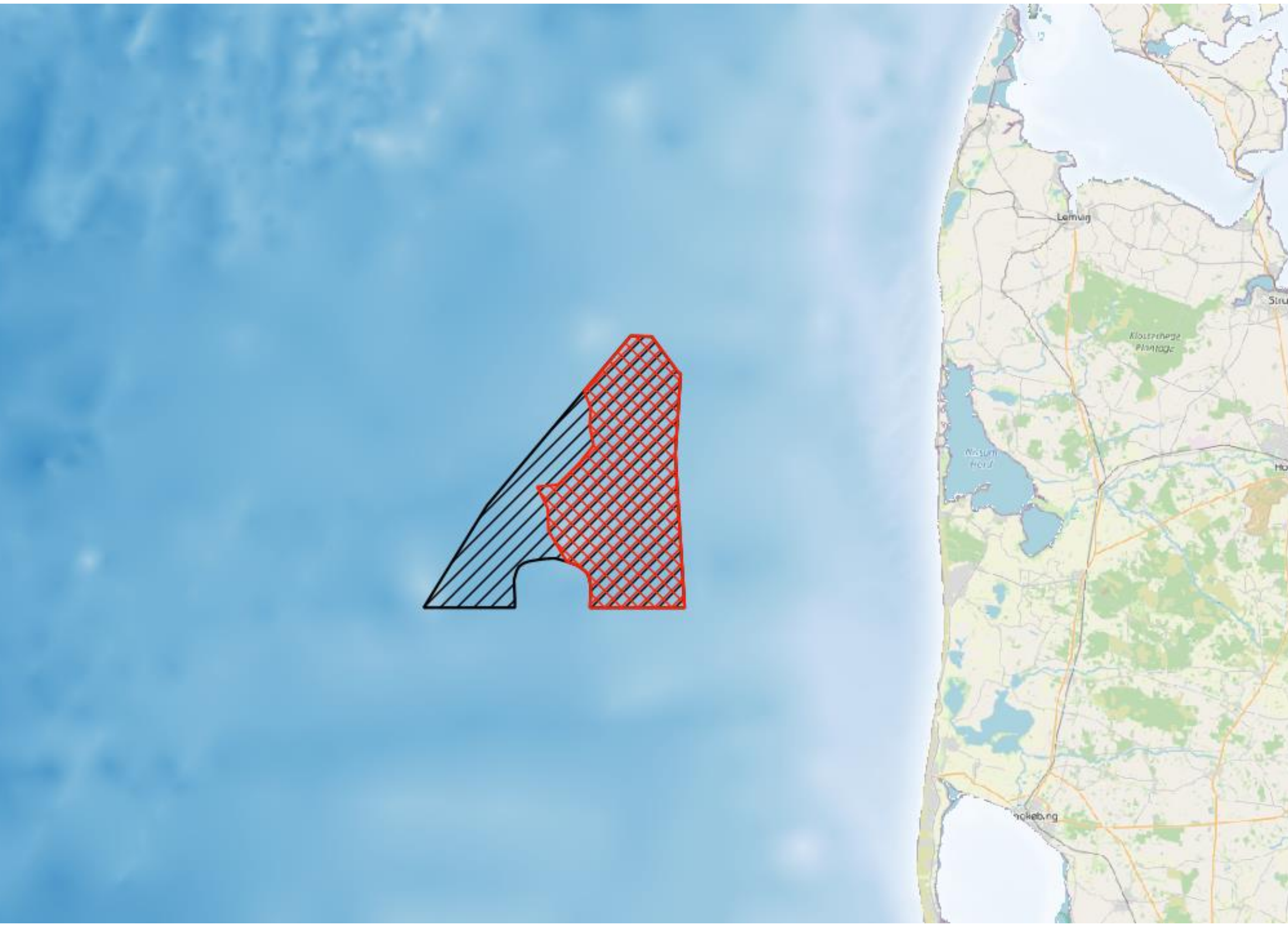

Thor Offshore Wind Farm

Underwater noise prognosis
Technical report

RWE

Date: 13 July 2023

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Contents

Summary

In connection with the environmental impact assessment for Thor Offshore Wind Farm (OWF) in the Danish part of the North Sea, approximately 20 km west of the shoreline, NIRAS has carried out underwater sound prognosis for the construction and operation of the wind farm. This to inform the impact assessment of marine mammals and fish.

Underwater sound emission was calculated for 4 worst case positions for Wind Turbine Generator foundations, 10 m diameter monopiles, as well as in a single position for the sub-station, a jacket foundation with 4x 2.5 m diameter pin piles.

A 3D acoustic model was created in dBSea 2.3.4, utilizing detailed knowledge of bathymetry, seabed sediment composition, water column salinity, temperature and sound speed profile as well as a source model based on best available knowledge. The underwater sound propagation prognosis follows the Danish authority guidelines (Energistyrelsen, 2022) for EIA and SEA underwater noise prognosis, and include an unmitigated calculation of impact and mitigation requirements, as well as appropriately mitigated scenarios.

Distance-To-Threshold (DTT) for relevant frequency weighted species-specific threshold levels were calculated from the sound propagation models. These include safe starting distance for harbour porpoise (*Phocoena phocoena*) and earless seals in order to prevent Permanent Threshold Shift (PTS) and Temporary Threshold Shift (TTS), based on threshold levels in (NOAA, April 2018), and calculation methods in Energistyrelsen (2022). For harbour porpoise, the distance to behaviour impact was also calculated.

DTT for TTS and injury threshold levels for cod (*Gadus morhua*), juvenile and adult, and herring (*Clupea harengus*), as well as injury for larvae and eggs were also calculated. Resulting mitigated impact ranges are shown in Table 1.1 for the fish, and in Table 1.2 for marine mammals.

Threshold distances for PTS and TTS describe the minimum distance from the source a marine mammal or fish must at least be, prior to onset of pile driving, in order to avoid the respective impact. It therefore does not represent a specific measurable sound level, but rather a safe starting position.

The threshold distance for behaviour, on the other hand, describes the specific distance, up to which, the behavioural response is likely to occur, when maximum hammer energy is applied to a pile strike. For pile strikes at lower than 100% hammer energy, this distance is shorter.

Table 1.1: Resulting threshold impact distances for fish, with mitigation applied.

Position	Distance-to-threshold (km)								
	Injury (r_{injury})					TTS (r_{TTS})			
	Stationary	Juvenile Cod	Adult Cod	Herring	Larvae and eggs	Stationary	Juvenile Cod	Adult Cod	Herring
1	1500 m	120 m	< 100 m	< 100 m	900 m	17.6 km	15.4 km	12.7 km	12.0 km
2	1300 m	< 100 m	< 100 m	< 100 m	800 m	15.9 km	13.7 km	11.2 km	10.4 km
3	1550 m	110 m	< 100 m	< 100 m	925 m	18.4 km	16.2 km	13.5 km	12.8 km
4	1250 m	< 100 m	< 100 m	< 100 m	750 m	13.4 km	11.4 km	8.8 km	8.1 km
S	525 m	< 100 m	< 100 m	< 100 m	375 m	5.8 km	1.4 km	<200 m	<200 m

Table 1.2: Resulting threshold impact distances for marine mammals with mitigation applied.

Position	Distance-to-threshold				
	PTS (r_{PTS})		TTS (r_{TTS})		Avoidance (r_{behav})
	Porpoise (VHF)	Seal (PCW)	Porpoise (VHF)	Seal (PCW)	Porpoise (VHF)
1	< 100 m	< 50 m	575 m	275 m	6.3 km
2	< 100 m	< 50 m	550 m	100 m	6.4 km
3	< 100 m	< 50 m	550 m	275 m	6.4 km
4	< 100 m	< 50 m	600 m	< 100 m	6.2 km
S	< 100 m	< 50 m	225 m	< 100 m	4.3 km

Underwater noise during operation was evaluated, based on available literature. A review by Tougaard et al. (2020) was examined, and the proposed trend for underwater noise emission as a function of wind turbine size was used to evaluate impact on marine mammals. Due to limitations in the available empirical data used, caution is however warranted. In a realistic worst case evaluation, the behaviour impact range, as well as PTS and TTS effects are all expected to be below 100 m from any individual turbine within the operational offshore wind farm.

Terminology

Full name	Abbreviation	Symbol
Sound Exposure Level	SEL	$L_{E,p}$
Cumulative Sound Exposure Level over 24 hours of a (moving) receptor	$SEL_{cum,24h}$	$L_{E,p,cum,24h}$
Sound Exposure Level - single impulse	SEL_{SS}	L_{E100}
Sound Pressure Level	SPL	$L_{p,rms}$
Source Level at 1 m	SL	L_S
Sound exposure source level at 1 m	ESL	$L_{S,E}$
Permanent Threshold Shift	PTS	
Temporary Threshold Shift	TTS	
National Oceanographic and Atmospheric Administration	NOAA	
Offshore Wind Farm	OWF	
Noise Abatement System	NAS	
Low-frequency	LF	
High-frequency	HF	
Very High-frequency	VHF	
Phocid Pinniped	PCW	
Big Bubble Curtain	BBC	
Double Big Bubble Curtain	DBBC	
Hydro Sound Damper	HSD	
IHC Noise Mitigation Screen	IHC-NMS	
World Ocean Atlas 2018	WOA18	
Normal modes	NM	
Parabolic Equation	PE	
Distance-To-Threshold	DTT	
Propagation loss	PL	N_{PL}
Sound Exposure Propagation loss	EPL	$N_{PL,E}$
Acoustic Deterrent Device	ADD	
National Marine Fisheries Service	NMFS	

1. Introduction

This report provides a prognosis for underwater noise for the Thor OWF in the Danish North Sea, see Figure 1.1. Underwater noise during construction is evaluated through site specific sound propagation modelling of the foundation installation scenarios for a worst case scenario. Underwater noise during operation is evaluated based on available literature.

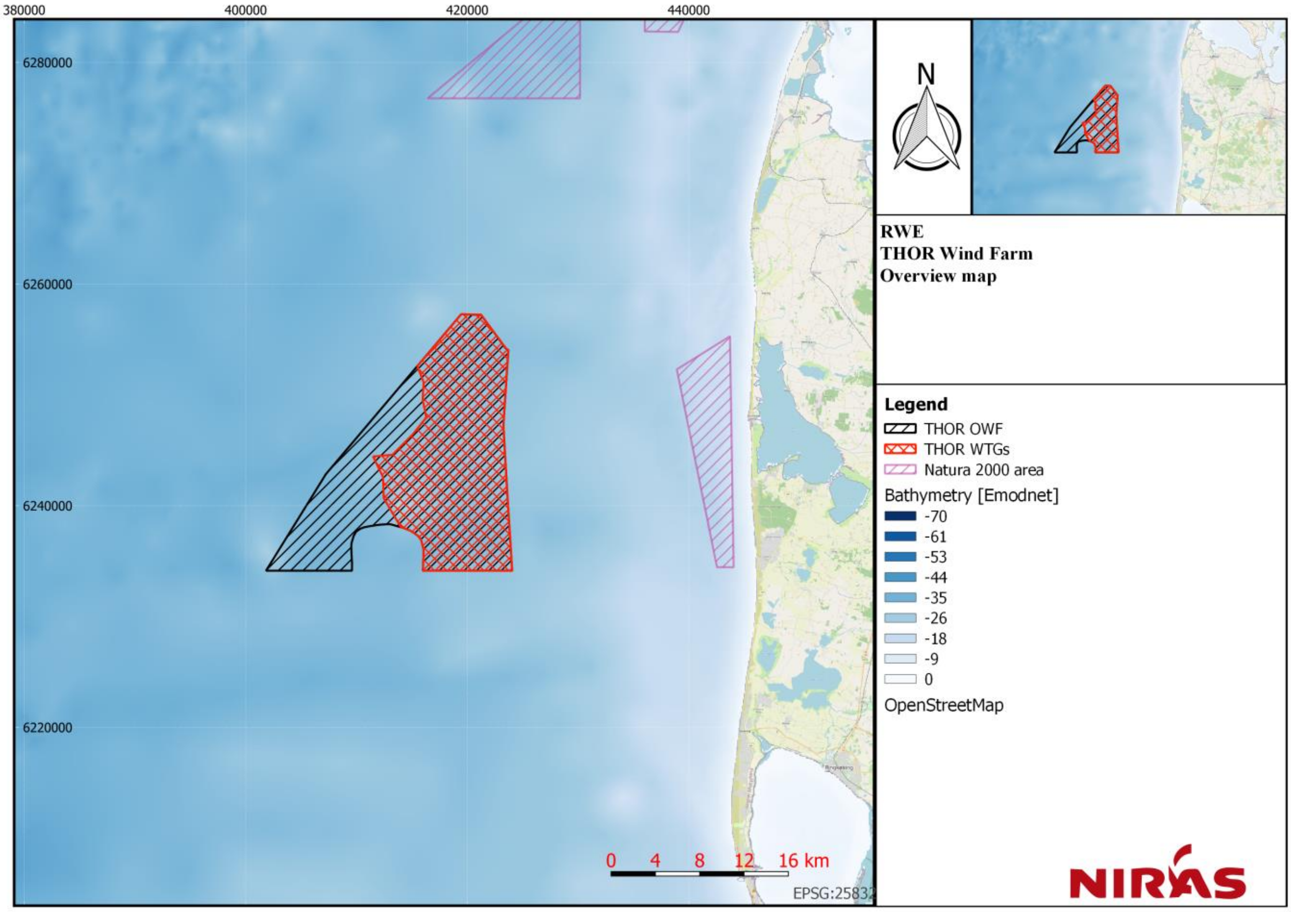

Figure 1.1: Project area for Thor Offshore Wind Farm (OWF).

Foundation types included in the prognosis are limited to 10 m monopile foundations for the wind turbines, and a jacket foundation with 4x 2.5 m pin piles for the substation. The different foundation types are evaluated further in section 4.1.1.

The underwater noise prognosis is carried out in line with current Danish guidelines for pile driving in EIA and SEA (Energistyrelsen, 2022), and are used to calculate impact ranges for injury, permanent and temporary threshold shift (PTS and TTS respectively) and behavioural response in marine mammals. Injury and TTS in fish are beyond the guidelines, however are also included in the prognosis.

2. Purpose

The purpose of this prognosis is to determine underwater noise impact on relevant marine mammals and fish species, resulting from the construction and operation of Thor OWF. For the construction phase, the purpose is to determine worst case impact ranges for marine mammals and fish, and to comply with prognosis requirements set forth by the Danish Energy Agency (Energistyrelsen).

3. Underwater sound definitions

This chapter provides general background knowledge for underwater noise, with definitions of used sound metrics, guideline requirements as well as threshold levels for quantifying the impact of noise.

3.1. Sound level metrics

In the following, the reader is introduced to the acoustic metrics used throughout the report for quantifying the sound levels. The terminology used throughout this report is in line with (DS/ISO 18405, 2017) and (DS/ISO 18406, 2017).

3.1.1. Sound pressure level

The Sound Pressure Level (SPL), $\mathrm{L_p}$, is used to describe the noise level. The definition for SPL is shown in Equation 1 (Erbe, 2011).

