it is the latter that dominates the noise.

Impulsive sources such as pile driving should have SLs expressed for a single pulse as either SEL with units of dB re 1 µPa^2 s, or as a peak-peak or zero-peak SPL, with units of dB re 1 µPa (Farcas *et al.*, 2016). Impact piling is impulsive in character with multiple pulses occurring at blow rates in the order of 30 to 60 impacts per minute. Typical SLs range from peak SPL of 190 to 245 dB re 1 µPa (DPTI, 2012). Most of the sound energy usually occurs at lower frequencies between 100 Hz and 1 kHz. Factors that influence the SL include the size, shape, length and material of the pile, the weight and drop height of the hammer, and the seabed material and depth.

The SL of the impact driving of sheet piles for the proposed works have been estimated from the loudest near-source (10 m from the source) sound pressure measurements (in peak SPL, RMS and SEL) for the percussive piling installation of the nearest-sized steel sheet piles (0.6 m) in a similar shallow water environment (approximately 15m water depth) (Illinworth & Rodkin, 2007; Rodkin and Pommerenck, 2014; Seiche Ltd., 2020). Back-calculating the sound pressure measurements to 1 m using the simple logarithmic spreading model (equation 1) provides a worst case estimated SL of 243 dB re 1 µPa m (peak SPL), 231 dB re 1 µPa m (RMS) and 219 dB re 1 µPa^2 s (SEL),

The peak SPL SL for impact sheet piling at KEP is assumed based on a near-source (10 m from the source) peak sound pressure measurement for a 0.6 m steel sheet impact piling installation within a shallow water environment (Illinworth & Rodkin, 2007; ICF Jones & Stokes and Illingworth and Rodkin, 2009). Back-calculating to 1 m using the simple logarithmic spreading model (equation 1) provides an estimated peak SPL SL of 223 dB re 1 µPa m.

4.2.2 Dredging

The Grutness Pier Improvement Works at North Haven is anticipated to involve the dredging of rock (rock breaking) and the dredging of soft material(sand/silts). It is assumed that there will be up to 10 hours of dredging per day. Dredging will take place over 7 months acknowledging that this would not be continuous dredging operations. The dredging activities are likely to involve the use of two barge-mounted excavators working concurrently. A further 5 days is anticipated to be required for seabed preparation activities which will involve local dredging and levelling of rock material.

The SLs associated with different types of dredging are reviewed in detail in Section 4.1.1. In summary, the dredgers involved in removing the rock and soft material during the proposed works at Grutness are anticipated to generate a worst case unweighted RMS SL of up to 188 dB re 1 µPa m. There will be two dredgers working simultaneously. Adding two identical sources (i.e., doubling the signal) will increase the received level by 3 dB. In other words, the unweighted RMS SL of concurrent dredging by more than one dredger is assumed to be 191 dB re 1 µPa m.

4.2.3 Rock armour placement

The proposed works at North Haven will involve the placement of rock armour on the existing breakwater and alongside the pier to create a new breakwater.

The underwater noise associated with rock placement activities is reviewed in more detail in Section 4.1.2. In summary, levels are low compared to vessel propulsion noise. On this basis, the potential effects on marine fauna are not considered to be significant and are, therefore, not considered further in this underwater noise assessment.

4.2.4 Vessel movements

Rock armour for the breakwater may be delivered by vessel during the construction phase of the project. As it is yet to be determined how much of the work will be carried out from sea and the likely requirements for vessel movements during construction, a worst-case scenario has been adopted which assumes the following for marine based vessel activity:

2024

- Barge mounted piling rig (on site for 3 months); and
- Vessel movement for delivery of materials/equipment/plant (maximum, on average, two vessels per week from February to October).

2025

- Two dredgers (on site for 7 months) (see Section 4.2.2); and
- Vessel movement for delivery of materials/equipment/plant (maximum, on average, two vessels per week from March to September).

Disposal of the dredged material at sea will also involve vessel movements between Grutness and a licensed disposal site. The new Roll-on/Roll-off (Ro-Ro) ferry vessel involved during the operation of the upgraded ferry terminal at Grutness will be a maximum of 24 m in length and the draught is likely to be similar to the existing (GSIV service draught 2.7m) with the aim of limiting dredging through vessel design.

The SLs associated with similar sized vessels to the new ferry and vessels anticipated to be involved in construction are reviewed in in Section 4.1.3. In summary, the vessels movements during construction and operation are anticipated to generate worst case unweighted RMS SLs of up to 166 dB re 1 µPa m. Continuous (24/7) noise generation from vessel activities has been assumed and as such, provides a precautionary assessment.

4.2.5 Other noise sources

Other potential sources of underwater noise during construction of the upgraded ferry facility at Grutness include the following:

- Installing various steel dowels into the rockhead: linkspan lifting dolphins and wing walls;
- Back filling pier with granular fill;
- Drilling; and
- ‘Silent’ non-explosive methods of rock breaking using either a ‘Cardox’ CO_2 rock breaking system, expanding concrete or similar.

These activities generate considerably lower levels of noise than dredging or piling and are not anticipated to result in any significant effects on marine fauna. They have, therefore, not been considered further in this assessment.

5 Hearing Sensitivity and Responses of Marine Fauna

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.

5.1 Benthic invertebrates

Benthic invertebrates lack a gas-filled bladder and are, therefore, unable to detect the pressure changes associated with sound waves (Carrol *et al.*, 2017). All cephalopods as well as some bivalves, echinoderms, and crustaceans, however, have a sac-like structure called a statocyst which includes a mineralised mass (statolith) and associated sensory hairs. Statocysts develop during the larval stage and may allow an organism to detect the particle motion associated with soundwaves in water to orient itself (Carrol *et al.*, 2017). In addition to statocysts, cephalopods have epidermal hair cells which help them to detect particle motion in their immediate vicinity, comparable to lateral lines in fish. Similarly, decapods have sensory setae on their body, including on their antennae which may be used to detect low-frequency vibrations. Whole body vibrations due to particle motion have been detected in cuttlefish and scallops, although species names and details of associated behavioural responses are not specified (Carrol *et al.*, 2017).

Scientific understanding of the potential effects of underwater noise on invertebrates is relatively underdeveloped (Hawkins *et al.*, 2015). There is limited research to suggest that exposure to near-field low-frequency sound may cause anatomical damage (Carrol *et al.*, 2017). Anecdotal evidence indicates there was pronounced statocyst and organ damage in seven stranded giant squid after nearby seismic surveys (Guerra *et al.*, 2004). Day *et al.* (2016) found airgun exposure caused damaged statocysts in rock lobsters up to a year later. No such effects, however, were detected in other studies (Christian *et al.*, 2003; Lee-Dadswell, 2009). The disparate results between studies seem to be due to differences in SELs and duration, in some cases due to tank interference, although taxa-specific differences in physical vulnerability to acoustic stress cannot be discounted (Carrol *et al.*, 2017).

There is increasing evidence to suggest that benthic invertebrates respond to particle motion[3] (Roberts *et al.*, 2016). For example, blue mussels *Mytilus edulis* vary valve gape, oxygen demand and clearance rates (Spiga *et al.*, 2016; Roberts *et al.*, 2016) and hermit crabs *Paganus bernhardus* shift their shell and at very high amplitudes, leave their shell, examine it and then return (Roberts *et al.*, 2016). The vibration levels at which these responses were observed generally correspond to levels measured near anthropogenic operations such as pile driving and up to 300 m from explosives testing (blasting) (Roberts *et al.*, 2016). A range of behavioural effects have also been recorded in decapod crustaceans, including a change in locomotion activity, reduction in antipredator behaviour and change in foraging habits (Tidau and Briffa, 2016). Population level and mortality effects, however, are considered unlikely. Effects on benthic invertebrates are, therefore, not considered further in this assessment.

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[3] 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.

5.2 Fish

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).

There is a wide diversity in hearing structures in fish which leads to different auditory capabilities across species (Webb *et al.*, 2008). All fish can sense the particle motion component of an acoustic field via the inner ear as a result of whole-body accelerations (Radford *et al.*, 2012), and noise detection ('hearing') becomes more specialised with the addition of further hearing structures. Particle motion is especially important for locating sound sources through directional hearing (Popper *et al.*, 2014; Hawkins *et al.*, 2015; Nedelec *et al.*, 2016). Although many fish are also likely to detect sound pressure[4], particle motion is considered equally or potentially more important (Hawkins and Popper, 2017).

