C3 - Sensitive

HUNTERSTON CONSTRUCTION YARD

SUBSEA NOISE TECHNICAL REPORT

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Glossary

Term	Meaning
Decibel (dB)	A relative scale most commonly used for reporting levels of sound. The actual sound measurement is compared to a fixed reference level and the "decibel" value is defined to be $10 \cdot \log_{10}$(“actual”/”reference”), where (“actual”/”reference”) is a power ratio. The standard reference for underwater sound pressure is 1 micro-Pascal (μPa), while 20 micro-Pascals is the standard for airborne sound. The dB symbol is often followed by a second symbol identifying the specific reference value (i.e. re 1 μPa).
Grazing angle	A glancing angle of incidence (the angle between a ray incident on a surface and the line perpendicular to the surface).
Permanent Threshold Shift (PTS)	A total or partial permanent loss of hearing caused by some kind of acoustic trauma. PTS results in irreversible damage to the sensory hair cells of the ear, and thus a permanent reduction of hearing acuity.
Temporary Threshold Shift (TTS)	Temporary loss of hearing as a result of exposure to sound over time. Exposure to high levels of sound over relatively short time periods will cause the same amount of TTS as exposure to lower levels of sound over longer time periods. The mechanisms underlying TTS are not well understood, but there may be some temporary damage to the sensory cells. The duration of TTS varies depending on the nature of the stimulus, but there is generally recovery of full hearing over time.
Sound Exposure Level (SEL)	The cumulative sound energy in an event, formally: “ten times the base-ten logarithm of the integral of the squared pressures divided by the reference pressure squared”. Equal to the often seen “L_E” or “dB SEL” quantity. Defined in: ISO 18405:2017, 3.2.1.5
Sound Pressure level (SPL)	The average sound energy over a specified period of time, formally: “ten times the base-ten logarithm of the arithmetic mean of the squared pressures divided by the squared reference pressure”. Equal to the deprecated “RMS level”, “dB_{rms}” and to Leq if the period is equal to the whole duration of an event. Defined in ISO 18405:2017, 3.2.1.1
Peak Level, Peak Pressure Level (L_P)	The maximal sound pressure level of an event, formally: “ten times the base-ten logarithm of the maximal squared pressure divided by the reference pressure squared” or “twenty time the base-ten logarithm of the peak sound pressure divided by the reference pressure, where the peak sound pressure is the maximal deviation from ambient pressure”. Defined in ISO 18405:2017, 3.2.2.1
Source Level (SL)	Here taken to mean the level (SEL/SPL/L_P) at 1 meter range. If not otherwise stated it’s assumed the source is omnidirectional (equal level in all directions). For sources larger than 1 m in radius the Source Level is back-calculated to 1 m.
decidecade	Used to refer to a step in frequency, similar to “one-third-octave”, defined as a ratio of $10^{0.1} \approx 1.259$ (one third octave is 21/3 ≈ 1.260). Used interchangeably with “3rd octave”.
noise	Sound that is irrelevant, unwanted or harmful to the organism(s) in question. Noise is often detrimental, but not necessarily so.

Acronyms

Term	Meaning
ADD	Acoustic Deterrent Device
LF	Low Frequency (Cetaceans)
HF	High Frequency (Cetaceans)
VHF	Very High Frequency (Cetaceans)
MF	Mid Frequency (Cetaceans) – **DEPRECATED** only for reference to NOAA/NMFS 2018 groups
OW/OCW	Otariid pinnipeds/Other Carnivores in water (refers to the same weighting and animal groups)
PW/PCW	Phocid pinnipeds
NMFS	National Marine Fisheries Service
RMS	Root Mean Square
SEL	Sound Exposure Level, [dB]
SPL	Sound Pressure Level, [dB]
L_P	Peak Pressure Level, [dB]
SL	Source Level [dB]
TTS	Temporary Threshold Shift
PTS	Permanent Threshold Shift
SSS	Side scan sonar – Towed sonar device typically positioned 10-15 m above the sediment, main purpose is to characterise the sediment surface texture.
MBES	Multi beam echosounder – Uses multiple narrow beams to measure the depth across a swath below the vessel.
SBP	Sub Bottom Profiler – Any device/system that uses acoustics to record echoes from within the sediment, examples include seismic arrays, sparkers, boomers, chirpers, pingers and associated recorder array.
USBL	Ultra Short Baseline Array – Small array of at least 4 hydrophones and a pinger to measure positions of equipment under water.
UHRS	Ultra High-Resolution Seismic survey – Usually a sparker driven sub bottom characterisation system.
c.	Circa, i.e., approximately

Units

Unit	Description
dB	Decibel (Sound)
Hz	Hertz (Frequency)
kHz	Kilohertz (Frequency)
kJ	Kilojoule (Energy)
km	Kilometre (Distance)
km^2	Kilometre squared (Area)
m	Metre
ms	Millisecond (10^{-3} seconds) (Time)
ms^{-1} or m/s	Metres per second (Velocity or speed)
kn	Knots (speed), 1 kn = 0.514 m/s, 1 m/s = 1.944 kn
µPa	Micro Pascal
Pa	Pascal (Pressure: newton/m^2)
psu	Practical Salinity Units (parts per thousand of equivalent salt in seawater, weight-based)

Unit	Description
kg/m^3	Specific density (of water, sediment or air)
Z	Acoustic impedance [$kg/(m^2 \cdot s)$ or $(Pa \cdot s)/m^3$]

Units will generally be enclosed in square brackets e.g.: “[m/s]”

1 INTRODUCTION

This Subsea Noise Technical Report presents the results of a desktop study considering the potential short-term effects of underwater noise on the marine environment from the proposed development of Hunterston Construction Yard (hereafter referred to as “the Project”). This development would see the upgrade of the existing Hunterston Construction Yard (HCY) into a harbour facility to support both the long-term sustainable development of various industrial users and future offshore wind industry activities.

HCY is located between the Hunterston Coal Terminal and Hunterston B Nuclear Power Station, to the south of the village of Fairlie and extends into the Firth of Clyde. The proposed construction works will cover an area of approx. 40 hectares, which includes the dry dock working area, access road and contractor compound. In general, the works relevant to this assessment will entail the construction of a new quay and associated quayside infrastructure on the western edge of the site and dredging to enable marine vessel access to quay area.

Sound is readily transmitted into the underwater environment and there is potential for the sound emissions from anthropogenic sources to adversely affect marine mammals and fish. At close ranges from a noise source with high noise levels, permanent or temporary hearing damage may occur to marine species, while at a very close range gross physical trauma is possible. At long ranges (several kms) the introduction of any additional noise could, for the duration of the activity, potentially cause behavioural changes, for example to the ability of species to communicate and to determine the presence of predators, food, underwater features, and obstructions.

This report provides an overview of the potential effects due to underwater noise from the Project on the surrounding marine environment based on the Southall et al. 2019 and Popper et al. 2014 frameworks for assessing impact from noise on marine mammals and fishes.

Consequently, the primary purpose of the underwater noise assessment is to predict the likely range of onset for potential physiological and behavioural effects due to increased anthropogenic noise as a result of the Project.

2 ASSESSMENT CRITERIA

2.1 General

To determine the potential spatial range of injury and disturbance, assessment criteria have been developed based on a review of available evidence including national and international guidance and scientific literature. The following sections summarise the relevant assessment criteria and describe the evidence base used to derive them.

Underwater noise has the potential to affect marine life in different ways depending on its noise level and characteristics. Assessment criteria generally separate sound into two distinct types, as follows:

- **Impulsive sounds** which are typically transient, momentary (less than one second), broadband, and consist of high peak sound pressure with rapid rise time and rapid decay (ANSI, 2005; ANSI, 1986; NIOSH, 1998). This category includes sound sources such as seismic surveys, impact piling and underwater explosions. Additionally included here are sounds under 1 second in duration with a weighted kurtosis over 40 (see note below*).
- **Non-impulsive** (and continuous) sounds which can be broadband, narrowband or tonal, momentary, brief or prolonged, continuous or intermittent and typically do not have a high peak sound pressure with rapid rise/decay time that impulsive sounds do (ANSI, 1995; NIOSH, 1998).This category includes sound sources such as continuous vibro-piling, running machinery, some sonar equipment and vessels. Additionally included here are sounds over 1 second in duration with a weighted kurtosis under 40 (see note below*).

* Note that the European Guidance: “Monitoring Guidance for Underwater Noise in European Seas, Part II: Monitoring Guidance Specifications” (MSFD Technical Subgroup on Underwater Noise, 2014) includes sonar as impulsive sources (see Section 2.2). However, the guidance suggests that *“all loud sounds of duration less than 10 seconds should be included”* as impulsive.
This contradicts research on impact from impulsive sounds suggesting that a limit for “impulsiveness” can be set at a kurtosis[1] of 40 (Martin, et al., 2020).
This latter criterion has been used for classification of impulsive versus non-impulsive for sonars and similar sources. The justification for departing from the MSFD criterion is that the Southall et al. 2019 and the Popper et al. 2014 framework limits are based on the narrower definition of impulsive as given in “Impulsive sounds” above.

The acoustic assessment criteria for marine mammals and fish in this report has followed the latest international guidance (based on the best available scientific information), that are widely accepted for assessments in the UK, Europe and worldwide (Southall, et al., 2019; Popper, et al., 2014).

2.2 Effects on Marine Animals

Underwater noise has the potential to affect marine life in different ways depending on its noise level and characteristics. Richardson *et al.* (1995) defined four zones of noise influence which vary with distance from the source and level, to which an additional zone has been added “zone of temporary hearing loss”.
These are:

- **The zone of audibility**: This is defined as the area within which the animal can detect the sound. Audibility itself does not implicitly mean that the sound will affect the animal.
- **The zone of masking**: This is defined as the area within which sound can interfere with the detection of other sounds such as communication or echolocation clicks. This zone is very hard to estimate due to a paucity of data relating to how animals detect sound in relation to masking levels (for example, humans can hear tones well below the numeric value of the overall sound level). Continuous sounds will generally have a greater masking potential than intermittent sound due to the latter providing some

[1] Statistical measure of the asymmetry of a probability distribution.

relative quiet between sounds. Masking only occurs of there is near-overlap in sound and signal, such that a loud sound at e.g., 1000 Hz will not be able to mask a signal at 10,000 Hz[2].

- **The zone of responsiveness**: This is defined as the area within which the animal responds either behaviourally or physiologically. The zone of responsiveness is usually smaller than the zone of audibility because, as stated previously, audibility does not necessarily evoke a reaction. For most species there is very little data on response, but for species like harbour porpoise there exists several studies showing a relationship between received level and probability of response (Graham IM, 2019; Sarnoci´nska J, 2020; BOOTH, 2017; Benhemma-Le Gall A, 2021).
- **The zone of temporary hearing loss**: The area where the sound level is sufficient to cause the auditory system to lose sensitivity temporarily, causing loss of “acoustic habitat”: the volume of water that can be sensed acoustically by the animal. This hearing loss is typically classified as Temporary Threshold Shift (TTS).
- **The zone of injury / permanent hearing loss**: This is the area where the sound level is sufficient to cause permanent hearing loss in an animal. This hearing loss is typically classified as Permanent Threshold Shift (PTS). At even closer ranges, and for very high intensity sound sources (e.g., underwater explosions), physical trauma or acute mortal injuries are possible.

For this study, it is the zones of injury (PTS) that are of primary interest, along with estimates of behavioural impact ranges. To determine the potential spatial range of injury and behavioural change, a review has been undertaken of available evidence, including international guidance and scientific literature. The following sections summarise the relevant thresholds for onset of effects and describe the evidence base used to derive them.

2.3 Thresholds for Marine mammals

The zone of injury in this study is classified as the distance over which a fleeing marine mammal can suffer PTS leading to non-reversible auditory injury. Injury thresholds are based on a dual criteria approach using both un-weighted L_P (maximal instantaneous SPL) and marine mammal hearing weighted SEL. The hearing weighting function is designed to represent the sensitivity for each group within which acoustic exposures can have auditory effects. The categories include:

- **Low Frequency (LF) cetaceans**: Marine mammal species such as baleen whales (e.g. minke whale *Balaenoptera acutorostrata*).
- **High Frequency (HF) cetaceans**: Marine mammal species such as dolphins, toothed whales, beaked whales and bottlenose whales (e.g., bottlenose dolphin *Tursiops truncatus* and white-beaked dolphin *Lagenorhynchus albirostris*).
- **Very High Frequency (VHF) cetaceans**: Marine mammal species such as true porpoises, river dolphins and pygmy/dwarf sperm whales and some oceanic dolphins, generally with auditory centre frequencies above 100 kHz) (e.g., harbour porpoise *Phocoena phocoena*).
- **Phocid Carnivores in Water (PCW)**: True seals, earless seals (e.g., harbour seal *Phoca vitulina* and grey seal *Halichoreus grypus*); hearing in air is considered separately in the group PCA.
- **Other Marine Carnivores in Water (OCW)**: Including otariid pinnipeds (e.g., sea lions and fur seals), sea otters and polar bears; in-air hearing is considered separately in the group Other Marine Carnivores in Air (OCA).
- **Sirenians (SI)**: Manatees and dugongs. This group is only represented in the NOAA guidelines.

[2] The exact limit of how near a noise can get to the signal in frequency before causing masking will depend on the receivers auditory frequency resolution ability, but for most practical applications noise and signal frequencies will need to be within 1/3rd octave to start to have a masking effect.

These weightings are used in this study and are shown in Figure 2-1. It should be noted that not all of the above hearing groups of marine mammal will be present in the Project area, but all hearing groups are presented in this report for completeness.

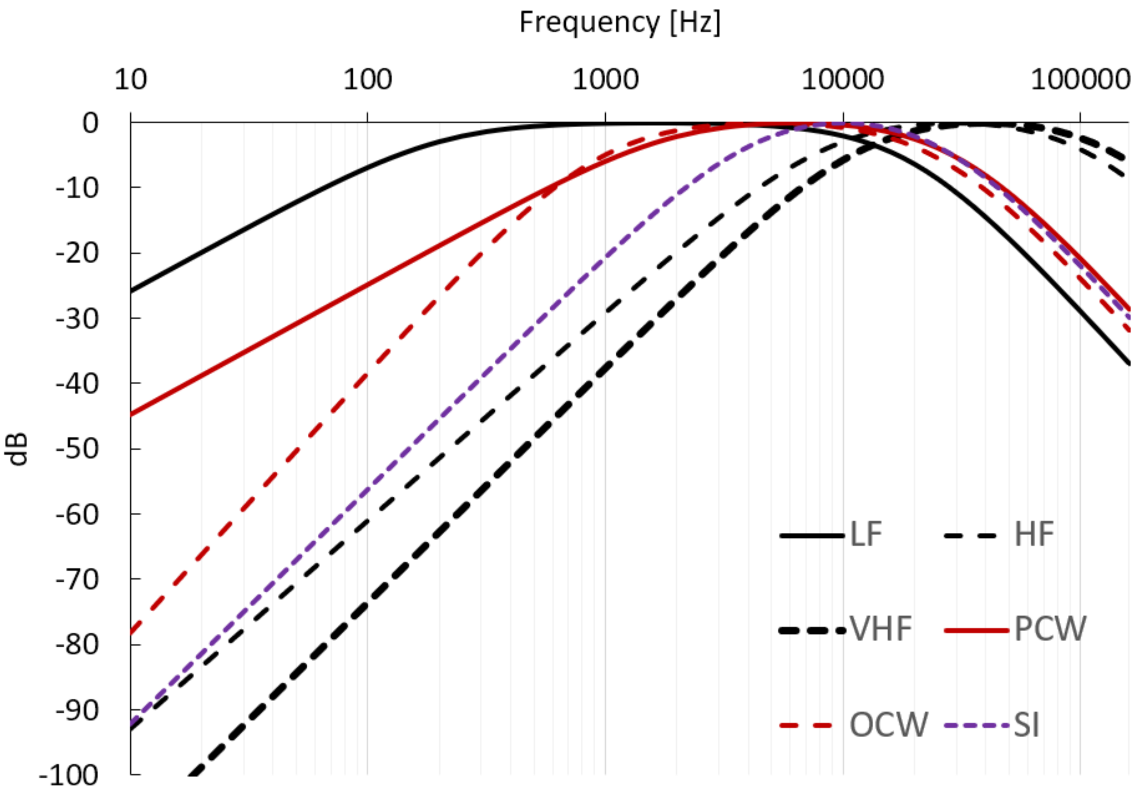

Figure 2-1: Hearing weighting functions for pinnipeds, cetaceans and sirenians (NMFS, 2018; Southall et al. 2019)

Both the criteria for impulsive and non-impulsive sound are relevant for this study given the nature of the sound sources used during the Project. The relevant PTS and TTS criteria proposed by Southall *et al*. (2019) are summarised in Table 2-1.

