

Scapa Deep Water Quay, UW Noise Modelling

Kirkwall, Orkney

RP001 Rv3 2022248 (Scapa DWQ, UW Modelling)

14 August 2024

PROJECT: SCAPA DEEP WATER QUAY, UW NOISE MODELLING

PREPARED FOR: ENVIROCENTRE
8 EAGLE STREET,
CRAIGHALL BUSINESS PARK,
GLASGOW, G4 9XA
SCOTLAND

ATTENTION: EMMA CORMACK

REPORT NO.: RP001 2022248 (Scapa DWQ, UW Modelling)

Disclaimer

This report is provided for the stated purposes and for the sole use of the named Client. Irwin Carr Ltd accepts responsibility to the Client alone that the report has been prepared with the skill, care and diligence of a competent engineer, but accepts no responsibility whatsoever to any parties other than the Client. Any such parties rely upon the report at their own risk.

Copyright

The concepts and information contained in this document are the property of Irwin Carr Ltd. Use or copying of this document in whole or in part without the written permission of Irwin Carr Ltd constitutes an infringement of copyright. Information shall not be assigned to a third party without prior consent.

Document Control

Status:	Rev:	Comments	Date:	Author:	Reviewer:
Draft	1.0		14 August 2024	Rasmus Sloth Pedersen [Redacted]	Shane Carr [Redacted]

EXECUTIVE SUMMARY

BRIEF DESCRIPTION OF WORK

In relation to the construction of a deep-water port in Scapa Flow, both dredging, drilling and piling is planned. The noise from these activities can adversely affect local fauna either through direct injury of sensory systems or indirect harm from noise pollution drowning out communication and foraging sounds. Noise modelling has been carried out in respect to the various noise sources and local animals to estimate impact from noise and what mitigation can/needs to be employed to keep impacts below levels of significant harm to the local wildlife.

Source sources (dredging, piling and blasting) are modelled from a combination of empirical models (based on recorded data) and numerical models (calculated source levels from inputs).

CONCLUSION & RESULTS SUMMARY

Dredging

The noise from dredging, while presenting a significant Permanent Threshold Shift (PTS (hearing injury) risk to ranges <210 m for the Very High Frequency (VHF) group (e.g., porpoise), this is only for animals staying close to the activity for extended periods (> 1 hour) and assumes continuous dredging with the dredger level as given by the 90th percentile. For the best estimate (model mean) the PTS risk range is 210m after 8 hours exposure. There is no acute risk of noise related injury related to the dredging, and animals have time to swim away. Further the area ensonified does not “block” access through a channel or strait.

Vibro piling

Prolonged exposure to vibro piling at close range (<50 m) carries some auditory risk for the animals assessed, specifically groups LF, VHF and P- (baleen whales, porpoises and salmon/trout), where the peak pressures in the noise have risk ranges up to 300 m for the VHF group. We therefore suggest surveillance takes place prior to piling to minimise the risk of impact on porpoises. While this is a significant risk for animals close to the activity, we stress that we have used a very conservative approach to estimating the source levels, and the realised emission will likely be significantly lower.

Further, animals will tend to move around, or away from noise, which will limit exposure. In Figure 16, p. 23 and Figure 18, p. 24 we show an example of the effect of using moving receivers (animals, modelled animals) to estimate what might be the effect of movement.

Table of Contents

Executive Summary	3
1 INTRODUCTION	7
1.1 Underwater Acoustics Basics	7
1.1.1 Sound Speed.....	7
1.1.2 Spreading loss	7
1.1.3 Absorption.....	7
1.1.4 Sediment	7
1.1.5 Sound Level Units.....	8
2 Site and local environment.....	9
2.1 Depth, Bathymetry.....	10
2.2 Water properties	10
2.2.1 Temperature	10
2.2.2 Soundspeed profile.....	10
2.3 Sediment properties	11
2.4 Background/Ambient Noise.....	12
3 Sound Source Modelling	14
3.1 Drilling.....	14
3.2 Vibration Piling Model	15
3.3 Dredging.....	16
4 Transmission Loss Modelling.....	18
5 Assessment criteria.....	18
5.1 Reporting units.....	18
5.2 Weighting of Noise Levels.....	18
5.2.1 Marine Mammal Weightings.....	18
5.3 Fishes etc.....	20
5.4 Threshold Interpretation	20
5.4.1 Threshold types.....	20
5.4.2 Masking	21
5.4.3 Dispersal.....	21
6 Conclusion & results summary	22
7 Results.....	23
7.1 Dredging.....	23
7.2 Vibro piling.....	24
8 Bibliography.....	26

APPENDIX A - dBSea	27
APPENDIX B – Underwater Acoustics Basics.....	30
APPENDIX C – Source Models	35
APPENDIX D – MODEL CALIBRATION	37
APPENDIX E – RESULTS	38

Abbreviations and Definitions:

PTS	Permanent Threshold Shift
VHF	Very High Frequency
SOFAR	Sound Fixing And Ranging
SSP	Sound Speed Profile
SPL	Sound Pressure Level
Hearing group	Refers to the Southall 2019 hearing groups (Southall, et al., 2019).
“,” and “.”	Comma “,” is used as thousands separator, while dot “.” is used as decimal separator.
TL, PL	Transmission Loss, Propagation Loss. Used interchangeably in this document.
Psu	Practical salinity unit, equivalent to parts per thousand as g/kg, mass of salts per mass of water.
Noise	Sound that causes, or is assumed to cause, annoyance or disadvantage. No automatic significance of impact is associated with this term.
Solver	Mathematical algorithm for calculating sound transmission losses in water.
[]	Square brackets are used throughout to denote units, e.g.: “Pressure [Pa]” means pressure in Pascals.
Degrees	Either angular degrees (0-360) or degrees Celsius
3 rd octave, decidecade	Refers to the subdivision of octaves (doublings of frequency) and decades (10x frequency). Using the appropriate base frequency, the two are identical for practical purposes.
Worst case	Used as “reasonable worst case”. E.g. use of MHWS instead of historical maximum for max water level. Or 90 th percentile as representative of worst-case.
Mean case	The expected case, both median and mean values will inform this.
Signature, Impulse	When in relation to a sound, this refers to the time-pressure signal associated with that sound, normally as a time-series of pressures relative to ambient pressure, in pascals.
Vibro	Vibration pile driving
MSL	Mean Sea Level
β, Log multiplier	Symbol used to denote the factor multiplied by the base ten Log in equations like: “TL = β × Log ₁₀ (range)”
SL, Source level	Apparent monopoint source level as viewed from the acoustic far field

1 INTRODUCTION

In relation to the construction of a deep-water port in Scapa Flow, both dredging, drilling and piling is planned. The noise from these activities can adversely affect local fauna either through direct injury of sensory systems or indirect harm from noise pollution drowning out communication and foraging sounds. Noise modelling has been carried out in respect to the various noise sources and local animals to estimate impact from noise and what mitigation can/needs to be employed to keep impacts below levels of significant harm to the local wildlife.

Source sources (dredging, piling and blasting) are modelled from a combination of empirical models (based on recorded data) and numerical models (calculated source levels from inputs).

1.1 Underwater Acoustics Basics

Underwater acoustics modelling is the application of physical models to characterise the behaviour of sound in environments under the surface of the sea and in the top layers of the seabed. As some familiarity with in-air acoustics is assumed the focus here is on key differences between in-air acoustics and underwater acoustics, making waterborne propagation more efficient than airborne propagation.

This chapter only gives reader a quick overview, please see APPENDIX B – Underwater Acoustics Basics APPENDIX for more detail.

1.1.1 SOUND SPEED

Water is much harder to compress than air, and a soundspeed of 1500 m/s is often used as a standard soundspeed in water¹ much as 340 m/s is in air.

The soundspeed changes with depth, “sound speed profile”, this is quite important in sound propagation, as refraction (changes in propagation angle) will occur when sound moves between layers of water with varying sound speed. These effects can lead to profoundly inhomogeneous sound fields and SOFAR (Sound Fixing And Ranging) channels.

The same relationships are valid in the sediment, though sediments commonly have soundspeeds higher than water. Soundspeeds from 1700 m/s (fine sand/silt) to 2500 m/s (gravel) are common for non-solid sediments, with solid sediments (rocks) having much higher soundspeeds 2800 m/s (Calcarenite) to 6000 m/s (some granite).

1.1.2 SPREADING LOSS

Most of the propagation loss (loss in dB from source to receiver, “PL”) that occurs initially is governed by “spreading loss”. It is the simple “thinning out” of acoustic energy as it spreads away from the source, usually in all directions – spherically. This means a reduction in received level of 6 dB per doubling of distance

At longer ranges the medium is no longer unbounded. We reach ranges where the sound has interacted with the surface (near perfect acoustic reflector) or the seabed (lossy acoustic reflector). Here we expect spreading loss to be ~3 dB per doubling of distance.

1.1.3 ABSORPTION

Besides the “thinning out” of the sound energy as described above, the sound is also dissipated into heat by the way the pressure changes interact with water, molecules and particles in its path. This absorption is salinity dependant. Frequencies under 1 kHz experiences almost no absorption, while high frequencies, over 10 kHz, can be attenuated by over 10 dB / km.

Small bubbles, wind or wave induced, will further attenuate especially the high frequencies.

1.1.4 SEDIMENT

Depending on the incident angle of the sound, the frequency and the acoustic properties of the sediment, sound can either mostly penetrate the sediment or mostly be reflected by it.

¹ Varies from 1450 m/s at 0° to 1550 m/s at 30° at salinity of 35 psu.

In shallow areas with soft sediment (acoustically similar to water), it is typical to find that close to the source, at high incidence angles and at low frequencies (<250 Hz) the sound will penetrate into the sediment and dissipate there, leading to very high transmission losses for these frequencies.

1.1.5 SOUND LEVEL UNITS

All references to sound pressure levels (SPL), peak pressure levels (L_p) and sound exposure levels (L_E) refer to a logarithmic ratio between a reported/measured pressure or exposure and a reference pressure or exposure. As an example, a level of 220 L_p (decibel zero-to-peak) is equal to a peak pressure of 100000 Pascals (Pa) over ambient pressure, while 120 L_p is equal to 1 Pa over ambient pressure.

To avoid dealing with these large numbers as pascals (as a linear scale), they are converted to a decibel ratio (Table 1 for definitions). Besides compressing large numbers to a smaller scale this also corresponds better to how animals are thought to perceive sound, namely as relative steps. This means that an increase from 1 to 2 Pa *sounds like* the same increase as from 100 to 200 Pa, even though the first step was only 1 Pa, while the second was 100 Pa. This is better reflected in a logarithmic scale based on ratios, where both steps are equal, here 3 dB.

However, while dBs are practical, they can be hard to compare between studies, due to vague definitions, and so we have adopted the standards set by ISO 18405-2017 (Table 1 below).

For ease of reference please see following overview for unit definition.

Table 1: Definitions.

Unit	Definition	Comments
SPL (dB _{RMS}) ISO 18405- 2017: 3.2.1.1	$SPL = 10 \cdot \text{Log}_{10} \left(\frac{1}{t_2 - t_1} \cdot \int_{t_1}^{t_2} p(t)^2 dt \right)$	Functionally equivalent to deprecated $20 \cdot \text{Log}_{10} \left(\frac{RMS}{1 \cdot 10^{-6} Pa} \right)$
L_p (dB _{Z-p}) ISO 18405- 2017: 3.2.2.1	$L_p = 20 \cdot \text{Log}_{10} \left(\frac{Pa_{max}}{1 \cdot 10^{-6} Pa} \right)$	This assumes that Pa_{max} is equal or greater than $\sqrt{Pa_{min}^2}$
L_{p-p} (dB _{p-p})	$L_{p-p} = 20 \cdot \text{Log}_{10} \left(\frac{Pa_{max} - Pa_{min}}{1 \cdot 10^{-6} Pa} \right)$	Often ² equivalent to $L_p + 6.02 \text{ dB}$
L_E (dB _{SEL}) ISO 18405- 2017: 3.2.1.5	$L_E = 10 \cdot \text{Log}_{10} \left(\frac{\int_{t_1}^{t_2} p(t)^2 dt}{1 \cdot 10^{-12} Pa} \right)$	For continuous sound this is equivalent to $SPL + 10 \cdot \text{Log}_{10}(t_2 - t_1)$ "t" is seconds

Unless otherwise stated SPL has an averaging period of 1 second, and L_E for the duration of the specified event, sometimes indicated as L_{E-time} or $L_{E-single \text{ blow}}$.

If the averaging period for SPL is equal to the total even duration then SPL is equal to "Leq" the "equivalent constant level".

When source levels are presented, the same units are used, and it is implicit that all source levels are given as if recorded 1 m from an omnidirectional mono-point source, unless otherwise specified.

² If maximum pulse rarefaction is below ambient pressure and compression and rarefaction phases are of equal size.

2 SITE AND LOCAL ENVIRONMENT

The site is located in Orkney, Scotland:

- Scapa DWQ at Lat: 58.920345, Lon: -2.965084. Mean water depths 5-30 m.

The site is sheltered from oceanic swell, with little current and with no major outflows from rivers, meaning that the conditions important for sound propagation are quite stable. The sediment is generally a soft upper layer of mud/silt and gravel overlaid a layer of weathered sedimentary rock, before a stronger layer of sedimentary rock (silt-/mud-/sand-/lime-stone).

Figure 1. General location of Scapa DWQ development (in red circle) on Main Island of the Orkney Islands. Hatston site (just north west of Kirkwall, shown for completeness).