From the few studies of hearing capabilities in fishes that have been conducted, it is evident that there are potentially substantial differences in auditory capabilities from one fish species to another (Hawkins and Popper, 2017). Since it is not feasible to determine hearing sensitivity for all fish species, one approach to understand hearing has been to distinguish fish groups on the basis of differences in their anatomy and what is known about hearing in other species with comparable anatomy (Popper *et al.*, 2014).

The Fair Isle Harbour Improvement Works Environmental Statement (ES) (Section 10.5) and Grutness Pier Improvement Works Environmental Report (Section 3.8) provide a detailed review of the fish receptors that occur in the study area. Categories proposed by Popper *et al.* (2014) for each of the key fish species are included in Table 1.

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

Swim Bladder or Air Cavities Aid Hearing	Swim Bladder Does Not Aid Hearing	No Swim Bladder
Herring (*Clupea harengus*) Sprat (*Spratus spratus*)	Atlantic cod (*Gadus morhua*) Blue Whiting (*Micromesistius poutassou*) European eel (*Anguilla anguilla*) European hake (*Merluccius merluccius*) Haddock (*Melanogrammus aeglefinus*) Ling (*Molva molva*) Norway pout (*Trisopterus esmarki*) Whiting (*Merlangius merlangus*)	Anglerfish (*Lophius piscatorius*) Basking shark (*Cetorhinus maximus*) Lemon sole (*Microstomus kitt*) Mackerel (*Scomber scombrus*) Sandeel (*Ammodytes* spp.) Skate (*Dipturus batis*-complex) Small-spotted catshark (*Scyliorhinus canicular*) Spotted ray (*Raja montagui*) Spurdog (*Squalus acanthias*)

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[4] 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.

The first category comprises fish that have special structures mechanically linking the swim bladder to the ear. These fish are sensitive primarily to sound pressure, although they also detect particle motion (Hawkins and Popper, 2017). They have a wider frequency range, extending to several kHz and generally show higher sensitivity to sound pressure than fishes in the other categories.

The second category comprises fish with a swim bladder where the organ does not appear to play a role in hearing. Some of the fish in this category are considered to be more sensitive to particle motion than sound pressure (see below) and show sensitivity to only a narrow band of frequencies, namely the salmonids (Salmonidae) (Hawkins and Popper, 2016). This second category also comprises fishes with swim bladders that are close, but not intimately connected, to the ear, such as codfishes (Gadidae) and eels (Anguillidae). These fish are sensitive to both particle motion and sound pressure, and show a more extended frequency range, extending up to about 500 Hz (Popper and Coombs, 1982; Popper and Fay, 2011; Hawkins and Popper, 2017).

The third category comprises fish which lack swim bladders that are sensitive only to sound particle motion and show sensitivity to only a narrow band of frequencies (e.g. flatfishes, sharks, skates and rays). Particle motion rather than sound pressure is considered to be potentially more important to fish without swim bladders. Acoustic particle motion in the water and seabed, for example, has been shown to induce behavioural reactions in sole (Mueler-Blenkle *et al*., 2010). However, there is no published literature on the levels of particle motion generated during construction activities (e.g. pile-driving) and the distance at which they can be detected. This may be due to the fact that there are far fewer devices (and less skill in their use) for detection and analysis of particle motion compared to hydrophone devices for detection of sound pressure (Martin *et al*., 2016). Direct measurements and estimations of particle motion have also been hampered in the past by the lack of guidance on analytical methods. The recently published best practice guide for underwater particle motion measurement for biological applications (Nedelec *et al*., 2021) aims to provide guidance for scientific researchers making particle motion measurements. This is likely to result in an increase in the publication of standardised measurements and a possible greater understanding of the potential effects of particle motion on marine fauna.

Particle velocity can be calculated indirectly from sound pressure measurements using relatively simple models (MacGillivray *et al*., 2004). However, such estimates of sound particle velocity are only valid in environments that are distant from reflecting boundaries and other acoustic discontinuities. These conditions are rarely met in the shelf-sea and shallow-water habitats that most aquatic organisms inhabit and that are applicable to the study area (Nedelec *et al*., 2016; Nedelec *et al*., 2021).

Steps that are required to improve knowledge of the effects of particle motion on marine fauna have recently been set out (Popper and Hawkins, 2018). Although particle motion measurement standards have recently been published (Nedelec *et al*., 2021), there continues to be a lack of easy to use and reasonably priced instrumentation to measure particle motion, and lack of sound exposure criteria for particle motion to determine the potential effects on marine fauna. As such, the scope for considering particle motion in underwater noise assessments is currently limited (Faulkner *et al*., 2018). The underwater noise assessment has, therefore, been based on the latest available evidence and focused on the effects of sound pressure.

The extent to which intense underwater sound might cause an adverse environmental impact in a particular fish species is dependent upon the level of sound pressure or particle motion, its frequency, duration and/or repetition (Hastings and Popper, 2005). The range of potential effects from intense sound sources, such as pile driving, includes immediate death, permanent or temporary tissue damage and hearing loss, behavioural changes and masking effects. Tissue damage can result in eventual death or may make the fish less fit until healing occurs, resulting in lower survival rates. Hearing loss can also lower fitness until hearing recovers. Behavioural changes can potentially result in animals avoiding migratory routes or leaving feeding or reproduction grounds with potential population level consequences. Biologically important sounds can also be masked where the received levels are marginally above existing background levels (Hawkins and Myrberg Jr, 1983). The ability to detect and localise the source of a sound is of considerable biological importance to many fish species and is often used to assess the suitability of a potential mate or during territorial displays and during predator prey interactions.

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

The Popper *et al.* (2014) quantitative instantaneous peak SPL and cumulative SEL criteria for different marine activities involved in the proposed works (i.e. piling, dredging and vessel movements) have been used to determine the mortality/potential mortal injury and recoverable injury for all the fish hearing categories representing the key fish species that occur in the study area (Table 1). These guidelines are based on an understanding that fish will respond to sounds and their hearing sensitivity.

While the Popper *et al.* (2014) noise exposure criteria provide thresholds for auditory impairment, there are many data gaps that preclude the setting of specific noise exposure criteria for behavioural responses in fish (Popper *et al*., 2014; Hawkins and Popper, 2017; Faulkner *et al*., 2018). The onset of behavioural responses is much more difficult to quantify as reactions are likely to be strongly influenced by behavioural or ecological context and the effect of a particular response is often unclear and may not necessarily scale with received sound level (Hawkins and Popper, 2014; Hawkins *et al*., 2015; Faulkner *et al*., 2018). In other words, behaviour may be more strongly related to the particular circumstances of the animal, the activities in which it is engaged, and the context in which it is exposed to sounds (Ellison *et al*., 2012; Pena *et al*., 2013). For example, a startle or reflex response to the onset of a noise source does not necessarily lead to displacement from the ensonified area.

This uncertainty is further compounded by the limitations of observing fish behavioural responses in a natural context. Few studies have conducted behavioural field experiments with wild fish and laboratory experiments may not give a realistic measure of how fish will respond in their natural environment (Hastings and Popper, 2005; Kastelein *et al*., 2008; Popper and Hastings, 2009). As a consequence, only hearing data based on behavioural experiments is considered acceptable for assessing the ability of fish to detect sound (Sisneros *et al*., 2016).

Recent studies have considered approaches to quantify the risk of behavioural responses, for example through dual criteria based on dose-response curves for proximity to the sound source and received sound level (Dunlop *et al*., 2017). An empirical behavioural threshold could also be adopted using *in situ* observed responses of fish to similar sound sources (Faulkner *et al*., 2018). A study observing the responses of caged fish to nearby air gun operations found that initial increases in swimming behaviour may occur at a level of 156 dB re 1 µPa RMS (McCauley *et al*., 2000). At levels of around 161-168 dB re 1 µPa RMS active avoidance of the air gun source would be expected to occur (Pearson *et al*., 1992; McCauley *et al*., 2000). These responses may, however, differ from those of unconfined fish.

Work has been undertaken by Hawkins *et al.* (2014) on the behavioural responses of schools of wild sprat and mackerel to playbacks of pile driving. At a single-pulse peak-to-peak SPL of 163 dB re 1 µPa[5], schools of sprat and mackerel were observed to disperse or change depth on 50 % of presentations. In the absence of similar data for other species, this threshold has been applied for all fish species (Table 2).

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[5] This is 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; NOAA (2022).

Table 2. Fish response criteria applied in this assessment

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

* Popper *et al.* (2014).