Table 2-1: PTS and TTS onset acoustic thresholds (Southall *et al., 2019*; Tables 6 and 7)

Hearing Group	Parameter	Impulsive [dB]		Non-impulsive [dB]	
		PTS	TTS	PTS	TTS
Low frequency (LF) cetaceans	L_P, (unweighted)	219	213	-	-
	SEL, (LF weighted)	183	168	199	179
High frequency (HF) cetaceans	L_P, (unweighted)	230	224	-	-
	SEL, (MF weighted)	185	170	198	178
Very high frequency (VHF) cetaceans	L_P, (unweighted)	202	196	-	-
	SEL, (HF weighted)	155	140	173	153
Phocid carnivores in water (PCW)	L_P, (unweighted)	218	212	-	-
	SEL, (PW weighted)	185	170	201	181
Other marine carnivores in water (OCW)	L_P, (unweighted)	232	226	-	-
	SEL, (OW weighted)	203	188	219	199
Sirenians (SI) (NOAA only)	L_P, (unweighted)	226	220	-	-
	SEL, (OW weighted)	190	175	206	186

These updated marine mammal injury criteria were published in March 2019 (Southall, et al., 2019). The paper utilised the same hearing weighting curves and thresholds as presented in the preceding regulations document NMFS (2018) with the main difference being the naming of the hearing groups and introduction of additional thresholds for animals not covered by NMFS (2018). A comparison between the two naming conventions is shown in Table 2-2.

The naming convention used in this report is based upon those set out in Southall *et al*. (2019). Consequently, this assessment utilises criteria which are applicable to both NMFS (2018) and Southall *et al*. (2019).

Table 2-2: Comparison of Hearing Group Names between NMFS (2018) and Southall *et al.* (2019)

NMFS (2018) hearing group name	Southall *et al*. (2019) hearing group name
Low-frequency cetaceans (LF)	LF
Mid-frequency cetaceans (MF)	HF
High-frequency cetaceans (HF)	VHF
Phocid pinnipeds in water (PW)	PCW
Otariid pinnipeds in water (OW)	OCW
Sirenians (SI)	Not included

2.4 Disturbance to Marine Mammals

Disturbance thresholds for marine mammals are summarised in Table 2-3. Note that the non-impulsive threshold can often be lower than ambient noise for coastal waters with some human activity, meaning that ranges determined using this limit will tend to be higher than actual ranges. However, the levels are unweighted and ranges to threshold will be dominated by low-frequency sound, which for most hearing groups is outside their hearing range. For hearing groups with low thresholds this can mean that their range to TTS/PTS is *larger* than the range to the behavioural threshold, e.g., the PTS threshold for impulsive sound for the VHS group is 155 dB SEL, while the behavioural threshold is 160 dB SPL. For a typical scenario, for 1 second's exposure (SEL equals SPL for 1-second durations) that means the range to the behavioural threshold will be approximately twice the range to the PTS threshold (a difference of 5 dB). This is just one of the reasons why this behavioural threshold should be interpreted with caution.

Table 2-3: Disturbance Criteria for Marine Mammals Used in this Study based on Level B harassment of NMFS (National Marine Fisheries Service, 2005)

Effect	Non-Impulsive Threshold	Impulsive Threshold
Disturbance (all marine mammals)	120 dB SPL	160 dB $SEL_{single\ impulse}$ or 1-second SEL

2.5 Injury and Disturbance to Fish and Sea Turtles

The injury criteria used in this noise assessment are given in Table 2-4 and Table 2-5 for impulsive noises and continuous noise respectively. L_P and SEL criteria presented in the tables are unweighted. Physiological effects relating to injury criteria are described below (Popper, et al., 2014):

- **Mortality and potential mortal injury**: either immediate mortality or tissue and/or physiological damage that is sufficiently severe (e.g., a barotrauma) that death occurs sometime later due to decreased fitness. Mortality has a direct effect upon animal populations, especially if it affects individuals close to maturity.

- **Recoverable injury ("PTS" in tables and figures)**: Tissue damage and other physical damage or physiological effects, that are recoverable, but which may place animals at lower levels of fitness, may render them more open to predation, impaired feeding and growth, or lack of breeding success, until recovery takes place.

The PTS term is used here to describe this, more serious impact, even though it is not strictly permanent for fish. This is to better reflect the fact that this level of impact is perceived as serious and detrimental to the fish.

- **Temporary Threshold Shift (TTS)**: Short term changes (minutes to few hours) in hearing sensitivity may, or may not, reduce fitness and survival. Impairment of hearing may affect the ability of animals to capture prey and avoid predators, and also cause deterioration in communication between individuals, affecting growth, survival, and reproductive success. After termination of a sound that causes TTS, normal hearing ability returns over a period that is variable, depending on many factors, including the intensity and duration of sound exposure.

Popper et al. 2014 does not set out specific TTS limits for L_P and for disturbance limits for impulsive noise for fishes. Therefore publications: “Washington State Department of Transport Biological Assessment Preparation for Transport Projects Advanced Training Manual” (WSDOT, 2011) and “Canadian Department of Fisheries and Ocean Effects of Seismic energy on Fish: A Literature review” (Worcester, 2006) on effects of seismic noise on fish are used to determine limits for these:

- The criteria presented in the Washington State Department of Transport Biological Assessment Preparation for Transport Projects Advanced Training Manual (WSDOT, 2011). The manual suggests an un-weighted sound pressure level of 150 dB SPL (assumed to be duration of 95 % of energy) as the criterion for onset of behavioural effects, based on work by (Hastings, 2002). Sound pressure levels in excess of 150 dB SPL are expected to cause temporary behavioural changes, such as elicitation of a startle response, disruption of feeding, or avoidance of an area. The document notes that levels exceeding this threshold are not expected to cause direct permanent injury but may indirectly affect the individual fish (such as by impairing predator detection). It is important to note that this threshold is for onset of potential effects, and not necessarily an ‘adverse effect’ threshold. The threshold is implemented here as either single impulse SEL or 1 second SEL, whichever is greater.

- The report from the Canadian Department of Fisheries and Ocean “Effects of Seismic energy on Fish: A Literature review on fish” (Worcester, 2006) found large differences in response between experiments. Onset of behavioural response varied from 107-246 dB L_P, the 10th percentile level for behavioural response was 158 dB L_P.

Given the large variations in the data from the two sources above, we have rounded the value to 160 dB L_P as the behavioural threshold for fishes for impulsive sound, and 150 dB SPL for non-impulsive sound.

Table 2-4: Criteria for onset of injury to fish and sea turtles due to impulsive noise

Type of animal	Unit	Mortality and potential mortal injury [dB]	Recoverable injury (PTS) [dB]	TTS [dB]	Behavioural [dB]
Fish: no swim bladder (particle motion detection)	SEL	219[1]	216[1]	186[1]	150[3]
	L_P	213[1]	213[1]	193[2]	160[2]
Fish: where swim bladder is not involved in hearing (particle motion detection)	SEL	210[1]	203[1]	186[1]	150[3]
	L_P	207[1]	207[1]	193[2]	160[2]
Fish: where swim bladder is involved in hearing (primarily pressure detection)	SEL	207[1]	203[1]	186	150[3]
	L_P	207[1]	207[1]	193[2]	160[2]
Sea turtles	SEL	210[1]	(*Near*) High (*Intermediate*) Low (*Far*) Low	-	-
	L_P	207[1]		-	-
Eggs and larvae	SEL	210[1]	(*Near*) Moderate (*Intermediate*) Low (*Far*) Low	-	-
	L_P	207[1]		-	-

[1] (Popper et al. 2014) [2] (Worcester, 2006) [3] (WSDOT, 2011)

Where Popper et al. 2014 present limits as “>” 207 or “>>” 186, we have ignored the “greater than” and used the threshold level as given.

Relevant thresholds for non-impulsive noise for fishes relating to PTS, TTS, and behaviour are given in the table below. Note that for the behaviour threshold we have used the impulsive threshold as basis for the continuous noise threshold, in absence of better evidence.

Table 2-5: Criteria for fish due to non-impulsive noise from Popper et al. 2014.

Type of animal	Unit	Mortality and potential mortal injury	Recoverable injury (PTS) [dB]	TTS [dB]	Behavioural [dB]
All fishes	SEL	-	222	210	150 [SPL]*

*This is based on the impulsive criteria.

3 METHOD, ENVIRONMENT AND SITE

The following sections are based on the information given in the documents:

- Hunterston Construction Yard Scoping Report dated September 2023.
- Hunterston Construction Yard Scoping Report Appendix 1 and 2 drawings.
- Written communication with the client or client's representative.

3.1 Site

The Project site and nearby surroundings is characterised by shallow water (<60 m), narrow straits and islands, silty to fine sandy sediment, but tidal flows keeping the water well mixed with the Irish sea (Figure 3-1).

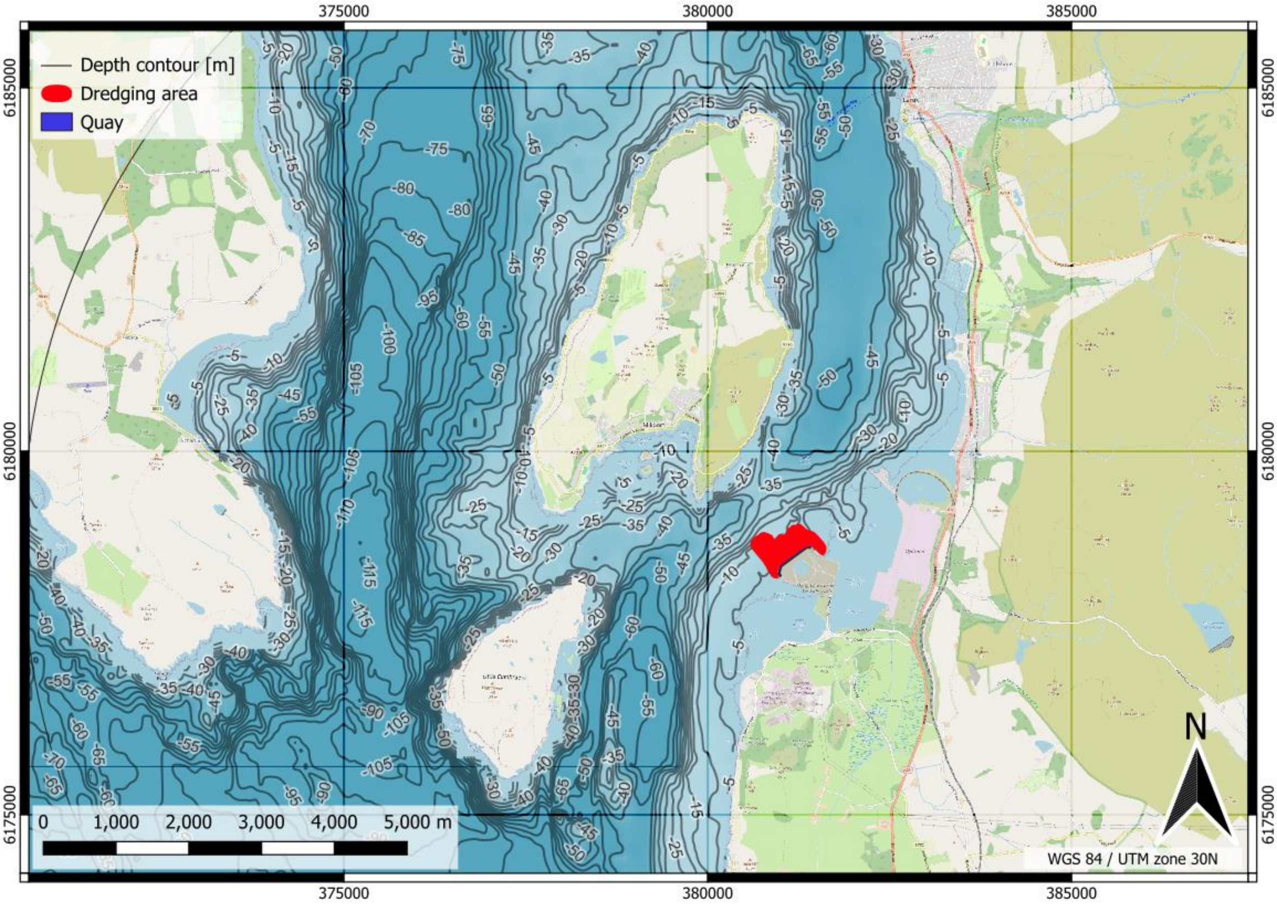

Figure 3-1: Site location in Firth of Clyde. Background map: OpenStreetMap

3.2 Development Description

Specific to the underwater environment, the following works are proposed as part of this project:

- The construction of a new quay.
- Dredging (including future maintenance) to enable marine vessel access to quay areas.
- Possible additional associated quayside infrastructure (dolphins) on the western edge of the site to berth vessels or barges. These are assessed here for completeness but might not be realised in the final project layout.

3.2.1 Quay Wall

Generally, the structure will take the form of a tied wall consisting of a combined wall to the front and rear, made up of large diameter steel tubular piles with sheet piles between. The front wall will be connected to the rear wall using steel tie rods. The tubular piles that will form the wall will be approximately 35 m long, driven to refusal/into rock in order to create sufficient deep water berthing options to support future operations – subject to final design load requirements. Additional tubular piles may be installed within the structure in order to allow increased loads in specific areas.

Design options are being considered in relation the quay wall design. All options include the demolition and infilling of the dry dock. However, there are three options in relation to the quay configuration:

- Option 1 sees the creation of a 450 m long quay wall on the north-western edge of the site with an additional 150 m long quay wall at the east.
- Option 2 sees the creation of a 450 m long quay wall on the western edge of the site with a 150 m long angled quay wall to the south-west.
- Option 3 sees the creation of a 250 m long quay on the western edge of the site.

All three options are covered in this report as a single assessment of the longer western quay wall.

3.2.2 Dolphins

Adjacent to the main quay wall three dolphins might be installed (to be confirmed) at c. 50, 100, 150 m in a north-western direction (Figure 3-2). These are based on tubular steel piles, vibrated or impacted into position.

3.2.3 Additional Works – Not Assessed Here

Additional works that are currently being considered to be installed on the seafloor adjacent to the new quay following dredging are:

- A Roll-on Roll-off (RO-RO) facility; and/or
- A grounding pad (not exceeding 250 m x 250 m, exact location to be confirmed) as a temporary fixed gravel platform for grounding two barges.
- A catwalk for access to the berthed barges.

These activities will be assessed as required in a subsequent document.

3.3 Construction Description

Specific to the marine environment, it is envisaged that construction works for all three quay wall options will involve the following:

- Tubular piles being vibrated/driven into deep strata which may need to be anchored by using a concrete pile toe bored into competent material through the tubular pile section.
- Sheet piles installed between the steel tubular piles which are to be vibrated to shallower depths than the tubular piles.
- Installation of a reinforced concrete capping beam to complete the quay wall.
- Potential tie-in and extension of existing quay wall and new quay wall.
- Dredging in front of the new quay wall to -12 m CD and further maintenance dredging.

3.4 Source Locations

Modelling was based on representative locations within the project area, prioritising either proposed locations (dolphins) or worst-case/most conservative locations (quay) (Figure 3-2).