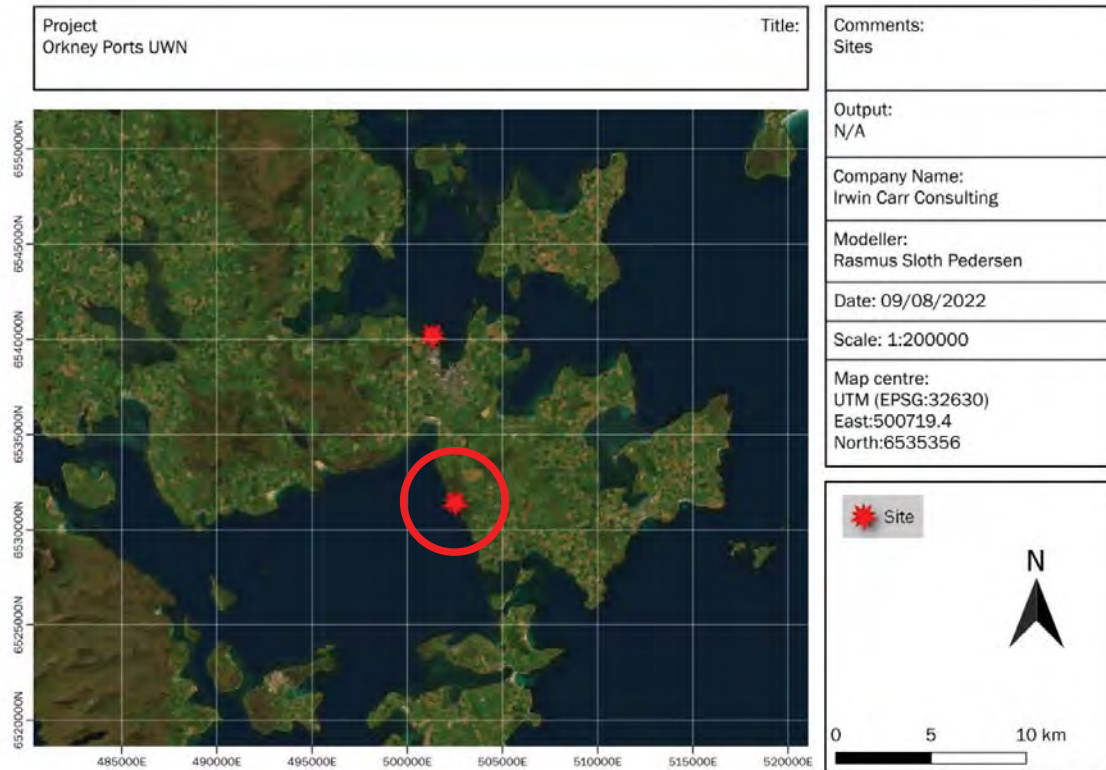
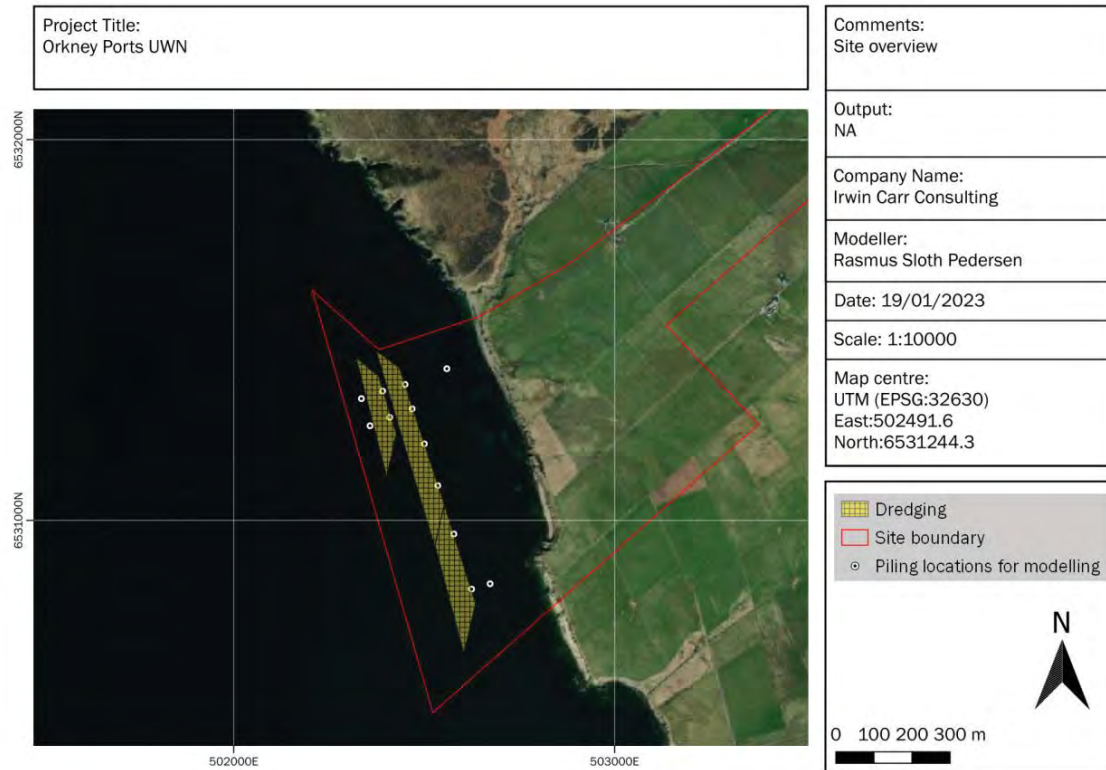


Figure 2. Overview of piling locations for modelling and approximate areas to be dredged.



2.1 Depth, Bathymetry

Depth data for the sites were collected from 3 sources:

- The proponent, detailed data near the site, 4 m resolution.
- EMODNet (European Marine Observation and Data Network, 2019), long range data, ~90 m resolution.
- Nautical charts such as <http://fishing-app.gpsnauticalcharts.com>, medium range data, variable resolution.

These were corrected to MSL and combined (using a mosaic method) to give the best possible total cover of the area.

For the “worst case” scenario the MHWS (Mean High Water Spring) level is used (deeper water decreases sound transmission loss).

2.2 Water properties

The water properties are important for the sound propagation. Generally the two sites have no major outflows of fresh water so salinity is expected to be near 35 psu (confirmed by (Marine Scotland, 2022)).

2.2.1 TEMPERATURE

The temperature was measured with the inbuilt thermometer of the Soundtrap hydrophone (used for on-site measurements).

Average water temperature at Scapa site during monitoring: 8.9 °C

The water columns are assumed to be well-mixed, given lack of nearby freshwater outflows, windy location, evaporation and generally shallow depths (<30 m).

2.2.2 SOUNDSPEED PROFILE

Given the water properties presented above, we assume the water soundspeed to be constant at all depths, with no significant deviations from the expected values.

The sound speed calculation is based on a widely used model for sound speed in water (Leroy, Robinson, & Goldsmith, 2008), with input of temperature, depth and salinity.

Sound speed in the water is calculated as 1486 m/s

2.3 Sediment properties

Given the project is a construction project there are sediment cores available for sediment characterisation provided by “Causeway Geotech”. These give good coverage in the areas close to the Scapa DWQ. For general sediment outside the development area, we have used data from British geological survey (British Geological Survey, 2022).

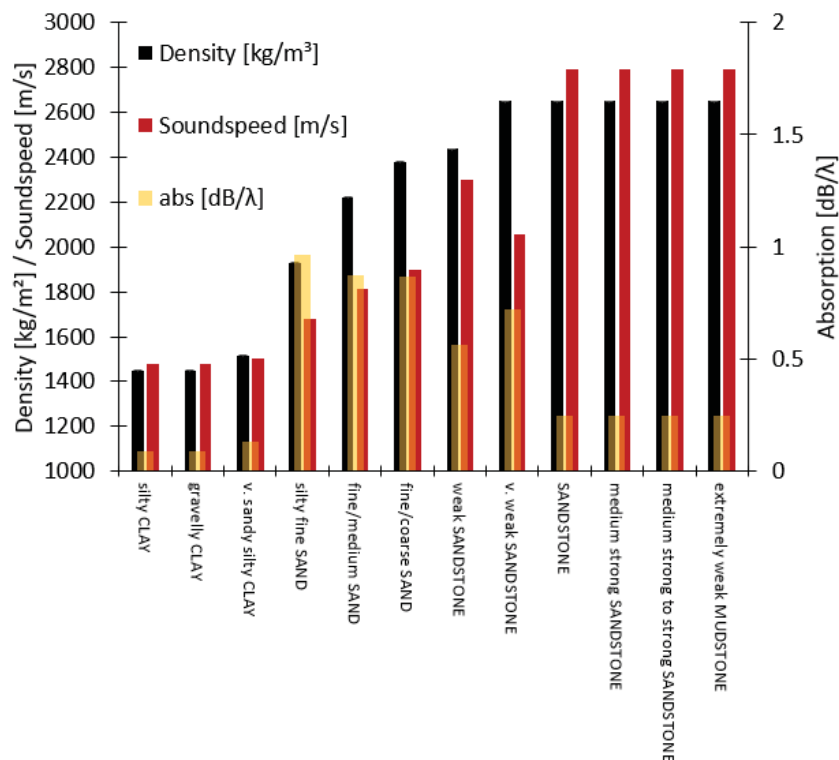
Where samples were taken we mapped the descriptions in the sediment core reports in relation to their Udden-Wentworth or Folk sediment description where these matched the nomenclature well. For other sediment types, e.g. sandstone/mudstone/limestone we have used given values for nominal “sandstone” (Jensen, Kuperman, Porter, & Schmidt, 2011; Boyce, 1981). The cores also contain classifications such as “weak sandstone” this was interpreted as loose, sandy sandstone, and we characterised this with density and soundspeed between that of sandstone and sand. This interpolation was based on an assumption that the scale “very weak-, weak-, medium weak-, sandstone” corresponds to linear interpolation between sand and sandstone (see Table 2 below). We have not changed the properties for categories indicating harder than usual sediments, such as “medium strong”, “very strong”.

Table 2. Example of interpolation scheme for Sand-sandstone.

Material	Interpolation value	Density [kg/m ³]
Sand	0	1931
Very weak sandstone	0.25	2111
Weak sandstone	0.5	2291
Medium weak sandstone	0.75	2470
Sandstone	1	2650

Where we had no direct properties (density, sound speed, absorption) for the sediment we have used a modelling approach to estimate them, following (Ainslie, 2010).

Figure 3. Sediment types. Note that absorption is read on the right vertical axis.



2.4 Background/Ambient Noise

Baseline noise monitoring was carried out on 29-30 November 2022. On both days the weather was very calm (< sea state 1) with no detectable current. The Scapa site was unexpectedly noisy with ~130 dB SPL for all measurements (unaffected by range to our vessel). There were multiple other vessels in the bay, but all far away (> 1km). The most likely source was the small oil platform stationed a few km to the south. This could have some active machinery causing the noise, indicated by the tonal components (seen as horizontal bands in spectrogram in Figure 4).

Note that ambient noise here excludes noise from nearby vessel passes, it is meant as the ambient noise with no identifiable noise sources.

Table 3. Typical background noise levels.

Site	SPL [dB]
Scapa	129.9
Hatston	107.2

Figure 4. Spectrogram of ambient noise at Scapa.

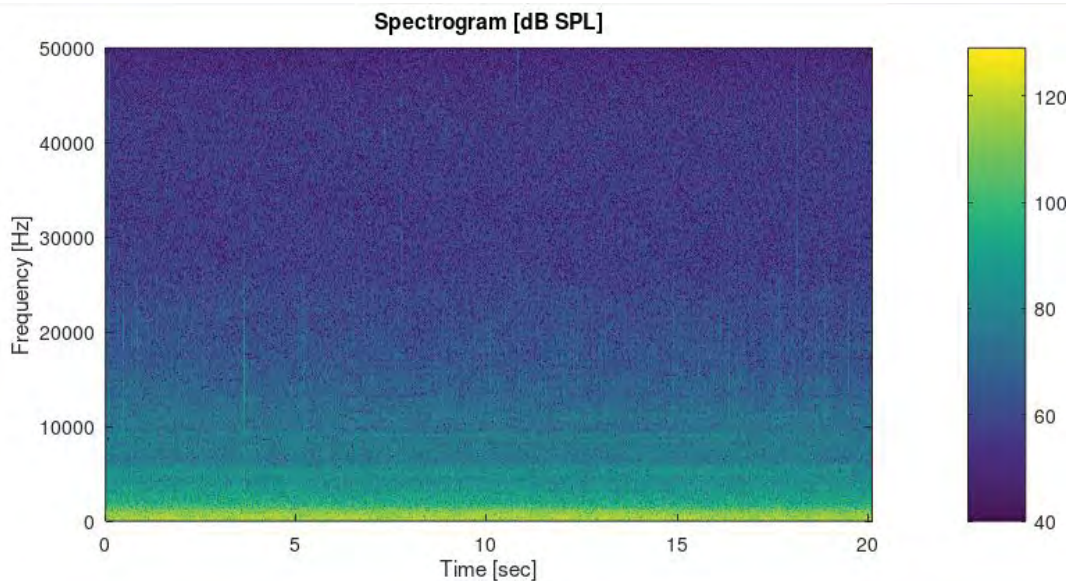


Figure 5. Spectrogram of ambient noise at Hatston.