** Hawkins *et al.* (2014).

Peak and RMS SPL is in dB re 1 µPa and cumulative SEL (SEL_{cum}) is in dB re 1 $\mu\text{Pa}^2\text{s}$.

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).

Auditory and non-auditory injuries in fish have not been observed or documented to occur in association with dredging (Thomsen *et al.*, 2009). The literature suggests that dredging noise is unlikely to cause direct mortality or instantaneous injury. However, the (predominantly) low-frequency sounds produced by dredging overlap with the hearing range of many fish species, which may pose a risk in TTS, auditory masking, and behavioural effects (McQueen *et al.*, 2019), as well increased stress-related cortisol levels in fish species (Wenger *et al.*, 2017). A TTS involves a temporary reduction of hearing capability caused by exposure to underwater noise. An intense short exposure can produce the same scale of TTS as a long-term, repeated exposure to lower sound levels. The significance of the TTS varies among species depending on their dependence on sound as a sensory cue for ecologically relevant functions. Furthermore, it is important to note that the biological significance of such responses is largely unknown.

Potential behavioural effects in the past have also been inferred by comparing the received sound level with the auditory threshold of marine fauna. Richardson *et al*. (1995) and Thomsen *et al*. (2006), for example, have used received levels of noise in comparison with the corresponding hearing thresholds of marine fauna in order to estimate the range of audibility and zones of influence from underwater sound sources. This form of analysis was taken a stage further by Nedwell *et al*. (2007b), where the underwater noise was 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 included behavioural thresholds, where received sound levels around 90 dB above hearing threshold (dB_{ht}) were 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.

The dB_{ht} criteria have been applied in a number of EIAs and the Environment Agency has previously recommended it to be used in impact assessments in coastal/estuarine environments (e.g. ABPmer, 2015; URS Scott Wilson, 2011). However, it is worth noting that the dB_{ht} criteria have not been validated by experimental study and have not been published in an independent peer-reviewed paper. The dB_{ht} approach does not take into account potential for sound sensitivity to changes with that of the life stage of the organism, time of year, animal motivation, or other factors that might affect hearing and behavioural responses to sound (Hawkins and Popper, 2017). Furthermore, the dB_{ht} criteria are based on measures of inner ear responses and should rather be based on behavioural threshold determinations (Popper *et al.*, 2014; Hawkins and Popper, 2017). The use of dB_{ht} criteria is, therefore, not advisable and has not been applied to this assessment (Hawkins and Popper, 2017).

5.3 Marine mammals

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.

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 for fish, 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.

At lower SPLs, it is more likely that behavioural responses to underwater sound will be observed. These reactions may include the animals leaving the area for a period of time, or a brief startle reaction. Masking effects may also occur at lower levels of noise. Masking is the interference with the detection of biologically relevant communication signals such as echolocation clicks or social signals. Masking has been shown in acoustic signals used for communication among marine mammals (see Clark *et al.*, 2009). Masking may in some cases hinder echolocation of prey or detection of predators. If the signal-to-noise ratio prevents detection of subtle or even prominent pieces of information, inappropriate or ineffective responses may be shown by the receiving organism.

NOAA (2018) provides technical guidance for assessing the effects of underwater anthropogenic (human-made) sound on the hearing of marine mammal species. Specifically, the received levels, or acoustic thresholds, at which individual marine mammals are predicted to experience changes in their hearing sensitivity (either temporary or permanent) for acute, incidental exposure to underwater anthropogenic sound sources are provided. These thresholds update and replace the previously proposed criteria in Southall *et al.* (2007) for preventing auditory/physiological injuries in marine mammals. Further recommendations have recently been published regarding marine mammal noise exposure by Southall *et al.* (2019) which complement the NOAA (2018) thresholds and also look at a wider range of marine mammals species, as well as the hearing sensitivity of amphibious mammals (e.g. seals, sea otters) to airborne noise.

The NOAA (2018) and Southall *et al.* (2019) thresholds are categorised according to marine mammal hearing groups. The Fair Isle Harbour Improvement Works ES (Section 10.5) and Grutness Pier Improvement Works Environmental Report (Section 3.8) provide a detailed review of the marine mammal receptors that occur in the study area. The key marine mammal species comprise grey seal (*Halichoerus grypus*), harbour seal (*Phoca vitulina*), harbour porpoise (*Phocoeaa phocoeana*) and minke whale (*Balaenoptera acutorostrata*). According to NOAA (2018), minke whales are categorised as low-frequency (LF) cetaceans, harbour porpoises are categorised as high-frequency (HF) cetaceans, and grey seals and harbour seals are categorised as pinniped phocids in water (PW) (earless *seals* or "true seals".

NOAA (2018) and Southall *et al.* (2019) provide weighted cumulative SEL acoustic thresholds for non-impulsive sources (e.g. dredging) and unweighted peak SPL and weighted cumulative SEL acoustic thresholds for impulsive sources (e.g. impact piling) which are categorised according to marine mammal hearing groups. The relevant acoustic thresholds for the onset of TTS and PTS due to non-impulsive and impulsive sound sources for the relevant marine mammal groups are presented in Table 3.

Table 3. Marine mammal response criteria applied in this assessment

Marine Mammal Hearing Group	Impulsive (Impact Piling)		Non-Impulsive (Dredging and Vessel Movements)	
	TTS	PTS	TTS	PTS
Low-frequency (LF) cetaceans (baleen whales)	168 dB SEL_{cum} 213 dB peak	183 dB SEL_{cum} 219 dB peak	179 dB SEL_{cum}	199 dB SEL_{cum}
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 cumulative SEL has a reference value of 1 $\mu Pa^2 s$.				

Peak SPL acoustic thresholds for impulsive sound sources provide an estimate of the instantaneous worst-case potential effects on marine mammals. Cumulative SEL is calculated from the energy in a representative single pile strike and the number of strikes over a 24 hour period. This measure assumes that all strikes have the same received single strike SEL value, which is rarely the case since the animal (or source) is likely to be moving relative to each other. It also assumes that the animal is stationary within the zone of potential effect for a 24 hour period which is highly unlikely. Furthermore, it does not take potential physiological or physical recovery from any effects of a single signal exposure into account. As such, this averaging metric has the potential to result in false conclusions on the effects of sound exposure and needs to be treated with more caution as noted by Hawkins and Popper (2017).

There are no equivalent SPL behavioural response criteria that would represent the sources of underwater noise associated with the proposed works. Behavioural reactions to acoustic exposure are less predictable and difficult to quantify than effects of noise exposure on hearing or physiology as reactions are highly variable and context specific (Southall *et al.*, 2007).

Field studies have demonstrated behavioural responses of harbour porpoises to anthropogenic noise (Cefas, 2020). A number of studies have shown avoidance of pile driving activities during offshore wind farm construction (Brandt *et al.*, 2011; Carstensen *et al.*, 2006; Dähne *et al.*, 2013), with the range of measurable responses extending to at least 21 km in some cases (Tougaard *et al.*, 2009). Seismic surveys have also elicited avoidance behaviour in harbour porpoises, albeit short-term (Thompson *et al.*, 2013), and monitoring of echolocation activity suggests possible negative effects on foraging activity in the vicinity of seismic operations (Pirotta *et al.*, 2014). There is a scarcity of studies quantifying behavioural impacts from dredging (Thomsen *et al.*, 2011). An investigation by Diederichs *et al.* (2011) showed that harbour porpoises temporarily avoided an area of sand extraction off the Island of Sylt in Germany. Diederichs *et al.* (2011) found that, when the dredging vessel was closer than 600 m to the porpoise detector location, it took three times longer before a porpoise was again recorded than during times without sand extraction. However, after the ship left the area, the clicks resumed to the baseline rate.

Few studies have documented responses of seals to underwater noise in the field (Cefas, 2020). Tracking studies found reactions of the grey seals to pile driving during the construction of windfarms were diverse (Aarts *et al.*, 2017). These included altered surfacing or diving behaviour, and changes in swim direction including swimming away from the source, heading into shore or travelling perpendicular to the incoming sound, or coming to a halt. Also, in some cases no apparent changes in their diving behaviour or movement was observed. Of the different behavioural changes observed a decline in descent speed occurred most frequent, which suggests a transition from foraging (diving to the bottom), to more horizontal movement. These changes in behaviour were on average larger and occurred more frequent at smaller distances from the pile driving events, and such changes were statistically significantly different at least up to 36 km. In addition to changes in dive behaviour, also changes in movement were recorded. There was evidence that on average grey seals within 33 km were more likely to swim away from the pile driving. In some cases, seals exposed to pile-driving at close range, returned to the same area on subsequent trips. This suggests that some seals had an incentive to go to these areas, which was stronger than the potential deterring effect of the pile-driving.