Equation 1

$$L_p = 20 * log_{10}\left(\sqrt{\left(\frac{1}{T}\right)\int_T p(t)^2}\right) \quad [dB\ re.1\mu Pa]$$

Where p is the acoustic pressure of the noise signal during the time of interest, and T is the total time. $\mathrm{L_p}$ is the average unweighted SPL over a measured period of time.

For ambient underwater noise and for operational underwater noise, $\mathrm{L_p}$ is the preferred metric.

In order to evaluate the behavioural response of the marine mammal a time window is needed. Often, a fixed time window of 125 ms. is used due to the integration time of the ear of mammals (Tougaard & Beedholm, 2018). The metric is then referred to as $\mathrm{L_{p,125ms}}$ and the definition is shown in Equation 2 (Tougaard, 2021).

Equation 2

$$L_{p,125ms} = L_{E,p} - 10 * log_{10}(0.125) = L_{E,p} + 9\ dB \quad [dB\ re.1\mu Pa]$$

Where $\mathrm{L_{E,p}}$is the sound exposure level, which are explained in the next section.

3.1.2. Sound exposure level

The Sound Exposure Level (SEL), $\mathrm{L_{E,p}}$, describes the total energy of a noise event (Jacobsen & Juhl, 2013). A noise event can for instance be the installation of a monopile by impact pile driving, from the start to the end, or it can be a single noise event like an explosion. The SEL is normalized to 1 second and is defined in (Martin, et al., 2019) through Equation 3.

Equation 3

$$L_{E,p} = 10\,log_{10}\left(\frac{1}{T_0 p_0^2}\int_0^T p^2(t)\right) \quad [dB\ re.1\mu Pa^2 s]$$

Where $\mathrm{T_0}$ is 1 second, 0 is the starting time and T is end time of the noise event, p is the pressure, and $\mathrm{p_0}$ is the reference sound pressure which is $1\ \mathrm{\mu Pa}$.

The relationship between SPL and SEL is given in Equation 4 (Erbe, 2011).

Equation 4 $$L_{E,p} = L_p + 10 * log_{10}(T)$$

When SEL is used to describe the sum of noise from more than a single event/pulse, the term Cumulative SEL, ($\mathrm{SEL_{cum,t}}$), $\mathrm{L_{E,cum,t}}$, is used while the SEL for a single event/pulse, is the single-strike SEL ($\mathrm{SEL_{SS}}$), $\mathrm{L_{E100}}$. The $\mathrm{SEL_{SS}}$ is calculated on the base of 100% pulse energy over the pulse duration.

Marine mammals can incur hearing loss, either temporarily or permanently as a result of exposure to high noise levels. The level of injury depends on both the intensity and duration of noise exposure, and the SEL is therefore a commonly used term to assess the risk of hearing impairment as a result of noise emitting activities (Martin, et al., 2019).

3.1.3. Source level

Two representations for the acoustic output of pile driving are used in this report, namely Source Level (SL), $\mathrm{L_S}$, and the sound exposure source level (ESL), $\mathrm{L_{S,E}}$.

Here, SL is defined for a continuous source as the mean-square sound pressure level at a distance of 1 m from the source with a reference value of $1\ \mu\mathrm{Pa} \cdot \mathrm{m}$.

ESL is used to describe a transient sound source and is defined as the time-integrated squared sound pressure level at a distance of 1 m from the source with a reference value of $1\ \mu\mathrm{Pa^2\ m^2\ s}$.

3.1.4. Cumulative sound exposure level

In the assessment of Temporary Threshold Shift (TTS), Permanent Threshold Shift (PTS) and injury caused by underwater noise on marine mammals and fish, cumulative SEL ($\mathrm{L_{E,cum,t}}$) is used to describe the total noise dose received by the receptors as a result of an underwater noise emitting activity.

For a stationary source, such as installation of a foundation, the installation procedure, as well as the swim speed for the receptor, must be included. The method for implementing such conditions in the calculation of cumulative SEL has been proposed by (Energistyrelsen, 2022), and is further described in section 3.2.1.

3.2. Underwater noise prognosis requirements

The prognosis must comply with guideline requirements in (Energistyrelsen, 2022), with the purpose of providing the basis for an assessment of the underwater noise impact on marine mammals. The prognosis must apply best-available knowledge for project specific installation parameters and local environmental conditions.

As per the guidelines (Energistyrelsen, 2022), the prognosis must include:

A. A detailed source model,
B. A site specific underwater sound propagation loss model, based on best-available knowledge and data,
C. Calculation of compliance with species specific impact threshold criteria for relevant auditory groups.

This prognosis will follow the guidelines, and in section 3.2.1, the technical procedure is explained briefly, and the reader is referred to the guideline document (Energistyrelsen, 2022) for further details.

In addition to the Danish guidelines, which solely concerns the impact on marine mammals, the prognosis also includes acoustic threshold impact ranges for relevant fish species, see section 3.3.1.

3.2.1. Danish guideline methodology

The Danish guidelines specify the level of details to be used for underwater noise prognosis of pile driving activities. This includes the number of model positions, source level details, propagation result representation and which impact threshold levels to comply with.

The first step in the methodology, is to document the unmitigated underwater noise emission as a result of the pile driving. From this calculation, the resulting impact ranges for Permanent Threshold Shift (PTS) must be evaluated against a maximum allowed impact range of 200 m on marine mammals.

The evaluation against PTS threshold values, is done through the use of Equation 5 (Energistyrelsen, 2022), where the cumulative noise exposure level over a 24 hour duration, $L_{E,cum,24h}$ is calculated. If multiple foundations are installed in the same 24-hour window, all must be included in the calculation.

Equation 5

$$L_{E,cum,24h} = 10 * log_{10}\left(\sum_{i=1}^{N} \frac{S_i}{100\%} * 10^{\left(\frac{L_{S,E} - X*log_{10}(r_0+v_f*t_i) - A*(r_0+v_f*t_i)}{10}\right)}\right)$$

Where:

- S_i is the percentage of full hammer energy of the i^{th} strike
- N is the total number of strikes for the pile installation
- $L_{S,E}$ is the sound exposure source level at 1 m distance at 100% hammer energy.
- X and A describe the sound exposure propagation losses (EPL) for the specific project site
- r_0 is the marine mammal distance to source at the onset of piling
- v_f is the swim speed of the marine mammal directly away from the source
- t_i is the time difference between onset of piling, and the i^{th} strike.

The parameters related to the source level, hammer energy, number of strikes and time interval between each strike must be based on realistic worst-case assumptions and can be achieved through a site-specific drivability analysis or a worst case assessment. The relationship between hammer energy level and pile strike number is referred to as the installation procedure for the remainder of the report.

The sound propagation parameters (X and A) must be determined through a sound propagation model, in which all relevant site-specific environmental parameters are considered.

For the unmitigated sound emission scenario, the starting distance "r_0" in Equation 5 is set to 200 m, and $L_{E,cum,24h}$ is then calculated. If the resulting $L_{E,cum,24h}$ value exceeds the PTS threshold levels listed in Table 3.2, Section 3.3.2, for any marine mammal species, the level of exceedance corresponds to a frequency weighted minimum mitigation requirement for that pile installation. If the threshold value is exceeded for multiple marine mammal species, the mitigation solution must ensure compliance for all of them.

A revised underwater noise emission calculation with the mitigation active must then be carried out, and impact ranges documented. Relevant impact ranges in this regard are described in section 3.3.2. For the mitigation solution, the implementation can be either theoretical, in the sense that it applies the exact combined mitigation required for compliance, or it can be an empirically achieved mitigation effect from previous pile installations. The latter is explored further in section 4.5.

3.3. Underwater noise impact criteria

The applied threshold values are briefly described in section 3.3.1 for fish, and in section 3.3.2 for marine mammals, and the reader is referred to the respective impact assessments for further details on the threshold values.

3.3.1. Applied threshold criteria for fish

Assessment of the noise impact on fish, larvae and eggs are all based on frequency unweighted threshold levels using the metric $L_{E,cum,24h}$, and are presented in Table 3.1. The thresholds and the swim speed included in the calculations of the respective thresholds are adopted from (Andersson, et al., 2016) and (Popper, et al., 2014). Modelling also includes calculations assuming stationary, non-fleeing fish.

Table 3.1: Unweighted threshold criteria for fish (Andersson, et al., 2016), (Popper, et al., 2014).

Species	Swim speed [m/s]	Species specific unweighted thresholds (Impulsive)	
		$L_{E,cum,24h,unweighted}$	
		TTS [dB]	Injury [dB]
Stationary (non-fleeing)	0.00	186	204
Juvenile cod	0.38	186	204
Adult cod	0.90	186	204
Herring	1.04	186	204
Larvae and eggs	-	-	207

3.3.2. Applied threshold criteria for marine mammals

Pile driving noise exposure can result in a change in hearing sensitivity either permanent or temporary, termed threshold shift. If hearing returns to normal after a recovery time, the effect is a temporary threshold shift (TTS); otherwise, it is a permanent threshold shift (PTS). TTS is considered auditory fatigue, whereas PTS is considered injury (Southall, et al., 2007). Sound intensity, frequency, and duration of exposure are important factors for the degree and magnitude of hearing loss, as well as the length of the recovery time (Popov, et al., 2011). Recovery from small amounts of TTS is fast (minutes to hours) and complete, whereas large prolonged exposures to noise, where the ear is re-exposed to TTS inducing sound pressure levels before it has had time to recover from previous TTS, may result in a building TTS, that can result in permanent threshold shift (PTS) (Ketten, 2012).

As required in the Danish guidelines (Energistyrelsen, 2022), frequency weighted $L_{E,cum,24h}$ is used to assess TTS and PTS impact ranges. This procedure is primarily based on a large study from the American National Oceanographic and Atmospheric Administration (NOAA), (NOAA, 2018), where species specific frequency weighting is proposed and accounts for the hearing sensitivity of each species when estimating the impact of a given noise source.

In NOAA (2018) the marine mammal species, are divided into four hearing groups, revised in wording in (Southall, et al., 2019), in regard to their frequency specific hearing sensitivities: 1) Low-frequency (LF) cetaceans, 2) High-frequency (HF) cetaceans, 3) Very High-frequency (VHF) cetaceans, 4) and Phocid pinnipeds (PCW) in water. For this project, VHF and PCW hearing groups are relevant. More details about the hearing groups, and their frequency sensitivities, are provided in section 3.3.4. The hearing group weighted threshold criteria, can be seen in Table 3.2.

A literature review of behavioural avoidance and onset threshold levels in Tougaard (2021), included both studies in captivity where pile driving noise was played back at greatly reduced levels, and field studies of reactions of wild porpoises to full-scale pile driving. From the review, the conclusion in Tougaard (2021) is that the behavioural avoidance threshold is in the range between $L_{p,125ms} = 95 - 110$ dB re. 1 μPa, and a suitable single value of $L_{p,125ms} = 103$ dB re. 1 μPa VHF-weighted is proposed. The single value is obtained from Band et al. (2016) which includes the largest amount of empirical data. In the present report, a behavioural threshold for harbour porpoises of $L_{p,125ms} = 103$ dB re. 1 μPa VHF-weighted is therefore used, see Table 3.2.

Table 3.2: Species specific weighted threshold criteria for marine mammals. This is a revised version of Table AE-1 in (NOAA, 2018) to highlight the important species in the project area (NOAA, 2018) including behaviour response.

Hearing group	Weighting (w)	Species specific weighted thresholds (non-impulsive)		Species specific weighted thresholds (Impulsive)		
		$L_{E,cum,24h,w}$ $[dB]$		$L_{E,cum,24h,w}$ $[dB]$		$L_{p,125ms,w}$ $[dB]$
		TTS	PTS	TTS	PTS	Behaviour
Very high frequency cetacean	VHF	153	173	140	155	103
Phocid pinniped in water	PCW	181	201	170	185	-

There is a general lack of quantitative information about behavioural reaction distances for both harbour seals and grey seals (PCW) and behaviour threshold values are therefore not proposed for this group.

Thresholds listed as "non-impulsive", apply for continuous noise (e.g., ship noise) and whilst impulsive noise is expected to transition towards continuous noise over distance from the source, this transition is not expected to occur within the distances at which PTS and/or TTS can potentially occur as a result of these activities. For impulsive sources such as pile driving, stricter threshold levels apply as listed in Table 3.2. Threshold levels for continuous noise are more lenient, than those for impulsive noise, and use of the impulsive noise criteria, therefore provides conservative distance-to-threshold. The non-impulsive thresholds will not be considered further in this report.

3.3.3. Distance to threshold

The impact criteria, as presented in section 3.3.1 and section 3.3.2, rely on determining the Distance-To-Threshold (DTT), $r_{<threshold>}$, which are the distances at which the various thresholds are likely to occur.

As such, DTT for PTS (DTT_{PTS}) is symbolized as r_{PTS} and TTS (DTT_{TTS}) is symbolized as r_{TTS}, both describing the minimum distance from the source, a marine mammal must be deterred to, prior to onset of the pile driving in order to avoid the respective impact. It does not represent a specific measurable sound level, but rather a safe starting distance.

The DTT for behaviour, r_{behav}, on the other hand, describes the specific distance, up to which a behavioural response is likely to occur.

It should be noted, that for impact pile driving, a significant portion of the installation time will not be carried out applying maximum hammer energy, however a steadily increasing amount of energy from soft start (10-15% of hammer energy) through ramp up (15%-99%) to full power (100%). Depending on the soil conditions, the hammer energy requirements through the ramp up and full power phases will vary from site to site, and even between individual pile locations within a project site.

3.3.4. Frequency weighting functions

As described in previous sections, the impact assessment for underwater noise includes frequency weighted threshold levels for marine mammals. In this section, a brief technical explanation of the frequency weighting method is given.

Humans are most sensitive to frequencies in the range of 2 kHz - 5 kHz and for frequencies outside this range, the sensitivity decreases. This frequency-dependent sensitivity correlates to a weighting function which, for the human auditory system, is called A-weighting. For marine mammals the same principle applies through the weighting function, $\mathbf{W(f)}$, defined through Equation 6.

Equation 6

$$W(f) = C + 10 * log_{10}\left(\frac{\left(\frac{f}{f_1}\right)^{2*a}}{\left[1+\left(\frac{f}{f_1}\right)^2\right]^a * \left[1+\left(\frac{f}{f_2}\right)^2\right]^b}\right)\ [dB]$$

Where:

- **a** is describing how much the weighting function amplitude is decreasing for the lower frequencies.
- **b** is describing how much the weighting function amplitude is decreasing for the higher frequencies.
- $\mathbf{f_1}$ is the frequency at which the weighting function amplitude begins to decrease at the lower frequencies [kHz]
- $\mathbf{f_2}$ is the frequency at which the weighting function amplitude begins to decrease at the higher frequencies [kHz]
- **C** is the function gain [dB].

For an illustration of the parameters see Figure 3.1.

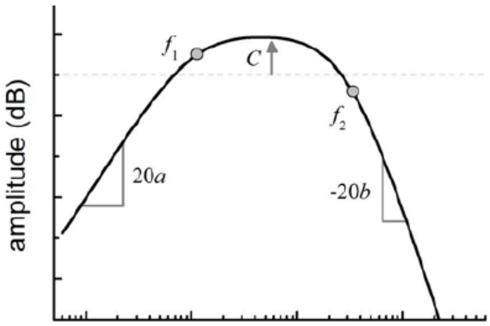

Figure 3.1: Illustration of the 5 parameters in the weighting function (NOAA, 2018).