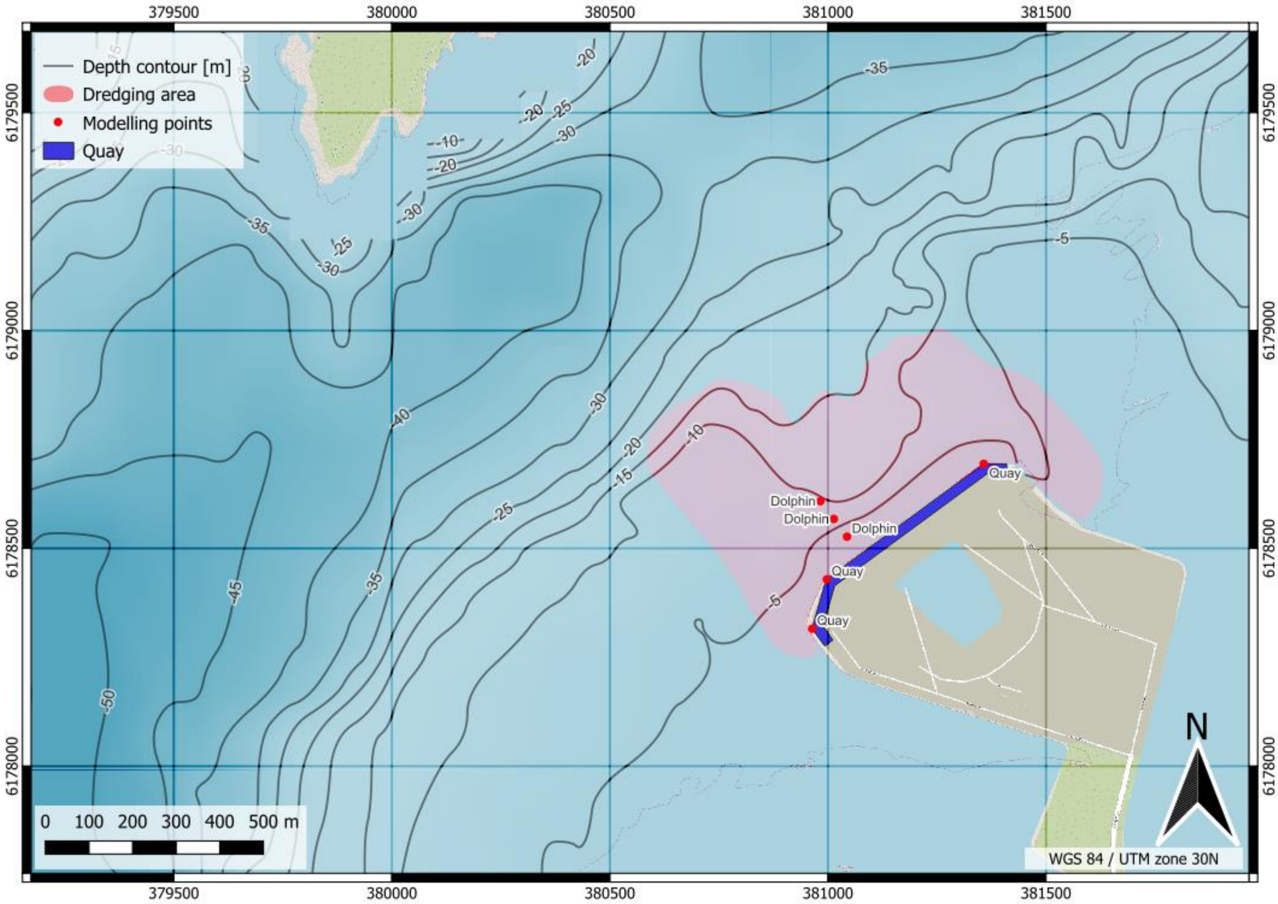

Figure 3-2. Overview of the site and nearby area, modelled piling locations and dredged area. Background map: OpenStreetMap

3.5 Water Properties

Water properties were determined from historical data for the area. Where a range of values are expected, the value leading to less transmission loss was chosen for a more conservative assessment. This thus covers seasonal variation.

- Temperature: 13°C – maximal temperature (during August) given by the Scottish Government for the Clyde Sea[3].
- Salinity: 30 psu – minimal salinity given by the Scottish Government for the Clyde Sea[3].
- Soundspeed profile: Assumed uniform given high mixing as a result of tidal flows. A uniform soundspeed profile is conservative compared to the likely downward refracting soundspeed profiles seen during summer months, causing increased loss to the sediment (higher temperature in the surface leads to higher soundspeeds).

3.6 Sediment Properties

Sediment properties are taken from the sediment sampling campaign detailed in the document “171500 Hunterston Sediment Sampling – Final.pdf” dated 16 July 2019. The campaign sampled locations (Figure 3-3).

[3] 3. THE ENVIRONMENT OF THE CLYDE SEA - Scottish Marine and Freshwater Science Volume 3 Number 3: Clyde Ecosystem Review - gov.scot (www.gov.scot)

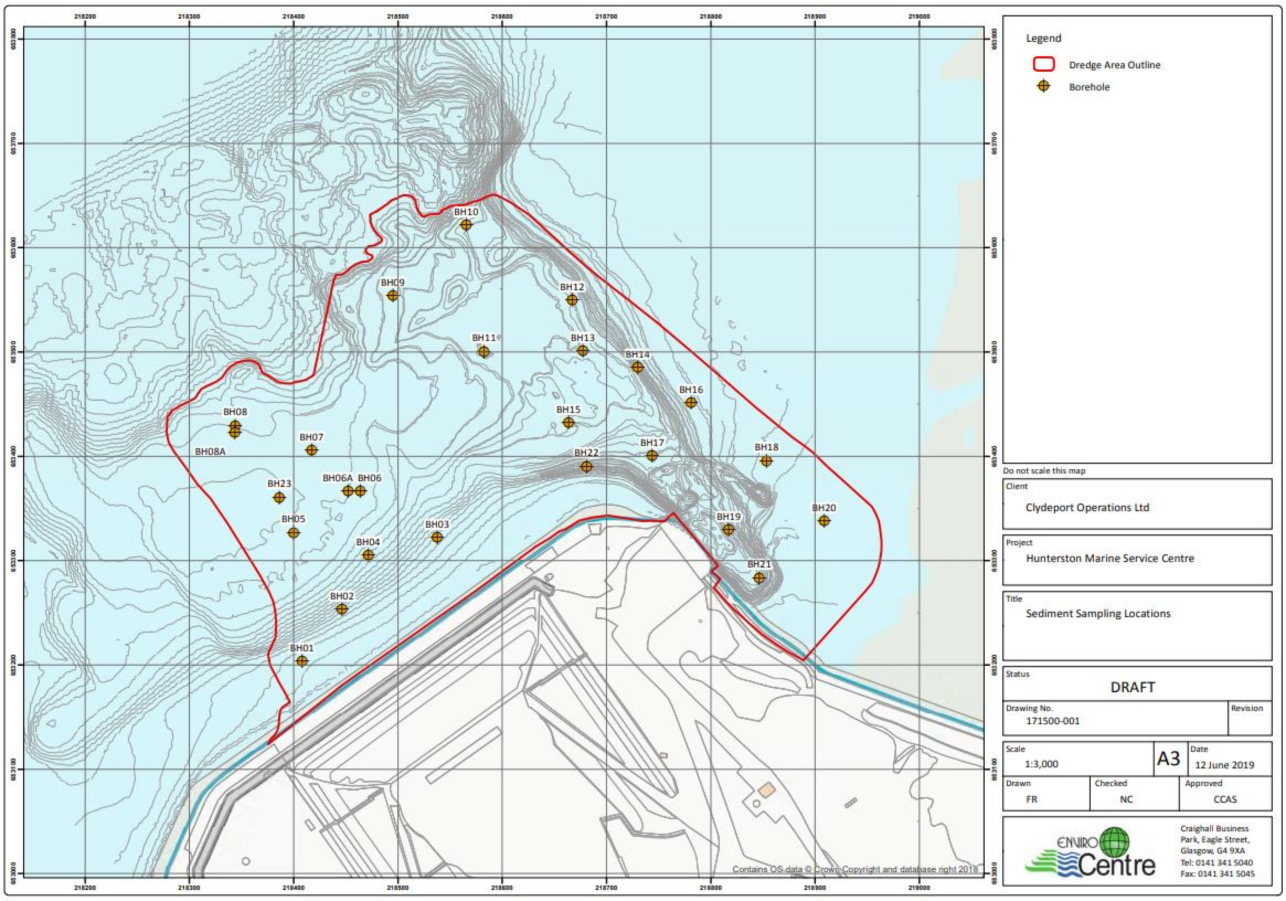

Figure 3-3. Borehole locations from Sediment sampling campaign (p. 18 of document).

The upper sediment layer from each location was used as basis for the surface sediment. A sediment model (Ainslie, 2010) was used to derive the acoustic properties of the sediment from the grain size. To simplify the modelling a single type of sediment is used throughout, defined as the 90th percentile value for both sediment soundspeed and density (Table 3-1).

Table 3-1: Sediment Properties. 90th percentile sediment properties used throughout (in bold font).

Sediment type*	Count	Density [kg/m³]	Soundspeed [m/s]	Grain size [mm] (nominal)
90th percentile		**1778**	**1642**	**0.064**
fine Sand	2	1806	1653	0.063
fine to coarse Sand	2	1884	1689	0.100
fine to medium Sand	1	1787	1644	0.056
sandy Silt	3	1531	1536	0.009
Silt	3	1484	1518	0.006
silt and fine Sand	1	1538	1539	0.010
silty fine Sand	9	1531	1536	0.009
silty gravelly fine to coarse Sand	1	1712	1611	0.035

*The capitalised word indicates the main sediment type, e.g.,”*silty gravelly fine to coarse **S**and*”.

4 SOURCE NOISE LEVELS

Underwater noise sources are usually quantified in dB scale with values generally referenced to 1 µPa pressure amplitude as if measured at a hypothetical distance of 1 m from the source (called the Source Level). In practice, it is not usually possible to measure at 1 m from a source, but the metric allows comparison and reporting of different source levels on a like-for-like basis. In reality, for a large sound source, this imagined point at 1 m from the acoustic centre does not exist. Furthermore, the energy is distributed across the source and does not all emanate from an imagined acoustic centre point. Therefore, the stated sound pressure level at 1 m does not occur for large sources. In the acoustic near-field (i.e. close to the source), the sound pressure level will be significantly lower than the value predicted by the back-calculated source level (SL).

4.1 Source Models

The noise sources and activities investigated during this assessment are summarised in Table 4-1. Source locations are given in Figure 3-2.

Note that:

1. Modelling for impact piling was done with two concurrent impact drivers, meaning that:
    a. Modelling for the dolphin locations had one active rig at the dolphin *and* one active rig at the quay.
    b. Modelling for the quay locations had two concurrent rigs impact piling.
2. The source level changes during a pile installation (here c. 20 dB), the impact piling model accounts for this and the loudest blows are used as representative for the installation and used as basis for further modelling as a conservative measure.

Table 4-1: Summary of Sound Sources and Activities Included in the Subsea Noise Assessment

Equipment	Source level [SPL] (as used in model)	Primary decidecade bands (-20 dB width)	Source model details	Impulsive/non-impulsive
Dredging vessel	192 dB SPL	10-125,000 Hz	Based on trailing suction hopper dredger	Non-impulsive
Dolphin impact piling (round piles)	Single blow: 218 dB SEL 251 dB L_P Accounting for blow rate, 0.57 Hz: 215 dB SPL	16-20,000 Hz	“Taranis” (Appendix B) Tubular steel pile, length 55 m, diameter 2 m, wall thickness 0.024 m. Hammer: CG300 (300 kJ rating)	Impulsive
Quay impact piling (round piles)	Single blow: 216 dB SEL 250 dB L_P Accounting for blow rate, 0.57 Hz: 213 dB SPL	16-20,000 Hz	“Taranis” (Appendix B) Tubular steel pile, length 40 m, diameter 2.032 m, wall thickness 0.024 m. Hammer: CG300 (300 kJ rating)	Impulsive
Quay vibratory piling (sheet piles)	183 dB SPL	16-20,000 Hz	90th percentile decidecade bands from previous installations.	Non-impulsive

4.2 Quay Wall Construction

The piling associated with the quay wall will be driving of round piles (vibratory and impact piling) and vibratory piling for sheet piles between the round piles.

4.2.1 Impact Piling

During the loudest part of the impact piling of round piles at the quay single blow levels of 216 dB SEL / 250 dB L_P are expected. Accounting for the blow rate of the hammer this equates 213 dB SPL. Peak pressure level of a single blow was modelled as up to 250 dB L_P. These levels are based on the pile dimensions, hammer rating and the sediment profile (Appendix B for details on source model).

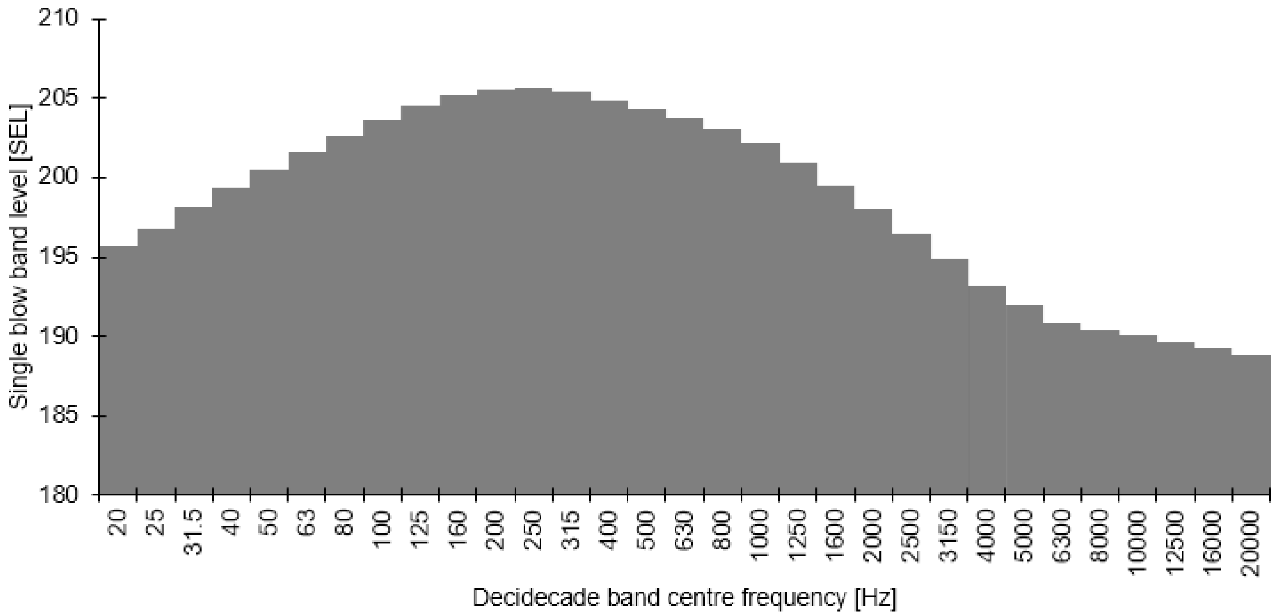

Figure 4-1: Decidecade band levels [SEL] for a single blow for impact piling of quay round piles.

4.2.2 Vibratory Piling

Sheet piles are vibrated in place between the round piles to form the quay wall. They are shorter (here assumed to be 10 m [4]), made of bent sheets rather than being round and are not “set” by impacting. Dimensions of sheet piles expected to be installed are described in Figure 4-2. The exact dimensions are not critical to the noise emissions and the final design might deviate from the stated dimension with no effect on this assessment’s outcome.

[4] The exact length is not critical for this assessment.