A telemetry study found no overall significant displacement of common seal during construction of a wind farm in The Wash, south-east England (Russell *et al.*, 2016). However, during piling, seal usage (abundance) was significantly reduced up to 25 km from the piling activity; within 25 km of the centre of the wind farm, there was a 19 to 83 % (95 % confidence intervals) decrease in usage compared to during breaks in piling, equating to a mean estimated displacement of 440 individuals. This amounts to significant displacement starting from predicted received levels of between 166 and 178 dB re 1 µPa (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.

Koschinski *et al.* (2003) conducted a playback experiment on harbour seals in which the recorded sound of an operational wind turbine was projected via a loudspeaker, resulting in modest displacement of seals from the source (median distance was 284 vs 239 m during control trials). Two further studies of ringed seals (*Phoca hispida*), which are closely related to both harbour and grey seals, have observed behaviour in response to anthropogenic noise: Harris *et al*., (2001) reported animals swimming away and avoidance within ~150 m of a seismic survey, while Moulton *et al*., (2003) found no discernible difference in seal densities in response to construction and drilling for an oil pipeline.

A number of field observations of harbour porpoise and pinnipeds to multiple pulse sounds have been made and are reviewed by Southall *et al.* (2007). The results of these studies are considered too variable and context-specific to allow single disturbance criteria for broad categories of taxa and of sounds to be developed. Another way to evaluate the responses of marine mammals and the likelihood of behavioural responses is by comparing the received sound level against species specific hearing threshold levels. Further information on the dB_{ht} metric and its limitations is provided in Section 5.2 and is, therefore, not repeated here.

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.

5.4 Seabirds

Diving seabird species may be exposed to elevated underwater noise levels as a result of the proposed works. The Fair Isle Harbour Improvement Works ES and Grutness Pier Improvement Works Environmental Report provide a detailed review of the seabird receptors that occur in the study area. Seabird species in the study area include Arctic Tern and Common Tern (shallow water plungers); Gannet (deep plunger); Black Guillemot, Cormorant, Guillemot, Little Auk, Puffin, Razorbill, Shag and Sooty Shearwater (pursuit divers/plungers), Kittiwake (surface feeder using dipping or shallow plunge diving); and Storm Petrel (dipping). Other seabirds that have been recorded in the wider area include Arctic Skua and Great Skua (aerial pursuit); Fulmar, Common Gull, Glaucous Gull, Great Black-backed Gull, Herring Gull and Lesser Black-backed Gull (surface seizing).

In general, there is very limited research on the effects of underwater noise on seabirds. Observations of impacts to seabirds from pile driving during the construction of Offshore Windfarm Egmond aan Zee in the North Sea, concluded that underwater noise effects were negligible, however, this may be in part due to the application of appropriate mitigation measures, including the use of pingers and soft start techniques to encourage potentially sensitive birds to disperse away from the site (Leopold and Camphuysen, 2007).

Recent research generally suggests that diving seabirds could be more sensitive to underwater noise than previously assumed. For example, hearing thresholds for Great Cormorant were found to be comparable to seals and toothed whales in the frequency band 1 to 4 kHz (Hansen *et al.*, 2017).

A number of assessments have, based on the limited information available, and the similar frequency ranges between seabirds and phocid pinniped and cetacean species, applied methodologies developed for pinnipeds or low frequency cetaceans in assessing seabird sensitivity to underwater noise (Teachout, 2012). The response criteria for low frequency cetaceans and phocid pinnipeds have, therefore, been applied to this underwater noise assessment as a worst-case approximation for considering potential effects on seabirds (see Table 3).

6 Noise Propagation Modelling Outputs

6.1 Fair Isle (North Haven)

The simple logarithmic spreading model (equation 1) described in Section 2 was applied to the worst case (highest) unweighted SLs associated with the proposed works activities at North Haven that were described in Section 4.1 (i.e. non-concurrent dredging for rock or soft sediments during construction and vessel movements during construction and operation) to determine the unweighted received levels with range. These received levels represent unweighted metrics as recommended in NPL (2014). Table 4 shows the results of this analysis at various distances from the sources of noise associated with the proposed works.

Table 4. Maximum predicted unweighted received levels during proposed activities at North Haven

Range (m)	Dredging (RMS in dB re 1 µPa)	Vessel Movements (RMS in dB re 1 µPa)
1	188	166
10	170	148

Range (m)	Dredging (RMS in dB re 1 µPa)	Vessel Movements (RMS in dB re 1 µPa)
100	152	130
200	146	124
600	135	113
1,000	129	107
3500	106	84
7,000	83	61
10,000	64	42

The levels of underwater noise generated by the proposed dredging activity at North Haven are predicted to reduce to around 129 dB re 1 µPa within 1 km of the source of dredging (i.e. beyond the existing rock armoured breakwater and within the wider bay area at this location). These levels are below the SLs generated by most anthropogenic activities (MMO, 2015) and are unlikely to be discernible against existing background noise.

The levels of underwater noise generated by vessel movements are significantly lower than the dredging activity and are predicted to reduce to around 124 dB re 1 µPa within 200 m of the vessel. It should be noted that the proposed works at North Haven are located at the existing ferry terminal which already experiences intermittent elevated levels of underwater noise of a similar scale to that which is predicted due to the ferry vessels that already operate in this area, nearby shipping channels and occasional maintenance dredging as required (Section 3.1).

6.2 Grutness

The simple logarithmic spreading model (equation 1) described in Section 2 was applied to the worst case (highest) unweighted SLs associated with the proposed works activities at Grutness that were described in Section 4.2 (i.e. impact piling, concurrent dredging for rock or soft sediments during construction and vessel movements during construction and operation) to determine the unweighted received levels with range. These received levels represent unweighted metrics as recommended in NPL (2014). Table 5 shows the results of this analysis at various distances from the sources of noise associated with the proposed works.

Table 5. Maximum predicted unweighted received levels during proposed activities at Grutness

Range (m)	Impact Piling (SEL in dB 1 µPa^2·s)	Concurrent Dredging (RMS in dB re 1 µPa)	Vessel Movements (RMS in dB re 1 µPa)
1	198	191	166
10	180	173	148
100	162	155	130
200	156	149	124
600	145	138	113
1,000	139	132	107
3500	116	109	84
7,000	93	86	61
10,000	74	67	42

The SEL received levels of underwater noise generated during impact piling for the proposed works at Grutness are predicted to reduce to around 139 dB 1 µPa^2·s within 1 km of the source of piling (i.e. within the outer part of the harbour and wider bay at this location). This SEL received level is equivalent to a peak SPL of 155 dB re 1 µPa using equation 2 (Section 2) and generally comparable to a small < 10 m length recreational boat (MMO, 2015).

The levels of underwater noise generated by the proposed concurrent dredging activity is predicted to reduce to around 132 dB re 1 µPa within 1 km of the source which is below the SL generated by most anthropogenic activities (MMO, 2015) and is unlikely to be discernible against existing background noise, particularly at this exposed location which is subject to high wave activity.

The levels of underwater noise generated by vessel movements are significantly lower than the dredging activity and are predicted to reduce to around 124 dB re 1 µPa within 200 m of the vessel. It should be noted that the proposed works at Grutness are located at the existing ferry terminal which already experiences intermittent elevated levels of underwater noise of a similar scale to that which is predicted due to the ferry vessels that already operate in this area, regular movements of recreational vessels and nearby shipping channels (Section 3.1).

7 Potential Effects

7.1 Fair Isle (North Haven)

7.1.1 Fish

Dredging

The relative risk and distances at which potential mortality/injury and behavioural effects in fish are predicted to occur as a result of the dredging associated with the proposed works at North Haven are included in Table 6.

The worst case SL generated by dredging is below the Popper *et al.* (2014) quantitative instantaneous peak SPL and cumulative SEL thresholds for pile driving, which indicates that there is no risk of mortality, potential mortal injury or recoverable injury in all categories of fish even at the very source of the dredger noise. This appears to correlate with the Popper *et al.* (2014) recommended qualitative guidelines for continuous noise sources which consider that the risk of mortality and potential mortal injury in all fish is low in the near, intermediate and far-field (Table 6).

According to Popper *et al*. (2014), the risk of recoverable injury is also considered low for fish with no swim bladder and fish with a swim bladder that is not involved in hearing. There is a greater risk of recoverable injury in fish where the swim bladder is involved in hearing (e.g. herring) whereby a cumulative noise exposure threshold is recommended (170 dB rms for 48 h). The distance at which recoverable injury is predicted in these fish as a result of dredging is 10 m (Table 6).