The parameters in Equation 6 are defined for all hearing groups, see Table 3.3, where the relevant species for the project area are in black, and the species which are not relevant in light grey.

Table 3.3: Parameters for the weighting function for all hearing groups, with relevant hearing groups (black) and other hearing groups (grey) (NOAA, 2018).

Hearing Group	a	b	$\mathbf{f_1}$ [kHz]	$\mathbf{f_2}$ [kHz]	C [dB]
Low frequency (LF) Cetaceans	1.0	2	0.2	19	0.13
High frequency (HF) Cetaceans	1.6	2	8.8	110	1.20
Very high frequency (VHF) Cetaceans	1.8	2	12	140	1.36
Phocid Pinniped (PCW) (Underwater)	1.0	2	1.9	30	0.75

By inserting the values from Table 3.3 into Equation 6, the following spectra are obtained for the relevant hearing groups, see Figure 3.2.

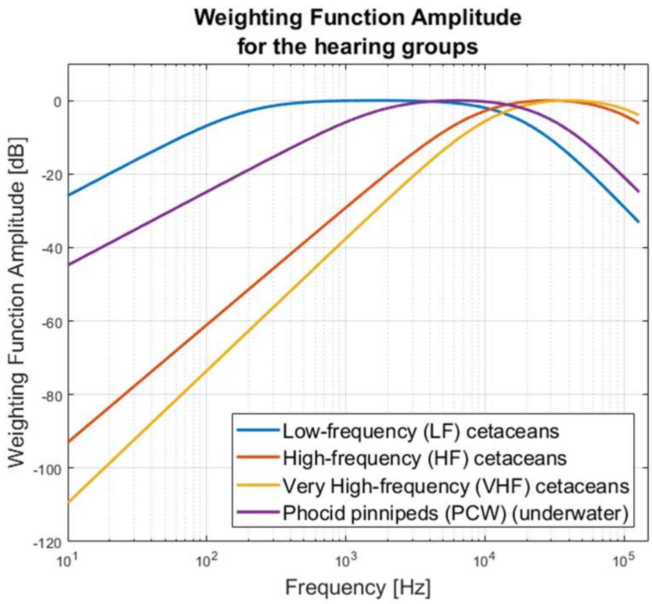

Figure 3.2: The weighting functions for the different hearing groups.

3.3.5. Masking

Masking occurs when a sound or noise signal eliminates or reduces an animal's ability to detect or identify other sounds such as communication signals, echolocation, predator and prey signals, and environmental signals. Masking depends on the spectral and temporal characteristics of signal and noise (Erbe, et al., 2019). Sound processing in the mammalian ear happens in a series of band-pass filters (Patterson, 1974) best described as one-third-octave band filters for marine mammals (Lemonds, et al., 2011). Masking of signals can therefore occur, if there is an overlap in frequency between the signal in question and the underwater noise (1/3 octave noise level).

Compensation mechanisms to overcome masking of communication signals have been described in several marine mammal species either increasing the amplitude of their signal or shifting the frequency of the signal (Holt, et al., 2009; Parks, et al., 2011). Masking can also be overcome by increasing the call duration or call rate increase the chance that a signal is detected or by waiting for the noise to cease (Brumm & Slabbekoorn, 2005).

Porpoises rely heavily on acoustic signals (echolocation) for all aspects of foraging, navigation, sexual displays and in communication between the mother and the calf (Clausen, et al., 2010). However, the emitted signals are in the ultrasonic frequency range between 129-145 kHz (Villadsgaard, et al., 2007), well above the frequency of the main energy in a pile driving signal and it is therefore unlikely that pile driving noise would mask communication or echolocation in porpoises.

Underwater signals are particularly important in courtship and mating behaviour in seals (Van Parijs, 2003). The communication signals of seals are in the low-frequency range and masking from the pile driving noise may occur. However, harbour seals and grey seals likely mainly vocalize in the context of mating and that takes place close to the haul-out sites. Thus, pile driving close to a seal haul-out can mask the communication signals whereas pile driving occurring far offshore, appears unlikely to have any significant potential to interfere with communication during mating displays (Tougaard & Mikaelsen, 2018).

Passive listening by both seals and porpoises could potentially be masked by pile driving noise. However, pile driving is an impulsive noise source and the duty cycle of a pile driving signal is relatively low, which leaves large gaps in between pulses, where signals can be detected. It is thus difficult to imagine a complete masking of passive listening by pile driving noise.

4. Underwater noise during construction phase

During the construction phase, the most significant underwater noise pressure on marine mammals, is noise from pile driving as it can potentially cause avoidance responses, TTS and PTS, and in the worst-case acoustic trauma to non-auditory tissue (Madsen, et al., 2006). Other noise sources during construction, such as noise from installation and support vessels, are not treated further in this report. The underwater sound propagation modelling requires three different parts.

Part 1 is a source model, which describes how the included underwater sound sources are defined with regards to source level and frequency content. This is described further in section 4.1.

Part 2 is a sound propagation model, defining how underwater noise emission is propagated within an environment. This is described in section 4.2.

Part 3 is the environmental model, which describes the physical properties of the environment in which the sound propagation model operates. This is described in section 4.3.

4.1. Source model

The source model must consider the type of noise source and the methodology used to represent it. First, the different source types are described, and their properties are defined with regards to source level and frequency content. Then, source positions chosen for the sound propagation model are described.

4.1.1. Foundation types

Monopile foundations with diameter up to 10 m will be used for the wind turbines. It is possible that smaller diameter monopile foundations will be sufficient, however to provide a conservative prognosis, the worst case scenario with 10 m diameter monopiles is used. The installation method for the monopiles will be impact piling with up to 6000 kJ hammer.

In addition to the wind turbine foundations, a sub-station within the site is planned to be installed on a jacket foundation with 4x 2.5 m pin piles.

Due to differences in the frequency spectrum and number of piles for monopile and jacket foundation types, both are included in sound propagation modelling. Source models for the two scenarios are described further in section 4.1.4.

The sound propagation modelling, carried out in this report assumes a single pile installation within any 24-hour period for the monopile foundation type, and up to 4 pin piles per 24 hours for jacket foundations.

The technical source model parameters are provided in Table 4.1 for the monopile foundation scenario, and in Table 4.2 for the jacket foundations scenario.

The pile installation procedure for both foundation types includes a soft start, at 10% of maximum hammer energy, a ramp up phase, where the energy is gradually increased from 10% - 100%, and a conservative estimate for the full power phase of the installation with 100% hammer energy.

Table 4.1: Technical specifications and pile driving procedure for scenario 1: 10 m monopile foundation

Technical specification for scenario 1			
Foundation type			Monopile
Impact hammer energy			6000 kJ
Pile Diameter			10 m
Total number of strikes pr. pile			6 800
Number of piles per foundation			1
Pile driving procedure			
Name	Number of strikes	% of maximum hammer energy	Time interval between strikes [s]
Soft start	500	10	2
Ramp-up	500 500 500 500	20 40 60 80	2 2 1 1
Full power	4 300	100	1

Table 4.2: Technical specifications and pile driving procedure for scenario 2: Jacket foundation with 4x 2.5m pin piles.

Technical specification for scenario 2			
Foundation type			Jacket
Impact hammer energy			3000 kJ
Pile Diameter			2.5 m
Total number of strikes pr. pile			6 800
Number of piles per foundation			4
Pile driving procedure			
Name	Number of strikes	% of maximum hammer energy	Time interval between strikes [s]
Soft start	500	10	2
Ramp-up	500 500 500 500	20 40 60 80	2 2 1 1
Full power	4 300	100	1

4.1.2. Source level methodology

The best available knowledge on the relationship between pile size and sound level, comes from a report on measured sound levels from pile driving activities in Bellmann et al. (2020), which provides a summary of measured sound levels at 750 m distance as a function of pile size. This is shown in Figure 4.1. The measurements are all normalized to 750 m distance from the pile.

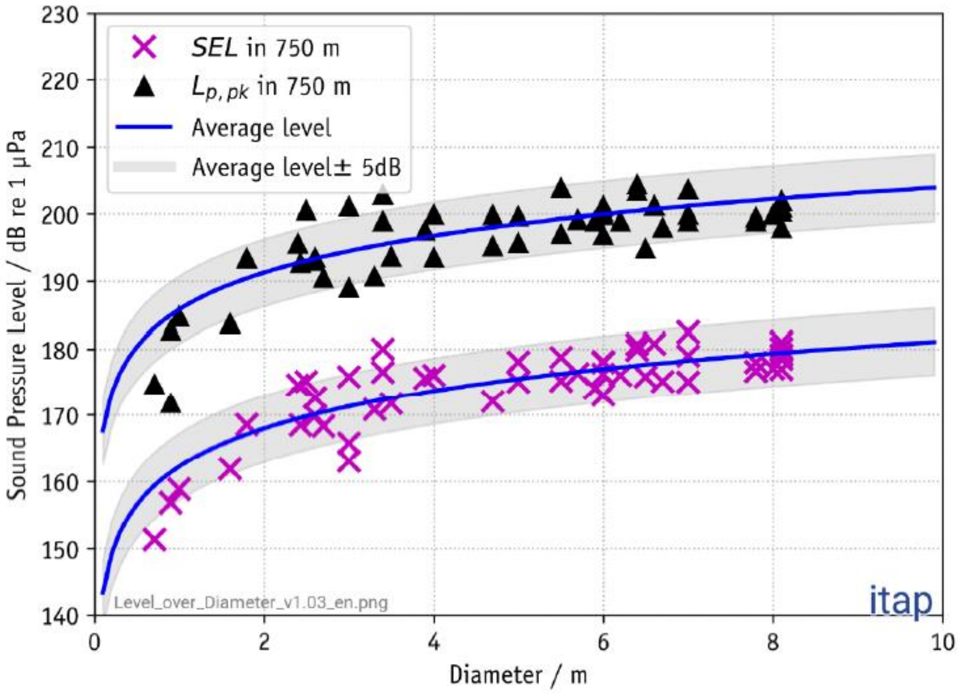

Figure 4.1: Relationship between measured SPL and SEL levels, measured at 750 m distance, and pile size (Bellmann, et al., 2020).

Examining Figure 4.1, the blue curve indicates the best fit of the measurement results. For the SEL results, this relationship between pile size and measured level is approximately $\Delta\mathrm{SEL} = 20 * \log 10\left(\frac{\mathrm{D2}}{\mathrm{D1}}\right)$ where D1 and D2 are the diameter of 2 piles, and ΔSEL is the dB difference in sound level between the two. This relationship indicates that when doubling the diameter, SEL increases by 6 dB.

In order to use this data in an underwater sound propagation model, the source level at 1 m distance must be known. A common method to achieve this is through back-calculating empirical data from measurements to 1 m, whereby an equivalent source level represented as a point source is obtained. This is done, using a combination of Thiele's equation for sound propagation (Thiele, 2002), as well as NIRAS' own calibration model based on several measurements at real sites. It should be noted that this approach will result in the measured sound levels at 750 m and provide accurate prognosis at further distances. It is however less accurate at distances closer to the source than 750 m as the near field is prone to significant positive and destructive interference patterns.

From Figure 4.1 it should be noted that variations in measured sound levels for a specific pile size do occur, as indicated by the spread of datapoints, around the fitted (blue) lines. This spread gives a 95%-confidence interval of ±5 dB which is indicated by the grey shaded areas. This is considered to be a result of varying site conditions and hammer efficiency applied for the individual pile installations and projects. For any project, it should therefore be considered whether the site and project specific conditions call for a more cautious source level estimate, than that of the average fitted line. In the following section, the different parameters which give rise to uncertainties regarding the source level, are examined.

4.1.2.1. Uncertainties in determining source level

In the following, several parameters influencing the actual source level for any specific installation are examined briefly.

Soil resistance

The foundation is installed by driving the piles into the seabed, which requires the predominant soil resistance has to be overcome. In general, the larger the soil resistance, the higher the blow energy required, which in turn increases the noise output (Bellmann, et al., 2020). For this reason, the harder, more compacted, and typically deeper, sediment layers require more force to be applied, thus increasing hammer energy and noise output as the piling progresses.

Water depth

The water depth can also influence the noise emission. As the water depth decreases, the cut-off frequency increases, which can be seen in Figure 4.2. Frequency content of the noise source, below the cut-off frequency, has difficulty propagating through the water column in shallow water, and will be attenuated at an increased rate, compared to frequency content above the cut-off (Bellmann, et al., 2020).

The cut-off frequency is dependent on, not only the water depth, but also the upper sediment type of the seabed.

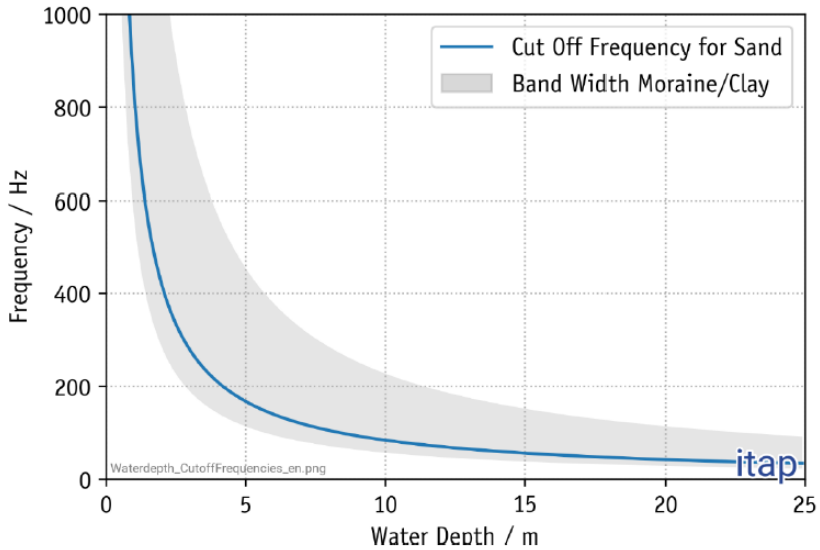

Figure 4.2: Cut off frequency and its dependency on sediment type and water depth (Bellmann, et al., 2020).

Hammer energy

An increase in hammer energy applied to a pile, will transfer more energy into the pile and therefore also results in a higher noise emission. In Figure 4.3, which shows the SEL versus penetration depth and blow energy, it can be observed how increasing the blow energy, also increases the measured SEL.

This relationship is approximated by 2-3 dB increase in measured SEL every time the blow energy is doubled (Bellmann, et al., 2020).