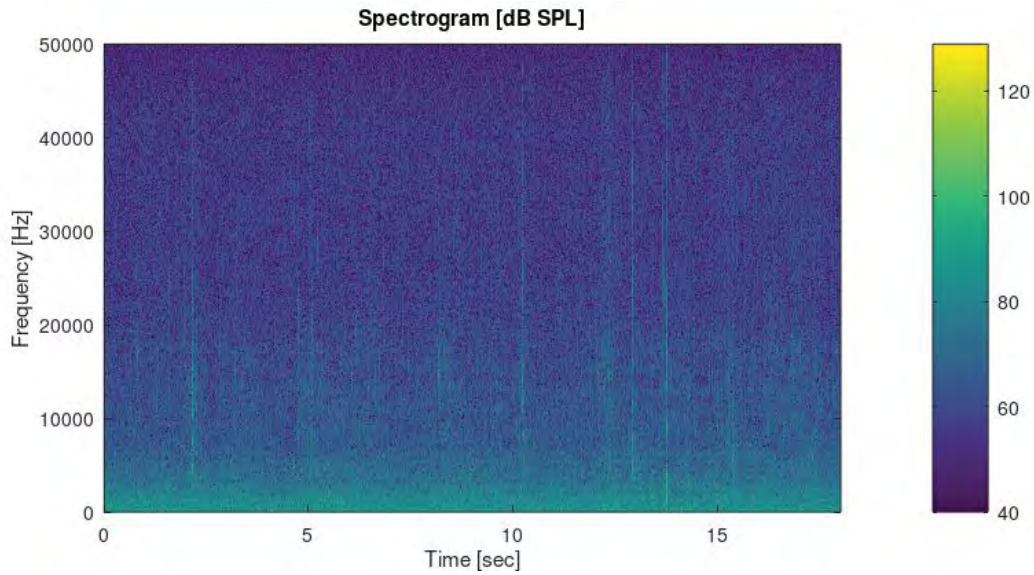
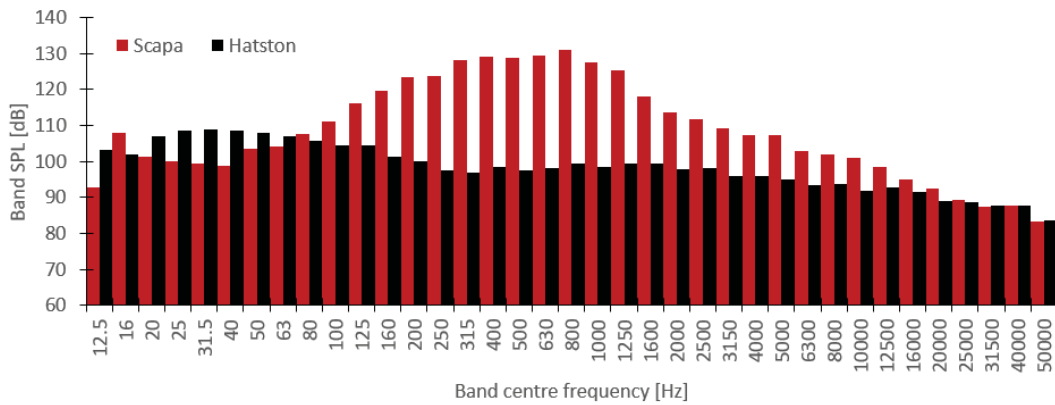


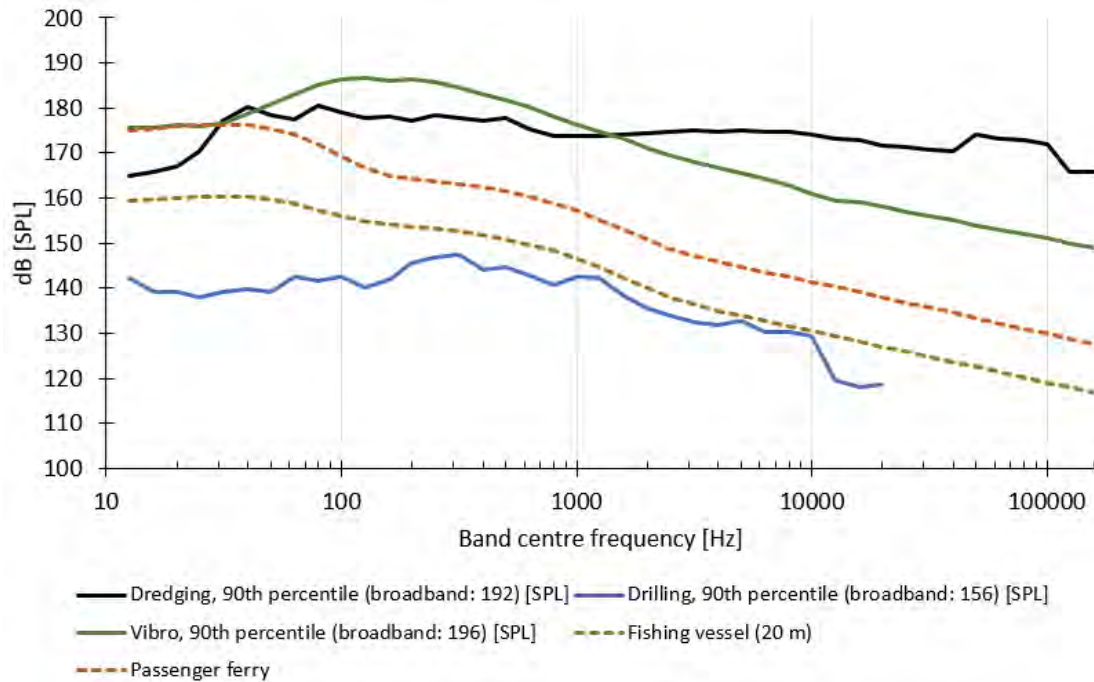
Figure 6. Typical band levels of ambient noise at Scapa and Hatston.



3 SOUND SOURCE MODELLING

We have considered three noise sources for this assessment, but have screened out the drilling as it is not loud enough to meaningfully assess in an environment with many vessels and general human activity (compare with vessel noise in Figure 7, below).

Figure 7. The three sound sources considered in this report. A fishing boat and a small ferry has been added for context.

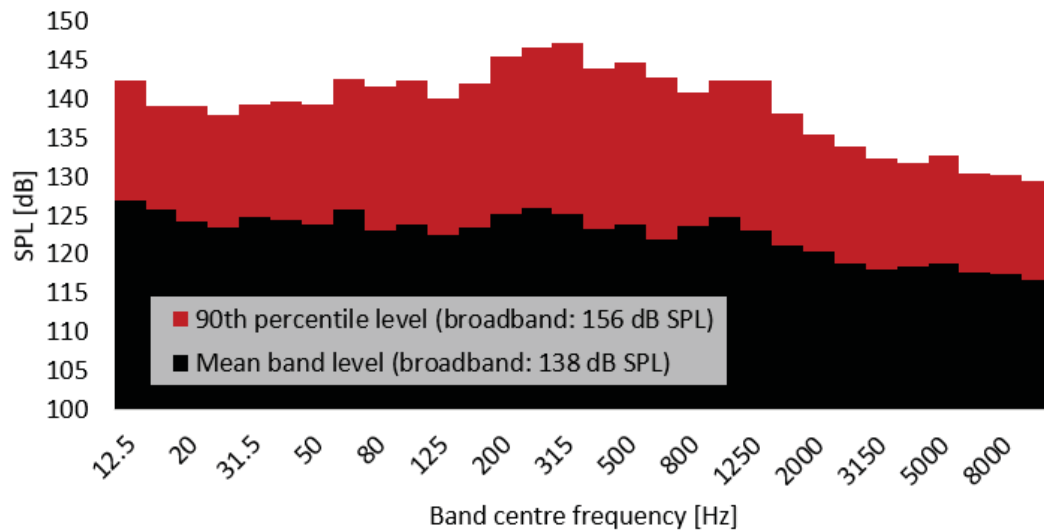


3.1 Drilling

As some hard sediment is expected round piles might be placed in pre-drilled holes, based on the range of noise levels presented in Figure 8, the drilling noise is assumed to be insignificant to the marine life.

The measured levels presented are a summary of 13 different recorded drilling episodes shows noise levels to vary considerably between sites and equipment, and there is no clear connection between drill size, power or sediment type to the emitted noise level. However, given the modest broadband level of even the 90th percentile level (156 dB SPL) this noise source can be ignored.

Figure 8. Example of drilling noise band levels. Data from various drills, diameter 0.1-1.2 m and various rock types.



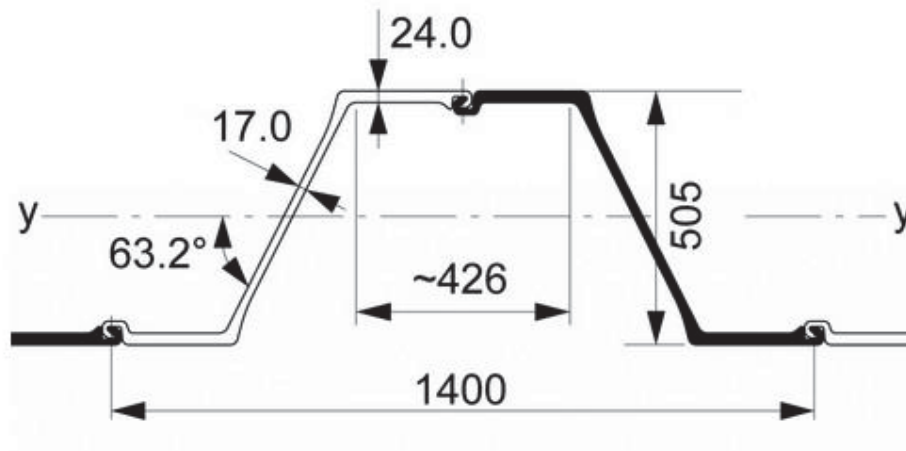
3.2 Vibration Piling Model

Two types of piles are expected to be used:

1. Tubular piles, expected to have a diameter of 2.1 m
2. Sheet piles (Arcelor Mittal AZ52-700³).

Both will be vibrated into the sediment or into holes left by the drilling campaign.

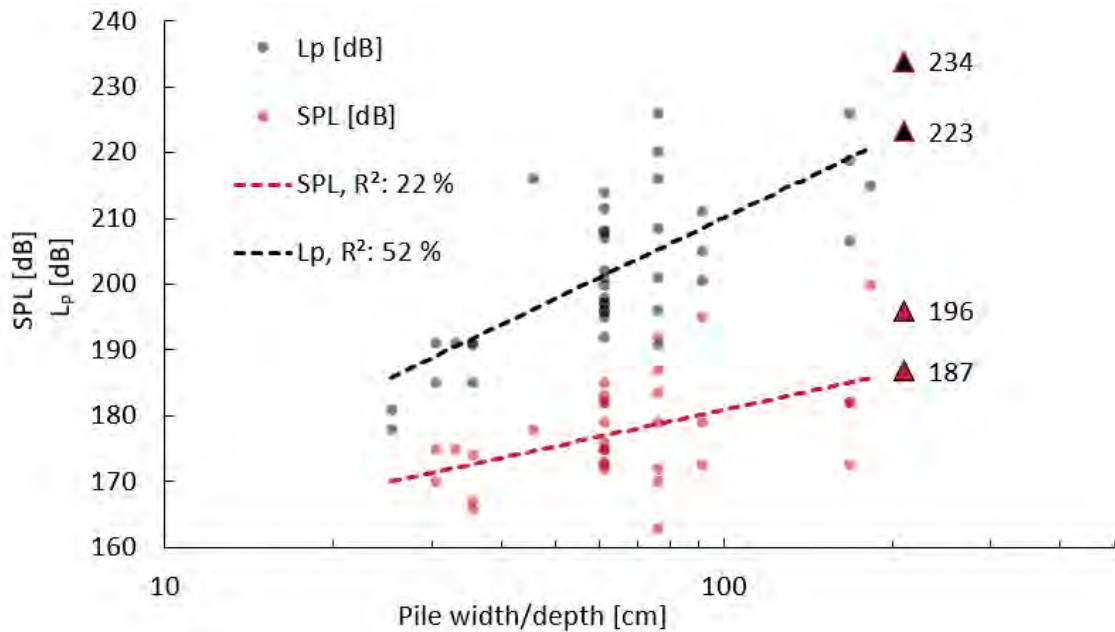
Figure 9. Schematic of the sheet piles.



The diameter of the tubular pile (210 cm) is used as a basis for an empirical model based on 50 recorded levels as from CalTrans (CalTrans, 2015).

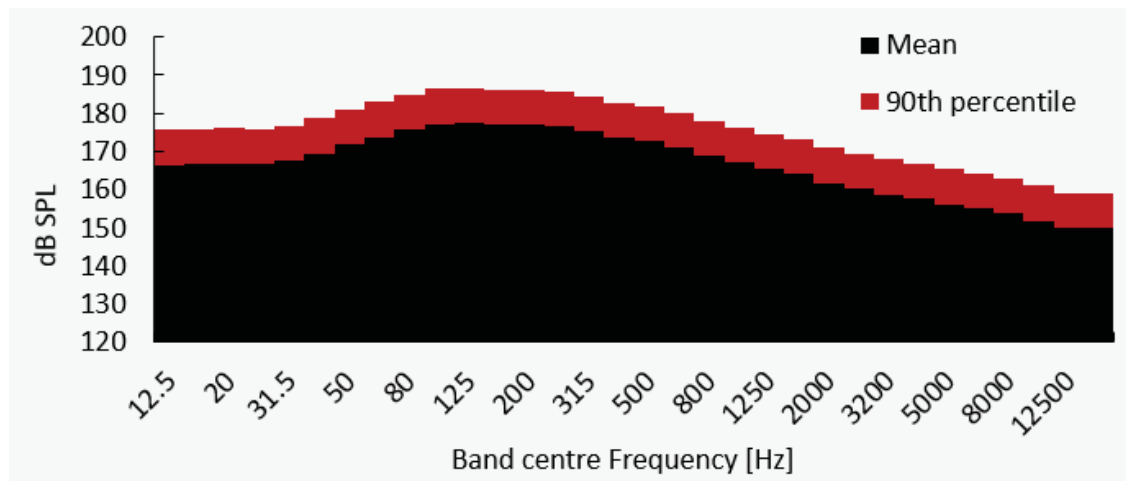
³ <https://sheetpiling.arcelormittal.com/products/az-52-700/>

Figure 10. Basis of vibro piling broad band source level as a function of pile size (210 cm diameter).



Given the low confidence we have in this approach (low R² values) we use the 90th percentile level as the broadband source level. L_p is estimated to be 234 dB and SPL 196 dB. The frequency content is assumed to be identical to that of the impact piling.

Figure 11. Band levels for vibro-piling.



3.3 Dredging

Dredging is done to chart Datum -15 metres, meaning this will likely be done with a cutter suction dredger (Max reach 15 m) and possible assistance from a backhoe dredger. For the cutter suction dredger a cutter power of 540 kW is assumed, equivalent to the Boskalis “Seine”⁴ cutter suction dredger. For cumulative modelling it’s assumed that the dredging is potentially active 24 hours per day. The Backhoe dredging is quieter and has been ignored in favour of using the louder method for the assessment.

⁴ https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKewibnqWF-SH8AhUQg1wKHfYmBVoQFnoECB8QAQ&url=https%3A%2F%2Fboskalis.com%2Fmedia%2Fqbjnfdlv%2Fseine_cutter_suction_dredger.pdf&usg=AOvVaw1bBD75xRPFc3H0TUXTFkD

Figure 12. Approximate extent of dredging campaign (yellow hatched area).