Popper *et al*. (2014) advise that there is a moderate risk of TTS occurring in the nearfield (i.e. tens of metres from the source) in fish with no swim bladder and fish with a swim bladder that is not involved in hearing and a low risk in the intermediate and far-field. There is a greater risk of TTS in fish where the swim bladder is involved in hearing (e.g. herring) whereby a cumulative noise exposure threshold is recommended (158 dB rms for 12 h). The distance at which TTS is predicted in these fish as a result of dredging is 46 m (Table 6).

Popper *et al.* (2014) guidelines suggest that there is considered to be a high risk of potential behavioural responses occurring in the nearfield (i.e. tens of metres from the source) for fish species with a swim bladder involved in hearing and a moderate risk in other fish species (Table 6). At intermediate distances (i.e. hundreds of metres from the source) there is considered to be a moderate risk of potential behavioural responses in all fish and in the farfield (i.e. thousands of metres from the source) there is considered to be a low risk of a response in all fish.

Overall, there is considered to be a low risk of any injury in fish as a result of the underwater noise generated by dredging, although recoverable injury could potentially occur in very close proximity to the dredger in fish where the swim bladder is involved in hearing (e.g. herring). The level of exposure will depend on the position of the fish with respect to the source, the propagation conditions which will be influenced by the tidal state, and the individual’s behaviour over time. However, it is unlikely that a fish would remain in the vicinity of a dredger for extended periods. Behavioural responses are anticipated to be spatially negligible in scale and fish will be able to move away and avoid the source of the noise as required. Furthermore, the proposed dredging activities involved during construction will be temporary and take place over a period of approximately 7 months acknowledging that this would not be continuous dredging operations.

Table 6. Relative risk and distances (metres) fish response criteria are reached during dredging

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

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

Vessel movements

The relative risk and distances at which potential mortality/injury and behavioural effects in fish are predicted to occur as a result of the vessel movements associated with the construction and operation of the upgraded ferry facility at North Haven are included in Table 7.

The worst case SL generated by the vessel movements is below the Popper *et al.* (2014) quantitative instantaneous peak SPL and cumulative SEL thresholds for pile driving, which indicates that there is no risk of mortality, potential mortal injury or recoverable injury in all categories of fish even at the very source of the vessel noise. This appears to correlate with the Popper *et al.* (2014) recommended qualitative guidelines for continuous noise sources which consider that the risk of mortality and potential mortal injury in all fish is low in the near, intermediate and far-field (Table 7).

According to Popper *et al.* (2014), the risk of recoverable injury is also considered low for fish with no swim bladder and fish with a swim bladder that is not involved in hearing. There is generally considered to be a greater risk of recoverable injury in fish where the swim bladder is involved in hearing (e.g. herring) whereby a cumulative noise exposure threshold is recommended (170 dB rms for 48 h). However, the SL for the new ferry falls below this threshold and, therefore, there is considered to be no potential risk of recoverable injury in any category of fish (Table 7).

The distance at which TTS (158 dB rms for 12 h) is predicted in the most sensitive fish where the swim bladder is involved in hearing (e.g. herring) as a result of the new ferry is 3 m (Table 7). There is considered to be no or very limited risk of TTS in the other less sensitive fish categories even at the very source of the vessel noise.

Popper *et al.* (2014) guidelines suggest that there is considered to be a high risk of potential behavioural responses occurring in the nearfield (i.e. tens of metres from the source) for fish species with a swim bladder involved in hearing and a moderate risk in other fish species (Table 7). 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.

Overall, there is considered to be a negligible risk of any injury in fish as a result of the underwater noise generated by the vessels involved during construction and the operation of the new ferry. Behavioural responses are anticipated to be spatially negligible in scale and fish will be able to move away and avoid the source of the noise as required.

Table 7. Relative risk and distances (metres) fish response criteria are reached during vessel movements

Fish Hearing Category	Mortality/ Potential Mortal Injury/ Recoverable Injury	Recoverable Injury	TTS	Behaviour
Swim bladder involved in hearing (primarily pressure detection)	(N) Low (I) Low (F) Low	-	3	(N) High (I) Moderate (F) Low
Swim bladder is not involved in hearing (particle motion detection)	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Moderate (F) Low
No swim bladder (particle motion detection)	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Moderate (F) Low
Eggs and larvae	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Moderate (F) Low

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

7.1.2 Marine mammals

Dredging

NOAA's user spreadsheet tool (NOAA, 2022) has been used to predict the range at which the weighted cumulative SEL acoustic thresholds (NOAA, 2018) for PTS and TTS are reached during the proposed dredging at North Haven.

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 activity. The model input values, and associated assumptions are included in Table 8.

Table 8. NOAA user spreadsheet tool input values for 'Tab C: Mobile source, non-impulsive, continuous ("safe distance" methodology)'

Model Inputs	Value	Assumptions
Weighting factor adjustment (kHz)	2.5	The maximum recommended default value provided in the user spreadsheet (NOAA, 2022) 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 dredging that will be involved in construction of the proposed works (see Section 4.1.1).
Source velocity (m/s)	1	Value is based on the minimum sailing speed of a dredging vessel as it removes material from the seabed. A lower source velocity value predicts greater ranges at which PTS and TTS are reached and, therefore, the lowest reasonable source velocity associated with the dredging and vessel activity has been applied as a worst case.

The distances at which PTS and TTS in marine mammals are predicted to occur during dredging associated with the construction of the proposed works at North Haven are included in Table 9.

Table 9. Approximate distances (metres) marine mammal response criteria are reached during dredging

Marine Mammal Hearing Group	PTS	TTS
Low-frequency (LF) cetaceans (minke whale)	<1	25
High-frequency (HF) cetacean (harbour porpoise)	<1	44
Phocid pinniped (PW) (grey seal and common seal)	<1	12

There is predicted to be no risk of PTS in any of the key marine mammal species found in the study area. The risk of TTS in minke whale is limited to within 25 m from the dredging activity, and within 44 m in harbour porpoise and 12 m in seals (Table 9).

Overall, there is not considered to be any risk of injury or significant disturbance to marine mammals from the proposed dredging activities at North Haven. Furthermore, the proposed dredging activities involved during construction will be temporary and take place over period of approximately 7 months acknowledging that this would not be continuous dredging operations.

Vessel movements

NOAA's user spreadsheet tool (NOAA, 2022) has been used to predict the range at which the weighted cumulative SEL acoustic thresholds (NOAA, 2018) for PTS and TTS are reached as a result of the vessels used during construction and the operation of the new ferry at North Haven.

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 vessel activity. The model input values, and associated assumptions are included in Table 10.

Table 10. NOAA user spreadsheet tool input values for 'Tab C: Mobile source, non-impulsive, continuous ("safe distance" methodology)'

Model Inputs	Value	Assumptions
Weighting factor adjustment (kHz)	2.5	The maximum recommended default value provided in the user spreadsheet (NOAA, 2022) that leads to the greatest predicted ranges for PTS and TTS and is, therefore, considered a worst case.

Source Level (L_{rms})	166	The maximum estimated RMS SL for vessel movements that will be involved in operation of the new ferry facility (see Section 4.1.3).
Source velocity (m/s)	1	Value is based on the minimum sailing speed of the vessel as it approaches the new ferry terminal. 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 vessel activity has been applied as a worst case.

The distances at which PTS and TTS in marine mammals are predicted to occur during vessel movements associated with the construction phase and operation of the new ferry terminal at North Haven are included in Table 11.

Table 11. Approximate distances (metres) marine mammal response criteria are reached during vessel movements

Marine Mammal Hearing Group	PTS	TTS
Low-frequency (LF) cetaceans (minke whale)	<1	<1
High-frequency (HF) cetacean (harbour porpoise)	<1	<1
Phocid pinniped (PW) (grey seal and common seal)	<1	<1

There is predicted to be no risk of PTS or TTS in any of the key marine mammal species found in the study area (Table 9). Overall, there is not considered to be any risk of injury or significant disturbance to marine mammals from the proposed vessel activities at North Haven even if the vessel movements were to take place continuously 24/7.

7.1.3 Diving Birds

Dredging

NOAA's user spreadsheet tool (NOAA, 2022) has been used to predict the range at which the weighted cumulative SEL acoustic thresholds (NOAA, 2018) for PTS and TTS are reached during the proposed dredging at North Haven.