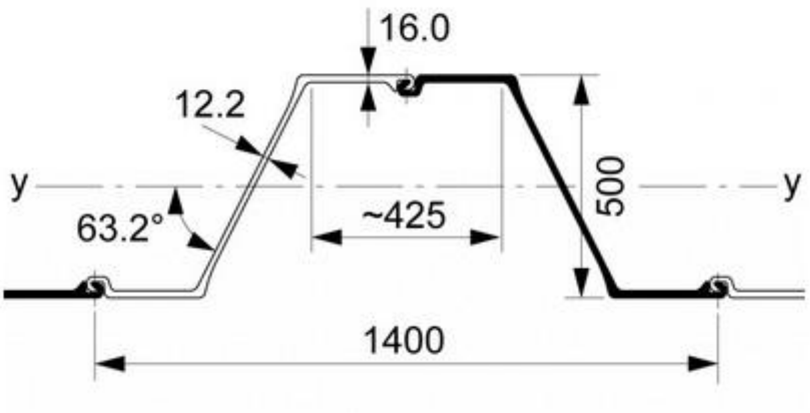

Figure 4-2: Nominal dimensions [mm] of a section of "AZ38/700" sheet pile viewed end-on.

The band levels for the vibratory piling (Figure 4-3) are based on available data from 80 measurements. As there was no clear trend in emitted sound in relation to driver energy, sheet pile dimensions or sediment, the 90th percentile band levels form the basis for the band levels used in this assessment.

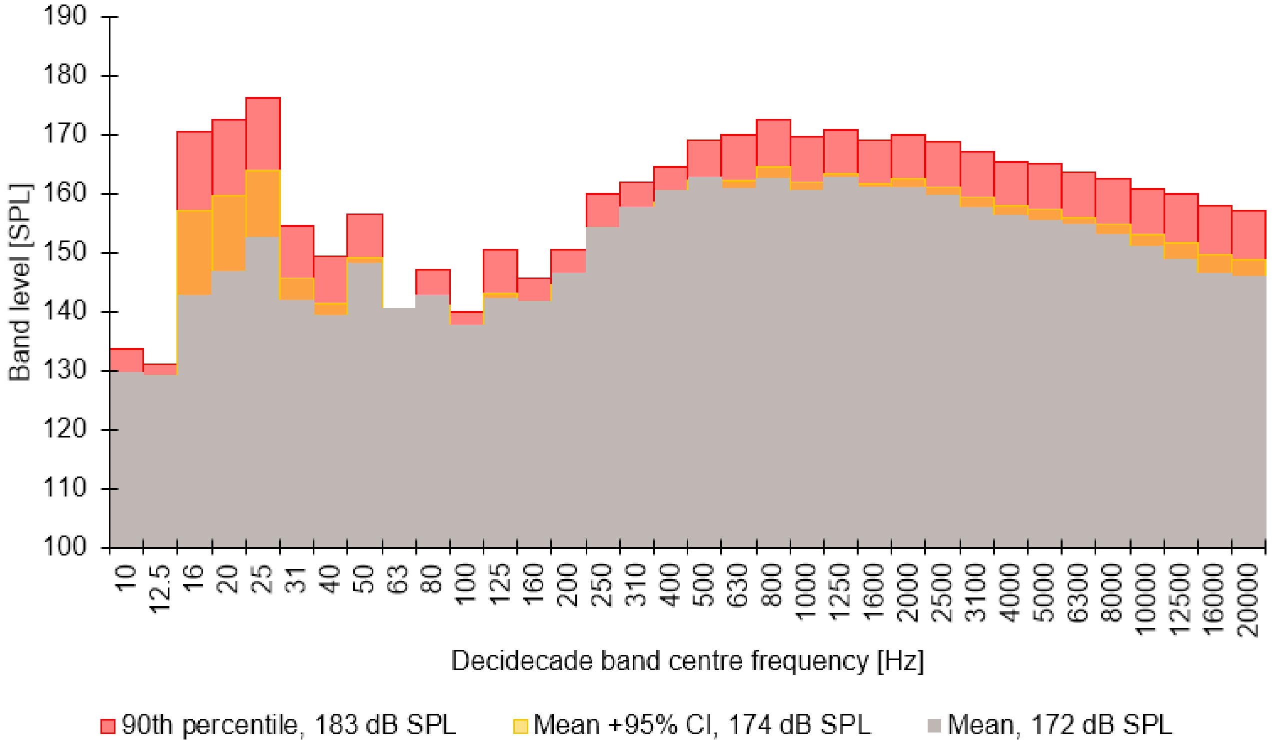

Figure 4-3: Decidecade band levels [SPL] for vibrated sheet piles. 90th percentile band levels used in the assessment.

4.3 Dolphins

During the loudest part of the impact piling of round piles at the quay single blow levels of 216 dB SEL / 250 dB L_P are expected. Accounting for the blow rate of the hammer this equates 213 dB SPL. Peak pressure level of a single blow was modelled as up to 251 dB L_P. These levels are based on the pile dimensions, hammer rating and the sediment profile (Appendix B for details on source model).

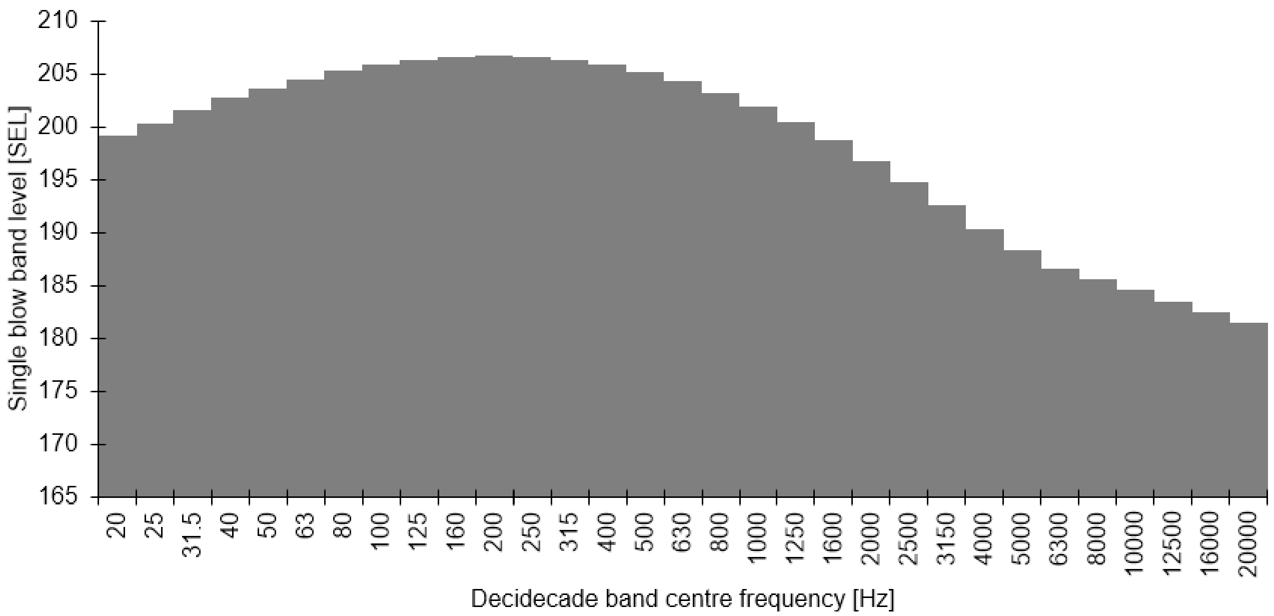

Figure 4-4: Decidecade band levels [SEL] for a single blow for impact piling of dolphin round piles.

4.4 Dredging

The dredging noise levels were based on active dredging band levels from published sources (Jong, et al., 2010; Reine, et al., 2021; Robinson, et al., 2011) as well as vessel models (Heitmeyer, 2001; Wittekind, 2014; Simard, et al., 2016). The broadband level for the dredger is 192 dB SPL with the dredging operation noise dominates at all but the lowest frequencies (<31.5 Hz).

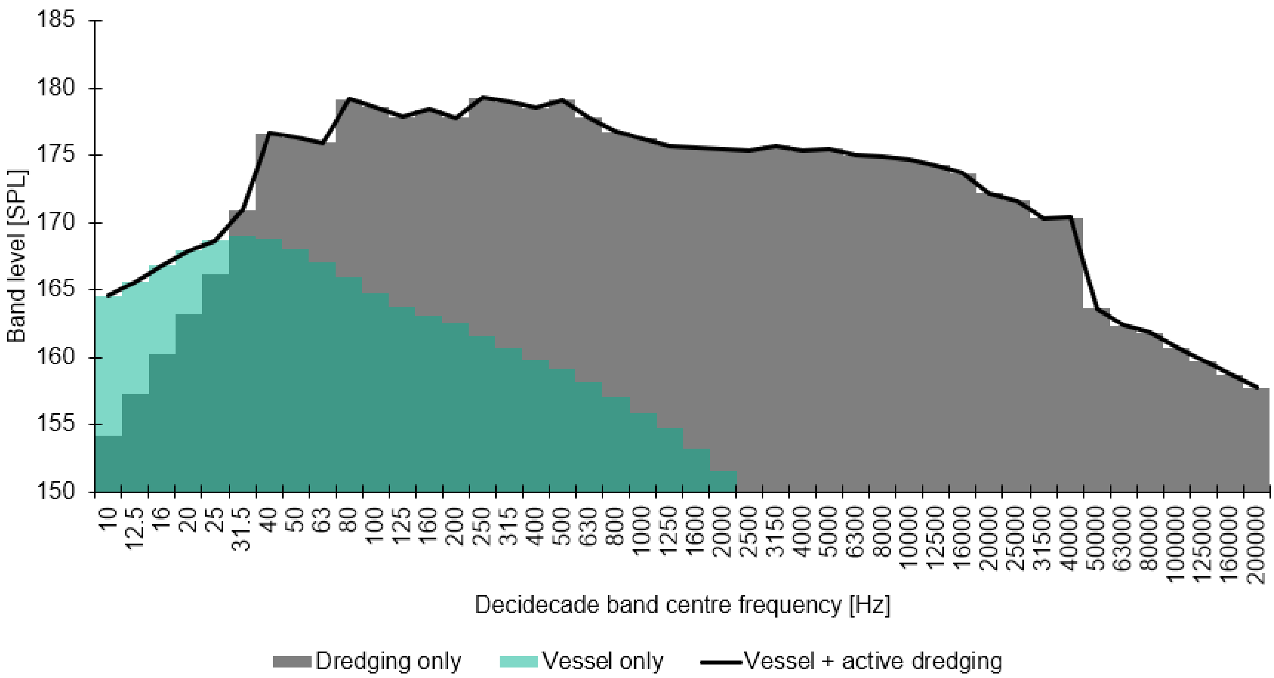

Figure 4-5: Decidecade band levels [SPL] for the active dredging noise as well as vessel noise only and dredging noise only.

5 SOUND PROPAGATION MODELLING METHODOLOGY

There are several methods available for modelling the propagation of sound between a source and receiver ranging from very simple models which simply assume spreading according to a $10 \cdot \log_{10}$(range) or $20 \cdot \log_{10}$(range) relationship to full acoustic models (e.g., ray tracing, normal mode, parabolic equation, wavenumber integration and energy flux models). In addition, semi-empirical models are available which lie somewhere in between these two extremes in terms of complexity (e.g., (Rogers, 1981; Weston, 1971)).

5.1 Semi-empirical Models

For simpler scenarios where the sediment is relatively uniform and mostly flat or where great detail in modelling is not warranted, due to uncertainty in model input or where the source level is relatively low compared to the receiver sensitivity, the speed of these simpler models is preferred over the higher accuracy of numerical models and are routinely used for these types of assessments. For this assessment we have used the “Roger’s” model (Rogers, 1981). This model is compared to measurements in the paper describing it and is capable of accurate modelling in acoustically simpler scenarios[5].

These semi-empirical models will tend to underestimate the transmission losses (leading to estimated greater than actual impact) due primarily to the omission of surface roughness, wind effects and shear waves in the sediment.

5.2 Analytical models

For the impulsive sources we have used the dBSea software’s ray tracing solver dBSeaRay, as this accounts for the full waveform propagation of an impulse. This means including surface and bottom reflections as well as time-of-arrival in the calculations. These are important to include to correctly estimate the effects of constructive and destructive interference. dBSea solvers are validated against a range of opensource solvers for so-called “standard scenarios” that have agreed solutions[6].

5.3 Exposure Calculations (dB SEL)

To compare modelled levels with the two impact assessment frameworks (Southall et al. 2019 & Popper et al. 2014) it’s necessary to calculate received levels as exposure levels, SEL, weighted for marine mammals, and unweighted for fishes. For ease of implementation sources have generally been converted to an SPL source level, meaning converting to SEL from SPL or from a number of events.
The conversion is relatively easy:

To convert from SPL to SEL the following relation can be used:

$$SEL = \text{SPL} + 10 \cdot Log_{10}(t_2 - t_1) \tag{1}$$

Or where it’s inappropriate to convert SEL from one event to SEL cumulative by relating to the number of events as:

$$SEL_{,n\ events} = SEL_{single\ event} + 10 \cdot Log_{10}(n) \tag{2}$$

And SPL from SEL:

$$SPL = SEL_{single\ event} + 10 \cdot Log_{10}\left(\frac{n}{t_2 - t_1}\right) \tag{3}$$

As an animal swims away from the sound source, the noise it experiences will become progressively more attenuated; the cumulative, fleeing SEL is derived by logarithmically adding the SEL to which the mammal is exposed as it travels away from the source. This calculation is used to estimate the approximate minimum start distance for an animal in order for it to be exposed to sufficient sound energy to result in the

[5] Simpler meaning shallow in relation to the wavelengths and with no significant sound speed gradient in the water column.

[6] https://www.dbsea.co.uk/validation/

exceedance of a threshold, or to check if a set exclusion zone is sufficient for an activity (e.g. will an exclusion zone of 500 m be sufficient to prevent exceeding a PTS threshold). It should be noted that the sound exposure calculations are based on the simplistic assumption that the animal will continue to swim away at a constant speed. The real-world situation is more complex, and the animal is likely to move in a more varied manner. Reported swim speeds are summarised in Table 5-1 along with the source papers for the assumptions.

For this assessment, we used a swim speed of 1.5 m/s for marine mammals, and 0.5 m/s for fishes including sharks.

For very long fleeing durations the ambient sound itself can exceed the thresholds, e.g., an ambient sound level of 117.5 dB, weighted for the VHF group, will exceed the non-impulsive TTS threshold of 153 dB SEL after 2 hour's exposure[7]. We here consider fleeing durations of 2 hours (7200 seconds, allowing 10800 m of fleeing), meaning that weighted levels of 117.5 dB SPL will exceed the VHF group's non-impulsive TTS threshold in the fleeing model.

Table 5-1: Swim speed examples from literature

Species	Hearing Group	Swim Speed (m/s)	Source Reference
Harbour porpoise	VHF	1.5	Otani *et al.,* 2000
Harbour seal	PCW	1.8	Thompson, 2015
Grey seal	PCW	1.8	Thompson, 2015
Minke whale	LF	2.3	Boisseau *et al.,* 2021
Bottlenose dolphin	HF	1.52	Bailey and Thompson, 2010
White-beaked dolphin	HF	1.52	Bailey and Thompson, 2010
Basking shark	Group 1 fish	1.0	Sims, 2000
All other fish groups	All fish groups	0.5	Popper *et al.,* 2014

[7] 117.5 dB SPL + 10*$\log_{10}$(3600 seconds) = 153.1 dB SEL, TTS non-impulsive threshold for the VHF group is 153 dB SEL.

6 RESULTS AND ASSESSMENT

Results are presented here as the geographical “risk range” to an auditory threshold (TTS/PTS/Behavioural) as given in section 2.3 & 2.5. A given risk range specifies the expected range, within which, a receiver would exceed the relevant threshold. Risk ranges are given for the estimated 90th percentile value. This value is based on the calculated 90th percentile, given mean and standard deviation of the modelled results.