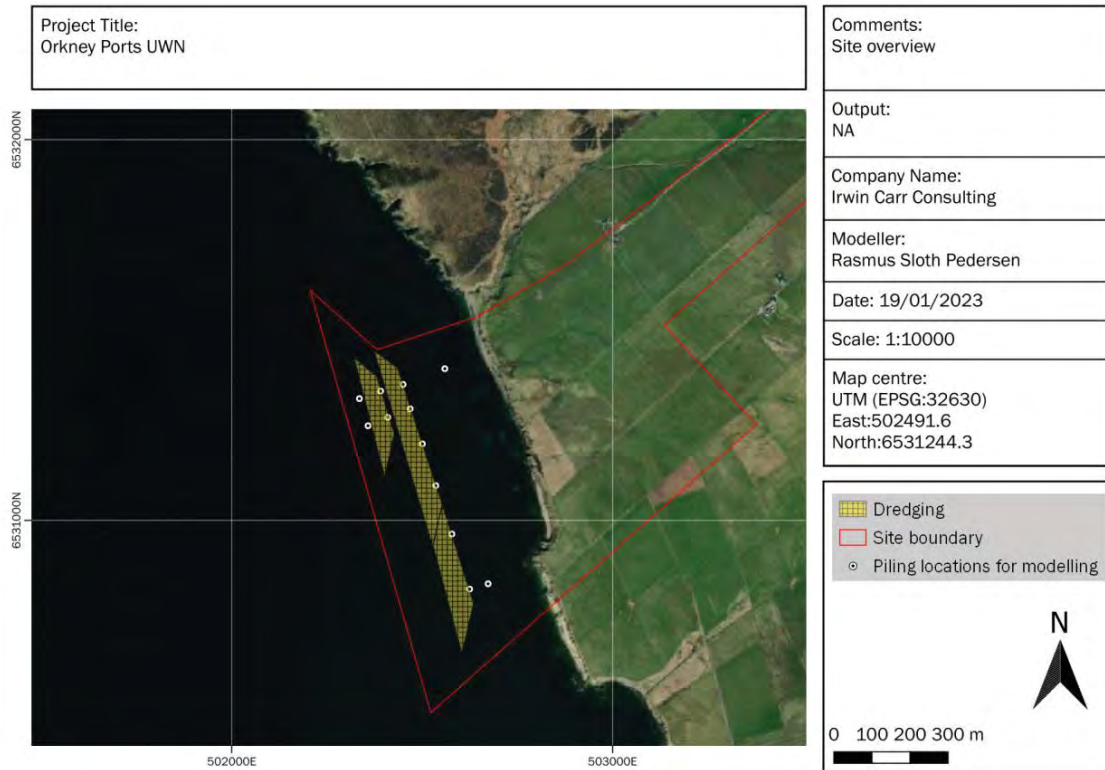
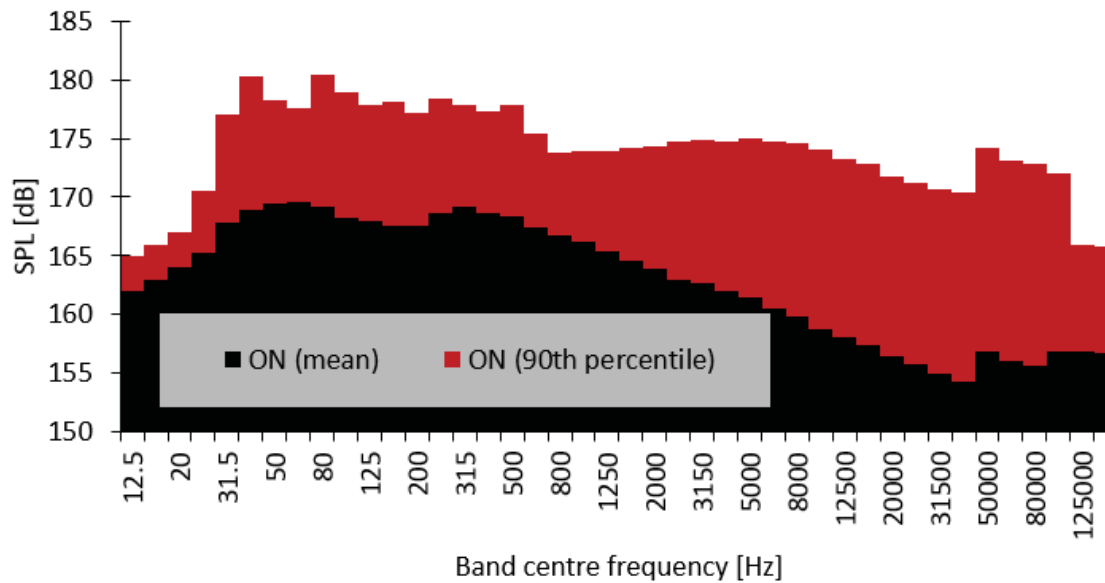


Figure 13. Band levels as modelled for a 540 kW cutter suction dredger with coarse sediment. "ON" refers to active dredging.



4 TRANSMISSION LOSS MODELLING

Transmission loss modelling is done using dBSea underwater noise modelling software.

This software is partially developed by us and can model frequencies from 10 Hz to 168 kHz, normally as 3rd octave bands, but any logarithmic band-spacing can be used. All solvers are range dependent (meaning all conditions can change with range not just depth).

Further details of this modelling software package can be found in APPENDIX A - dBSea.

The sound sources from section 3, Sound Source Modelling, p. 14, was used sources for the model, both as band levels when modelling energy transmission losses (L_E , SPL) and as timeseries/impulse for modelling peak pressure (L_P).

Previous to this assessment measurements of the actual transmission loss for the two sites were measured along two transects for each site. The modelling has been calibrated to match the measurements of these recordings (details in APPENDIX D – MODEL CALIBRATION).

The measurements show a broadband transmission loss consistent with $\sim 12 \times \text{Log}_{10}(\text{range})$ at Scapa. However, these are frequency specific, and these losses are not consistent across all frequencies. We have matched the frequency-wise transmission losses to the extent that they are less than $20 \times \text{Log}_{10}(\text{range})$ as we find it unlikely that a transmission loss, even for higher frequencies, of $> 20 \times \text{Log}_{10}(\text{range})$ is sufficiently representative for the site as a whole.

5 ASSESSMENT CRITERIA

5.1 Reporting units

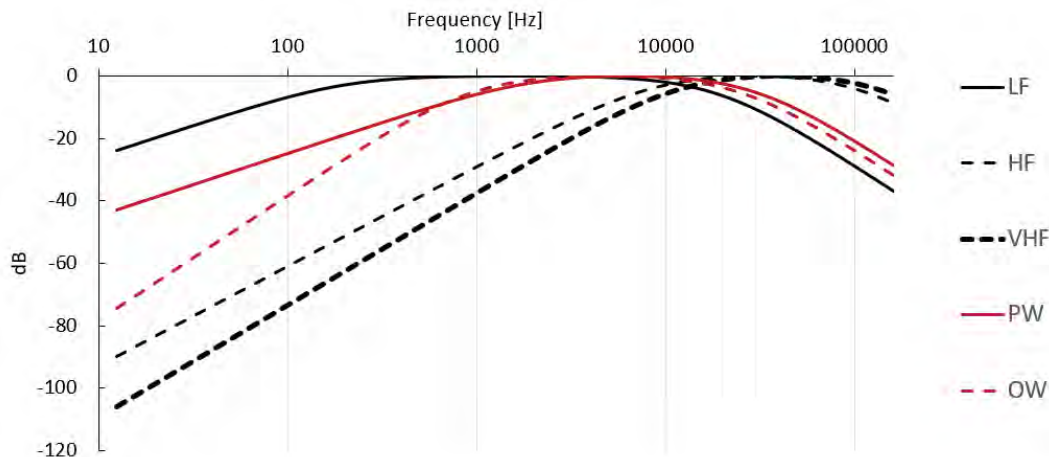
See 1.1.5, p. 8 for definitions.

5.2 Weighting of Noise Levels

When not reporting L_p or L_{p-p} levels, the noise levels are often weighted according to a generalised hearing sensitivity profile for up to ten different hearing groups. This is done to better reflect the actual impact on the species in question, much like dB(C) level unit for humans.

See Table 4, for full group names and limits.

Figure 14. Weightings for various hearing groups. For L_E levels, the weightings are applied to the noise level to give the weighted noise level (similar to dB(A) or dB(C)-weighted noise for humans).



5.2.1 MARINE MAMMAL WEIGHTINGS

For the marine/aquatic mammals present we will adhere to the thresholds described in “Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing” (National Marine Fisheries Service, 2018), which determines impact from an assessment of area wherein the noise will induce either

“Temporary Threshold Shift” (TTS) or “Permanent Threshold Shift” (PTS)⁵ as judged by the weighted SEL level (L_{E-24}) over a typical 24-hour period or by L_p levels, for the different hearing groups.

Please note that the Southall 2019 thresholds and weightings are identical to the NMFS 2018 criteria, only the nomenclature has changed (Southall, et al., 2019; National Marine Fisheries Service, 2018).

Thresholds for behavioural disruption are set by NOAA fisheries⁶. These are 120 dB RMS⁷ for continuous noise and 160 dB SPL⁸ for impulsive noise.

The hearing groups from the Southall 2019 and the NMFS 2018 guidance were specified by collating available information on marine mammal hearing and generalising their hearing sensitivity into representative groups. This grouping represents a significant research effort and are reviewed by the leading experts (academic, industrial and conservation) on the topic. Because of the large amount of work this represents and the widespread acceptance of the method, the thresholds and the methodology associated, have become de-facto standards for assessing noise impact on marine mammals and represents best available knowledge and practise.

Along with weighting curves, similar in function to the human dB(C) curves, a set of thresholds for hearing impact and injury is associated with the framework and allows for conversion of threshold exceedance into ranges with risk of impact. E.g. we might see that the PW group (true seals) has a risk of PTS at ranges shorter than 50 meters, and a risk of TTS at ranges shorter than 200 meters.

All marine mammal species are covered by the hearing groups and a full list of species in the different groups can be found in the “Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects” (Southall, et al., 2019), but in general the groups cover the following species:

Table 4. Summary of Southall 2019 thresholds and groups with species examples. For full species list see source (National Marine Fisheries Service, 2018; Southall, et al., 2019)

Hearing group	Species examples	Non-impulsive TTS/PTS threshold [L_{E-24} hours]	Impulsive TTS/PTS threshold [L_{E-24} hours]	Impulsive TTS/PTS threshold [L_p]
PW	Harbour seal, Grey seal	181/201	170/185	212/218
OW	Otters	199/219	188/203	226/232
LF	Minke whale, Humpback whale	179/199	168/183	213/219
HF	Sperm whale, Common dolphin, Bottlenose dolphin, Killer whale, Risso’s dolphin, Pilot whales	178/198	170/185	224/230
VHF	Porpoise	153/173	140/155	196/202

It’s important to note that the assessment is thus based on the received level of receptors with the above-described auditory sensitivity and not based on the sensitivity of the individual species.

⁵ TTS/PTS. A temporary/permanent change in hearing sensitivity caused by acoustic stimuli.

⁶ Available from: https://archive.fisheries.noaa.gov/wcr/protected_species/marine_mammals/threshold_guidance.html

⁷ Here taken as meaning “SPL”

⁸ Assumed to be SPL of 90 % of energy in one impulse or SPL of total duration (L_{Eq}).

5.3 Fishes etc.

Impacts of noise on fishes is less well established than for marine mammals, but a review from 2014 (Popper, et al., 2014) provides guidelines on exposure limits for fish and turtles. The report does not directly use the PTS nomenclature (as above for mammals) as many fish have the capacity to repair structural damage to their ear, and even structural damage then cannot be said to be “permanent”.

We use “PTS” here to cover the categories “Mortality and potential mortal injury” and “Recoverable injury”.

Note that we use the impulsive limits from piling for all impulsive sources as the information for explosions is rather less well documented (and limits are significantly higher).

TTS is directly used in the report, and we use it in the same way here.

As there are no TTS/PTS limits for non-impulsive noise, we apply the limits for cumulative impulsive noise.

Table 5. Overview of Impact piling thresholds from (Popper, et al., 2014) (Table 7.3). We use these for all impulsive noise, even though explosions have separate thresholds (Table 7.2 in report).

Hearing group	Species examples	Impulsive TTS/PTS threshold [L _{E-24 hours}]	Impulsive TTS/PTS threshold [L _p]
P* (Fish with no swim bladder)	Sharks, Rays	186/216	TTS not specified/213
P- (Fish with swim-bladder, but not involved in hearing)	Salmon, Trout, Cod, Herring	186/203	TTS not specified/207
P+ (swim-bladder used in hearing)	Carp, Catfish	186/203	TTS not specified/207

5.4 Threshold Interpretation

5.4.1 THRESHOLD TYPES

The three threshold types refer to different ways that sound can affect the hearing of an animal and are **important to keep in mind** when evaluating the results of this report:

5.4.1.1 Non-impulsive, L_{E-24 hours}

The threshold, over which an effect (TTS/PTS) occurs, taking into account **continuous**⁹ sound received by the animal over a typical 24-hour period as sound exposure, L_E.

When presented as a zone on a map, this refers to the area, within which, an animal would suffer the effect, if it stayed there for 24 hours (or the full duration of the activity or as otherwise specified). We thus identify areas given by this limit as areas of TTS-**risk** or PTS-**risk** respectively, i.e., an animal within the area has a risk of suffering from either TTS or PTS within the zone. Alternatively this can be thought of as the total sound-dose limit over 24 hours.

Weightings are applied for non-impulsive L_E (for mammals only¹⁰).

5.4.1.2 Impulsive, L_{E-24 hours}

The threshold, over which an effect (TTS/PTS) occurs, taking into account **impulsive** sound received by the animal over a typical 24-hour period as sound exposure, L_E.

⁹ Please see (National Marine Fisheries Service, 2018) for definitions of “non-impulsive” and “impulsive”. For quick reference, if a sound is shorter than 1 second and is clearly intermittent in nature, it is impulsive – otherwise, it’s continuous.

¹⁰ When assessing for fish groups levels are not weighted.

When presented as a zone on a map, this refers to the area, within which, an animal would suffer the effect, if it stayed there for 24 hours (or the full duration of the activity or as otherwise specified). We thus identify areas given by this limit as areas of TTS-risk or PTS-risk respectively, i.e., an animal within the area has a risk of suffering from either TTS or PTS within this zone.