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 activity. The model input values, and associated assumptions are included in Table 8.

The distances at which PTS and TTS in LF cetaceans and phocid pinnipeds (a worst case approximation for considering potential effects on seabirds) are predicted to occur during dredging associated with the construction of the proposed works at North Haven are included in Table 9. There is predicted to be no risk of PTS in diving birds. The risk of TTS is limited to within 12 to 25 m assuming diving birds were to remain within the water column for 24 h which is not realistic.

Overall, there is not considered to be any risk of injury or significant disturbance to diving birds from the proposed dredging activities at North Haven. Furthermore, the proposed dredging activities involved during construction will be temporary and take place over period of approximately 7 months acknowledging that this would not be continuous dredging operations.

Vessel movements

NOAA's user spreadsheet tool (NOAA, 2022) has been used to predict the range at which the weighted cumulative SEL acoustic thresholds (NOAA, 2018) for PTS and TTS are reached as a result of the vessels involved during construction and the operation of the new ferry at North Haven.

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 vessel activity. The model input values, and associated assumptions are included in Table 10.

The distances at which PTS and TTS in LF cetaceans and phocid pinnipeds (a worst-case approximation for considering potential effects on seabirds) are predicted to occur during vessel movements associated with the construction phase and the operation of the new ferry terminal at North Haven are included in Table 11. There is predicted to be no risk of PTS or TTS in diving birds.

Overall, there is not considered to be any risk of injury or significant disturbance to diving birds from the proposed vessel activities at North Haven even if the vessel movements were to take place continuously 24/7.

7.2 Shetland (Grutness)

7.2.1 Fish

Impact piling

The calculator developed by NMFS (2022) 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 Popper *et al.* (2014) instantaneous peak and cumulative SEL thresholds for pile driving are reached as a result of the proposed works at Grutness. The model input values and associated assumptions for impact piling are included in Table 12.

Table 12. NMFS piling calculator input values for impact piling

Model Inputs	Value	Assumptions
Number of strikes per pile	675	Maximum published value provided for existing field data of percussive piling of steel piles and, therefore, considered a reasonable worst case (WSDOT, 2017 cited in NMFS, 2021).
Number of piles per day	8	The maximum impact piling scenario is for the marine works to comprise the installation of up to 8 sheet piles each day (see Section 4.2.1).
Peak SPL SL (dB re 1 µPa m)	223	Loudest near-source (10 m from the source) sound pressure measurements for the percussive piling installation of the nearest-sized sheet piles (0.6 m) in a similar shallow water environment (approximately 15 m water depth) (Illinworth & Rodkin, 2007; Rodkin and Pommerenck, 2014; Seiche Ltd., 2020) back-calculated to 1 m (see Section 4.2.1).

Model Inputs	Value	Assumptions
SEL SL (dB re 1 µPa^2 s)	198	As above.
Distance from source (m)	1	The sound levels that were measured for percussive piling installation of the nearest-sized sheet piles (0.6 m) in a similar shallow water environment (approximately 15 m water depth) (Illinworth & Rodkin, 2007; Rodkin and Pommerenck, 2014; Seiche Ltd., 2020) have been back-calculated to 1 m from the source (see Section 4.2.1).
Noise reduction due to abatement (dB)	NA	Not applicable.
Transmission loss coefficient	17.91	Derived from 11 observations of transmission loss coefficient collected from a number of construction projects undertaken in shallow water estuarine and coastal locations (see Section 2).

The distances at which potential mortality/injury and behavioural effects in fish are theoretically predicted to occur during impact piling activities associated with the construction of the proposed works are included in Table 13.

The Grutness ferry terminal is located near Sumburgh Head on the southern tip of the Shetland Mainland, opposite Sumburgh Airport. The harbour is generally sheltered from the south and west by land and open to the north and east. The harbour is very exposed from the east through to the north-east. The study area is described in more detail in Section 2 of the Grutness Pier Improvement Works Environmental Report. The distances at which peak SPL and cumulative SEL thresholds for mortality/potential mortal injury and recoverable injury are reached are all well within the harbour and local to the piling activity. Given the mobility of fish, any individuals that might be present within the relatively localised areas associated with potential mortality/injury during pile driving activities would be expected to move away and avoid harm. Overall, the potential mortality/injury effects of the proposed percussive piling activities on fish are not considered to be significant.

Table 13. Approximate distances (metres) fish response criteria are reached during impact piling

Fish Hearing Category	Mortality/ Potential Mortal Injury		Recoverable Injury		Behaviour
	Peak	SEL$_{cum}$	Peak	SEL$_{cum}$	Peak
Swim bladder involved in hearing (primarily pressure detection)	8	38	8	64	876
Swim bladder is not involved in hearing (particle motion detection)	8	26	8	64	876
No swim bladder (particle motion detection)	4	8	4	12	876
Eggs and larvae	8	26	(N) Moderate (I) Low (F) Low		876

Behavioural reactions are anticipated to be limited to within the wider bay at Grutness. The scale of the behavioural response within this predicted zone of influence is partly dependent on the hearing sensitivity of the species. Fish with a swim bladder involved in hearing (e.g. herring and sprat) 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. Atlantic salmon and European eel) are likely to display a milder behavioural reaction. Fish without a swim bladder (e.g. lemon sole and skate) are anticipated to only show very subtle changes in behaviour in this zone.

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.

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 6 months. However, piling will not take place continuously as there will be periods of downtime, pile positioning and set up. Furthermore, the piling works will be undertaken for a maximum of 10 hours per day (between 07:00 and 19:00) for 4 days, followed by 12 days of non-piling activities, repeated for 10 cells; or for 5.5 days per week (with similar working hour patterns as above) for approximately 3 months if undertaken from a barge mounted piling rig (Section 4.2.1). There will, therefore, be extended periods when fish will not be disturbed by any impact piling noise. The actual proportion of impact piling in any 24-hour period is estimated to be around 42 %. In other words, any fish that remain within the predicted behavioural effects zone at the time of percussive piling will be exposed to this disturbance only 42 % of the time.

It is also important to consider the noise from piling against existing background or ambient noise conditions (Section 3). The area in which the construction will take place already experiences regular vessel operations and, therefore, fish are likely to be habituated to a certain level of intermittent anthropogenic background noise.

Dredging

The relative risk and distances at which potential mortality/injury and behavioural effects in fish are predicted to occur as a result of the concurrent dredging associated with the proposed works at Grutness are included in Table 14.

The worst case SL generated by concurrent dredging is below the Popper *et al.* (2014) quantitative instantaneous peak SPL and cumulative SEL thresholds for pile driving, which indicates that there is no risk of mortality, potential mortal injury or recoverable injury in all categories of fish. This appears to correlate with the Popper *et al.* (2014) recommended qualitative guidelines for continuous noise sources which consider that the risk of mortality and potential mortal injury in all fish is low in the near, intermediate and far-field (Table 14).

According to Popper *et al.* (2014), the risk of recoverable injury is also considered low for fish with no swim bladder and fish with a swim bladder that is not involved in hearing. There is a greater risk of recoverable injury in fish where the swim bladder is involved in hearing (e.g. herring) whereby a cumulative noise exposure threshold is recommended (170 dB rms for 48 h). The distance at which recoverable injury is predicted in these fish as a result of concurrent dredging is 15 m (Table 14).

Popper *et al.* (2014) advise that there is a moderate risk of TTS occurring in the nearfield (i.e. tens of metres from the source) in fish with no swim bladder and fish with a swim bladder that is not involved in hearing and a low risk in the intermediate and far-field. There is a greater risk of TTS in fish where the swim bladder is involved in hearing (e.g. herring) whereby a cumulative noise exposure threshold is recommended (158 dB rms for 12 h). The distance at which TTS is predicted in these fish as a result of concurrent dredging is 67 m (Table 14).

Popper *et al.* (2014) guidelines suggest that there is considered to be a high risk of potential behavioural responses occurring in the nearfield (i.e. tens of metres from the source) for fish species with a swim bladder involved in hearing and a moderate risk in other fish species (Table 14). 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.

Overall, there is considered to be a low risk of any injury in fish as a result of the underwater noise generated by concurrent dredging, although recoverable injury could potentially occur in very close proximity to the dredgers (within 15 m) in fish where the swim bladder is involved in hearing (e.g. herring). The level of exposure will depend on the position of the fish with respect to the sources, the propagation conditions which will be influenced by the tidal state, and the individual's behaviour over time. However, it is unlikely that a fish would remain in the vicinity of a dredgers for extended periods. Behavioural responses are anticipated to be spatially negligible in scale and fish will be able to move away and avoid the sources of the noise as required. Furthermore, the proposed concurrent dredging activities involved during construction will be temporary and take place over 7 months acknowledging that this would not be continuous dredging operations (Section 4.2.2).