The main assumptions for the validity of the results are:

1. At least one of the following two methods of soft start for impact piling can be realised:
    a. “Blow-energy reduction only” – For the duration of the soft start the impact driver is running at minimal energy, nominally 30 kJ per blow, yielding a 15 dB reduction in source levels during soft start.
    b. “Blow-energy & blow-rate reduction” – For the duration of the soft start the impact driver is running at minimal energy, nominally 30 kJ per blow and with a 10x reduction in blow rate to 1 blow per 28 seconds, yielding a 25 dB reduction in source levels during soft start.
2. Animals fleeing the area will not return within a 24-hour period.
3. Animals flee for up to 2 hours after which they will be up to 10.8 km & 3.6 km away, for marine mammals and fish respectively.
4. There will be concurrent impact piling either as “quay & quay” simultaneously or as “dolphin & quay” simultaneously.
5. Only outermost dolphin modelled as this will be the worst-case scenario for the row of dolphins.
6. Modelling assumes high tide; this is a worst-case assumption.

Result types

Several result types are presented for each activity to inform this assessment and to provide flexibility in mitigation:

1. **“1 second exposure risk range”:**
   This is the range of acute risk of impact from the activity (a one second exposure) and is presented to indicate instantaneous risk and for comparison with other studies.
   This assumes a stationary animal (during the 1-seond exposure) with all equipment operating at full power and does not include a soft start.

2. **“Minimal starting range for a fleeing animal with no soft start”:**
   The minimal range a fleeing animal needs to start fleeing from to avoid being exposed to noise exceeding its TTS/PTS threshold. Animals are moving in a straight line away from the source at a constant speed of 1.5 m/s.

3. **“Minimal starting range for a fleeing animal with a 30 min, -15 dB soft start”:**
   The minimal range a fleeing animal needs to start fleeing from to avoid being exposed to noise exceeding its TTS/PTS threshold. Animals are moving in a straight line away from the source at a constant speed of 1.5 m/s. Assuming soft start of 30 minutes with 15 dB reduction in source levels.

4. **“Minimal starting range for a fleeing animal with a 60 min, -15 dB soft start”:**
   The minimal range a fleeing animal needs to start fleeing from to avoid being exposed to noise exceeding its TTS/PTS threshold. Animals are moving in a straight line away from the source at a constant speed of 1.5 m/s. Assuming soft start of 60 minutes with 15 dB reduction in source levels.

5. **“Minimal starting range for a fleeing animal with a 30 min, -25 dB soft start”:**
   The minimal range a fleeing animal needs to start fleeing from to avoid being exposed to noise exceeding its TTS/PTS threshold. Animals are moving in a straight line away from the source at a constant speed of 1.5 m/s. Assuming soft start of 30 minutes with 25 dB reduction in source levels.

6. **“Minimal starting range for a fleeing animal with a 60 min, -25 dB soft start”:**
   The minimal range a fleeing animal needs to start fleeing from to avoid being exposed to noise

exceeding its TTS/PTS threshold. Animals are moving in a straight line away from the source at a constant speed of 1.5 m/s. Assuming soft start of 60 minutes with 25 dB reduction in source levels.

The next four result types (points “7” to “10”) are an effort to simplify mitigation choice by estimating the required soft start duration to avoid TTS/PTS while having specified an either 500 m or 1000 m exclusion zone.
These are based on modelling 20, 30, 40, 50 & 60-minute soft starts and deriving soft start duration from that set of results.

7. **“Estimated soft start duration for a 500 m exclusion range with a -15 dB soft start”:** The estimate soft start duration required for animals to avoid being exposed to noise exceeding their TTS/PTS threshold. Animals are moving in a straight line away from the source at a constant speed of 1.5 m/s. Assuming soft start with 15 dB reduction in source levels.

8. **“Estimated soft start duration for a 1000 m exclusion range with a -15 dB soft start”:** The estimate soft start duration required for animals to avoid being exposed to noise exceeding their TTS/PTS threshold. Animals are moving in a straight line away from the source at a constant speed of 1.5 m/s. Assuming soft start with 15 dB reduction in source levels.

9. **“Estimated soft start duration for a 500 m exclusion range with a -25 dB soft start”:** The estimate soft start duration required for animals to avoid being exposed to noise exceeding their TTS/PTS threshold. Animals are moving in a straight line away from the source at a constant speed of 1.5 m/s. Assuming soft start with 25 dB reduction in source levels.

10. **“Estimated soft start duration for a 1000 m exclusion range with a -25 dB soft start”:** The estimate soft start duration required for animals to avoid being exposed to noise exceeding their TTS/PTS threshold. Animals are moving in a straight line away from the source at a constant speed of 1.5 m/s. Assuming soft start with 25 dB reduction in source levels.

11. **“Peak level risk range”:** The range of acute risk of impact from peak pressure levels associated with the impulsive sources. *This measure is not included in tables as the range to the lowest TTS limit (fish 186 dB L_P) was ~50 m (all other groups are shorter).*

12. **“Behavioural response range”:** The range at which the behavioural limit for the marine mammals (160 dB SPL) or the fishes (150 dB SPL) behavioural limits for impulsive noise is exceeded.

6.1 Results

6.1.1 1-second exposure risk range

Risk ranges for a single second of exposure. For impact piling these are representative for the loudest part of the installation.

“<10” indicates the lower bound of model resolution.

PTS risk ranges are up to 400 for the VHF group for impact piling. With remaining hearing groups below 200 m.

For continuous noise (vibratory piling and dredging) all risk ranges (TTS and PTS) are below 10 m.

Table 6-1: Risk ranges for TTS and PTS for all hearing groups and locations for 1-second exposure.

Location	LF (TTS / PTS) [m]	HF (TTS / PTS) [m]	VHF (TTS / PTS) [m]	PCW (TTS / PTS) [m]	OCW (TTS / PTS) [m]	Fish (TTS / PTS) [m]
Dolphin, north-west	1200 / 200	100 / <10	1500 / 300	200 / 100	<10 / <10	200 / <10
Quay, north-east	200 / 100	100 / <10	1700 / 400	200 / 100	<10 / <10	100 / <10
Quay, mid	300 / 100	100 / <10	1700 / 400	200 / 100	<10 / <10	100 / <10
Quay, south	300 / 100	100 / <10	1700 / 400	200 / 100	<10 / <10	100 / <10
Vibratory, north-west	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10
Vibratory, mid	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10
Vibratory, south	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10
Dredging	<10 / <10	<10 / <10	100 / <10	<10 / <10	<10 / <10	<10 / <10

6.1.2 Minimal starting range for a fleeing animal with no soft start

Minimal starting ranges for animals fleeing to avoid TTS and PTS, assuming no soft start and piling at full power/during noisiest part of installation.

PTS risk ranges for the VHF hearing group are up to 5.4 km (Dolphin impact piling), meaning that a VHF group animal (harbour porpoise) would likely need to be >5.4 km away before the activity commences to avoid exceeding the PTS threshold.

For the LF hearing group the PTS ranges for the impact piling are up to 1.9 km (Dolphin impact piling), with quay impact piling ranges up to 600 m.

The PCW hearing group has PTS ranges up to 1.2 km (Dolphin impact piling), with remaining locations having risk ranges up to 400 m.

The Fish hearing group has PTS ranges up to 600 m (Dolphin impact piling), with remaining locations having risk ranges up to 100 m.

The HF hearing group has PTS ranges up to 200 m for impact piling.

For all hearing groups vibratory piling and Dredging lead to risk ranges below 10 m.

Table 6-2: Risk ranges for TTS and PTS for all hearing groups and locations when fleeing, but with no soft start.

Location	LF (TTS / PTS) [m]	HF (TTS / PTS) [m]	VHF (TTS / PTS) [m]	PCW (TTS / PTS) [m]	OCW (TTS / PTS) [m]	Fish (TTS / PTS) [m]
Dolphin, north-west	7600 / 1900	1800 / 100	7600 / 5400	6200 / 1200	800 / <10	1900 / 600
Quay, north-east	1800 / 300	1500 / 100	5400 / 3600	1800 / 200	200 / <10	500 / 100
Quay, mid	2100 / 300	1600 / 200	6400 / 4400	2000 / 300	200 / <10	500 / 100
Quay, south	2700 / 600	1700 / 200	6800 / 4600	2500 / 400	300 / <10	800 / 100
Vibratory, north-west	<10 / <10	<10 / <10	100 / <10	<10 / <10	<10 / <10	<10 / <10
Vibratory, mid	<10 / <10	<10 / <10	100 / <10	<10 / <10	<10 / <10	<10 / <10
Vibratory, south	<10 / <10	<10 / <10	100 / <10	<10 / <10	<10 / <10	<10 / <10
Dredging	200 / <10	<10 / <10	1800 / 100	100 / <10	<10 / <10	<10 / <10

6.1.3 Minimal starting range for a fleeing animal with a 30 min, -15 dB soft start

For the VHF group a 30-minute soft start at minimal blow energy for the impact piling the start ranges for fleeing animals are up 2.7 km to avoid exceeding the PTS threshold.

The LF hearing group has risk ranges up to 600 m for impact piling at the outermost dolphin.

Remaining hearing groups all have risk range at or below 100 m for all locations and activities.

Table 6-3: Risk ranges for TTS and PTS for all hearing groups and locations when fleeing, with a 30-minute, -15 dB source level soft start.

Location	LF (TTS / PTS) [m]	HF (TTS / PTS) [m]	VHF (TTS / PTS) [m]	PCW (TTS / PTS) [m]	OCW (TTS / PTS) [m]	Fish (TTS / PTS) [m]
Dolphin, north-west	5000 / 600	200 / <10	4900 / 2700	3600 / 100	<10 / <10	1100 / 100
Quay, north-east	300 / 100	200 / <10	2700 / 1400	300 / 100	<10 / <10	100 / <10
Quay, mid	400 / 100	200 / <10	3700 / 1900	300 / 100	<10 / <10	200 / <10
Quay, south	700 / 100	200 / <10	4100 / 2100	600 / 100	<10 / <10	200 / <10
Vibratory, north-west	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10
Vibratory, mid	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10
Vibratory, south	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10
Dredging	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10

6.1.4 Minimal starting range for a fleeing animal with a 60 min, -15 dB soft start

For the VHF group a 60-minute soft start at minimal blow energy for the impact piling the start ranges for fleeing animals are up 1.2 km to avoid exceeding the PTS threshold.

The LF hearing group has risk ranges up to 600 m for impact piling at the outermost dolphin.

Remaining hearing groups all have risk range at or below 100 m for all locations and activities.

Table 6-4: Risk ranges for TTS and PTS for all hearing groups and locations when fleeing, with a 60-minute, -15 dB source level soft start.

Location	LF (TTS / PTS) [m]	HF (TTS / PTS) [m]	VHF (TTS / PTS) [m]	PCW (TTS / PTS) [m]	OCW (TTS / PTS) [m]	Fish (TTS / PTS) [m]
Dolphin, north-west	2900 / 600*	100 / <10	2300 / 1100	1600 / 100	<10 / <10	900 / <10
Quay, north-east	300 / 100	100 / <10	2300 / 1000	200 / 100	<10 / <10	100 / <10
Quay, mid	300 / 100	200 / <10	2400 / 1100	300 / 100	<10 / <10	200 / <10
Quay, south	600 / 100	200 / <10	2500 / 1200	500 / 100	<10 / <10	200 / <10
Vibratory, north-west	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10
Vibratory, mid	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10
Vibratory, south	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10
Dredging	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10

*The rounding of the results make it seem that there is no reduction from 30-minute soft start (Table 6-3) to a 60-minute soft start, but there is an actual c. 50 m difference.

6.1.5 Minimal starting range for a fleeing animal with a 30 min, -25 dB soft start

For the VHF group a 30-minute soft start at minimal blow energy and longer inter-blow-interval for the impact piling the start ranges for fleeing animals are up 2.7 km to avoid exceeding the PTS threshold.

The LF hearing group has risk ranges up to 600 m for impact piling at the outermost dolphin.

Remaining hearing groups all have risk range at or below 100 m for all locations and activities.

Table 6-5: Risk ranges for TTS and PTS for all hearing groups and locations when fleeing, with a 30-minute, -25 dB source level soft start.

Location	LF (TTS / PTS) [m]	HF (TTS / PTS) [m]	VHF (TTS / PTS) [m]	PCW (TTS / PTS) [m]	OCW (TTS / PTS) [m]	Fish (TTS / PTS) [m]
Dolphin, north-west	4900 / 100	<10 / <10	4900 / 2700*	3500 / <10	<10 / <10	1000 / <10
Quay, north-east	100 / 100	<10 / <10	2700 / 900	100 / <10	<10 / <10	100 / <10
Quay, mid	200 / 100	<10 / <10	3700 / 1700	100 / <10	<10 / <10	100 / <10
Quay, south	400 / 100	<10 / <10	4100 / 1900	200 / <10	<10 / <10	100 / <10
Vibratory, north-west	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10
Vibratory, mid	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10
Vibratory, south	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10
Dredging	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10

*The rounding of the results make it seem that there is no reduction from 30-minute soft start (Table 6-3).

6.1.6 Minimal starting range for a fleeing animal with a 60 min, -25 dB soft start

For the VHF group a 60-minute soft start at minimal blow energy and longer inter-blow-interval for the impact piling the start ranges for fleeing animals are up 400 m to avoid exceeding the PTS threshold.

Remaining hearing groups all have risk range at or below 100 m for all locations and activities.

Table 6-6: Risk ranges for TTS and PTS for all hearing groups and locations when fleeing, with a 60-minute, -25 dB source level soft start.

Location	LF (TTS / PTS) [m]	HF (TTS / PTS) [m]	VHF (TTS / PTS) [m]	PCW (TTS / PTS) [m]	OCW (TTS / PTS) [m]	Fish (TTS / PTS) [m]
Dolphin, north-west	2200 / 100	<10 / <10	2200 / 400	900 / <10	<10 / <10	400 / <10
Quay, north-east	100 / 100	<10 / <10	1000 / 300	100 / <10	<10 / <10	100 / <10
Quay, mid	200 / 100	<10 / <10	1100 / 300	100 / <10	<10 / <10	100 / <10
Quay, south	200 / 100	<10 / <10	1400 / 300	100 / <10	<10 / <10	100 / <10
Vibratory, north-west	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10
Vibratory, mid	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10
Vibratory, south	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10
Dredging	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10	<10 / <10

6.1.7 Estimated soft start duration for a 500 m exclusion range with a -15 dB soft start.

A 500 m exclusion zone paired with a 60-minute, -15 dB soft start for impact piling will prevent exceedance of the PTS threshold by fleeing receivers of the VHF hearing group.

All other groups have lower requirement for soft start duration.

Table 6-7: Required soft start duration with -15 dB source level soft start to achieve a 500 m exclusion zone.

Location	LF (TTS / PTS) [minutes]	HF (TTS / PTS) [minutes]	VHF (TTS / PTS) [minutes]	PCW (TTS / PTS) [minutes]	OCW (TTS / PTS) [minutes]	Fish (TTS / PTS) [minutes]
Dolphin, north-west	90 / 40	30 / 0	80 / 70	80 / 30	20 / 0	70 / 0
Quay, north-east	40 / 0	30 / 0	80 / 60	40 / 0	0 / 0	0 / 0
Quay, mid	40 / 0	30 / 0	80 / 60	40 / 0	0 / 0	0 / 0
Quay, south	50 / 0	30 / 0	80 / 60	40 / 0	0 / 0	20 / 0
Vibratory, north-west	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0
Vibratory, mid	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0
Vibratory, south	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0
Dredging	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0

6.1.8 Estimated soft start duration for a 1000 m exclusion range with a -15 dB soft start.

A 1000 m exclusion zone paired with a 60-minute, -15 dB soft start for impact piling will prevent exceedance of the PTS threshold by fleeing receivers of the VHF hearing group.

All other groups have lower requirement for soft start duration.

Table 6-8: Required soft start duration with -15 dB source level soft start to achieve a 1000 m exclusion zone.

Location	LF (TTS / PTS) [minutes]	HF (TTS / PTS) [minutes]	VHF (TTS / PTS) [minutes]	PCW (TTS / PTS) [minutes]	OCW (TTS / PTS) [minutes]	Fish (TTS / PTS) [minutes]
Dolphin, north-west	80 / 30	20 / 0	80 / 60	70 / 0	0 / 0	50 / 0
Quay, north-east	20 / 0	20 / 0	70 / 50	20 / 0	0 / 0	0 / 0
Quay, mid	30 / 0	20 / 0	70 / 60	30 / 0	0 / 0	0 / 0
Quay, south	40 / 0	20 / 0	80 / 60	30 / 0	0 / 0	0 / 0
Vibratory, north-west	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0
Vibratory, mid	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0
Vibratory, south	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0
Dredging	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0

6.1.9 Estimated soft start duration for a 500 m exclusion range with a -25 dB soft start.

A 500 m exclusion zone paired with a 60-minute, -25 dB soft start for impact piling will prevent exceedance of the PTS threshold by fleeing receivers of the VHF hearing group.