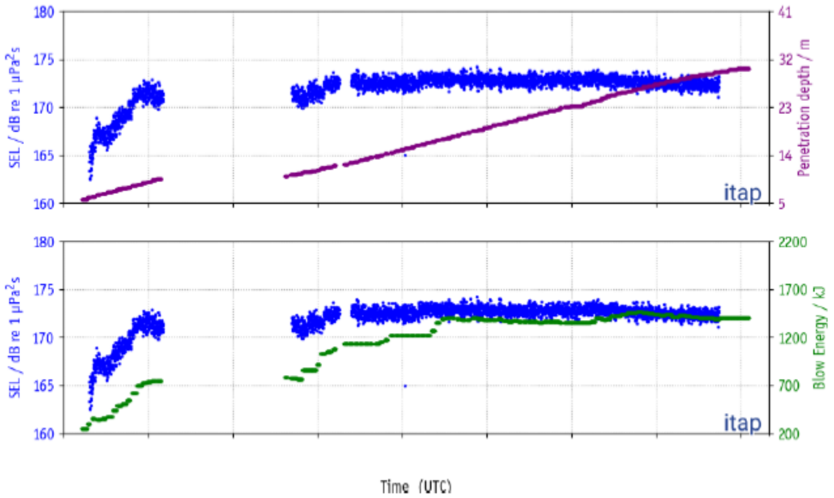

Figure 4.3: Relationship between SEL versus penetration depths and blow energy (Bellmann, et al., 2020).

Impact hammer type

Modern impact pile drivers typically consist of a large mass, or weight, suspended inside a hydraulic chamber, where the pressurized hydraulic fluid is used to push up the weight to the desired height, after which it is dropped. The impact is then transferred through an inner construction of shock absorbers and an anvil connected to the pile top. This motion transfers a large part of the applied energy to drive the pile downwards (Adegbulugbe, et al., 2019).

Using a large impact hammer with a heavy falling mass at 50-60% of its full capacity will, for acoustic reasons, lead to lower noise output compared to that from a smaller impact hammer using 100% capacity to achieve the same blow energy. While the two hammers will deliver the same energy to the pile, the maximum amplitude will be lower for the large impact hammer due to extended contact duration between hammer and pile-head. Different impact hammers can give up to several decibels difference (Bellmann, et al., 2020).

Pile length and degree of water immersion

A pile installation can be carried out through either above sea level piling, where the pile head is located above water level, or through below sea level piling, where the pile head is located below the water line. The former is typically the case for monopiles, while the latter is often the case for jacket piles (Bellmann, et al., 2020). A combination of the two is also possible, where the pile head is above water at the beginning of the pile installation and is fully submerged in the late stages of the piling.

Above water level piling automatically means that part of the pile is in contact with the entire water depth, and thus has a large radiating area. For below water level piling, this is not the case, as parts of the water column might no longer be occupied by the pile, but rather the hammer. For this reason, a higher noise emission is to be expected if the pile head is above water level (Bellmann, et al., 2020).

4.1.3. Source frequency spectrum methodology

Due to the natural variations of measured frequency content, Figure 4.4 (grey lines), between sites, piles, water depths, hammer energy levels and other factors, it is almost guaranteed that the frequency response measured for one pile will differ from that of any other pile, even within the same project.

Since it is practically impossible to predict the exact frequency spectrum for any specific pile installation, an averaged spectrum (red line), for use in predictive modelling, is proposed by (Bellmann, et al., 2020).

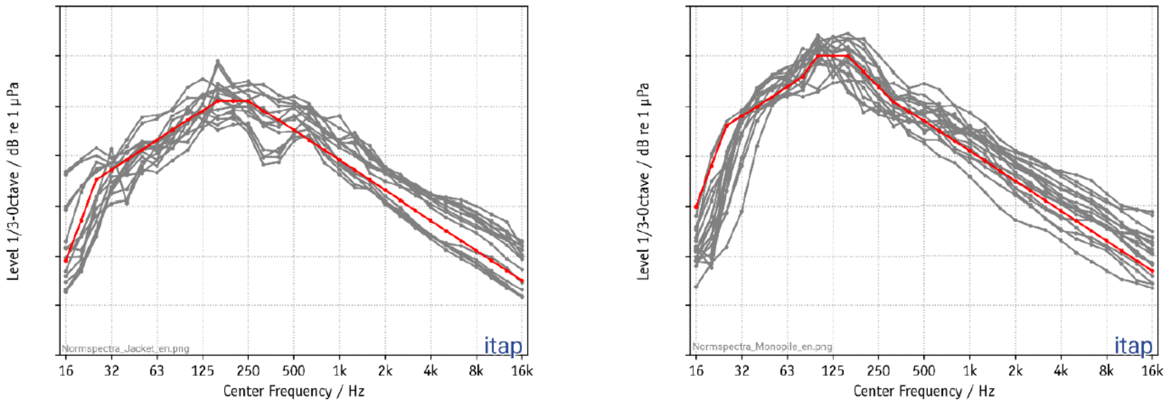

Figure 4.4: Measured pile driving frequency spectrum (grey lines) at 750m, with the averaged spectrum shown as the red line (Bellmann, et al., 2020). Left: pin piles up to 3.5 m diameter, Right: Monopiles of minimum 6 m diameter. The spectrum ranges from 110-180 dB re 1µPa.

The spectrum shown to the left in Figure 4.4 is the pile driving frequency spectrum (grey lines) measured at 750 m for pin piles with diameters up to 3.5 m. The red line indicates the averaged spectrum and is proposed to be used as a theoretical model spectrum for sound propagation modelling of pin piles.

The right side of Figure 4.4 is showing the pile driving frequency spectrum (grey lines) measured at 750 m for monopiles with diameters of minimum 6 m. The red line indicates the averaged spectrum and is proposed to be used as a theoretical model spectrum for sound propagation modelling of monopiles for the measured spectrums.

For the monopile foundation scenario, the monopile spectrum is used, however shifted 2/3 octaves downward (towards lower frequencies) to compensate for the larger pile diameter. The shift value was chosen based on the observed frequency shift visible in Figure 4.4, between small pin piles, and larger monopiles.

The Danish guidelines require a source frequency spectrum covering at least 12.5 Hz – 25 kHz, and preferably even higher. While source models can theoretically be implemented using a 12.5 Hz – 125 kHz frequency spectrum, covering the entire hearing range of marine mammals, it is often chosen to use a reduced frequency spectrum for numerical calculations. For this prognosis, it was chosen to limit the source frequency spectrum to 12.5 Hz - 32 kHz. In order to ensure a conservative prognosis for high frequency sensitive marine mammal groups, the source level at 32 kHz has however been increased by 5 dB. This value comes from a calculation of the missing energy in the span 40 kHz – 125 kHz. This method is considered conservative also due to the fact that higher frequencies attenuate faster than low frequencies, and by shifting the 5 dB contribution downwards, it will propagate further than would otherwise be the case for a full spectrum model.

4.1.4. Source levels and spectrum for source scenarios

Following the methodology presented in the previous sections, source levels and frequency spectrum for the two foundation scenarios are defined in the following subsections.

4.1.4.1. Foundation scenario 1: 10 m diameter monopile

For the monopile foundation scenario, the unmitigated and unweighted SEL at 750 m was derived to be: $\mathrm{SEL_{@750m}} = 181.6\ \mathrm{dB\ re.\ 1\ \mu Pa^2 s}$. Back-calculating this level to 1 m, results in $L_{S,E} = 224.8\ \mathrm{dB\ re.\ 1\ \mu Pa^2\ m^2\ s}$. The source level is presented in all relevant metrics, with and without frequency weighting, see Table 4.3.

Table 4.3: Broadband source level for monopile foundation scenario, with and without frequency weighting.

Frequency weighting	Source level $(L_{S,E})[\mathrm{dB\ re.\ 1\mu Pa^2 m^2 s}]$
Unweighted	224.8
VHF Cetaceans	179.5
Phocid Carnivores in water (PCW)	203.1

The unweighted ESL frequency spectrum in 1/3 octave bands for this foundation scenario is provided in Table 6.1, Appendix 1.

4.1.4.2. Foundation scenario 2: Jacket foundation with 4x 2.5m pin piles

For the jacket foundation scenario, the unmitigated and unweighted SEL at 750 m was derived to be: $\mathrm{SEL_{@750m}} = 170.4\ \mathrm{dB\ re.\ 1\ \mu Pa^2 s}$. Back-calculating this level to 1 m, results in $L_{S,E} = 212.3\ \mathrm{dB\ re.\ 1\ \mu Pa^2\ m^2\ s}$. The source level is presented in all relevant metrics, with and without frequency weighting, see Table 4.4.

Table 4.4: Broadband source level for jacket foundation scenario, with and without frequency weighting.

Frequency weighting	Source level $(L_{S,E})[\mathrm{dB\ re.\ 1\mu Pa^2 m^2 s}]$
Unweighted	212.3
VHF Cetaceans	174.1
Phocid Carnivores in water (PCW)	192.5

The unweighted ESL frequency spectrum in 1/3 octave bands for this foundation scenario is provided in Table 6.2, Appendix 1.

4.1.5. Source positions

The underwater sound propagation modelling includes the calculation of DTT from foundation installations at a total of 4 positions within the project area for wind turbine foundations (position 1 – 4), and 1 position for the substation foundation (position S), see Figure 4.5. The positions were chosen to reflect the likely worst case locations for sound propagation during impact piling of wind turbine foundations, and sound propagation for the currently planned location of the substation during piling. Parameters influencing the chosen locations sound speed, bathymetry and sediment conditions as the primary factors. This is further covered in section 4.2 It should be noted that chosen positions for wind turbine foundations do not represent actual foundation locations.

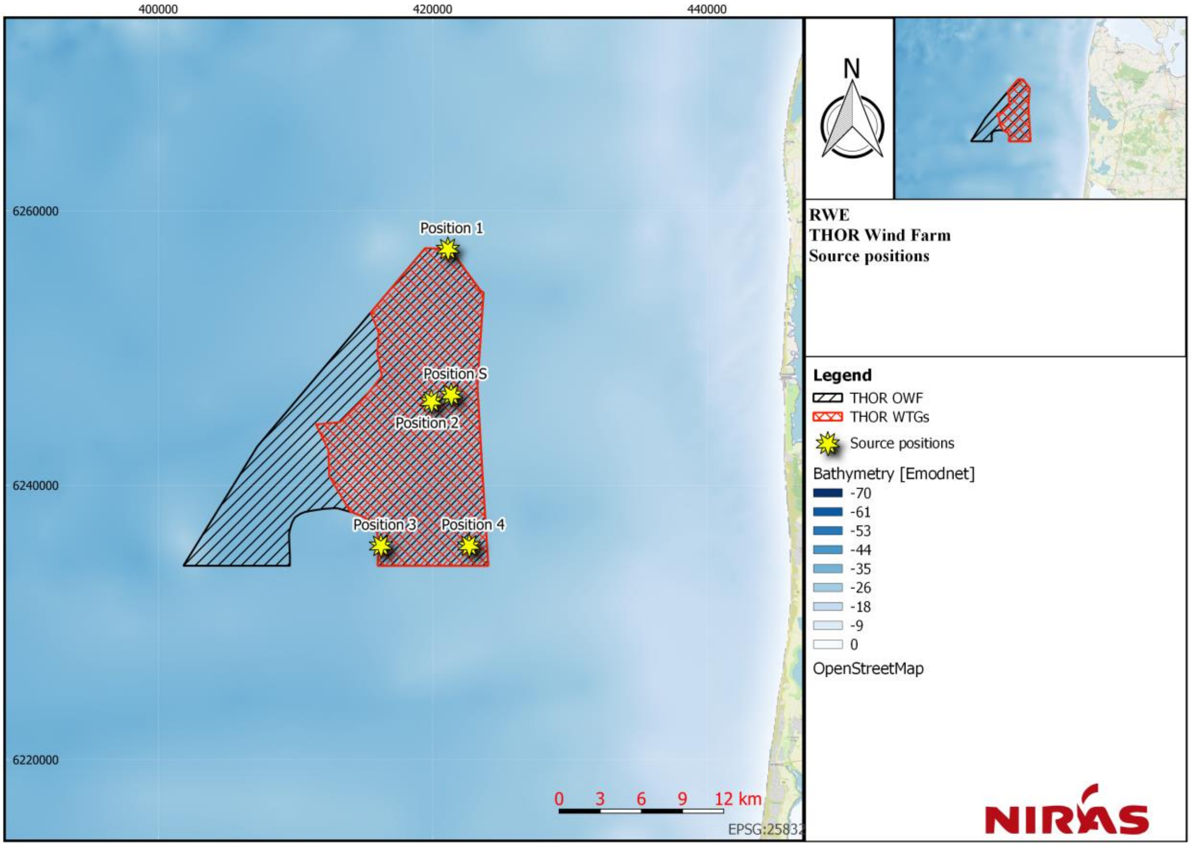

Figure 4.5 Source positions chosen for sound propagation modelling.

4.2. Underwater sound propagation model

This chapter provides a brief overview of underwater sound propagation theory and the software program used in the modelling, followed by a description of the inputs used for the propagation model.

4.2.1. Underwater sound propagation basics

This section is based on (Jensen, et al., 2011) chapter 1 and chapter 3 as well as (Porter, 2011), and seeks to provide a brief introduction to sound propagation in saltwater. The interested reader is referred to (Jensen, et al., 2011) chapter 1, for a more detailed and thorough explanation of underwater sound propagation theory.

Sound levels generally decrease with increasing distance from the source, which is known as the propagation loss (PL), $\mathrm{N_{PL}}$. The PL is affected by a number of parameters making it a complex process.

The speed of sound in the sea, and thus the sound propagation, is a function of both pressure, salinity and temperature, all of which are dependent on depth and the climate above the ocean and as such are very location dependent.

The theory behind the sound propagation is not the topic of this report, however it is worth mentioning one aspect of the sound speed profile importance, as stated by Snell's law, Equation 7.

Equation 7
$$\frac{cos(\theta)}{c} = constant$$

Where θ is the ray angle [°] and c is the speed of sound $\left[\frac{\mathrm{m}}{\mathrm{s}}\right]$.

This relationship implies that sound waves bend toward regions of low sound speed (Jensen, et al., 2011). The implications for sound in water are, that sound that enters a low velocity layer in the water column can get trapped there. This results in the sound being able to travel far with very low PL.

When a low velocity layer occurs near the sea surface, with sound speeds increasing with depth, it is referred to, as an upward refraction. This causes the sound waves to be reflected by sea surface more than by the seabed. As the sea surface is often modelled as a calm water scenario (no waves), it causes reduced PL, and thus a minimal loss of sound energy. This scenario will always be the worst-case situation in terms of sound PL. For some sound propagation models, this can introduce an overestimation of the sound propagation, if the surface roughness is not included.

When a high velocity layer occurs near the sea surface with the sound speed decreasing with depth, it is referred to, as a downward refraction. This causes the sound waves to be angled steeper towards the seabed rather than the sea surface, and it will thus be the nature of the seabed that determines the PL. Depending on the composition of the seabed some of the sound energy will be absorbed by the seabed and some will be reflected. A seabed composed of a relatively thick layer of soft mud will absorb more of the sound energy compared to a seabed composed of hard rock, that will cause a relatively high reflection of the sound energy.

In any general scenario, the upward refraction scenario will cause the lowest sound PL and thereby the highest sound levels over distance. In waters with strong currents, the relationship between temperature and salinity is relatively constant as the water is well-mixed throughout the year.

As an example, in the inner Danish and Swedish waters, as Kattegat, Skagerrak and the Baltic Sea, an estuary-like region with melted freshwater on top, and salty sea water at the bottom, the waters are generally not well-mixed and great differences in the relation between temperature and salinity over depth can be observed. Furthermore, this relation depends heavily on the time of year, where the winter months are usually characterized by upward refracting or iso-velocity sound speed profiles. In the opposite end of the scale, the summer months usually have downward refracting sound speed profiles. In between the two seasons, the sound speed profile gradually changes between upward and downward refracting.