Table 14. Relative risk and distances (metres) fish response criteria are reached during dredging

Fish Hearing Category	Mortality/ Potential Mortal Injury/ Recoverable Injury	Recoverable Injury	TTS	Behaviour
Swim bladder involved in hearing (primarily pressure detection)	(N) Low (I) Low (F) Low	15	67	(N) High (I) Moderate (F) Low
Swim bladder is not involved in hearing (particle motion detection)	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Moderate (F) Low
No swim bladder (particle motion detection)	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Moderate (F) Low
Eggs and larvae	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Moderate (F) Low

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

Vessel movements

The relative risk and distances at which potential mortality/injury and behavioural effects in fish are predicted to occur as a result of the vessel movements associated with the construction and operation of the upgraded ferry facility at Grutness are the same as those at North Haven (Table 7, Section 7.1.1) and are, therefore, not repeated here.

In summary, there is considered to be a negligible risk of any injury in fish as a result of the underwater noise generated by the vessels involved during construction and the operation of the new ferry.

Behavioural responses are anticipated to be spatially negligible in scale and fish will be able to move away and avoid the source of the noise as required.

7.2.2 Marine mammals

Impact piling

NOAA's user spreadsheet tool (NOAA, 2022) has been used to predict the range at which the NOAA (2018) weighted cumulative SEL and instantaneous peak SPL acoustic thresholds for the onset of PTS and TTS are reached during the proposed impact piling activity at Grutness.

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 are included in Table 15.

Table 15. NOAA user spreadsheet tool input values for 'Tab E.1: Impact pile driving (stationary source: impulsive, intermittent)'

Model Inputs	Value	Assumptions
Weighting factor adjustment (kHz)	2	Default value for impact pile driving hammers provided in the NOAA instructions (NOAA, 2022).
Lp,0-pk specified at "x" meters (dB re 1 µPa)	223	Loudest near-source (10 m from the source) sound pressure measurements for the percussive piling installation of the nearest-sized sheet piles (0.6 m) in a similar shallow water environment (approximately 15 m water depth) (Illinworth & Rodkin, 2007; Rodkin and Pommerenck, 2014; Seiche Ltd., 2020) back-calculated to 1 m (see Section 4.2.1).
Single Strike SELss (LE,p, single strike) specified at "x" meters (dB re 1 µPa^2 s)	198	As above.
Distance of Lp,0-pk measurement (m)	1	The sound levels that were measured for percussive piling installation of the nearest-sized sheet piles (0.6 m) in a similar shallow water environment (approximately 15 m water depth) (Illinworth & Rodkin, 2007; Rodkin and Pommerenck, 2014; Seiche Ltd., 2020) have been back-calculated to 1 m from the source (see Section 4.2.1).
Number of strikes per pile	675	Maximum published value provided for existing field data of percussive piling of steel piles and, therefore, considered a reasonable worst case (WSDOT, 2017 cited in NMFS, 2021).
Number of piles per day	8	The maximum impact piling scenario is for the marine works to comprise the installation of up to 2 tubular piles each day (see Section 4.1).
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 2).
Distance of single strike SELss (LE,p, single	1	The sound levels that were measured for percussive piling installation of the nearest-sized sheet piles (0.6 m) in a similar shallow water environment (approximately 15 m

Model Inputs	Value	Assumptions
strike) measurement (m)		water depth) (Illinworth & Rodkin, 2007; Rodkin and Pommerenck, 2014; Seiche Ltd., 2020) have been back-calculated to 1 m from the source (see Section 4.2.1).

The distances at which PTS and TTS in marine mammals are theoretically predicted to occur during impact piling activities associated with the construction of the proposed works are included in Table 16.

Table 16. Approximate distances (metres) marine mammal response criteria are reached during impact piling

Marine Mammal Hearing Group	PTS		TTS	
	SEL_{cum}	Peak	SEL_{cum}	Peak
Low-frequency (LF) cetaceans (minke whale)	834	2	5,735	4
High-frequency (HF) cetaceans (harbour porpoise)	965	15	6,640	32
Phocid pinnipeds in water (PW) (true seals)	494	2	3,397	4

There is theoretically predicted to be a risk of instantaneous PTS and TTS in minke whales and seals within 2 m and 4 m respectively from the source of the percussive piling noise, and in harbour porpoise within 15 m and 32 m respectively. If the propagation of underwater noise from impact piling were unconstrained by any boundaries, the maximum theoretical distance at which the predicted cumulative SEL weighted levels of underwater noise during impact piling is within the limits of PTS and TTS in minke whales is 834 m and 5.7 km respectively, and in harbour porpoise is 965 m and 6.6 km respectively. The maximum distance for PTS and TTS in seals is 494 m and 3.4 km respectively. The propagation of noise, however, will be significantly limited by the existing bathymetry (shallow water) and physical (hard) constraints of the study area at Grutness (see Section 2) and potential effects will be largely limited to within the harbour and wider bay area.

Assuming a lower worst case swimming speed of 1.5 m/s for all marine mammal species (including both adults and juveniles), the maximum time that would take minke whale to leave the cumulative SEL weighted PTS and TTS injury zones during impact piling is estimated to be around 9 minutes and 1.1 hours respectively. In harbour porpoise, it is estimated to be 11 minutes and 1.2 hours respectively. The maximum time that would take seals to leave the PTS and TTS zones is estimated to be 6 and 38 minutes respectively. These durations equate to 4 %, 5 % and 3 % of the time that would be required for a temporary injury to occur in minke whales, harbour porpoise and seals respectively and, therefore, assuming marine mammals evade the injury effects zone, they are not considered to be at risk of any permanent or temporary injury during impact piling.

Any marine mammals present are likely to evade the area. Behavioural responses could include movement away from a sound source, aggressive behaviour related to noise exposure (e.g. tail/flipper slapping, fluke display, abrupt directed movement), visible startle response and brief cessation of reproductive behaviour (Southall *et al.*, 2007). Mild to moderate behavioural responses of any individuals within these zones could include movement away from a sound source and/or visible startle response (Southall *et al.*, 2007).

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 6 months. However, piling will not take place continuously as there will be periods of downtime, pile positioning and set up. Furthermore, the piling works will be undertaken for a maximum of 10 hours per day (between 07:00 and 19:00) for 4 days, followed by 12 days of non-piling activities, repeated for 10 cells; or for 5.5 days per week (with similar working hour patterns as above) for approximately 3 months if undertaken from a barge mounted piling rig (Section 4.2.1). There will, therefore, be extended periods when marine mammals will not be disturbed by any impact piling noise. The actual proportion of impact piling in any 24-hour period is estimated to be around 42 %. In other words, any marine mammals that remain within the predicted behavioural effects zone at the time of percussive piling will be exposed to this disturbance only 42 % of the time.

It is also important to consider the noise from piling against existing background or ambient noise conditions (Section 3). The area in which the construction will take place already experiences regular vessel operations from the existing ferry, the nearby shipping lane and recreational vessel activity within the bay, and, therefore, marine mammals are likely to be habituated to a certain level of intermittent anthropogenic background noise.

Dredging

NOAA's user spreadsheet tool (NOAA, 2022) has been used to predict the range at which the weighted cumulative SEL acoustic thresholds (NOAA, 2018) for PTS and TTS are reached during the proposed concurrent dredging at Grutness.

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 concurrent dredging activity. The model input values, and associated assumptions are included in Table 17.

Table 17. NOAA user spreadsheet tool input values for 'Tab C: Mobile source, non-impulsive, continuous ("safe distance" methodology)'

Model Inputs	Value	Assumptions
Weighting factor adjustment (kHz)	2.5	The maximum recommended default value provided in the user spreadsheet (NOAA, 2022) that leads to the greatest predicted ranges for PTS and TTS and is, therefore, considered a worst case.
Source Level (L_{rms})	191	The maximum estimated RMS SL for concurrent dredging by the two vessels that will be involved in construction of the proposed works (see Section 4.2.2).
Source velocity (m/s)	1	Value is based on the minimum sailing speed of a dredging vessel as it removes material from the seabed. A lower source velocity value predicts greater ranges at which PTS and TTS are reached and, therefore, the lowest reasonable source velocity associated with the dredging and vessel activity has been applied as a worst case.