All other groups have lower requirement for soft start duration.

Table 6-9: Required soft start duration with -25 dB source level soft start to achieve a 500 m exclusion zone.

Location	LF (TTS / PTS) [minutes]	HF (TTS / PTS) [minutes]	VHF (TTS / PTS) [minutes]	PCW (TTS / PTS) [minutes]	OCW (TTS / PTS) [minutes]	Fish (TTS / PTS) [minutes]
Dolphin, north-west	80 / 30	30 / 0	80 / 60	70 / 30	20 / 0	60 / 0
Quay, north-east	30 / 0	30 / 0	70 / 50	30 / 0	0 / 0	0 / 0
Quay, mid	40 / 0	30 / 0	70 / 50	30 / 0	0 / 0	0 / 0
Quay, south	40 / 0	30 / 0	70 / 60	40 / 0	0 / 0	20 / 0
Vibratory, north-west	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0
Vibratory, mid	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0
Vibratory, south	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0
Dredging	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0

6.1.10 Estimated soft start duration for a 1000 m exclusion range with a -25 dB soft start.

A 1000 m exclusion zone paired with a 50-minute, -25 dB soft start for impact piling will prevent exceedance of the PTS threshold by fleeing receivers of the VHF hearing group.

All other groups have lower requirement for soft start duration.

Table 6-10: Required soft start duration with -25 dB source level soft start to achieve a 1000 m exclusion zone.

Location	LF (TTS / PTS) [minutes]	HF (TTS / PTS) [minutes]	VHF (TTS / PTS) [minutes]	PCW (TTS / PTS) [minutes]	OCW (TTS / PTS) [minutes]	Fish (TTS / PTS) [minutes]
Dolphin, north-west	80 / 20	20 / 0	80 / 60	60 / 0	0 / 0	40 / 0
Quay, north-east	20 / 0	20 / 0	60 / 40	20 / 0	0 / 0	0 / 0
Quay, mid	30 / 0	20 / 0	70 / 50	20 / 0	0 / 0	0 / 0
Quay, south	30 / 0	20 / 0	70 / 50	30 / 0	0 / 0	0 / 0
Vibratory, north-west	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0
Vibratory, mid	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0
Vibratory, south	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0
Dredging	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0

6.1.11 Peak level risk range

Table 6-11: Risk ranges for TTS and PTS for all hearing groups and locations for peak pressure [dB L_P].

Location	LF (TTS / PTS) [m]	HF (TTS / PTS) [m]	VHF (TTS / PTS) [m]	PCW (TTS / PTS) [m]	OCW (TTS / PTS) [m]	Fish (TTS / PTS) [m]
Dolphin, north-west	200 / 100	100 / 100	1400 / 600	300 / 100	100 / 100	1500 / 400
Quay, mid	200 / 100	100 / 100	1000 / 700	300 / 100	100 / 100	1500 / 400

6.1.12 Behavioural response range

Behavioural response ranges for all activities.

Marine mammal threshold for impulsive noise is 160 dB SPL, and 120 dB SPL for non-impulsive.

Fish limits are assumed to be 150 dB SPL or 150 dB $SEL_{1\text{-second}}$, whichever is exceeded first, for both noise types (section 2.5).

As noted in section 2.4 and 2.5 these behavioural limits are often problematic given that they are not backed by the same rigorous scientific work as the TTS/PTS thresholds and being unweighted ignores frequency-dependent propagation effects and variations in hearing capability between hearing groups.

Behavioural disturbance ranges for impulsive noises (impact piling) are below 1.7 km for marine mammals, and up to 2.8 km for fish. For non-impulsive noise (dredging and vibratory piling) these ranges are 1.3-7.7 km for marine mammals and 80-530 m for fish.

Table 6-12: Behavioural response ranges. Note that all marine mammals have the same threshold for behavioural response.

Location	Marine mammals [m]	Fish [m]
Dolphin, north-west	1680	2800
Quay, north-east	370	1010
Quay, mid	400	1070
Quay, south	640	1238
Vibratory, north-west	1300	80
Vibratory, mid	1500	120
Vibratory, south	1700	110
Dredging	7700	530

6.2 Results Summary

6.2.1 Impact piling

All impact piling modelled resulted in large risk ranges. While these ranges are expected where the animal remains in a straight line-of-sight from the activity, they are exceedingly conservative where an animal swims around an acoustic obstacle. For this site, given the land geometry and presence of several islands (Figure 3-1), this effect may be significant in reducing the needed fleeing durations for a proportion of the animals.

6.2.1.1 Dolphin

For the unmitigated impact piling the risk ranges for PTS are up to 5.4 km for the VHF hearing group, meaning a fleeing path starting 5.4 km from the impact piling location can avoid exceeding the PTS Threshold (Table 6-2).

The VHF hearing group is the group requiring largest ranges/longest softs starts and is the focus here, but the LF and PCW groups have significant risk ranges too.

6.2.1.2 Quay

For the unmitigated impact piling the risk ranges for PTS are up to 4.6 km for the VHF hearing group, meaning a fleeing path starting 4.6 km from the impact piling location can avoid exceeding the PTS Threshold (Table 6-2).

The VHF hearing group is the group requiring largest ranges/longest soft starts and is the focus here, but the LF and PCW groups have significant risk ranges too.

6.2.2 Vibratory Piling

All hearing groups have risk ranges shorter than 10 m for vibratory piling.

6.2.3 Dredging

The VHF hearing group has a PTS risk range to 100 m, while the remaining groups have risk ranges shorter than 10 m for the dredging activity.

6.2.4 Mitigation

No mitigation is required for vibratory piling or dredging, the two impact piling location are addressed separately below.

6.2.4.1 Dolphin

To reduce risk ranges, soft starts (or other mitigation) is necessary with two examples outlined below.

To achieve an exclusion zone of 500 m:

- Introduce either a 70-minute soft start with a -15 dB reduction in source level (1.a, section 6) or
- A 60-minute soft start with a 25 dB reduction in source level (1.b, section 6)

To achieve a 1000 m exclusion zone:

- Introduce either a 60-minute soft start with a -15 dB reduction in source level (1.a, section 6) or
- A 60-minute soft start with a 25 dB reduction in source level (1.b, section 6)[8].

These exclusion zones should be verified as absent of marine mammals in accordance with JNCC guidance in relation to pile driving (JNCC, 2010) prior to the commencement of the soft starts.

Alternative mitigation (not modelled as part of this assessment) can be pursued, such as:

- Only piling during low tide, given the shallow water, there is a significant difference in sound propagation between tidal states, and it's likely that acoustic impact could be significantly lessened. E.g., assuming low tide (MSL-1.68 m) the risk range for the VHF group is reduced to 1.6 km (from 2.6 km) for a 30 min soft start, and from 5.4 km to 4.0 km with no soft start.
- Adding an attenuator, e.g., a cofferdam or a bubble net around the piling operation – this is costly, but effective and practical given the shallow depths.

6.2.4.2 Quay

To reduce risk ranges soft starts (or other mitigation) is necessary with two examples outlined below.

To achieve an exclusion zone of 500 m:

- Introduce either a 60-minute soft start with a -15 dB reduction in source level (1.a, section 6)

To achieve a 1000 m exclusion zone:

- Introduce either a 60-minute soft start with a -15 dB reduction in source level (1.a, section 6) or
- A 50-minute soft start with a 25 dB reduction in source level (1.b, section 6).

These exclusion zones should be verified as absent of marine mammals in accordance with JNCC guidance in relation to pile driving (JNCC, 2010) prior to the commencement of the soft starts.

Alternative mitigation (not modelled as part of this assessment) can be pursued, such as:

- Only piling during low tide, given the shallow water, there is a significant difference in sound propagation between tidal states, and it's likely that acoustic impact could be significantly lessened (see example in section 6.2.4.1).
- Adding an attenuator, e.g., a cofferdam or a bubble net around the piling operation – this is costly, but effective and practical given the shallow depths.

[8] Due to the logarithmic nature of transmission losses and rounding of results values (to nearest 10 m or two significant digits), this figure is not meaningfully different from a 500 m exclusion zone for the VHF hearing group.

7 CONCLUSIONS

This assessment concludes that the vibratory piling and dredging associated the Project pose little to no risk of causing auditory injury to marine mammals or fish.

For the impact piling adherence to soft-start procedures as described in section 6.2.4 are required to mitigate the risk of auditory injury to marine mammals.

Given the large risk ranges or long soft start periods required, we suggest additional modelling be carried out to establish the effects of introducing other mitigation measures such as limited impact piling during high tide or the use of sound barriers (cofferdams or bubble nets) to shorten both risk ranges and soft start durations.

The large risk ranges can be cause for concern in terms of dispersing animals a significant distance, this is further cause for seeking alternative or additional mitigation measures.

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Appendix A – Acoustic Concepts and Terminology

Sound travels through water as vibrations of the fluid particles in a series of pressure waves. The waves comprise a series of alternating compressions (positive pressure variations) and rarefactions (negative pressure fluctuations). Because sound consists of variations in pressure, the unit for measuring sound is usually referenced to a unit of pressure, the Pascal (Pa). The unit usually used to describe sound is the decibel (dB) and, in the case of underwater sound, the reference unit is taken as 1 µPa, one micro-pascal, whereas airborne sound is usually referenced to a pressure of 20 µPa. To convert from a sound pressure level referenced to 20 µPa to one referenced to 1 µPa, a factor of 20 log (20/1) i.e. 26 dB has to be added to the former quantity. Thus, a sound pressure of 60 dB re 20 µPa is the same as 86 dB re 1 µPa, although care also needs to be taken when converting from in air sound to in water sound levels due to the different sound speeds and densities of the two mediums resulting in a conversion factor of approximately 62 dB for comparing intensities (watt/m²), see Table 8-1 , below.

Table 8-1: Comparing sound quantities between air and water.

	Constant intensity		Constant pressure	
Properties	**Air**	**Water**	**Air**	**Water**
Soundspeed (C) [m/s]	340	1500	340	1500
Density (ρ) [kg/m³]	1.293	1026	1.293	1026
Acoustic impedance (Z=C·ρ) [kg/(m²·s) or (Pa·s)/m³]	440	1539000	440	1539000
Sound intensity (I=p²/Z) [Watt/m²]	1	1	22.7469	0.0065
Sound pressure (p=(I*Z)^½) [Pa]	21	1241	100	100
Particle velocity (I/p) [m/s]	0.04769	0.00081	0.22747	0.00006
dB re 1 µPa²	146.4	**181.9**	160.0	**160.0**
dB re 20 µPa²	**120.4**	155.9	**134.0**	134.0
Difference dB re 1 µPa² & dB re 20 µPa²	**61.5**		**26.0**	

All underwater sound pressure levels in this report are described in dB re 1 µPa². In water, the sound source strength is defined by its sound pressure level in dB re 1 µPa², referenced back to a representative distance of 1m from an assumed (infinitesimally small) point source. This allows calculation of sound levels in the far-field. For large, distributed sources, the actual sound pressure level in the near-field will be lower than predicted.

There are several descriptors used to characterise a sound wave. The difference between the lowest pressure deviation (rarefaction) and the highest pressure deviation (compression) from ambient is the peak to peak (or pk-pk) sound pressure (L_{P-P} for the level in dB), Note that L_{P-P} can be hard to measure consistently, as the maximal duration between the lowest and highest pressure deviation is not standardised. The difference between the highest deviation (either positive or negative) and the ambient pressure is called the peak pressure (L_P for the level in dB). Lastly, the average sound pressure is used as a description of the average amplitude of the variations in pressure over a specific time window (SPL for the level in dB). SPL is equal to the L_{eq} when the time window for the SPL is equal to the time window for the total duration of an event. The cumulative sound energy from pressure is the integrated squared pressure over a given period (SEL for the level in dB). These descriptions are shown graphically in Figure 8-1 and reflect the units as given in ISO 18405:2017, "Underwater Acoustics – Terminology".

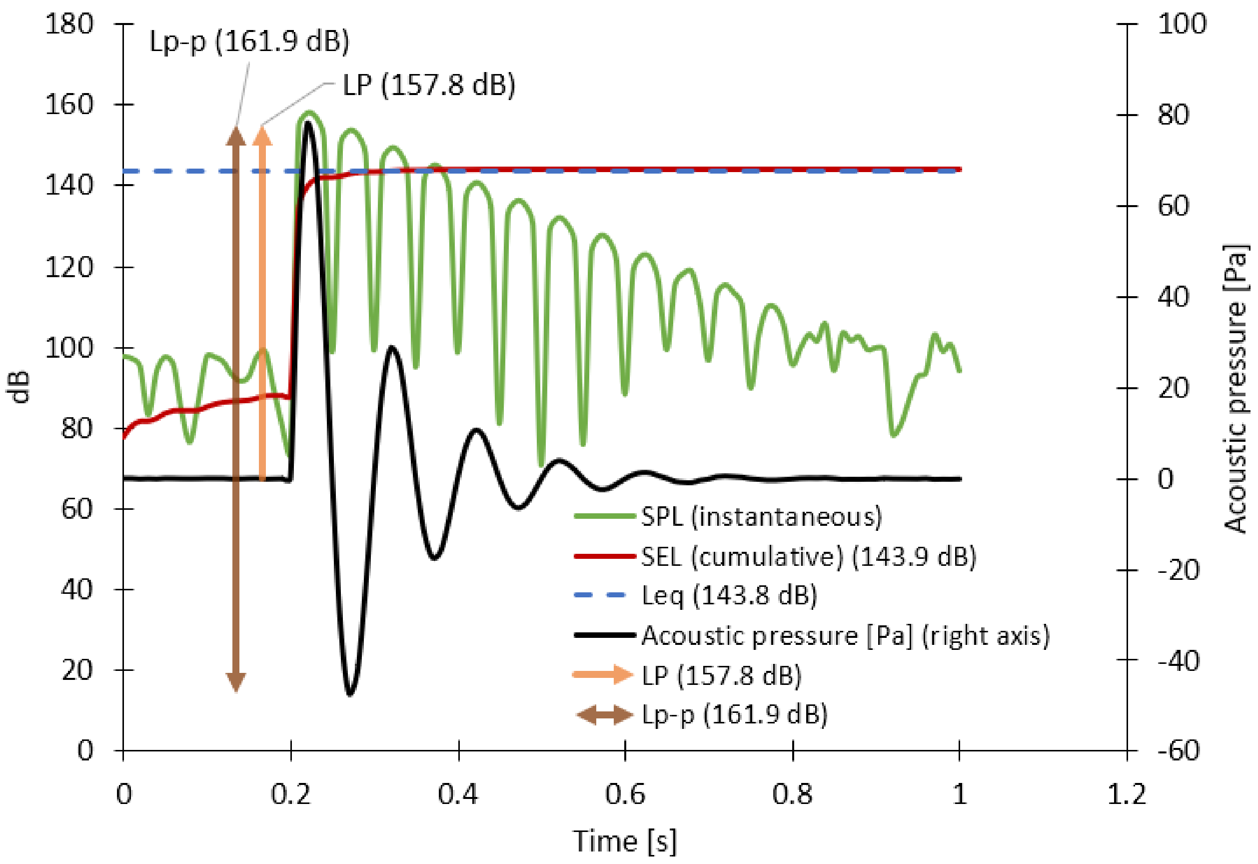

Figure 8-1: Graphical representation of acoustic wave descriptors ("LE" = SEL).

The sound pressure level (SPL[9]) is defined as follows (ISO 18405:2017, 3.2.1.1):

$$SPL = 10 \cdot Log_{10}\left(\frac{\overline{p^2}}{1 \cdot 10^{-12} Pa}\right) \quad (1)$$

Here $\overline{p^2}$ is the arithmetic mean of the squared pressure values. Note that L_P is simply the instantaneous SPL (ISO 18405:2017, 3.2.2.1).