Another example is the North Sea, where a gradual shift in sound speed profile from near-iso speed in the winter, to downward refracting in the summer is observed based on temperature and salinity readings throughout the year. The readings comes from the NOAAs World Ocean Atlas database (WOA18), freely available from the "National Oceanic and Atmospheric Administration" (NOAA) at https://www.nodc.noaa.gov/OC5/woa18/, (NOAA, 2019).

The physical properties of the sea surface and the seabed further affect the sound propagation by reflecting, absorbing and scattering the sound waves. Roughness, density and sound speed are among the surface/seabed properties that define how the sound propagation is affected by the boundaries.

The sea surface state is affected mainly by the climate above the water. The bigger the waves, the rougher the sea surface, and in turn, the bigger the PL from sound waves hitting the sea surface. In calm seas, the sea surface acts as a very reflective interface with very low sound absorption, causing the sound to travel relatively far. In rough sea states, the sound energy will to a higher degree be reflected backwards toward the source location, and thus result in an increased PL. As previously mentioned, this is not always possible to include in sound propagation models, and the PL can therefore be under-estimated, leading to higher noise propagation than what would actually occur.

Another parameter that has influence on especially the high frequency PL over distance is the volume attenuation, defined as an absorption coefficient dependent on chemical conditions of the water column. This parameter has been approximated by Equation 8 (Jensen, et al., 2011):

Equation 8 $$\alpha' \cong 3.3 \times 10^{-3} + \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} + 3.0 \times 10^{-4} f^2 \quad \left[\frac{dB}{km}\right]$$

Where f is the frequency of the wave in kHz. This infers that increasing frequency leads to increased absorption.

4.2.2. Numerical sound propagation models

There are different algorithms for modelling the sound propagation in the sea, all building on different concepts of seabed interaction and sound propagation. Commonly used sound propagation models for long distance modelling tasks are Ray tracing, Normal Modes (NM), and Parabolic Equation (PE).

Ray tracing has a good accuracy when working with frequencies above 200 Hz, however in very shallow waters, the minimum frequency would be higher, as the rays need space to properly propagate. Different techniques can be applied for ray tracing to improve and counteract certain of its inherent shortcomings (Jensen, et al., 2011). Ray tracing, furthermore, is the only algorithm that inherently supports directional sources, that is, sources that do not radiate sound equally in all directions.

The normal mode algorithm makes it possible to calculate the sound field at any position between the source and receiver. Since the modes grow linearly with frequency, the algorithm is usually used for low frequencies, because at high frequencies it is hard to find all the modes which contributed to the sound field (Wang, et al., 2014).

Last is the parabolic equation method, which is usually used for low frequencies, due to increasing computational requirements with frequency squared. This method is generally not used for frequencies higher than 1 kHz. The method is however more accepting of discontinuous sound speed profiles (Wang, et al., 2014).

In Table 4.5, an overview of the application range of the different sound propagation models is shown.

Table 4.5: An overview which indicates where the different sound propagation models are most optimal (Wang, et al., 2014).

Shallow water - low frequency	Shallow water - high frequency	Deep water – low frequency	Deep water - high frequency
Ray theory	Ray theory	Ray theory	Ray theory
Normal mode	Normal mode	Normal mode	Normal mode
Parabolic equation	Parabolic equation	Parabolic equation	Parabolic equation
Green – suitable; Amber – suitable with limitations; Red – not suitable or applicable			

In most real world sound propagation scenarios, a combination of two algorithms is typically preferred to cover the entire frequency range of interest, such as normal modes for the low frequencies and ray tracing for the high frequencies. In this regard, the split between the two is typically defined as $f = \frac{8 \cdot c}{d}$ [Hz], where c is the speed of sound in [m/s] and d is the average bathymetry depth in [m]. This however assumes, that the change in bathymetry is not several orders of magnitude. If the bathymetry ranges from very shallow to very deep, it is likely that an optimal split frequency does not exist. In such cases, it might be necessary to choose between calculation range and calculation accuracy.

In sound propagation modelling using mitigation systems, the sound levels of interest usually occur up to a few tens of km from the source, and in most cases, the relevant bathymetry will either be shallow or deep, but rarely both. For sound propagation modelling using unmitigated source levels, where it is desired to prognosticate the propagation loss over tens to hundreds of km, it is however very likely that the bathymetry variation becomes problematic.

4.2.3. Underwater sound propagation modelling software

NIRAS uses the underwater noise modelling software: dBSea version 2.3.4, developed by Marshall Day Acoustics.

The software uses 3D bathymetry, sediment and sound speed models as input data to build a 3D acoustic model of the environment and allows for the use of either individual sound propagation algorithms or combinations of multiple algorithms, based on the scenario and need. dBSea sound propagation results are afterwards post-processed in NI-RAS' software package SILENCE, where distances to relevant thresholds are calculated and sound propagation curve fits are created.

4.2.4. Underwater sound propagation model settings

For this project, the dBSea settings listed in Table 4.6 were used.

Table 4.6: dBSea Settings

Technical Specification		
Octave bands		1/3
Grid resolution (Range step, depth)		25 m x 0.25 m
Number of transects		45 (8°)
Sound Propagation Model Settings		
Model	Start frequency band	End frequency band
dBSeaModes (Normal Modes)	12.5 Hz	250 Hz
dBSeaPE (Parabolic equation)	315 Hz	32 kHz

4.3. Environmental model

The sound propagation depends primarily on the site bathymetry, sediment and sound speed conditions. In the following, these input parameters are described in greater detail.

4.3.1. Bathymetry

dBSea incorporates range-dependent bathymetry modelling and supports raster and vector bathymetry import.

Figure 4.6 shows a map of the bathymetry for Europe, where darker colours indicate deeper areas, and lighter colours indicate more shallow water. The resolution of the map is 115 x 115 meters. EMODnet has created the map using Satellite Derived Bathymetry (SDB) data products, bathymetric survey data sets, and composite digital terrain models from several sources. Where no data is available EMODnet has interpolated the bathymetry by integrating the GEBCO Digital Bathymetry (EMODnet, 2021).

Figure 4.6: Bathymetry map over European waters from Emodnet, where light blue indicates shallow waters and dark blue indicates deeper waters (EMODnet, 2021).

Figure 4.7 shows the bathymetry for the wind farm site and nearby waters (extracted from the Emodnet bathymetry map in Figure 4.6).

In the project area, the bathymetry ranges from a depth of 40 m, indicated by the darker colours, to a depth of 20 m, indicated by the lighter colours. For each source position, described in section 4.1.5, a bathymetry extract with 12 km radius from the source position was extracted for use in dBSea.

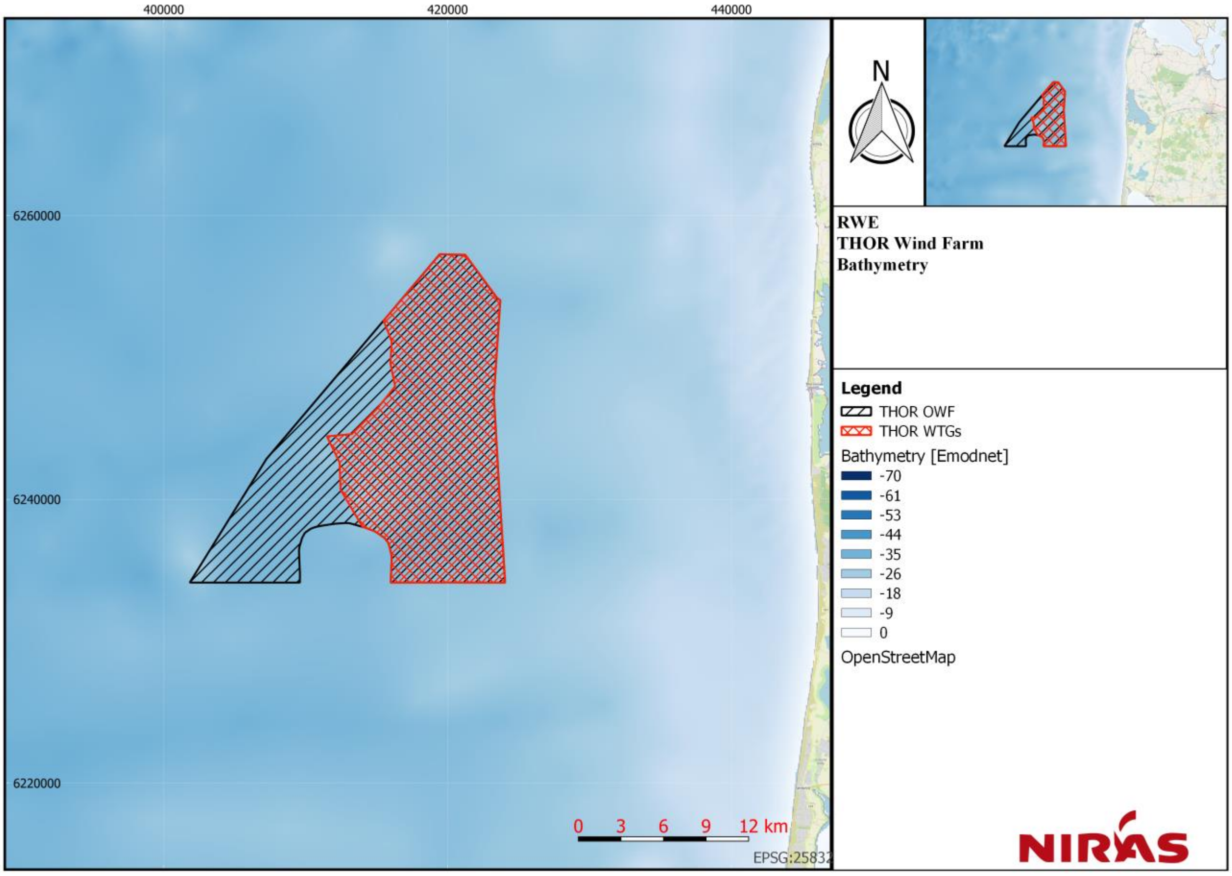

Figure 4.7: Bathymetry map for project area and surroundings.

4.3.2. Sediment

In dBSea, the sound interaction with the seabed is handled through specifying the thickness and acoustic properties of each seabed layer, where the uppermost layer is the most important. The thickness and acoustic properties of the layers, from seabed to bedrock, is generally obtained thought literature research in combination with available site-specific survey findings.

For determining the top layer type, the seabed substrate map (Folk 7) from https://www.emodnet-geology.eu/, see Figure 4.8, along with top soil sediment map from RWEs geological survey campaign, see Figure 4.9. The resulting discretized top sediment model implemented in dBSea is shown in Figure 4.10.

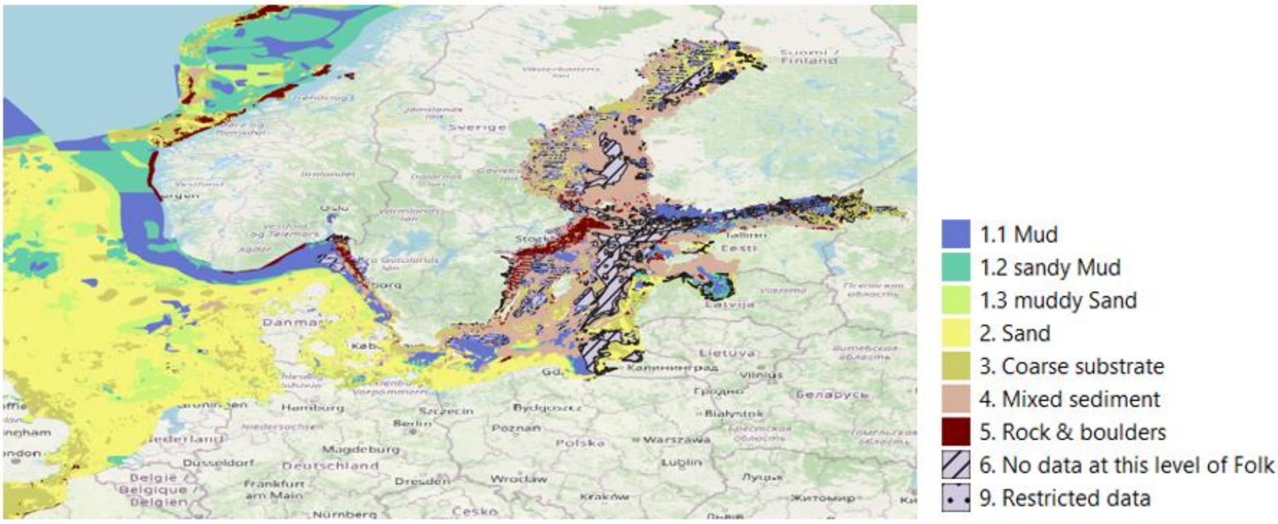

Figure 4.8: A section of the seabed substrate map, (Folk 7) (EMODnet, 2021).

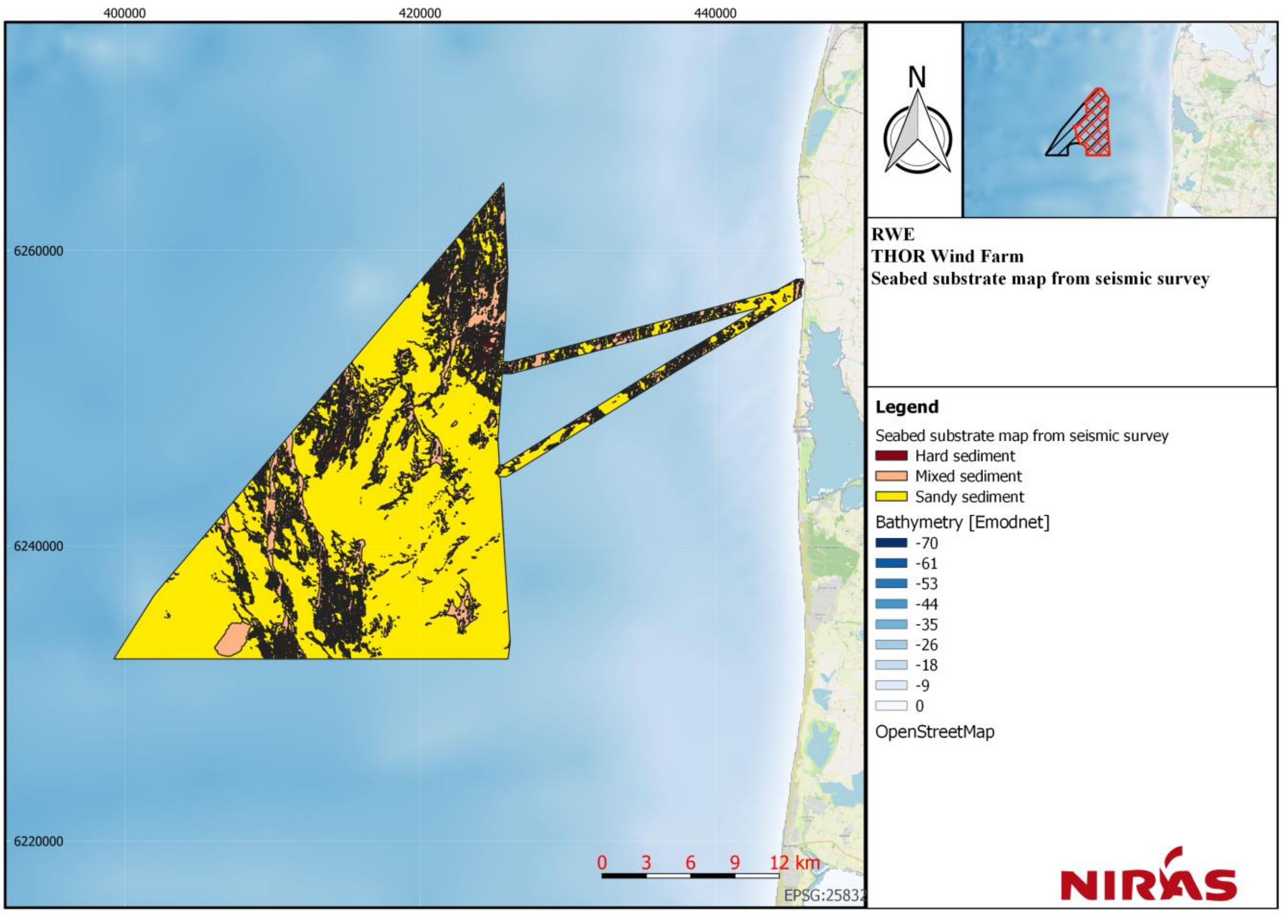

Figure 4.9: Geological survey results for top soil sediments.