The distances at which PTS and TTS in marine mammals are predicted to occur during the concurrent dredging associated with the construction of the proposed works at Grutness are included in Table 18.

Table 18. Approximate distances (metres) marine mammal response criteria are reached during concurrent dredging

Marine Mammal Hearing Group	PTS	TTS
Low-frequency (LF) cetaceans (minke whale)	<1	49
High-frequency (HF) cetacean (harbour porpoise)	<1	89
Phocid pinniped (PW) (grey seal and common seal)	<1	23

There is predicted to be no risk of PTS in any of the key marine mammal species found in the study area. The risk of TTS in minke whale is limited to within 49 m from the concurrent dredging activity, and within 89 m in harbour porpoise and 23 m in seals (Table 18).

Overall, there is not considered to be any risk of injury or significant disturbance to marine mammals from the proposed concurrent dredging activities at Grutness. Furthermore, the proposed dredging activities will be temporary and take place over a period of 7 months acknowledging that this would not be continuous dredging operations (Section 4.2.2).

Vessel movements

The relative risk and distances at which PTS and TTS in marine mammals are predicted to occur as a result of the vessel movements associated with the construction and operation of the upgraded ferry facility at Grutness are the same as those at North Haven (Table 11, Section 7.1.2) and are, therefore, not repeated here.

In summary, there is not considered to be any risk of injury or significant disturbance to marine mammals from the proposed vessel activities at Grutness even if the vessel movements were to take place continuously 24/7.

7.2.3 Diving birds

Impact piling

NOAA's user spreadsheet tool (NOAA, 2022) has been used to predict the range at which the NOAA (2018) weighted cumulative SEL and instantaneous peak SPL acoustic thresholds for the onset of PTS and TTS are reached during the proposed impact piling activity at Grutness.

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 are included in Table 15.

The distances at which PTS and TTS in LF cetaceans and phocid pinnipeds (a worst case approximation for considering potential effects on seabirds) are theoretically predicted to occur during impact piling activities associated with the construction of the proposed works are included in Table 16. There is theoretically predicted to be a risk of instantaneous PTS and TTS in diving seabirds within 2 m and 4 m respectively from the source of the percussive piling noise. If the propagation of underwater noise from impact piling were unconstrained by any boundaries, the maximum theoretical distance at which the predicted cumulative SEL weighted levels of underwater noise during impact piling is within the limits of PTS in diving birds is 494 m to 834 m. The maximum distance for TTS is 3.4 to 5.7 km. The propagation of noise, however, will be significantly limited by the existing bathymetry and physical constraints of the study area at Grutness and potential effects will be largely limited to within the harbour and wider bay area.

Diving birds species will only be within the water column for very short periods of time (seconds to minutes) and well below the 24 hour period required for a permanent or temporary injury to occur within the predicted distances. They are, therefore, not considered to be at risk of any permanent or temporary injury during impact piling.

The effects of piling noise on diving birds also need to be considered in terms of the duration of exposure. Piling noise will take place over a period of approximately 6 months. However, piling will not take place continuously as there will be periods of downtime, pile positioning and set up. Furthermore, the piling works will be undertaken for a maximum of 10 hours per day (between 07:00 and 19:00) for 4 days, followed by 12 days of non-piling activities, repeated for 10 cells; or for 5.5 days per week (with similar working hour patterns as above) for approximately 3 months if undertaken from a barge mounted piling rig (Section 4.2.1). There will, therefore, be extended periods when diving birds will not be disturbed by any underwater noise during impact piling. The actual proportion of impact piling in any 24-hour period is estimated to be around 42 %. In other words, any diving birds that are feeding below water within the predicted behavioural effects zone at the time of percussive piling will be exposed to this disturbance only 42 % of the time. It is, however, important to recognise that diving seabirds are diurnal feeders and therefore will be able to feed undisturbed during any periods of daylight outside of the piling working day (between 07:00 and 19:00). As the breeding period, when food requirements are highest, overlaps with the longer summer days this will allow several hours of undisturbed feeding each day within the confines of the bay.

It is also important to consider the noise from piling against existing background or ambient noise conditions (Section 3). The area in which the construction will take place already experiences regular vessel operations, and, therefore, diving birds are likely to be habituated to a certain level of intermittent anthropogenic background noise.

Dredging

NOAA’s user spreadsheet tool (NOAA, 2022) has been used to predict the range at which the weighted cumulative SEL acoustic thresholds (NOAA, 2018) for PTS and TTS are reached during the proposed concurrent dredging at Grutness.

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 concurrent dredging activity. The model input values, and associated assumptions are included in Table 17.

The distances at which PTS and TTS in LF cetaceans and phocid pinnipeds (a worst case approximation for considering potential effects on seabirds) are predicted to occur during the concurrent dredging associated with the construction of the proposed works at Grutness are included in Table 18. There is predicted to be no risk of PTS in diving birds. The risk of TTS is limited to within 23 to 49 m assuming diving birds were to remain within the water column for 24 h which is not realistic.

Overall, there is not considered to be any risk of injury or significant disturbance to diving birds from the proposed concurrent dredging activities at Grutness. Furthermore, the proposed dredging activities will be temporary and take place over a period of 7 months acknowledging that this would not be continuous dredging operations (Section 4.2.2).

Vessel movements

The relative risk and distances at which PTS and TTS in diving birds are predicted to occur as a result of the vessel movements associated with the construction and operation of the upgraded ferry facility at

Grutness are the same as those at North Haven (Table 11, Section 7.1.3) and are, therefore, not repeated here.

In summary, there is not considered to be any risk of injury or significant disturbance to diving birds from the proposed vessel activities at Grutness even if the vessel movements were to take place continuously 24/7.

8 Summary and Conclusions

This report presents the underwater noise assessment 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 proposed Fair Isle Ferry Upgrade Project at North Haven (Fair Isle) and Grutness (Shetland).

In accordance with available guidance (NPL, 2014; Farcas *et al.*, 2016; Faulkner *et al.*, 2018), a simple logarithmic spreading model has been selected to predict the propagation of sound pressure from the key sources of underwater noise, taking account of its limitations and constraints. The predicted levels of underwater noise have been compared against peer-reviewed noise exposure criteria to determine the potential risk of impact on marine fauna (Hawkins *et al.*, 2014; Popper *et al.*, 2014; NOAA, 2018; Southall *et al.*, 2019).

In summary, there is not considered to be a risk of significant injury or disturbance to fish, marine mammals and diving birds from the proposed dredging and vessel activities at Grutness and North Haven. At Grutness, where impact piling is taking place, marine mammals are anticipated to evade the injury effects zones. A number of mitigation measures are proposed to reduce or minimise potential significant adverse behavioural effects during construction:

- **Soft start**: The gradual increase of piling power, incrementally, until full operational power is achieved will be used as part of the piling methodology. This will give marine fauna the opportunity to move away from the area before the onset of full impact strikes. The duration of the soft start is proposed to be 20 minutes in line with the JNCC piling protocol (JNCC, 2010);
- **Vibro piling**: Vibro piling is proposed to be used where possible (which produces lower peak source noise levels than percussive piling). However, in order to drive the piles to the required design level in certain circumstances percussive piling is likely to be required given the underlying geology and depth of piling that is required to ensure the necessary structural integrity and stability of the piles; and
- **Marine Mammal Observer**: In addition, in order to further reduce the significance of the impact to marine mammals the JNCC "Statutory nature conservation agency protocol for minimising the risk of injury to marine mammals during piling" (JNCC, 2010) will be followed during percussive piling.

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10 Abbreviations/Acronyms

ABP	Associated British Ports
CEDA	Centre for Environmental Data Analysis
Cefas	Centre for Environment, Fisheries and Aquaculture Science
dB	Decibel
Defra	Department for Environment, Food and Rural Affairs
DPTI	Department for Infrastructure and Transport
ES	Environmental Statement
EU	European Union
HF	High Frequency
IFM	Institute of Fisheries Management
JNCC	Joint Nature Conservation Committee
MSFD	Marine Strategy Framework Directive
µPa	microPascal
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NPL	National Physical Laboratory
Pa	Pascal
RMS	Root Mean Square
SD	Standard Deviation
SEL	Sound Exposure Level
SL	Source Level
SPL	Sound Pressure Level
TSHD	Trailing Suction Hopper Dredger
TTS	Temporary Threshold Shift
UKMMAS	UK Marine Monitoring Assessment Strategy
WODA	World Organisation of Dredging Associations

Cardinal points/directions are used unless otherwise stated.

SI units are used unless otherwise stated.

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