The peak sound pressure level, L_P, is the instantaneous decibel level of the maximal deviation from ambient pressure and is defined in (ISO 18405:2017, 3.2.2.1) and can be calculated as:

$$L_P = 10 \cdot Log_{10}\left(\frac{max(p^2)}{1 \cdot 10^{-12} Pa}\right)$$

Another useful measure of sound used in underwater acoustics is the Exposure Level, or SEL. This descriptor is used as a measure of the total sound energy of a single event or a number of events (e.g. over the course of a day). This allows the total acoustic energy contained in events lasting a different amount of time to be compared on a like for like basis. Historically, use was primarily made of SPL and L_P metrics for assessing the potential effects of sound on marine life. However, the SEL is increasingly being used as it allows exposure duration and the effect of exposure to multiple events over e.g. a 24-hour period to be taken into account. The SEL is defined as follows (ISO 18405:2017, 3.2.1.5):

$$SEL = 10 \cdot Log_{10}\left(\frac{\int_{t_1}^{t_2} p(t)^2 dt}{1 \cdot 10^{-12} Pa}\right) \quad (2)$$

To convert from SEL to SPL the following relation can be used:

$$SEL = \mathrm{SPL} + 10 \cdot Log_{10}(t_2 - t_1) \quad (3)$$

[9] Equivalent to the commonly seen "RMS-level".

Converting from a single event to multiple events for SEL:

$$SEL_{n\ events} = SEL_{single\ event} + 10 \cdot Log_{10}(n) \tag{4}$$

The frequency, or pitch, of the sound is the rate at which these oscillations occur and is measured in cycles per second, or Hertz (Hz). When sound is measured in a way which approximates to how a human would perceive it using an A-weighting filter on a sound level meter, the resulting level is described in values of dB(A). However, the hearing faculties of marine mammals and fish are not the same as humans, with marine mammals hearing over a wider range of frequencies, fish over a typically smaller range of frequencies and both with different sensitivities. It is therefore important to understand how an animal's hearing varies over the entire frequency range to assess the effects of sound on marine life. Consequently, use can be made of frequency weighting scales to determine the level of the sound in comparison with the auditory response of the animal concerned. A comparison between the typical hearing response curves for fish, humans and marine mammals is shown in Figure 8-2. Note that hearing thresholds are sometimes shown as audiograms with sound level on the y axis rather than sensitivity, resulting in the graph shape being the inverse of the graph shown. It is also worth noting that some fish are sensitive to particle velocity rather than pressure, although paucity of data relating to particle velocity levels for anthropogenic sound sources means that it is often not possible to quantify this effect.

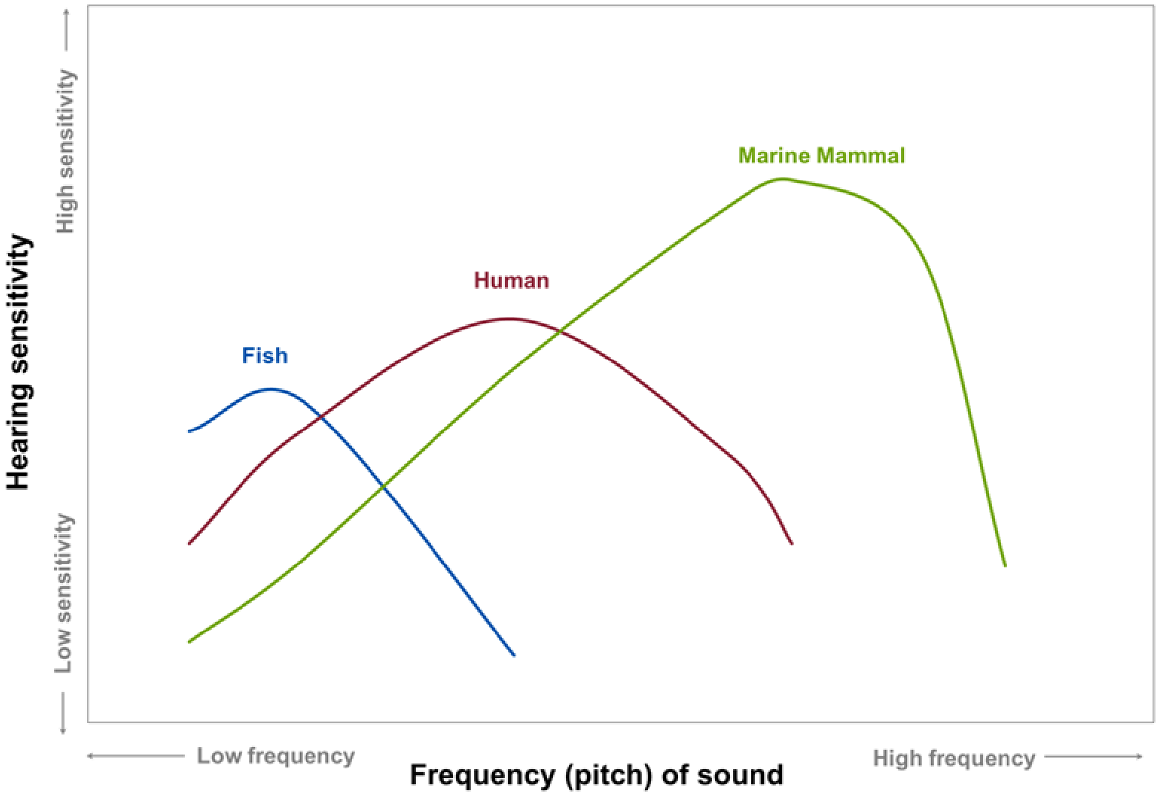

Figure 8-2: Comparison between hearing thresholds of different marine animals and humans.

Review of Sound Propagation Concepts

Increasing the distance from the sound source usually results in the level of sound getting lower, due primarily to the spreading of the sound energy with distance, analogous to the way in which the ripples in a pond spread after a stone has been thrown in.

The way that the sound spreads will depend upon several factors such as water column depth, pressure, temperature gradients, salinity, as well as water surface and seabed conditions. Thus, even for a given locality, there are temporal variations to the way that sound will propagate. However, in simple terms, the sound energy may spread out in a spherical pattern (close to the source, with no boundaries) or a cylindrical pattern (much further from the source, bounded by the surface and the sediment), although other factors mean that decay in sound energy may be somewhere between these two simplistic cases.

In acoustically shallow waters[10] in particular, the propagation mechanism is coloured by multiple interactions with the seabed and the water surface (Lurton, 2002; Etter, 2013; Urick, 1983; Brekhovskikh and Lysanov 2003, Kinsler et al., 1999). Whereas in deeper waters, the sound will propagate further without encountering the surface or bottom of the sea, in shallower waters the sound is reflected many times by the surface and sediment.

At the sea surface, the majority of sound is reflected back into the water due to the difference in acoustic impedance (i.e. sound speed and density) between air and water. However, scattering of sound at the surface of the sea is an important factor with respect to the propagation of sound from a source. In an ideal case (i.e. for a perfectly smooth sea surface), the majority of sound wave energy will be reflected back into the sea. However, for rough waters, much of the sound energy is scattered (Eckart, 1953; Fortuin, 1970; Marsh, Schulkin, and Kneale, 1961; Urick and Hoover, 1956). Scattering can also occur due to bubbles near the surface such as those generated by wind or fish or due to suspended solids in the water such as particulates and marine life. Scattering is more pronounced for higher frequencies than for low frequencies and is dependent on the sea state (i.e. wave height). However, the various factors affecting this mechanism are complex. Generally, the scattering effect at a particular frequency depends on the physical size of the roughness in relation to the wavelength of the frequency of interest.

As surface scattering results in differences in reflected sound, its effect will be more important at longer ranges from the source sound and in acoustically shallow water (i.e. where there are multiple reflections between the source and receiver). The degree of scattering will depend upon the water surface smoothness/wind speed, water depth, frequency of the sound, temperature gradient, grazing angle and range from source. Depending upon variations in the aforementioned factors, significant scattering could occur at sea state 3 or more for higher frequencies (e.g. 15 kHz or more). It should be noted that variations in propagation due to scattering will vary temporally (primarily due to different sea-states/wind speeds at different times) and that more sheltered areas (which are more likely to experience calmer waters) could experience surface scattering to a lesser extent, and less frequently, than less sheltered areas which are likely to encounter rougher waters. However, over shorter ranges (e.g. within 10-20 times the water depth) the sound will experience fewer reflections and so the effect of scattering should not be significant. Consequently, over the likely distances over which injury will occur, this effect is unlikely to significantly affect the injury ranges presented in this report, and not including this effect will overestimate the impact.

When sound waves encounter the seabed, the amount of sound reflected will depend on the geoacoustic properties of the seabed (e.g. grain size, porosity, density, sound speed, absorption coefficient and roughness) as well as the grazing angle (see Figure 8-3[11]) and frequency of the sound (Cole, 1965; Hamilton, 1970; Mackenzie, 1960; McKinney and Anderson, 1964; Etter, 2013; Lurton, 2002; Urick, 1983). Thus, seabeds comprising primarily of mud or other acoustically soft sediment will reflect less sound than acoustically harder seabeds such as rock or sand. This effect also depends on the profile of the seabed (e.g. the depth of the sediment layers and how the geoacoustic properties vary with depth below the sea floor). The sediment interaction is less pronounced at higher frequencies (a few kHz and above) where interaction is primarily with the top few cm of the sediment (related to the wavelength). A scattering effect (similar to that which occurs at the surface) also occurs at the seabed (Essen, 1994; Greaves and Stephen, 2003; McKinney and Anderson, 1964; Kuo, 1992), particularly on rough substrates (e.g. pebbles and larger).

[10] Acoustically, shallow water conditions exist whenever the propagation is characterised by multiple reflections with both the sea surface and seabed (Etter, 2013). Consequently, the depth at which water can be classified as acoustically deep or shallow depends upon numerous factors including the sound speed gradient, water depth, sediment type, frequency of the sound and distance between the source and receiver.

[11] The density of “rays” indicate difference in effective propagation angle from the source, with acoustically harder sediments (gravel) having better reflection at steeper angles leading to more “rays” being effectively propagated (no significant bottom attenuation) in the waveguide. Beam shape indicated in left chart, with the black line showing the same received level.

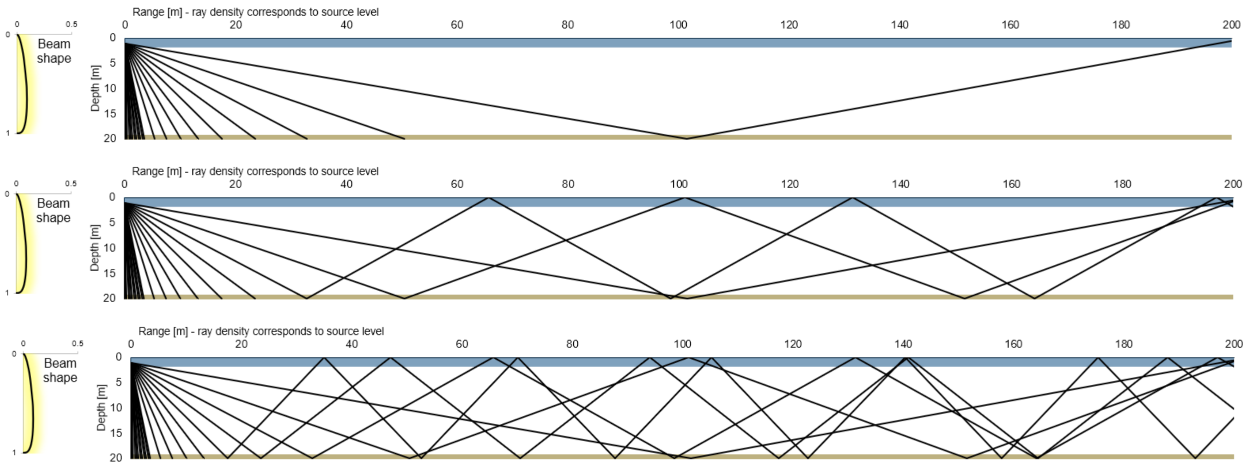

Figure 8-3: Schematic of the effect of sediment on sources with narrow beams. Sediments range from fine silt (top panel), sand (middle panel), and gravel (lower panel).

Another phenomenon is the waveguide effect which means that shallow water columns do not allow the propagation of low frequency sound (Urick, 1983; Etter, 2013). The cut-off frequency of the lowest mode in a channel can be calculated based on the water depth and knowledge of the sediment geoacoustic properties. Any sound below this frequency will not propagate far due to energy losses through multiple reflections. The cut-off frequency as a function of water depth is shown in Figure 8-4 for a range of seabed types. Thus, for a water depth of 10m (i.e. shallow waters typical of coastal areas and estuaries) the cut-off frequency would be approximately 70Hz for sand, 115Hz for silt, 155Hz for clay and 10Hz for bedrock.

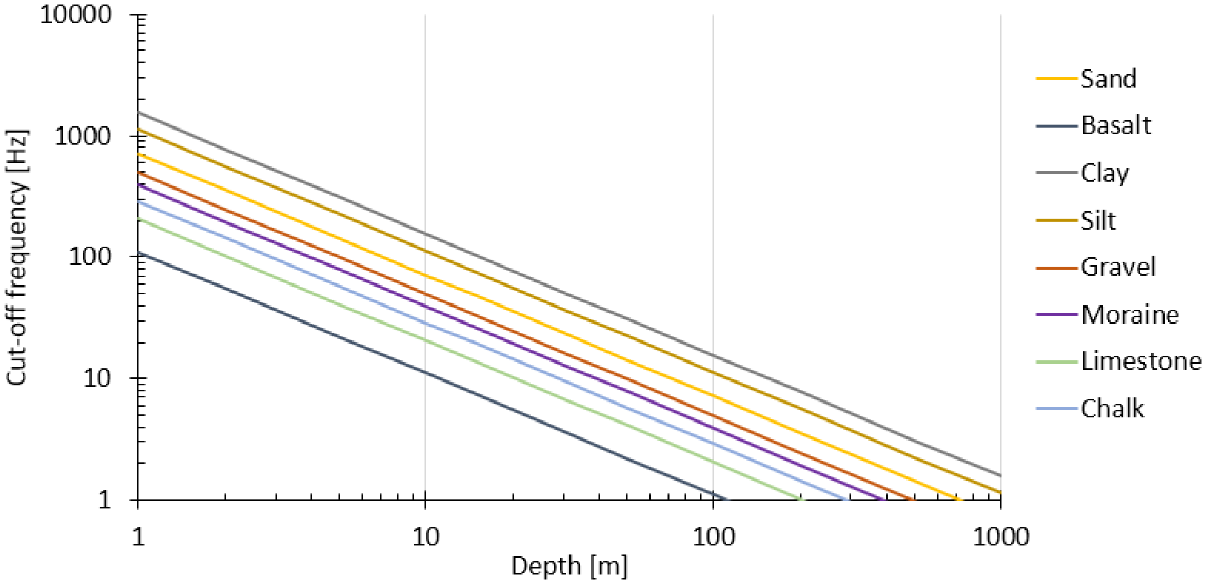

Figure 8-4: Lower cut-off frequency as a function of depth for a range of seabed types.

Changes in the water temperature and the hydrostatic pressure with depth mean that the speed of sound varies throughout the water column. This can lead to significant variations in sound propagation and can also lead to sound channels, particularly for high-frequency sound. Sound can propagate in a duct-like manner within these channels, effectively focussing the sound, and conversely, they can also lead to shadow zones. The frequency at which this occurs depends on the characteristics of the sound channel but, for example, a 25m thick layer would not act as a duct for frequencies below 1.5kHz. The temperature gradient can vary throughout the year and thus there will be potential variation in sound propagation depending on the season.