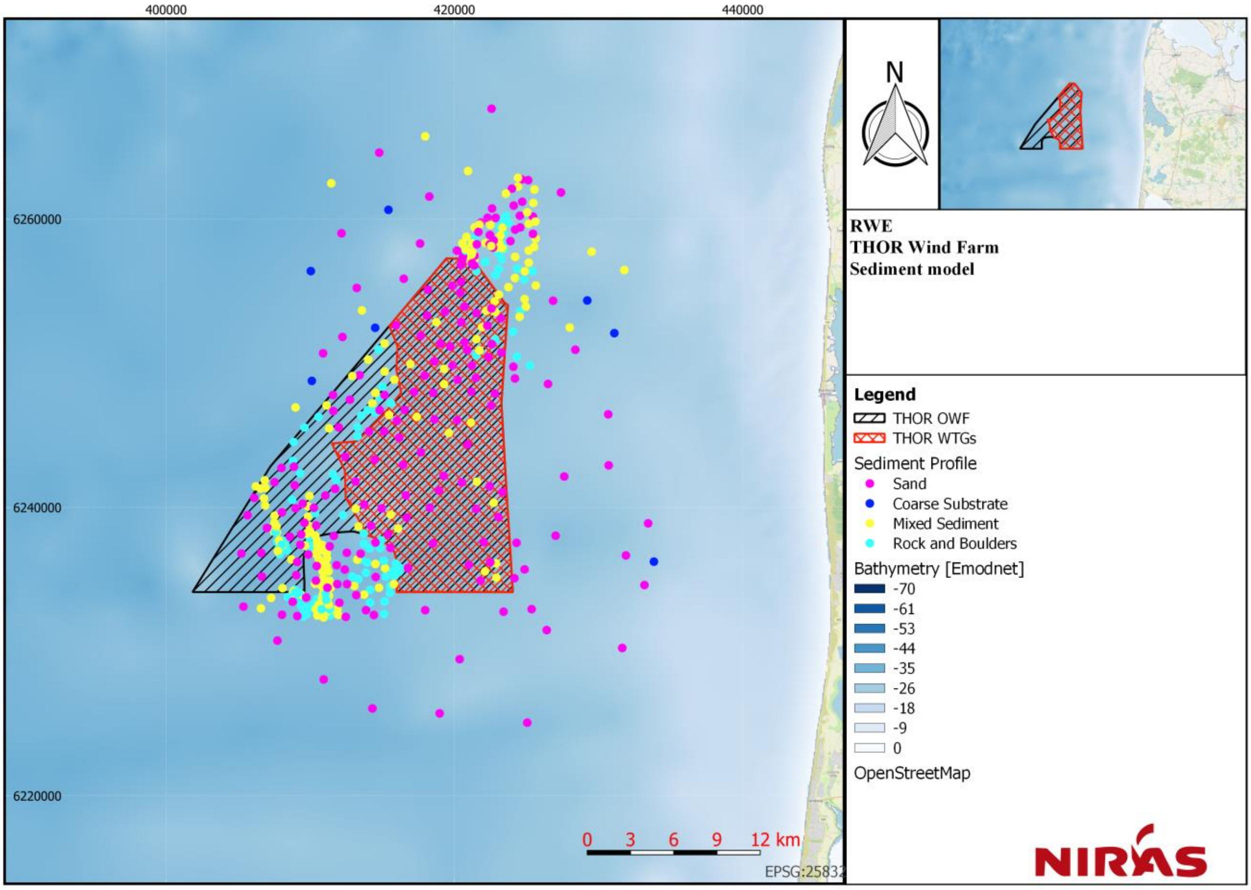

Figure 4.10: Sediment model for project area and surroundings.

The top soil thickness was determined from 10 m. Lower layers include moraine and mixed sediments, below which pre-Quaternary layers are reached, see Figure 4.11. The profiles are from survey transects obtained near the project site, which provide information on local layer depths (Naturstyrelsen, 2010).

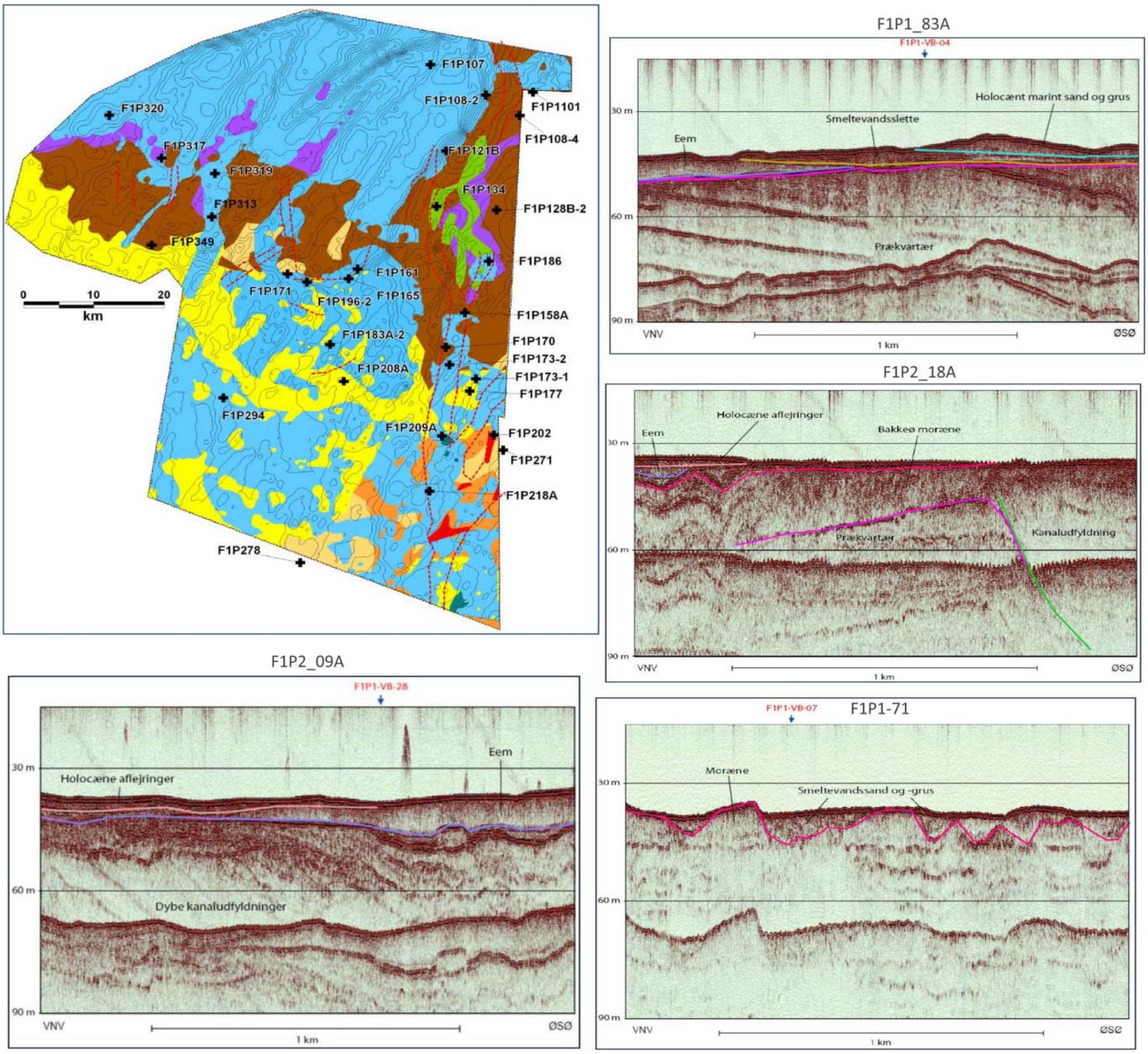

Figure 4.11: Geological sediment profiles from the project area (Naturstyrelsen, 2010), where the top left plot indicates the transect line locations, and the other three plots show the transect profiles.

For each point in the sediment model shown in Figure 4.10, the sediment layer types were translated into geoacoustic parameters, in accordance with Table 4.7, utilizing information from Jensen et al. (2011) and Hamilton (1980). For mixed layers, such as muddy sand, the geoacoustic profile was chosen to be 85% main layer and 15% of the secondary layer. It is recognized that this approach does not accurately reflect actual conditions, however it is not deemed possible to make a more accurate model without detailed seismic survey results, and even then, the results would only be applicable within the surveyed area.

Table 4.7: Geoacoustic properties of sediment layers used in the environmental model. Sources: (Jensen, et al., 2011), (Hamilton, 1980). Note, mixed sediment is based on a mix of sand, silt and gravel. Moraine boulders is similarly a mix of primarily moraine with boulders.

Sediment	Sound Speed [m/s]	Density [kg/m^3]	Attenuation factor [dB/λ]
Clay	1500	1500	0.2
Silt	1575	1700	1.0
Mud (clay-silt)	1550	1500	1.0
Sandy mud	1600	1550	1.0
Sand	1650	1900	0.8
Muddy sand	1600	1850	0.8
Coarse substrate	1800	2000	0.6
Gravel	1800	2000	0.6
Mixed sediment	1700	1900	0.7
Moraine	1950	2100	0.4
Moraine Boulders	2200	2200	0.3
Rock and boulders	5000	2700	0.1
Chalk	2400	2000	0.2

4.3.3. Temperature, salinity and temperature

The sound propagation also depends on the season and location dependent sound speed profile. To create an accurate sound speed profile, the temperature and salinity must be known throughout the water column for the time of year where the activities take place. As weather conditions prior to, and during installation can have an effect on the salinity and temperature profiles, early prognosis based on historical values will be connected with a degree of uncertainty. For the North Sea, this variation is however expected to be relatively low as it is very well mixed and stable throughout the year.

NIRAS uses NOAAs WOA18, freely available from the "National Oceanic and Atmospheric Administration" (NOAA) at https://www.nodc.noaa.gov/OC5/woa18/, (NOAA, 2019) which contains temperature and salinity information at multiple depths throughout the water column.

For each of the sediment model positions, the nearest available sound speed profile, as well as average temperature and salinity are extracted for the desired months.

4.3.3.1. Sound speed profiles

Figure 4.12 shows the sound speed profiles at the available positions for all months of the year. Note that the gridded layout of the sound speed profiles indicates their respective position geographically. Examining Figure 4.12, this would indicate March as the worst-case month followed closely by January and February. A time table for the installation has however been provided by RWE, to be during April – July. The worst case month during this time frame is April, and it was therefore chosen to use this month as input for the environmental conditions. In Figure 4.13 the sound speed profiles for the worst-case month of April are shown.

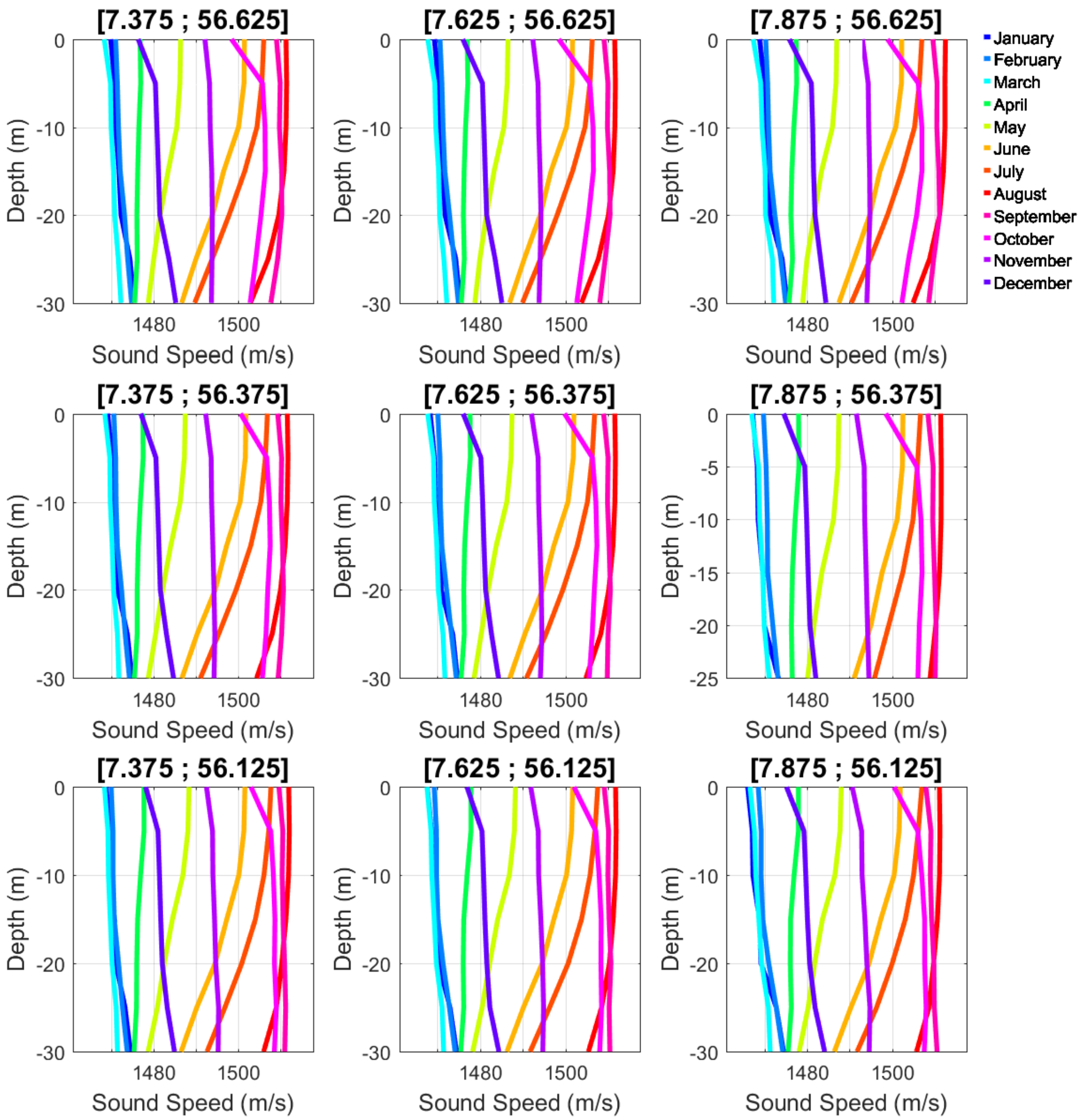

Figure 4.12: Historic averages for sound speed profiles, for the Thor project area, for all months of the year.