Alternatively this can be thought of as the total sound-dose limit over 24 hours.

5.4.1.2.1 Impulsive L_E single impulse / L_E # impulses

It is sometimes useful to assess the impact of a single/a number of impulse(s). When we do this, we will refer to it as “LE single impulse / LE # impulses”.

Like for the L_p , when single-impulse L_E is presented as an impact zone, this refers to the area, within which, an animal would suffer the effect acutely/instantly.

Weightings are applied for Impulsive L_E (for mammals only).

5.4.1.3 Impulsive, L_p

The threshold over which an effect (TTS/PTS) occurs, taking into account *impulsive* sound received by the animal at any instant as maximal peak pressure.

When presented as a zone on a map, this refers to the area, within which, an animal would suffer the effect acutely/instantly and from just one exposure.

Weightings are **not** applied for Impulsive L_p .

5.4.2 MASKING

Levels that are not over threshold can still cause significant impact, if that noise makes foraging, navigation or communication harder due to masking or where biologically relevant sounds are “drowned out” by the anthropogenic noise. Continuous noise is more likely than impulsive noise to cause this form of impact.

5.4.3 DISPERSAL

Many animals can recognise sounds and might be dispersed from an area at noise levels well below TTS limits. Quantifying a level of dispersal from desk-spaced studies is very challenging and not done here.

6 CONCLUSION & RESULTS SUMMARY

Dredging

The noise from dredging, while presenting a significant PTS risk to ranges >500 m for the VHF group, this is only for animals staying close to the activity for extended periods (> 1 hour) and assumes continuous dredging with the dredger level as given by the 90th percentile. For the best estimate (model mean) the PTS risk range is 450 m after 8 hours exposure. There is no acute risk of noise related injury related to the dredging, and animals have time to swim away. Further the area ensonified does not “block” access through a channel or strait.

There is no issue identified for species outside the VHF range.

Vibro piling

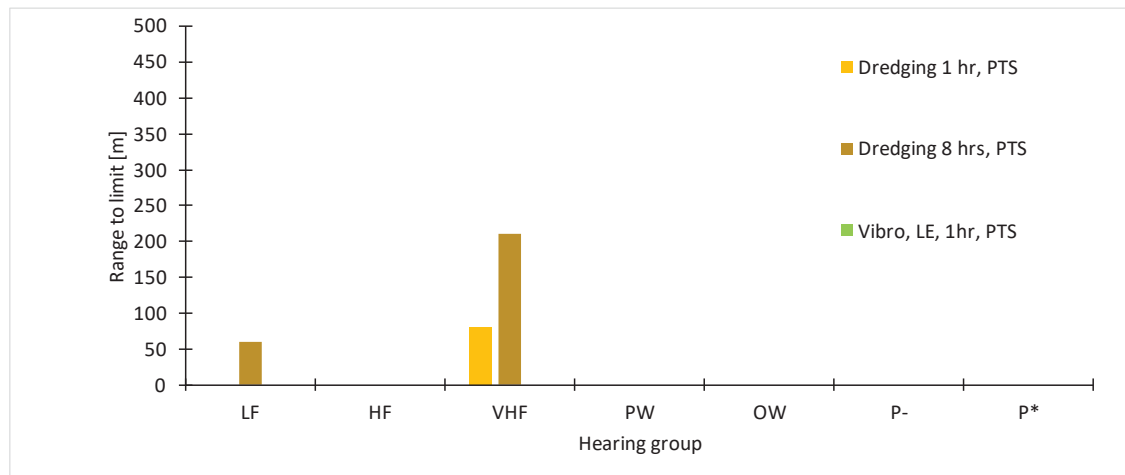
Prolonged exposure to vibro piling at close range (<100 m) carries some auditory risk for the animals assessed, specifically groups LF, VHF and P- (baleen whales, porpoises and salmon/trout), where the peak pressures in the noise have risk ranges up to 300 m for the VHF group. We therefore suggest surveillance takes place prior to piling to minimise the risk of impact on porpoises. While this is a significant risk for animals close to the activity, we stress that we have used a very conservative approach to estimating the source levels, and the realised emission will likely be significantly lower.

Further, animals will tend to move around, or away from noise, which will limit exposure. In Figure 16 and Figure 18 we show an example of the effect of using moving receivers (animals, modelled animals) to estimate what might be the effect of movement.

Table 6. Overview of maximal ranges to limits [m].

Activity Dose Hearing group	Dredging				Vibro piling			
	1 hr L _E		8 hrs L _E		1 hr L _E		Peak pressure L _p	
	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS
LF	230	<50	1250	60	760	<50	<50	<50
HF	60	<50	160	<50	<50	<50	<50	<50
VHF	620	80	1350	210	180	<50	550	300
PW	70	<50	250	<50	100	<50	100	<50
OW	<50	<50	<50	<50	<50	<50	<50	<50
P-	120	<50	600	<50	390	<50	<50	125
P*	120	<50	600	<50	390	<50	<50	<50

Figure 15. Overview of PTS risk ranges



7 RESULTS

The noise maps for each activity and hearing group are presented in APPENDIX E – Results.

7.1 Dredging

While exposure to 8 hours of dredging has significant PTS risk ranges (< 210 m) for 2 hearing groups: LF (baleen whales) and VHF (porpoises), but only after prolonged exposure (> 1 hour). The relatively low (compared to limits) source level of the dredging means that there is not acute risk from noise and animals have time to swim away.

Using a model approach to have moving receivers (animats, see Figure 18, p. 24) we can estimate the impact on moving animals. The animats in the model move 0.5-4 m/s depending on the received level and evade levels >120 dB.

Figure 16. Summary of total exposure (L_E) of 225 animats of the VHF group in the soundfield of the dredging. 44 exceeded TTS limit (20 %), none exceeded the PTS limit.

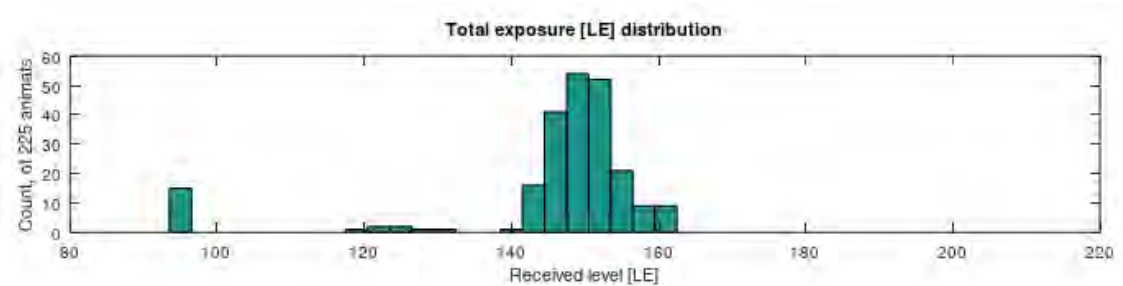


Figure 17. TTS and PTS risk ranges for all groups.

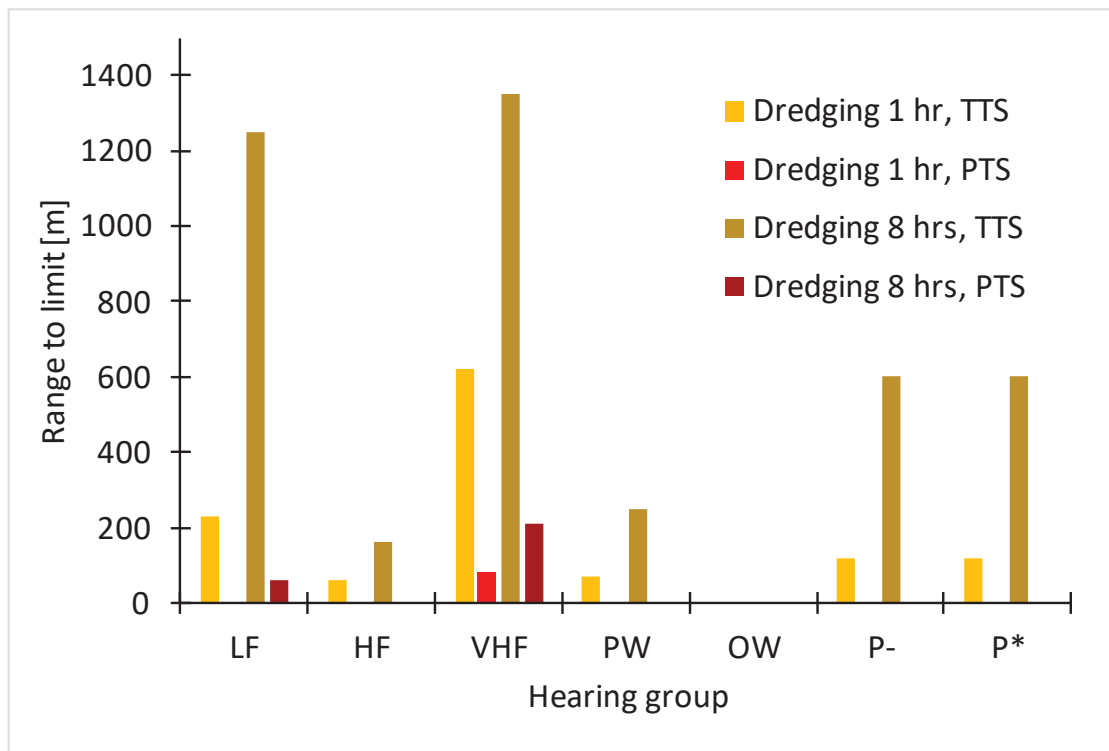
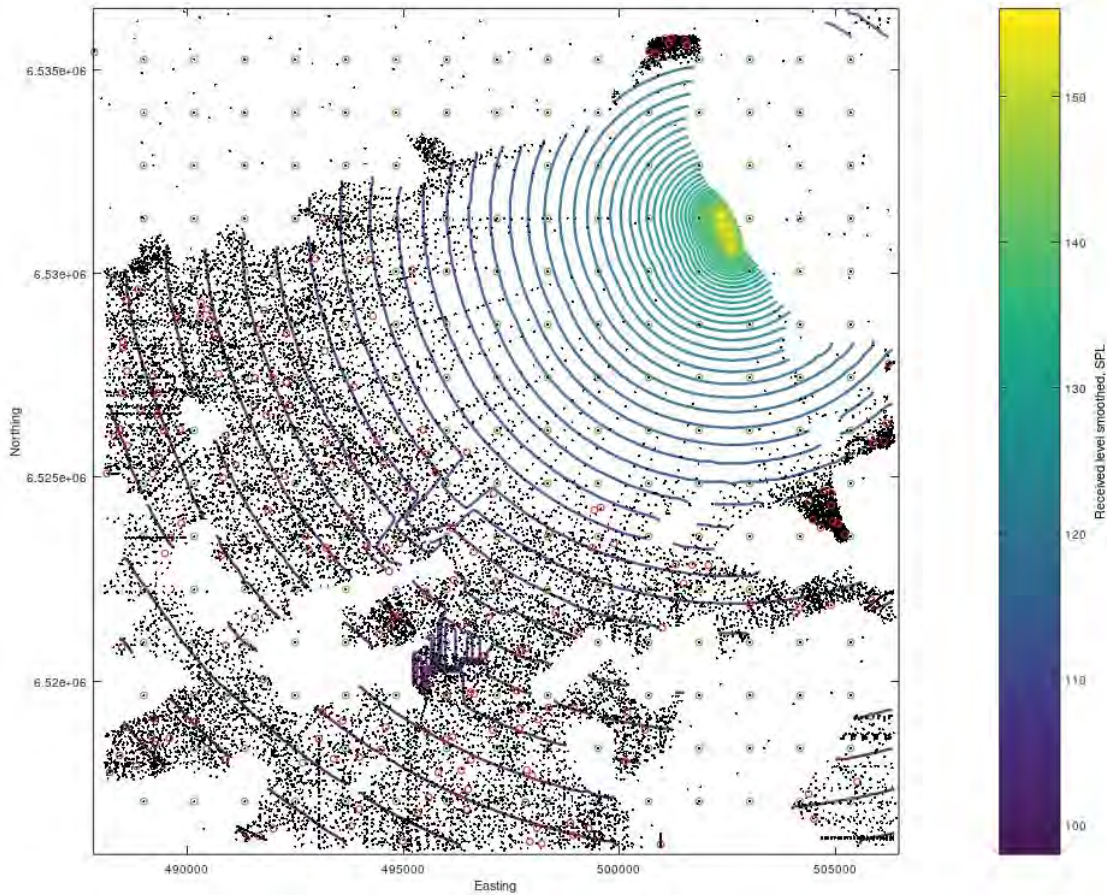


Figure 18. 225 “animats” in the dredger soundfield for 8 hours. Green spots are starting points, and red spots end points. Area covers Scapa Flow.a



7.2 Vibro piling

Longer exposures (> 1 hour) lead to significant PTS risk zones within 50 for all groups, but the proposed duration of vibro piling on this site is less than 1-hour per day.

The peak pressures in the vibro piling have a PTS risk zone max range of 50m. While the risk for the LF and P- groups is only for prolonged exposure, the risk to the VHF group is acute, i.e. the animal has no chance to swim away to avoid the risk.

Figure 19. TTS and PTS risk ranges for all groups.