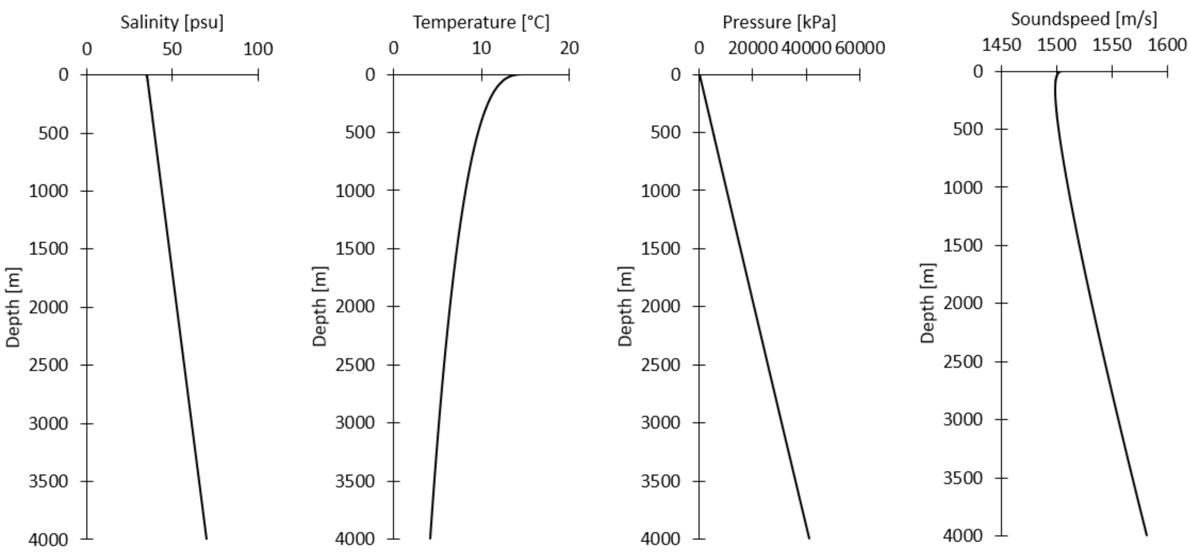

Figure 8-5: Soundspeed profile as a function of salinity, temperature and pressure.

Wind can make a significant difference to the soundspeed in the uppermost layers as the introductions of bubbles decreases the soundspeed and refracts (bends) the sound towards the surface, where the increased roughness and bubbles from the wind will cause increased transmission loss.

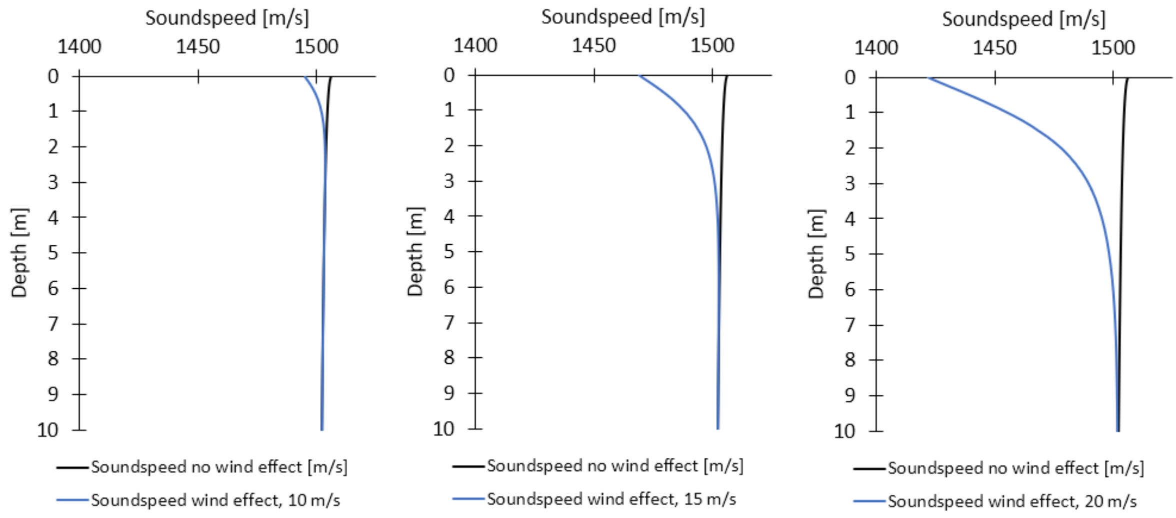

Figure 8-6: Effect of wind (at 10 m height) on upper portion of soundspeed profile.

Sound energy can also be absorbed due to interactions at the molecular level converting the acoustic energy into heat. This is another frequency dependent effect with higher frequencies experiencing much higher losses than lower frequencies. This is shown in Figure 8-7 where the variation of the absorption (sometimes called volume attenuation) is shown for various salinities and temperatures. As the effect is proportional to the wavelength, colder water, with slower soundspeed/period and being slightly more viscous, will have more absorption. Higher salinity slightly decreases absorption at low frequencies (mostly due to increase in soundspeed and wavelength/period), but much higher absorption at higher frequencies where interaction with pressure sensitive molecules of magnesium sulphite and boric acid increase the conversion acoustic energy to heat.

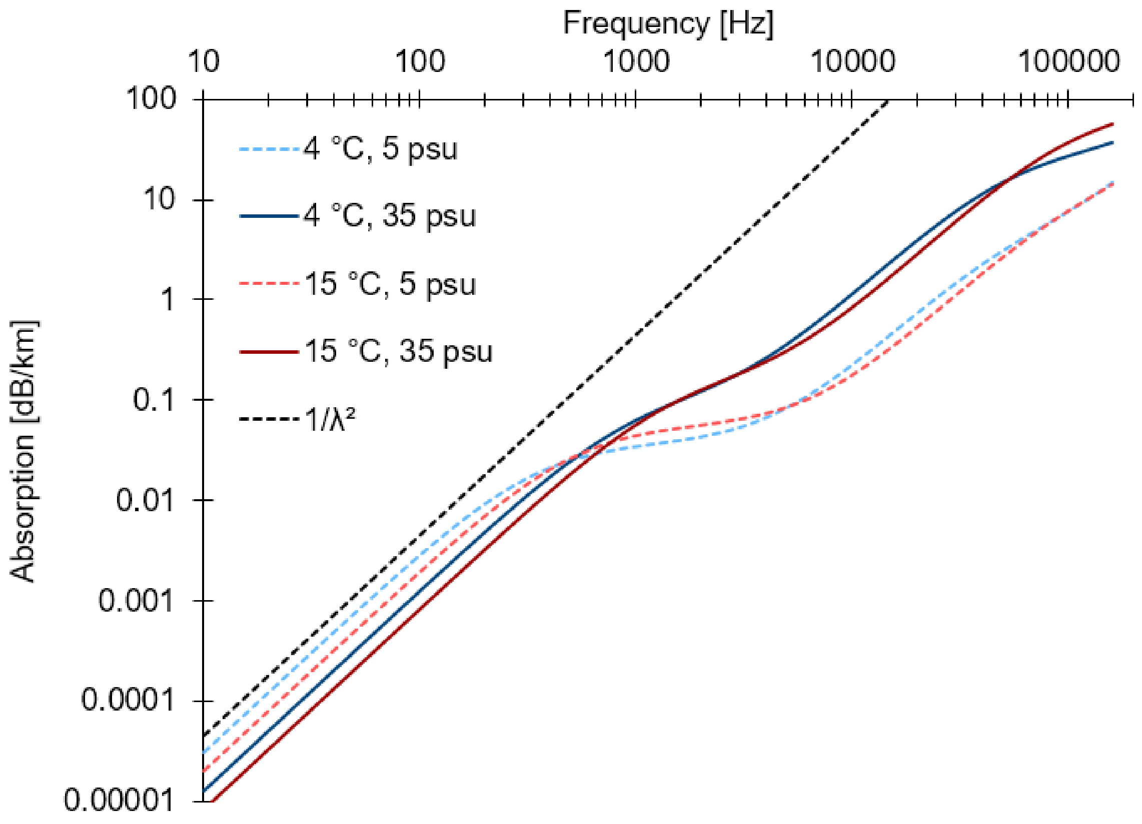

Figure 8-7: Absorption loss coefficient (dB/km) for various salinities and temperature.

Appendix B – Taranis impact piling model

RPS has developed a hybrid model for prediction of source levels from impact piling – "Taranis". The model is part numerical and part empirical, taking the best of both worlds in that it is fast like an empirical model, but also able to predict source levels from sites where no data exists, like a numerical model. The model has been validated against a large dataset of measured data from installation of piles from 0.5 - 9 m diameter in both nearshore and offshore settings for varying sediment conditions and hammer sizes and types. By outputting both per-blow band levels & time-series impulses it is an excellent tool for prediction of impact piling source levels. Additionally, because the model has a large validation dataset it reports the statistical uncertainty for the generated output, to give the user a full understanding of the confidence they can have in any given set-up.

The model was compared and calibrated against a range of real-world recordings that were back-calculated, using a combination of simple spreading relations, Rogers model (Rogers, 1981) and dBSea[12] propagation modelling software, accounting for the specific environment of the recording location. This means that the model has greater validity when used within the range of conditions of the measurements, and within those bounds we further know the statistical uncertainty of the model. Outside those bounds the model is essentially extrapolating, but care has been taken to ensure the model is "stable" and results outside the bounds change in a predictable manner.

Below is a graphical representation of the model coverage.

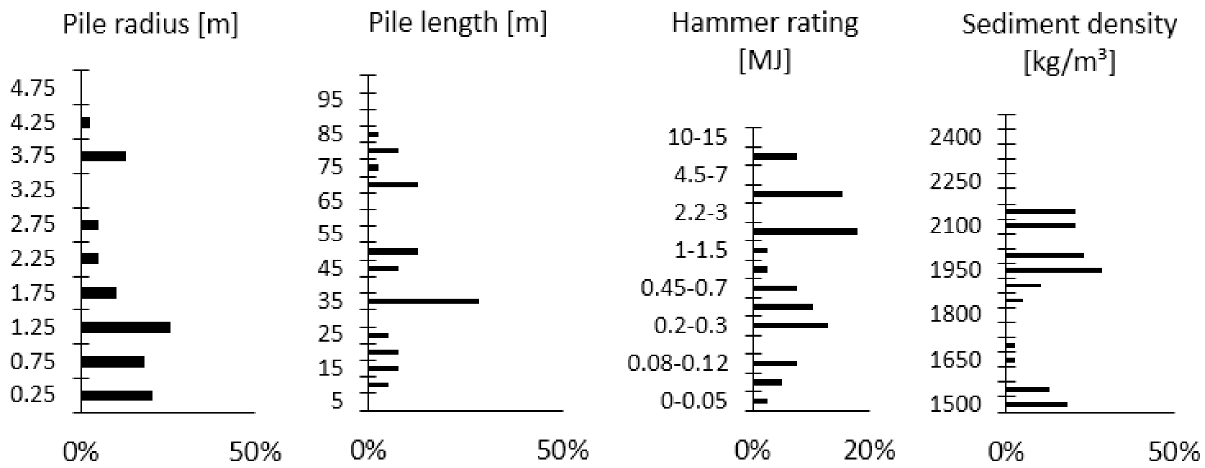

Figure 8-8. Overview of equipment and environmental parameters covered in the validation.

These cover a multidimensional space, and even if within all parameter limits, that particular combination of parameters might not have been tested, but given that the model has shown no "run-away" predictions we are confident that such combinations will still give representative results.

Table 8-2. Overview of the Taranis model's inputs.

Model part	Parameter [unit] (default value)
Sediment	Density [kg/m³] as list (2100) Soundspeed [m/s] as list (2000) Grain size (diameter) [m] as list (0.35)
Water	Depth at piling site [m] Salinity [psu] (35) Temperature [degrees C] (15)
Hammer	Minimal blow energy [kJ] Maximal planned blow energy [kJ] Maximal rated blow energy [kJ]

[12] www.dBSea.co.uk

Model part	Parameter [unit] (default value)
Pile	Length [m] Radius [m] Penetration at desired installation depth [m] Density [kg/m³] (8050) Young's modulus [Pa] (2e11) Soundspeed [m/s] (5900) Wall thickness [m] (radius/50) Raking angle [degrees] (0.0)

Generally (>50 % of cases) the model predicts band levels within 6 dB of recorded levels with broad band levels being within 4 dB and peak levels within 7.5 dB (Figure 8-9, p. 39). There seems to be a bias in the band-wise errors showing a tendency for Taranis to underpredict levels at higher frequencies. This tendency is driven by a single validation case where Taranis' predictions for higher frequencies were >20 dB below the recorded. This case is included in the data, but remind the reader that something was likely different about this case making it a non-representative case. It is likely that the piling was done with the piles somewhat restricted and not free to move as assumed by the model (piles are assumed to be fixed at one end only).

The approach for model validation was to collate available data for recordings of impact piling where information on the hammer, the pile dimensions, the sediment and the water conditions where available. Recorded levels were back-calculated to an "equivalent monopoint source[13]". The back-calculation was mostly done using "Roger's model" (Rogers, 1981) when bathymetry was flat, dBSeaPE for longer ranges in range-dependent scenarios, and spherical spreading if the range to the source from the receiver was shorter than the depth. Roger's model and dBSea take into account the additional loss at low frequencies often not accounted for in simpler transmission loss calculations.

The main metrics used for accuracy estimation are:

- Band-wise error: The per decidecade band error for single blow SEL in dB
- Broadband error: The broadband error for single blow SEL in dB
- Peak error: The error in predicted L_P in dB

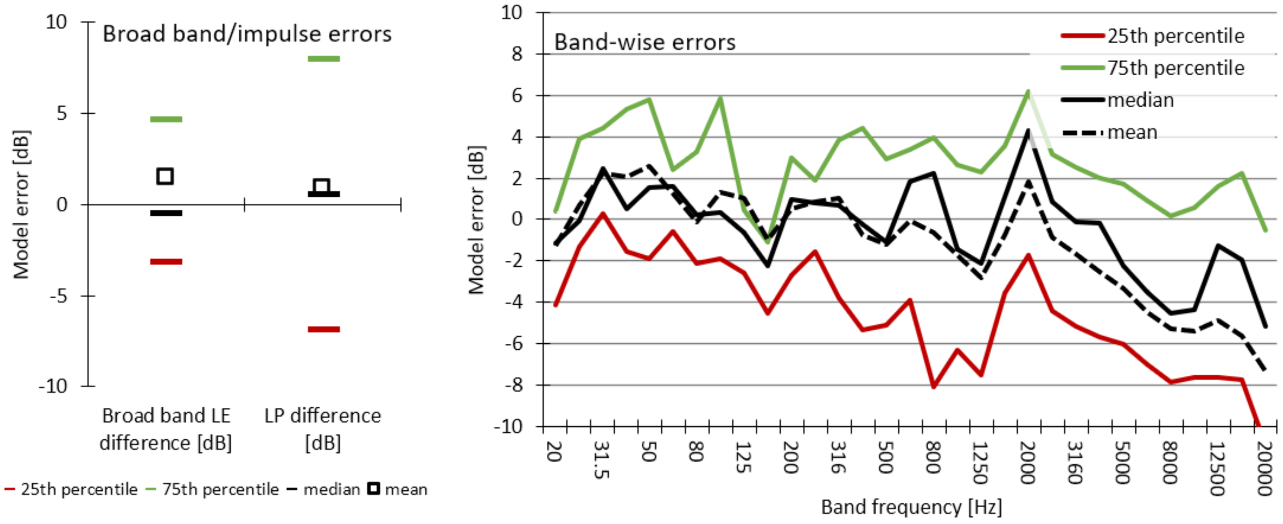

Figure 8-9. An overview of the broadband, peak and band-wise performance of the Taranis model.

Comparisons against other models (here a FE model) are favourable to this model for the 3 cases we have data for, where the FE model used in the case report has 50 % of is predictions within 14.6 dB, Taranis is

[13] Non-exiting quantity used to compare source levels at 1 meter from a point. In reality pile act like line or moving sources that have a "mach cone" (supersonic pressure front).

within 3.3 dB. This serves only as an example that in at least this case the simpler approach from Taranis was not inferior to an FE model that’s being used commercially by other actors.