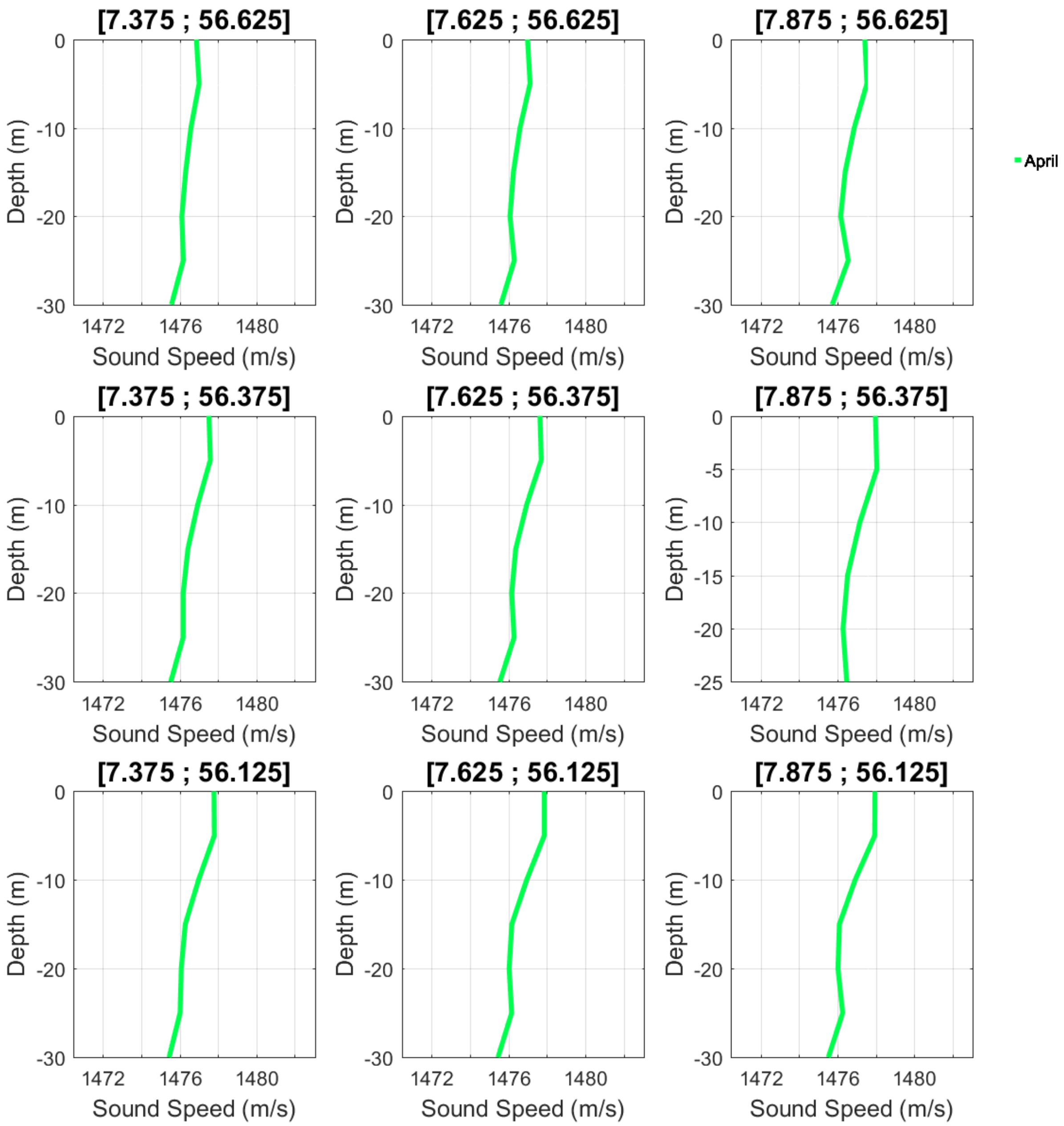

Figure 4.13: Historic averages for sound speed profiles, for the Thor project area, for April.

4.3.3.2. Salinity profiles

Figure 4.14 shows the salinity profiles for all months of the year, and Figure 4.15 shows the salinity profiles for the worst-case month of April.

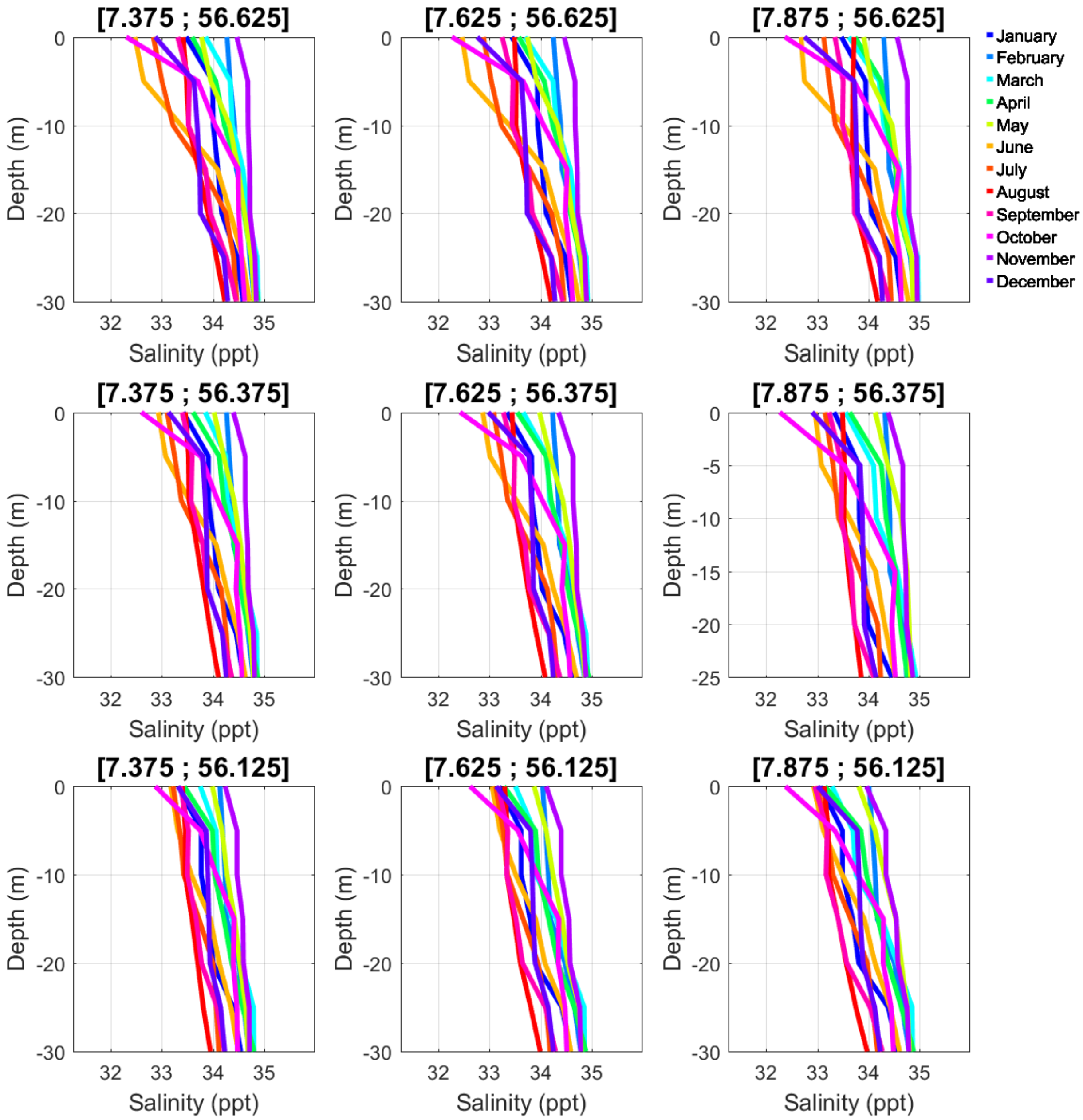

Figure 4.14: Historic averages for salinity profiles, for the Thor project area, for all months of the year.

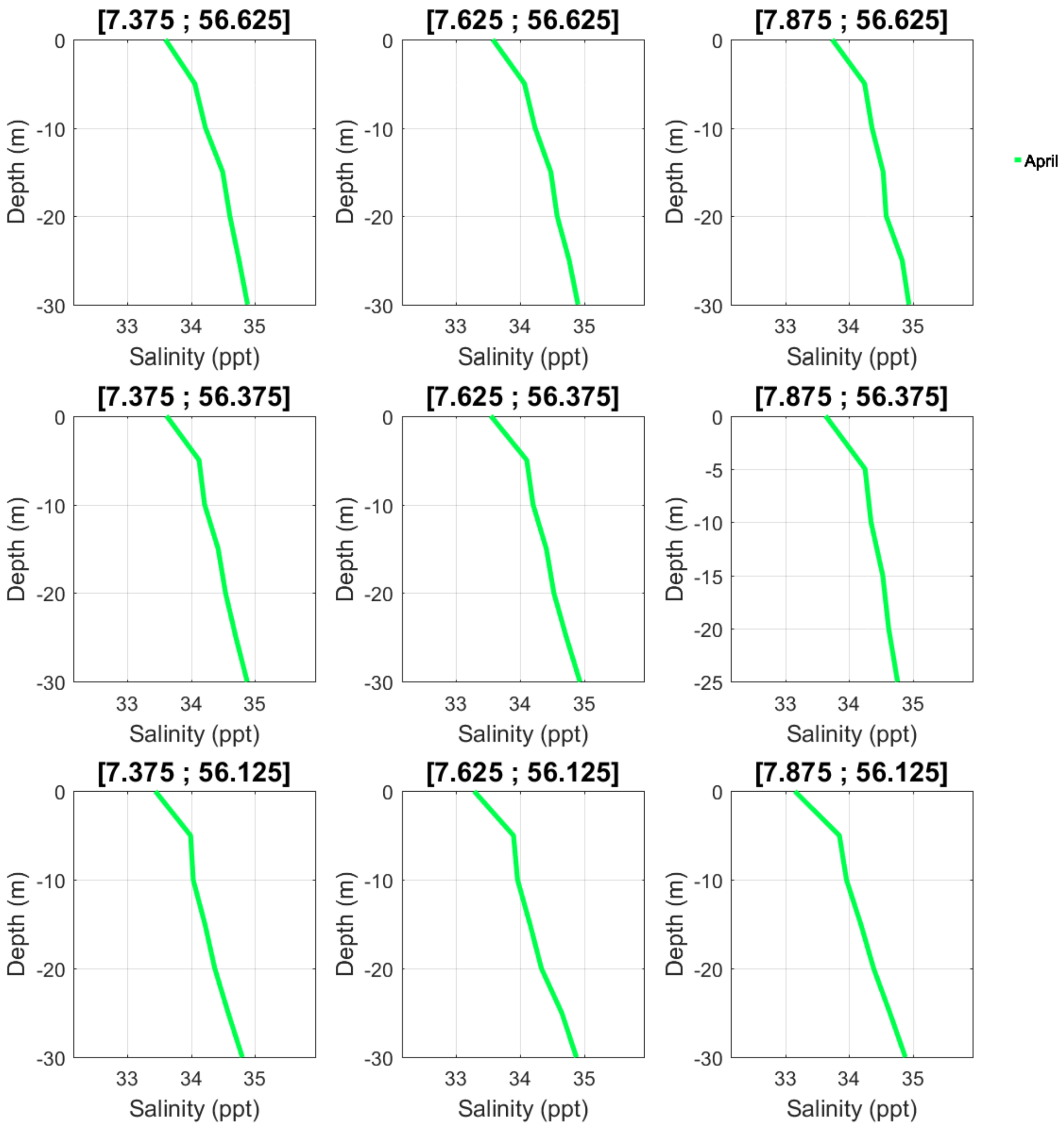

Figure 4.15: Historic averages for salinity profiles, for the Thor project area, for April.

4.3.3.3. *Temperature profiles*

Figure 4.16 shows the temperature profiles for all months of the year, and Figure 4.17 shows the temperature profiles for the worst-case month of April.

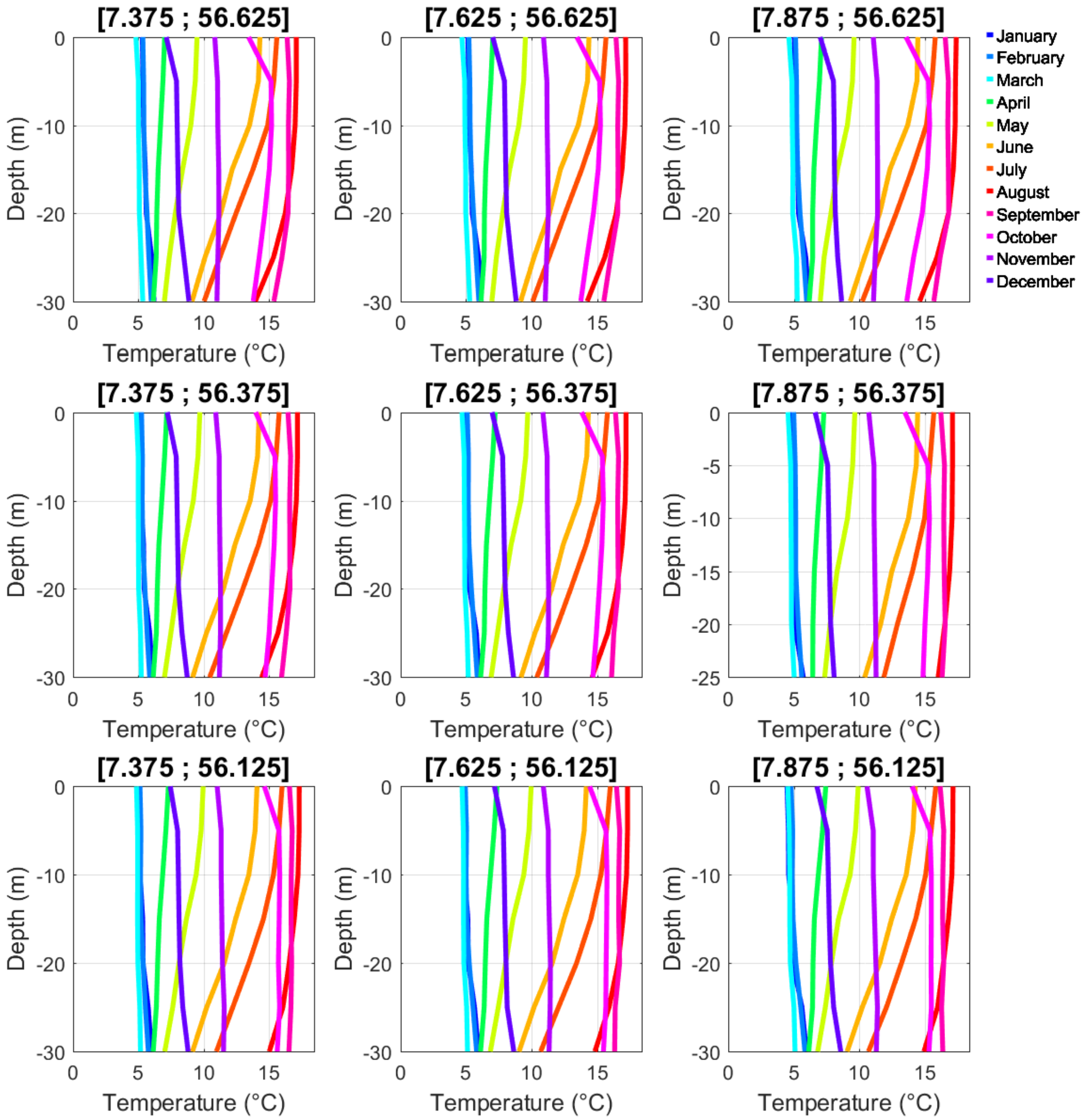

Figure 4.16: Historic averages for temperature profiles, for the Thor project area, for all months of the year.