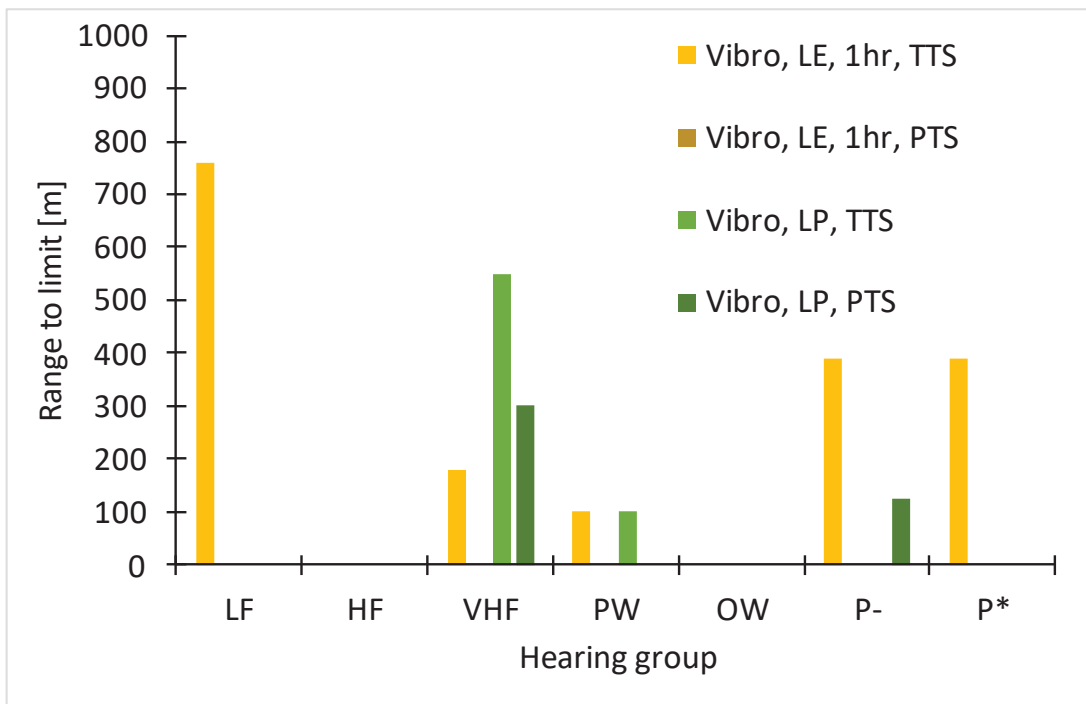
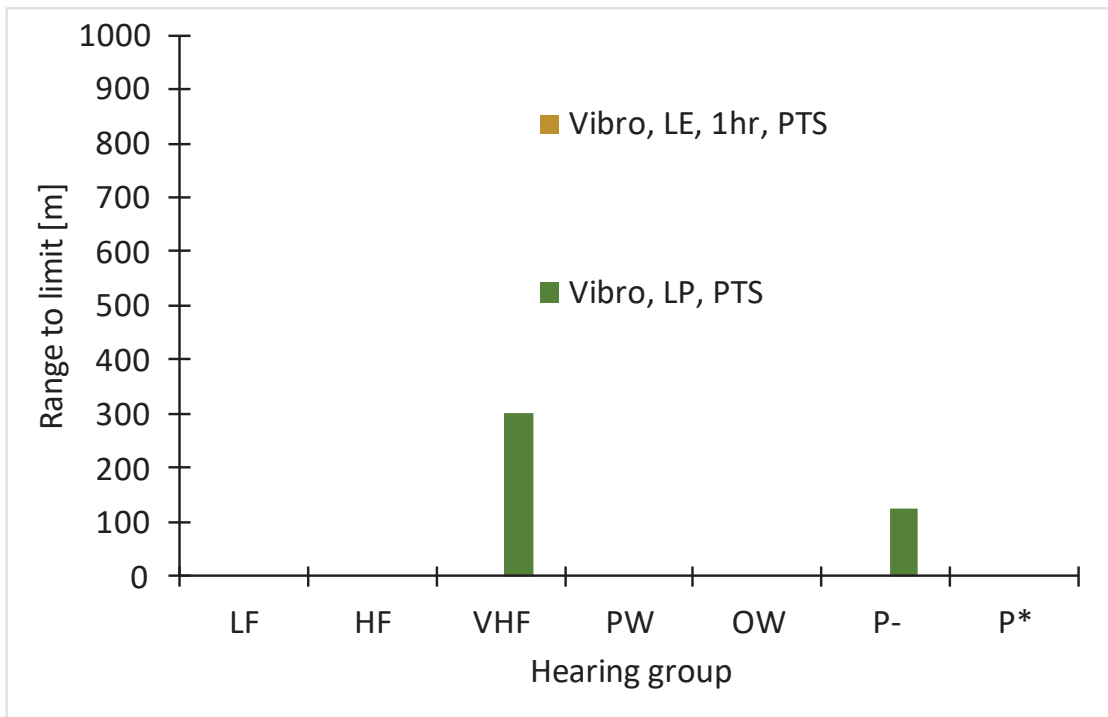


Figure 20. PTS risk ranges for all hearing groups.



8 BIBLIOGRAPHY

- Ainslie, M. A. (2010). *Principles of Sonar Performance Modelling*. Heidelberg: Springer. doi:10.1007/978-3-540-87662-5
- Audoly, V. M. (2020). Accounting for sea floor properties in the assessment of underwater noise radiated from ships in shallow water. *Proceedings of Meetings on Acoustics* .
- Boyce, R. E. (1981). *LABORATORY-DETERMINED SOUND VELOCITY, POROSITY, WET-BULK DENSITY, ACOUSTIC IMPEDANCE, ACOUSTIC ANISOTROPY, AND REFLECTION COEFFICIENTS FOR CRETACEOUS-JURASSIC TURBIDITE SEQUENCES AT DEEP SEA DRILLING PROJECT SITES 370 AND 416 OFF THE COAST OF MOROCCO*. La Jolla: Scripps institution of Oceanography.
- British Geological Survey. (2022, June 30). *Geology of Britain Viewer*. Retrieved from British Geological Survey: <https://mapapps2.bgs.ac.uk/geoindex/home.html>
- CalTrans. (2015). *Technical Guidance for the Assessment of Hydroacoustic Effects of Pile Driving on Fish*, CALTRANS. Sacramento: California Department of Transportation.
- European Marine Observation and Data Network. (2019, May 01). *Bathymetry portal*. Retrieved from EMODnet: <http://portal.emodnet-bathymetry.eu/>
- Jensen, F. B., Kuperman, W. A., Porter, M. B., & Schmidt, H. (2011). *Computational Ocean Acoustics, Second Edition*. Springer. doi:10.1007/978-1-4419-8678-8
- Leroy, C. C., Robinson, S. P., & Goldsmith, M. J. (2008). A new equation for the accurate calculation of sound speed in all oceans. *The Journal of the Acoustical Society of America*, 2774-2782.
- Marine Scotland. (2022, 12 12). *Salinity*. Retrieved from Marine Scotland: <https://marine.gov.scot/sma/assessment/salinity>
- National Marine Fisheries Service. (2018). *Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0)*. Silver Spring: U.S. Department of Commerce.
- Popper, A. N., Hawkins, A. D., Fay, R. R., Mann, D. A., Bartol, S., Carlson, T. J., . . . Travolga, W. (2014). *Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI. Springer Briefs in Oceanography*, S3.
- Southall, B. L., Finneran, J. J., Reichmuth, C., E.Nachtigall, P., Ketten, D. R., Bowles, A. E., . . . Tyack, P. L. (2019). Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects. *Aquatic Mammals*, 125-232. doi:10.1578/AM.45.2.2019.125

APPENDIX A - DBSEA

A summary of dBSea's models in standard scenarios can be found in the document (online):
<http://www.dbsea.co.uk/media/30782/dBSea-Benchmark-Testing.pdf>
(also see Figure 23, p. 29 for one example).

All solvers in dBSea are based on Jensen et al. 2011 (Jensen, Kuperman, Porter, & Schmidt, 2011)

dBSea has four primary models of calculation:

- **Range dependent Parabolic Equation model - dBSeaPE**
dBSeaPE uses a split-step, wide angle parabolic equation method. It uses either Greene's approximation or several Padé terms (as set by user) to get very wide propagation with low phase error.

dBSeaPE is best suited to deeper scenarios (>50 m) or where sediment interaction is not dominant relative to sound speed profile. The model is very efficient for low frequencies and only suffers a small efficiency penalty for higher frequencies.

dBSeaPE will generally be used for deeper/long range scenarios in the frequency interval 10-1000 Hz.

- **Range dependent Normal Modes model - dBSeaModes**
dBSeaModes is especially suited to shallower and sediment dependent scenarios and will typically be used where water is shallower than 50 m and depth changes are a large proportion of the total depth, or where sediment effects are thought to play a significant role. dBSeaModes incurs a significant efficiency-penalty at high frequencies and will normally be used in the frequency range 10-1000 Hz.
- **Ray tracing**
dBSea uses a Gaussian raytracing method, dBSeaRay, to calculate transmission losses for higher frequencies (scenario dependent, but normally from 500 Hz). dBSeaRay compares favourably with the open-source BELLHOP model, in that it is accurate to lower frequencies and agrees well with PE and NM models.
- **Full waveform propagation**
dBSeaRay also supports full waveform propagation in the frequency range 10 Hz to 168 kHz (limited by the waveform sample rate). Used in this way dBSeaRay takes into account all scenario range dependence (as models above) as well as the arrival time, phase information and transmission loss of all significant paths to any number of receivers in the scenario (the results grid).

General notes:

- dBSea is an "Nx2D" solver, meaning it models transmission losses in "N" number of vertical radial slices from the source (Figure 22, p. 28). There is no backwards propagation towards the source, and no sideways reflection/refraction (We're testing dBSea with full 3D solvers currently).
- dBSea models the sediment propagation only for compressional waves, not for shear waves. This generally means that the transmission loss will be slightly underestimated as no energy is transferred into shear waves, and also means that dBSeaRay does not propagate into the sediment, but relies on a complex reflection coefficient (calculated from the sediment layers) to calculate the reflection/refraction properties of the sediment. Given that dBSeaRay is generally only used for higher frequencies, this has very little practical effect, as higher frequencies will only interact weakly with deeper layers of the sediment.
- The individual sources in a scenario are modelled radially (radial coordinates) from the source at several depths. In post-processing levels are transferred to a cartesian "results grid". This results grid stores levels from all sources so that the cumulative level at any point in the scenario can be investigated immediately.
- Levels can be, and are often post-processed to apply a conservative margin and smooth results (Figure 21, p. 28). Radial smoothing (triangular kernel of variable width) is carried out to mitigate modelling artefacts arising from low environment sampling density or chance occurrences. Levels are often made to decrease monotonically from the source to make general trends more visible and decrease the risk of misinterpreting impact ranges.

- When refereeing to a level at a certain range, this usually refers to the greatest level at any depth at that range (unless specifically mentioned otherwise).

Figure 21. Post-processing to eliminate artefacts and ease interpretation. Level are radially smoothed by default, and are made to be monotonically decreasing with increasing range from the source.

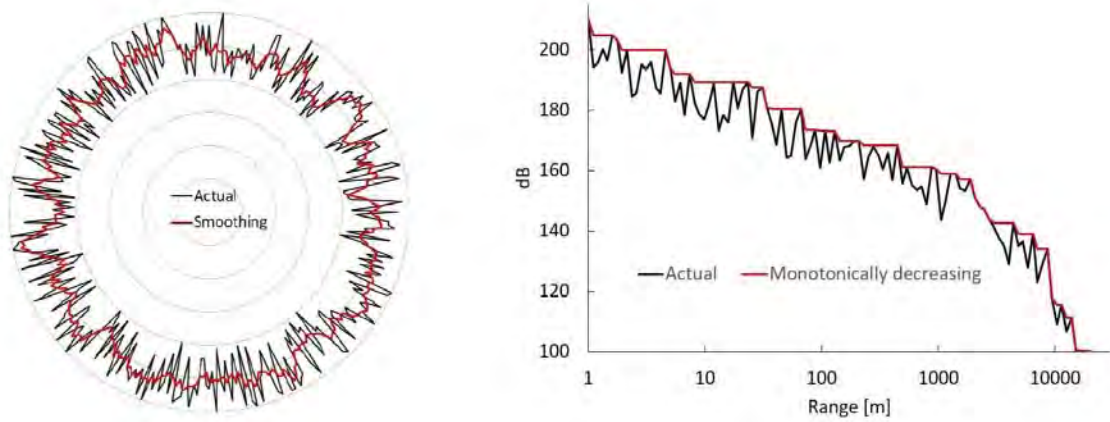


Figure 22. Low resolution schematic of the dBSea modelling space. Source transmission loss is modelled radially from the sources at a number of depths. Results are extracted from a “square” 3D grid that hold cumulative levels from all sources in the scenario.

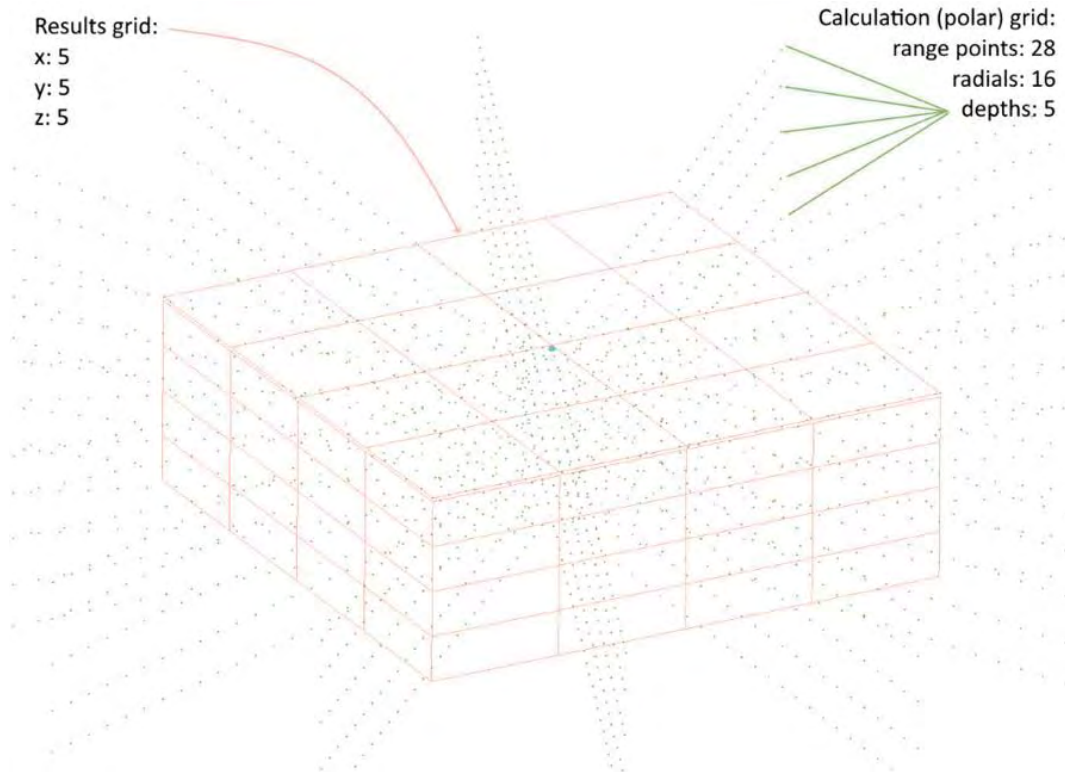
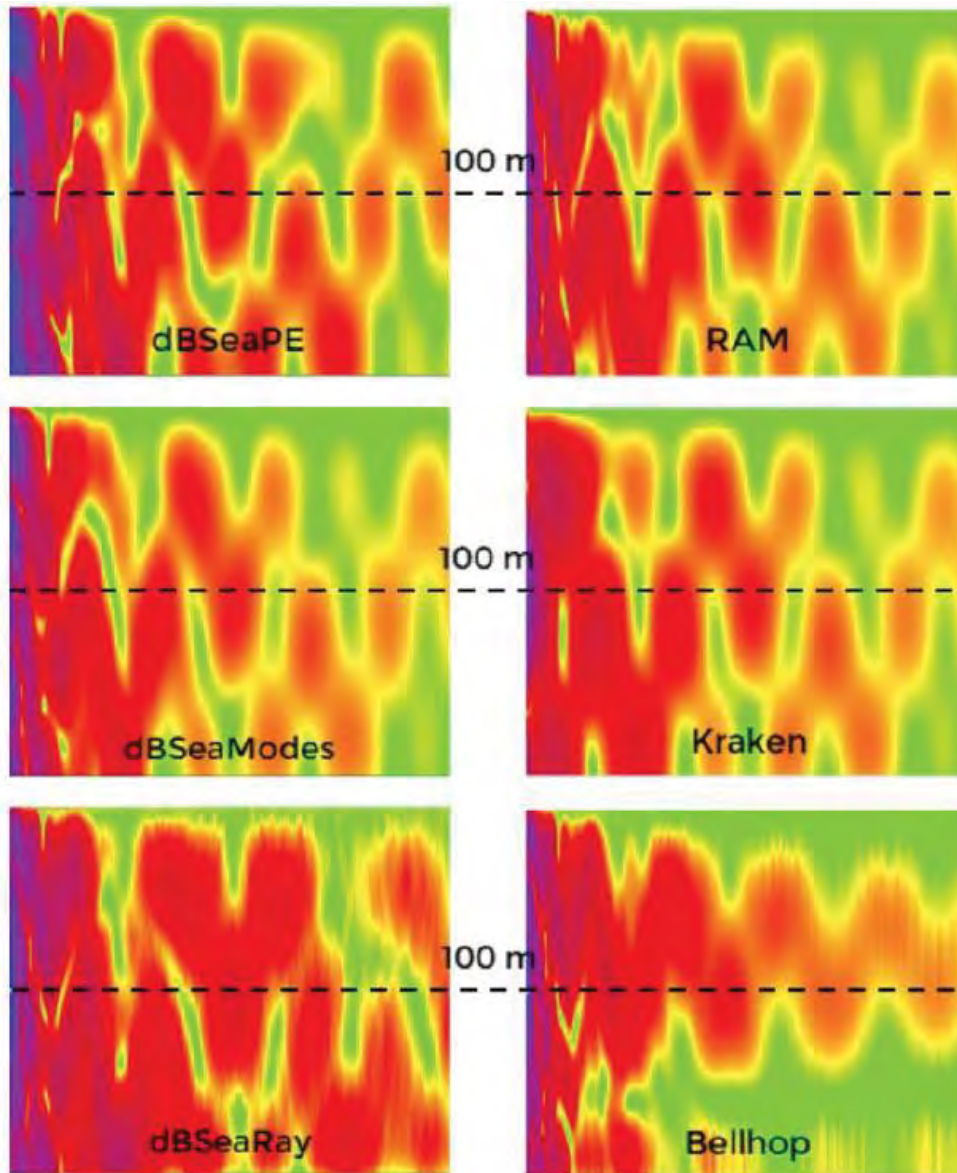


Figure 23. the “Pekeris” standard problem, a low frequency problem. Note that due to sediment effects, neither dBSeaRay nor Bellhop should be relied upon for low frequency problems, and are only include for completeness.



APPENDIX B – UNDERWATER ACOUSTICS BASICS

Sound Speed

Water is much harder to compress than air, and a soundspeed of 1500 m/s is often used as a standard soundspeed in water¹¹ much as 340 m/s is in air. Soundspeed is given by the following equation:

$$c = \frac{Z}{\rho}$$

$$\text{Soundspeed [m/s]} = \frac{\text{Acoustic impedance} \left[\frac{\text{kg}}{\text{m}^2 \cdot \text{s}} \right]}{\text{Specific density [kg/m}^3\text{]}}$$

Because changes to pressure, salinity and temperature occur with changes in depth, the specific density and acoustic impedance of water changes with depth, and thus the soundspeed changes as well.

The soundspeed profile is quite important in sound propagation, as refraction (changes in propagation angle) will occur when sound moves between layers of water with varying sound speed. This change is quantified in “Snell’s Law” and results in sound being “bent” towards the depth of minimal soundspeed. These effects can lead to profoundly inhomogeneous sound fields and SOFAR channels.

The same relationships are valid in the sediment, though sediments commonly have soundspeeds higher than water. Soundspeeds from 1700 m/s (fine sand/silt) to 2500 m/s (gravel) are common for non-solid sediments, with solid sediments (rocks) having much higher soundspeeds 2800 m/s (Calcarenite) to 6000 m/s (some granite).

Spreading loss

Most of the propagation loss (loss in dB from source to receiver, “PL”) that occurs initially is governed by “spreading loss”. It is the simple “thinning out” of acoustic energy as it spreads away from the source, usually in all directions – spherically.

For a sound source in an unbound medium the initial PL will be dominated by spherical PL:

$$\text{Received level} = \text{Source level}_{\text{at reference range}} - 20 \cdot \log_{10} \left(\frac{\text{range}}{\text{reference range}} \right)$$

This means a reduction in received level of 6 dB per doubling of distance and explains the rapid reduction in received levels often seen close to the source, e.g.: with a reference range of 1 m, at 16 meters range, there has been 4 doublings of distance, and thus 24 dB loss (4×6 dB).

At longer ranges the medium is no longer unbounded. We reach ranges where the sound has interacted with the surface (near perfect acoustic reflector) or the seabed (lossy acoustic reflector). Also, at greater ranges a doubling of distance is no longer trivial as the PL from spherical spreading loss from 500 m to 1000 m is also just 6 dB.

Sound Channels and Wave guides

In bounded mediums where the sound energy is confined to cylindrical spreading, the PL (ignoring absorption) is often well-characterised by:

$$\text{Received level} = \text{Source level}_{\text{at reference range}} - 10 \cdot \log_{10} \left(\frac{\text{range}}{\text{reference range}} \right)$$

This means a reduction of received level of 3 dB per doubling of distance. Depending on the sediment this kind of “waveguide” can sustain efficient transmission of sound over long ranges, provided the sediment is acoustically hard and there is low absorption (such as is the case for low frequencies or in low salinity).

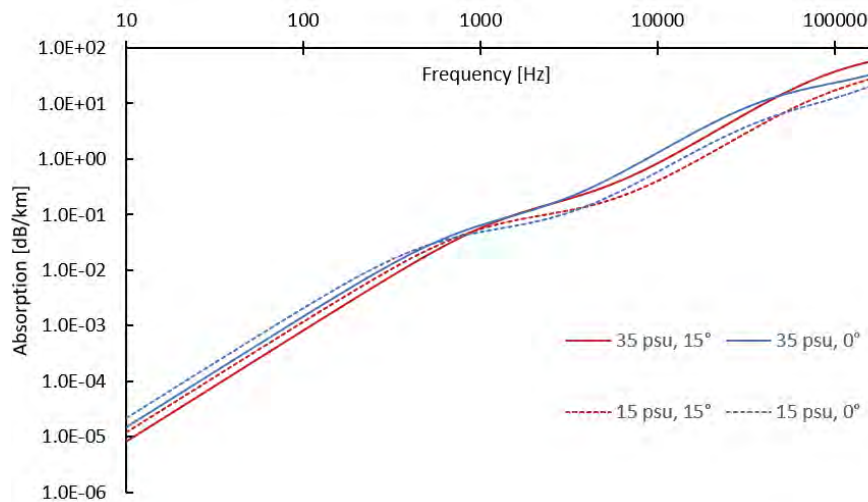
In absence of a bounding from the surface or the seabed, a soundspeed profile with a clear low-speed region, surrounded by higher soundspeeds can act a sound channel, by focusing the sound towards a single depth (with lower soundspeed), limiting the PL from spherical to cylindrical (a SOFAR channel is formed).

¹¹ Varies from 1450 m/s at 0° to 1550 m/s at 30° at salinity of 35 psu.

Absorption

Besides the “thinning out” of the sound energy as described above, the sound is also dissipated into heat by the way the pressure changes interact with water, molecules and particles in its path. This absorption is mostly governed by the concentration of boric acid and magnesium sulphate and is very dependent on the frequency, with lower frequencies, <1 kHz, experiencing almost no absorption, while high frequencies, > 10 kHz, can be attenuated by over 10 dB / km.

Figure 24. Absorption comparison at salinities of 35 psu & 15 psu and temperatures of 0° and 15° . Both scales are logarithmic. Note how increased salinity increases high-frequency absorption (solid v dashed lines), while a decrease in temperature increases absorption at lower frequencies (red v blue lines).



Small bubbles, wind or wave induced, will further attenuate especially the high frequencies, but as modelling is often done to estimate a worst-reasonable case, or for weather sensitive activities, fair weather with little wind and waves are assumed, thus ignoring this attenuation effect.

Sediment

Depending on the incident angle of the sound, the frequency and the acoustic properties of the sediment, sound can either mostly penetrate the sediment or mostly be reflected by it.

In shallow areas with soft sediment (acoustically similar to water), it is typical to find that close to the source, at high incidence angles and at low frequencies (<250 Hz) the sound will penetrate into the sediment and dissipate there, leading to very high transmission losses for these frequencies. This effect coupled with the high absorption at high frequencies often leads to the soundscape being dominated by frequencies from a few hundred hertz to a few thousand hertz. In deeper water, or with an upward refracting soundspeed profile, low frequencies will tend to dominate the soundscape away from sound sources, as there is no efficient mechanism for attenuating them.

A “cut-off¹²” frequency, below which, there will be high sediment-associated attenuation can be approximated by:

$$f_{cut-off} = \frac{c_{water}}{4 \cdot D \cdot \sqrt{1 - \left(\frac{c_{water}}{c_{sediment}}\right)^2}}$$

With “C_{water}” and “C_{sediment}” being the soundspeed in the water and the sediment respectively, and “D” the local depth (Jensen, Kuperman, Porter, & Schmidt, 2011).

¹² The cut-off is not an immediate loss of energy in frequencies under this frequency, but rather something like a high pass, 1st-order, Butterworth filter (Audoly, 2020).

In water with lower salinity and less absorption, the soundscape will tend to have a relatively higher content of high frequencies as these are absorbed much less efficiently when the salinity is lower.

Sound transmission Across Interfaces

Sound waves are reflected and refracted (Snell's law) as they travel through interfaces. Also, depending on acoustic impedance and interface angles only a proportion of the incident acoustic energy is transmitted through that interface (the rest is reflected).

In the following: *W*: Watt; *Pa*: Pascal; *s*: second; *m*: metre; *N*: Newton; *J*: Joule; θ : angle; *v*: soundspeed; *Z*: acoustic impedance; *p*: pressure from ambient;

Snell's law:

$$\frac{\sin \theta_{in}}{\sin \theta_{out}} = \frac{v_{in}}{v_{out}}$$

- rearranged to give transmission angle from incidence angle and soundspeeds:

$$\sin^{-1} \left(\frac{\sin \theta_{in}}{\frac{v_{in}}{v_{out}}} \right) = \theta_{out}$$

Transmission fraction of sound pressure for plane waves (part of the Fresnel equations):

$$\frac{p_{out}}{p_{in}} = \frac{2 \cdot Z_{out} \cdot \cos \theta_{in}}{Z_{out} \cdot \cos \theta_{in} + Z_{in} \cdot \cos \theta_{out}}$$

Reflection fraction of sound pressure for plane waves (part of the Fresnel equations):

$$\frac{p_{out}}{p_{in}} = \frac{Z_{out} \cdot \cos \theta_{in} - Z_{in} \cdot \cos \theta_{out}}{Z_{out} \cdot \cos \theta_{in} + Z_{in} \cdot \cos \theta_{out}}$$

It follows from these relations that for transmission from an acoustically relatively slow medium like water to an acoustically faster medium here exists an incident angle above which there is total reflection, and thus no transmission of acoustic energy through the interface (real interfaces are rugged and lumpy, and perfect reflection is not realistic).

For the water/sediment interface presented here (sediment is sand with a soundspeed of 2000 m/s) this occurs at 0.84 radians (~48.5 degrees) from normal incidence.

The fraction of pressure transmission from water (soundspeed 1500 m/s) to sediment (2000 m/s) is around 146 % at normal incidence and drops as the incidence angle increases away from normal, much faster for water-to-sediment than for sediment-to-water.

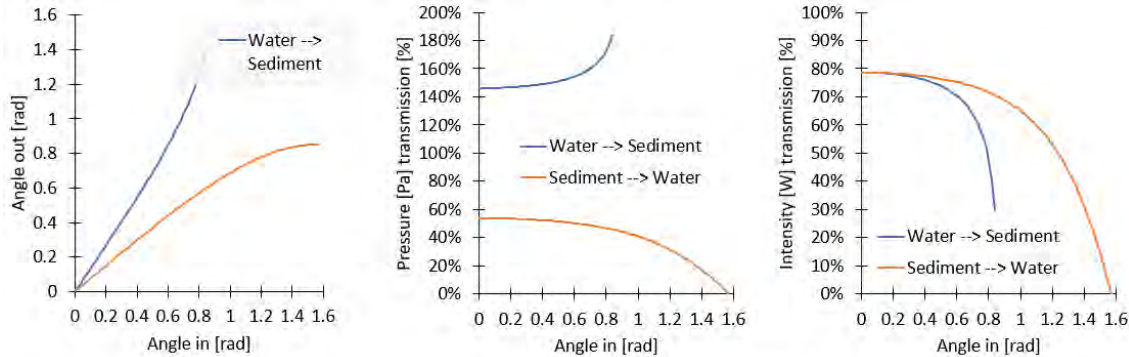
While it may seem counter-intuitive that pressure can increase after transmission over an interface, remember that the energy in the sound is a function of pressure *and* acoustic impedance:

$$I = \frac{p^2}{Z}$$

$$\text{With units: } [W] = \frac{[Pa]^2}{\left[\frac{m^3}{m^3}\right]} = \frac{\frac{N^2}{m^4}}{\frac{N}{m^2} \cdot s} = \frac{N^2 \cdot m^3}{m^4 \cdot \frac{N}{m^2} \cdot s} = \frac{N}{m \cdot m^{-2} \cdot s} = \frac{J \cdot m}{m^{-1} \cdot s} = \frac{J}{s} = W$$

Thus, if the transmitted intensity fraction is 80 % then the reflected intensity is 20 %; there is energy conservation.

Figure 25. Transmission angles [radians] and fractions as function of incident angle between water and sediment (sand). Note that total reflection from water to sediment occurs around incident angle of 0.84 [rad] (48.5 degrees), meaning there is no transmission of sound at greater incidence angles.



Simplified Propagation Loss Model

Taking all the above into account we can construct a simplified model, that will give a good indication of the expected propagation loss (PL) in scenarios of constant depth:

$$PL = \left\{ \begin{array}{l} r < D : \quad -20 \cdot \log_{10} \left(\frac{r}{r_0} \right) \\ r > D : \quad -20 \cdot \log_{10} \left(\frac{D}{r_0} \right) - 10 \cdot \log_{10} \left(\frac{D}{r_0} \right) \end{array} \right\} - \alpha(f) \cdot r - l(f) \cdot r$$

Where:

- “r” is horizontal range from source.
- “D” depth at source.
- “r₀” the reference range of the source (often 1 m).
- “f” the frequency,
- “l” the frequency specific leakage loss to the sediment.
- “α” the frequency specific absorption.

Sound Level Units

All references to sound pressure levels, peak pressure levels and sound exposure levels refer to a logarithmic ratio between a reported/measured pressure or exposure and a reference pressure or exposure. As an example, a level of 220 L_p (decibel zero-to-peak) is equal to a peak pressure of 100000 Pascals (Pa) over ambient pressure, while 120 L_p is equal to 1 Pa over ambient pressure.

To avoid dealing with these large numbers as pascals (as a linear scale), they are converted to a decibel ratio (Table 1 for definitions). Besides compressing large numbers to a smaller scale this also corresponds better to how animals are thought to perceive sound, namely as relative steps. This means that an increase from 1 to 2 Pa *sounds like* the same increase as from 100 to 200 Pa, even though the first step was only 1 Pa, while the second was 100 Pa. This is better reflected in a logarithmic scale based on ratios, where both steps are equal, here 3 dB.

However, while dBs are practical, they can be hard to compare between studies, due to vague definitions, and so we have adopted the standards set by ISO 18405-2017 (Table 1 below).

For ease of reference please see following overview for unit definition.

Table 7: Definitions.

Unit	Definition	Comments
SPL (dB _{RMS}) ISO 18405-2017: 3.2.1.1	$SPL = 10 \cdot \text{Log}_{10} \left(\frac{1}{t_2 - t_1} \cdot \int_{t_1}^{t_2} p(t)^2 dt \right)$	Functionally equivalent to deprecated $20 \cdot \text{Log}_{10} \left(\frac{RMS}{1 \cdot 10^{-6} Pa} \right)$
L _p (dB _{z-p}) ISO 18405-2017: 3.2.2.1	$L_p = 20 \cdot \text{Log}_{10} \left(\frac{Pa_{max}}{1 \cdot 10^{-6} Pa} \right)$	This assumes that Pa_{max} is equal or greater than $\sqrt{Pa_{min}^2}$
L _{p-p} (dB _{p-p})	$L_{p-p} = 20 \cdot \text{Log}_{10} \left(\frac{Pa_{max} - Pa_{min}}{1 \cdot 10^{-6} Pa} \right)$	Often ¹³ equivalent to $L_p + 6.02 \text{ dB}$
L _E (dB _{SEL}) ISO 18405-2017: 3.2.1.5	$L_E = 10 \cdot \text{Log}_{10} \left(\frac{\int_{t_1}^{t_2} p(t)^2 dt}{1 \cdot 10^{-12} Pa} \right)$	For continuous sound this is equivalent to $SPL + 10 \cdot \text{Log}_{10}(t_2 - t_1)$ “t” is seconds

Unless otherwise stated SPL has an averaging period of 1 second, and L_E for the duration of the specified event, sometimes indicated as L_E-“time” or L_E-single blow.

If the averaging period for SPL is equal to the total even duration, then SPL is equal to “Leq” the “equivalent constant level”.

When source levels are presented, the same units are used, and it is implicit that all source levels are given as if recorded 1 m from an omnidirectional mono-point source, unless otherwise specified.

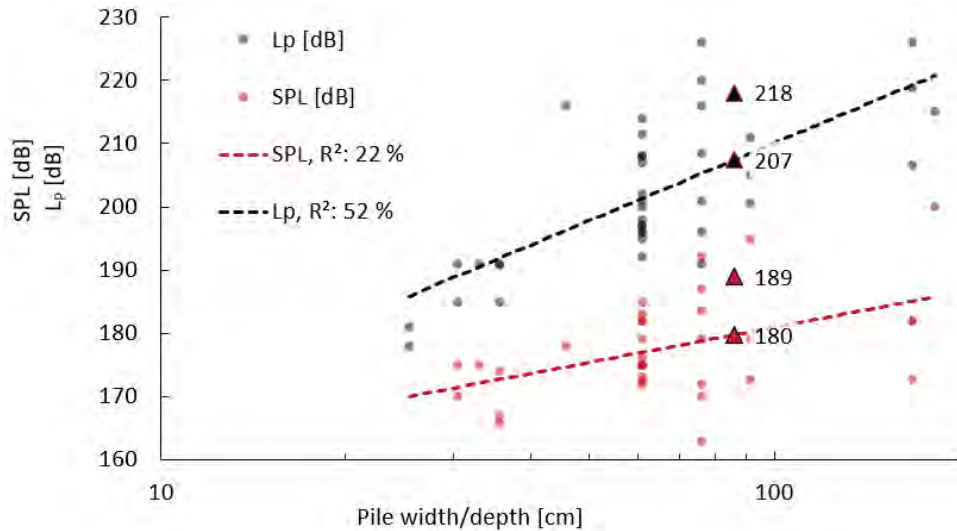
¹³ If maximum pulse rarefaction is below ambient pressure and compression and rarefaction phases are of equal size.

APPENDIX C – SOURCE MODELS

Vibration piling model

We only have a few recordings (50) from vibration piling and have no dedicated source model for this type of piling. Instead, we rely on published recorded levels as from CalTrans (CalTrans, 2015).

Figure 26. Basis of vibro piling broad band source level as a function of pile size.



Given the low confidence we have in this approach (low R^2 values) we use the 90th percentile level as the broadband source level. L_p is estimated to be 218 dB and SPL 189 dB. The frequency content is assumed to be identical to that of the impact piling.

Table 8. Sources decade band levels.

Band centre frequency [Hz]	Dredging, Mean (broadband : 182) [SPL]	Dredging, 90th percentile (broadband: 192) [SPL]	Drilling, Mean (broadband d: 138) [SPL]	Drilling, 90th percentile (broadband: 156) [SPL]	Vibro, Mean (broadband d: 187) [SPL]	Vibro, 90th percentile (broadband: 196) [SPL]
12.5	162	165	127	142	166	176
16	163	166	126	139	167	176
20	164	167	124	139	167	176
25	165	170	123	138	167	176
31.5	168	177	125	139	168	177
40	169	180	124	140	169	179
50	169	178	124	139	172	181
63	170	178	126	143	174	183
80	169	180	123	142	176	185
100	168	179	124	142	177	186
125	168	178	123	140	178	187
160	168	178	123	142	177	186
200	168	177	125	146	177	186
250	169	178	126	147	177	186
315	169	178	125	147	175	184
400	169	177	123	144	174	183
500	168	178	124	145	173	182
630	167	175	122	143	171	180

800	167	174	124	141	169	178
1000	166	174	125	142	167	176
1250	165	174	123	142	165	175
1600	165	174	121	138	164	173
2000	164	174	120	135	162	171
2500	163	175	119	134	160	169
3150	163	175	118	132	159	168
4000	162	175	118	132	158	167
5000	162	175	119	133	156	165
6300	161	175	118	130	155	164
8000	160	175	117	130	154	163
10000	159	174	117	129	152	161
12500	158	173	110	120	150	159
16000	157	173	109	118	150	159
20000	156	172	109	119	149	158
25000	156	171			148	157
31500	155	171			147	156
40000	154	170			146	155
50000	157	174			145	154
63000	156	173			144	153
80000	156	173			143	152
100000	157	172			142	151
125000	157	166			141	150
160000	157	166			140	149

APPENDIX D – MODEL CALIBRATION

Recorded Transmission losses

Scapa

Broadband transmission losses for exposure levels (L_E) show good consistency between measurements and a transmission loss consistent with $-14.7 \times \text{Log}_{10}(\text{range})$, suggesting a sediment with some ability to reflect sound back into the water column and form a waveguide.

Transmission loss for peak pressure levels (L_P) were near spherical spreading loss which is consistent with a poorly reflecting bottom resulting in little overlap in arrival times for the source impulse.

There was a clear pattern in the transmission losses versus frequency, with higher frequencies experiencing much higher losses, likely due to interaction with a rough sediment resulting in a lot of scattering.

Note that for the bands 50 – 1250 Hz the ambient noise at Scapa was above the source level, while we have tried to compensate for this, those values are still subject to considerable uncertainty (Figure 28).

Figure 27. Broadband transmission losses at Scapa. L_P losses follow a near spherical loss pattern while L_E shows a tendency to follow a waveguide with some absorption losses. Thick lines are best fit of logarithmic loss, while thin lines are for loss accounting for the depth at the source. Error bars are expected 95 % of measurements.

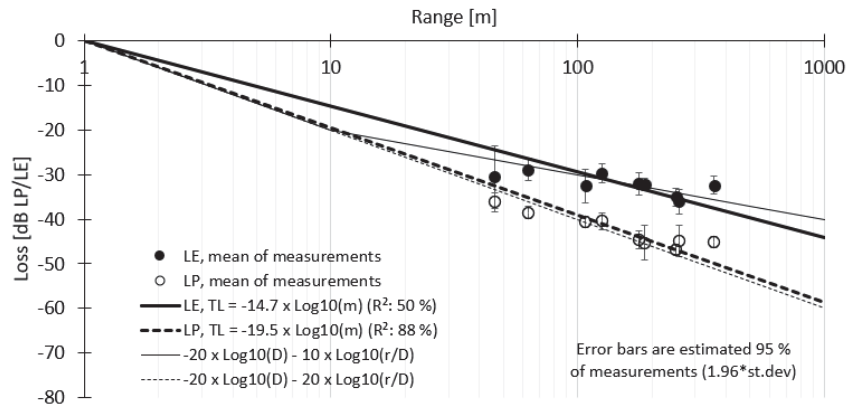
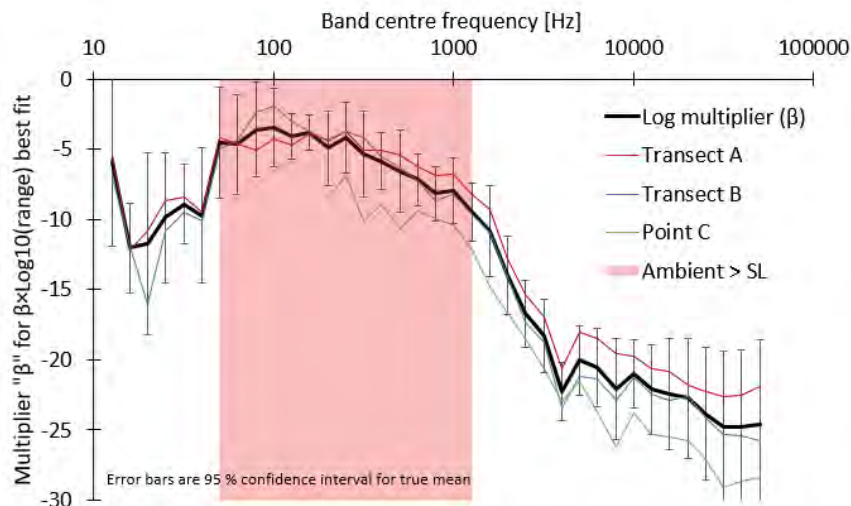


Figure 28. Transmission losses per band shown as the best fit multiplier “ β ” for a simple logarithmic transmission loss. Error bars are 95 % confidence interval for the true mean. While Transects A & B have some difference, this was not significant at a 10 % level in a t-test. Bands 50 – 1250 Hz have been corrected for contributing ambient noise as ambient noise was near or above recorded levels (red band).



APPENDIX E – RESULTS

Maps are presented with impact for different hearing groups as summarised here

Note that some maps have areas marked as “model artefacts”, these are areas where the levels are assumed to not be realistic, but rather an example of a digitisation problem with the bathymetry.

Group	Description	Example species
LF	Low frequency, baleen whales	Mike whale, Fin whale, Blue whale
HF	High frequency, most dolphins	Common dolphin, Risso’s dolphin, beaked whales, Bottlenose dolphin, Sperm whale, Killer whale
VHF	Very high frequency, few dolphins and porpoises	Harbour porpoise, Hourglass dolphin
PW	Phocid water, True seals	Harbour seal, Grey seal
OW	Otariid + other water, Fur seals, walruses and aquatic mammals	Walrus, Otter, Polar bear
P-	Fish with swim bladder, not coupled to inner ear	Salmon, Trout, Cod, Herring
P*	Fish with no swim bladder	Sharks and rays