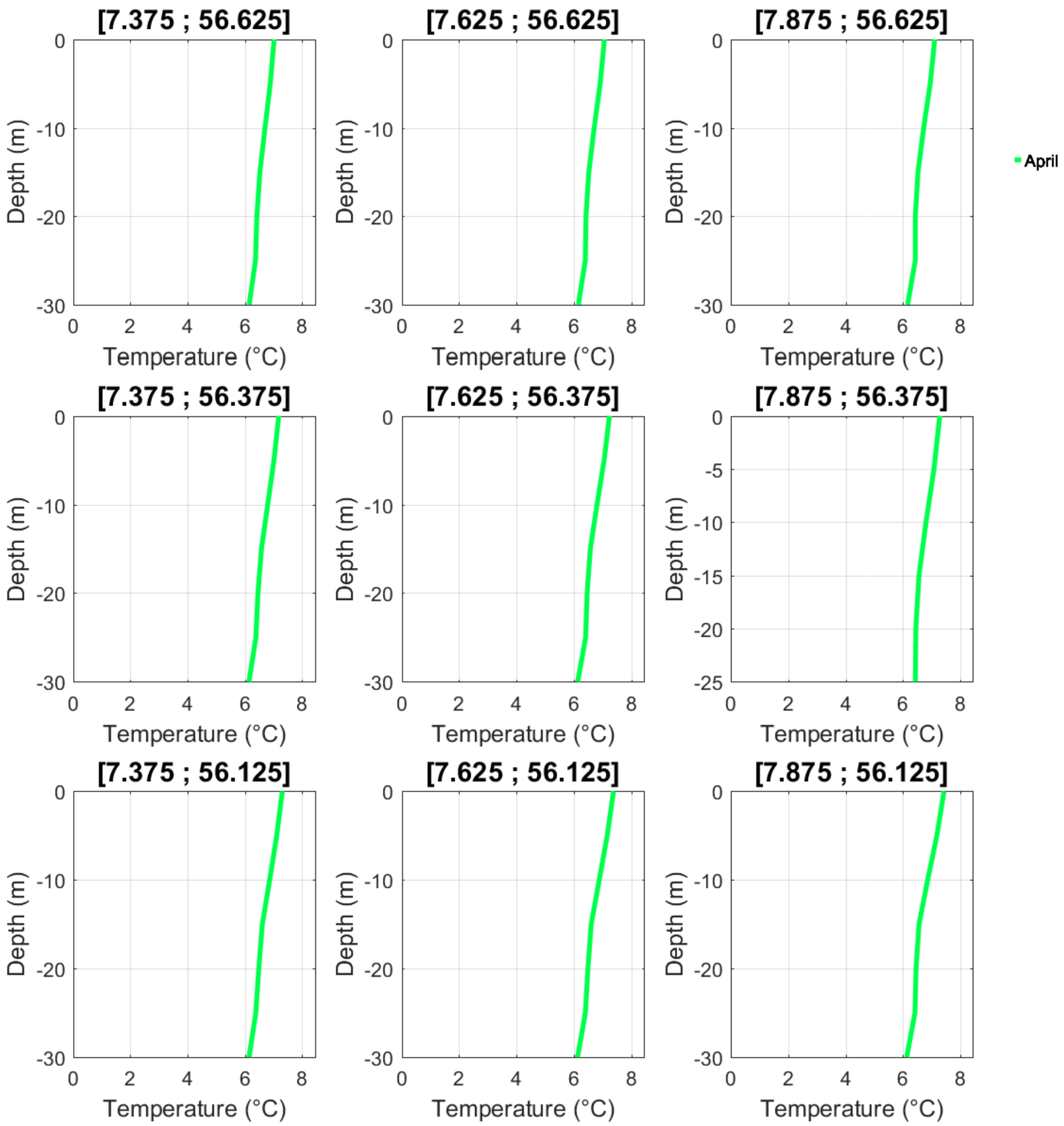

Figure 4.17: Historic averages for temperature profiles, for the Thor project area, for April.

4.4. Unmitigated underwater noise emission results

The Danish guidelines require the following documentation for the unmitigated underwater noise modelling:

1. Curve fits must be shown for both unweighted as well as for marine mammal species specific frequency weightings. This is covered in section 4.4.1.
2. The PTS impact range, r_{PTS}, must be calculated for the proposed installation scenario for each of the relevant marine mammal species. This, along with extrapolated distances for TTS and avoidance behaviour, as well as for fish injury and TTS are reported in section 4.4.2.
3. If $r_{PTS} > 200\ m$ for any marine mammal species, the mitigation requirement must be calculated according to the procedure outlined in section 3.2.1. This is covered in section 4.4.3.

4.4.1. Unmitigated curve fits

As required by the guidelines, curve fits for unweighted and frequency weighted underwater noise emission must be documented for the worst case transects for each source position. Due to the number of curve fits, the totality for the unmitigated models is available in Appendix 2 for the monopile scenario. Only the worst case position for each frequency weighting, as well as unweighted, is shown here in Figure 4.18 – Figure 4.20. For Jacket foundations, only 1 position was included, and all curve fits are therefore presented in Figure 4.21 – Figure 4.23.

4.4.1.1. Curve fits for foundation scenario 1: 10 m diameter monopile

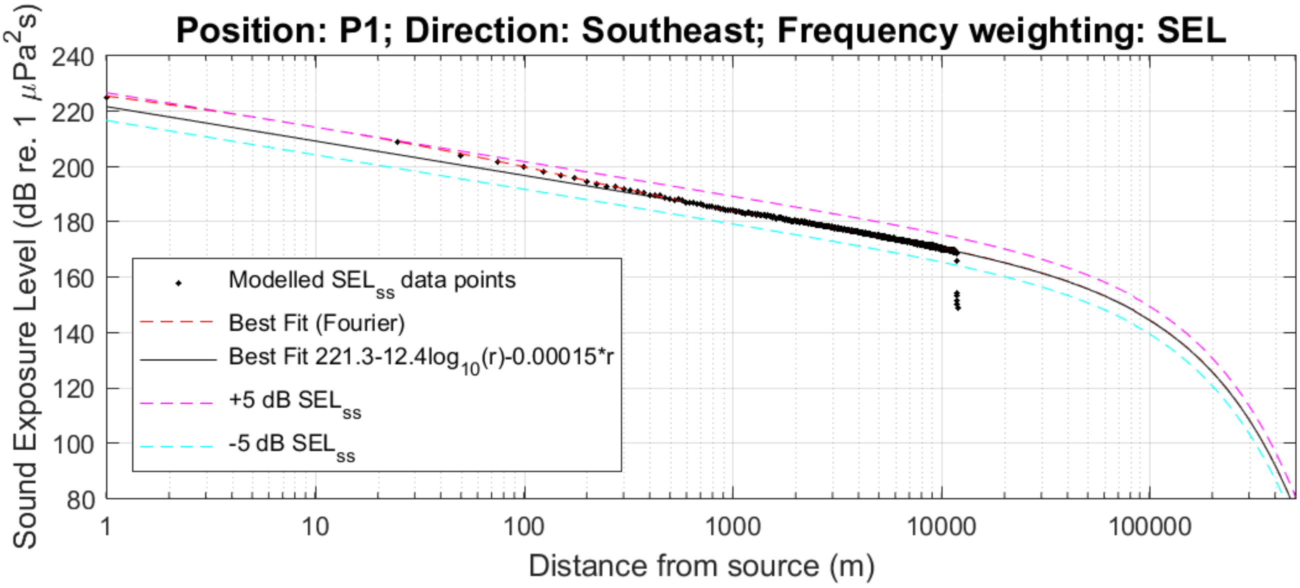

Figure 4.18: Sound propagation model curve fits and data points for the worst-case position in the worst-case direction for monopile installation without mitigation, unweighted. Fourier curve fit (red) is used for determining impact ranges, while logR curve fit (black) is the reference curve fit used for describing overall sound propagation properties.

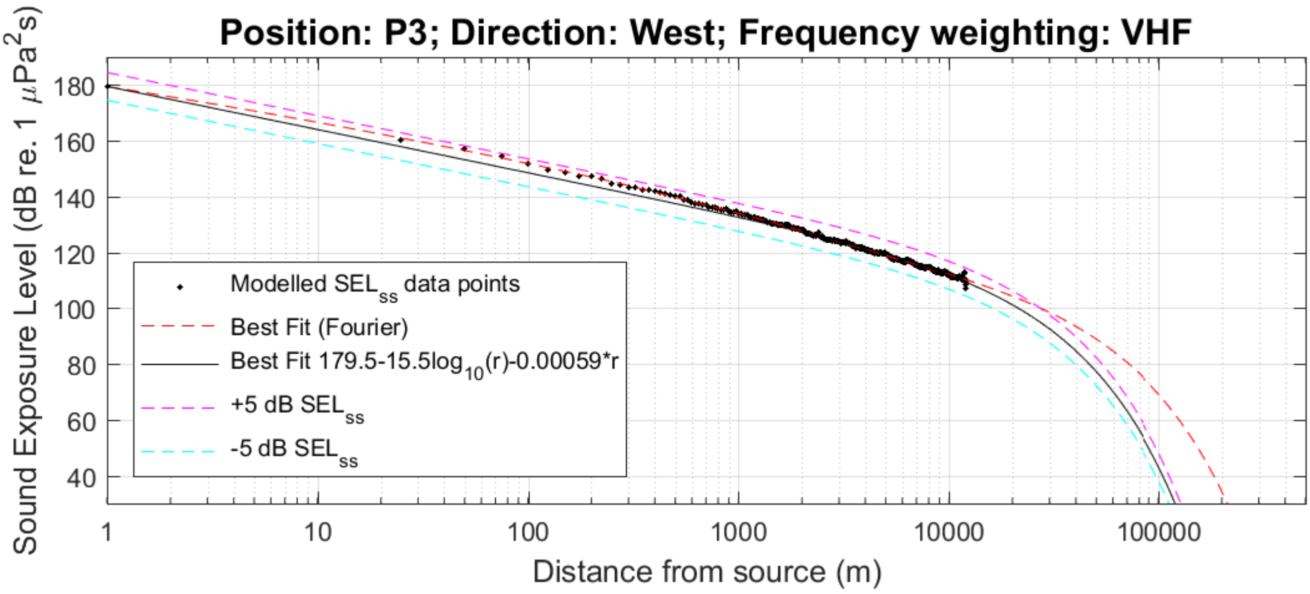

Figure 4.19: Sound propagation model curve fits and data points for the worst-case position in the worst-case direction for monopile installation without mitigation, VHF weighted. Fourier curve fit (red) is used for determining impact ranges, while logR curve fit (black) is the reference curve fit used for describing overall sound propagation properties.

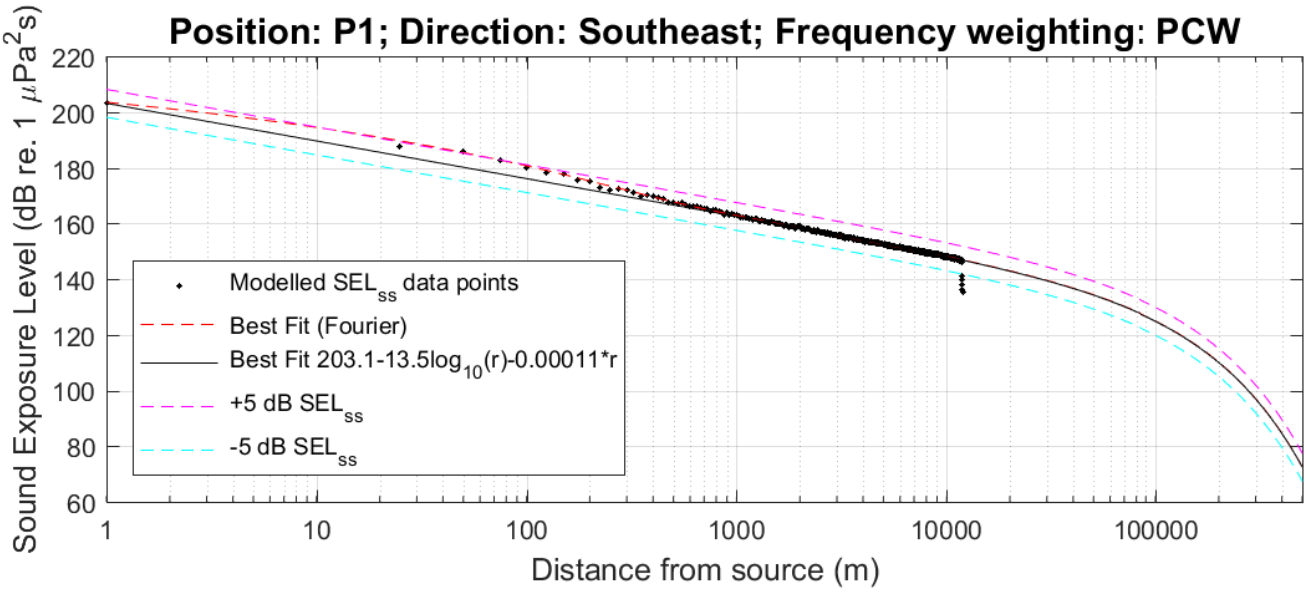

Figure 4.20: Sound propagation model curve fits and data points for the worst-case position in the worst-case direction for monopile installation without mitigation, PCW weighted. Fourier curve fit (red) is used for determining impact ranges, while logR curve fit (black) is the reference curve fit used for describing overall sound propagation properties.

4.4.1.2. *Curve fits for foundation scenario 2: Jacket foundation with 4x 2.5m diameter pin piles*

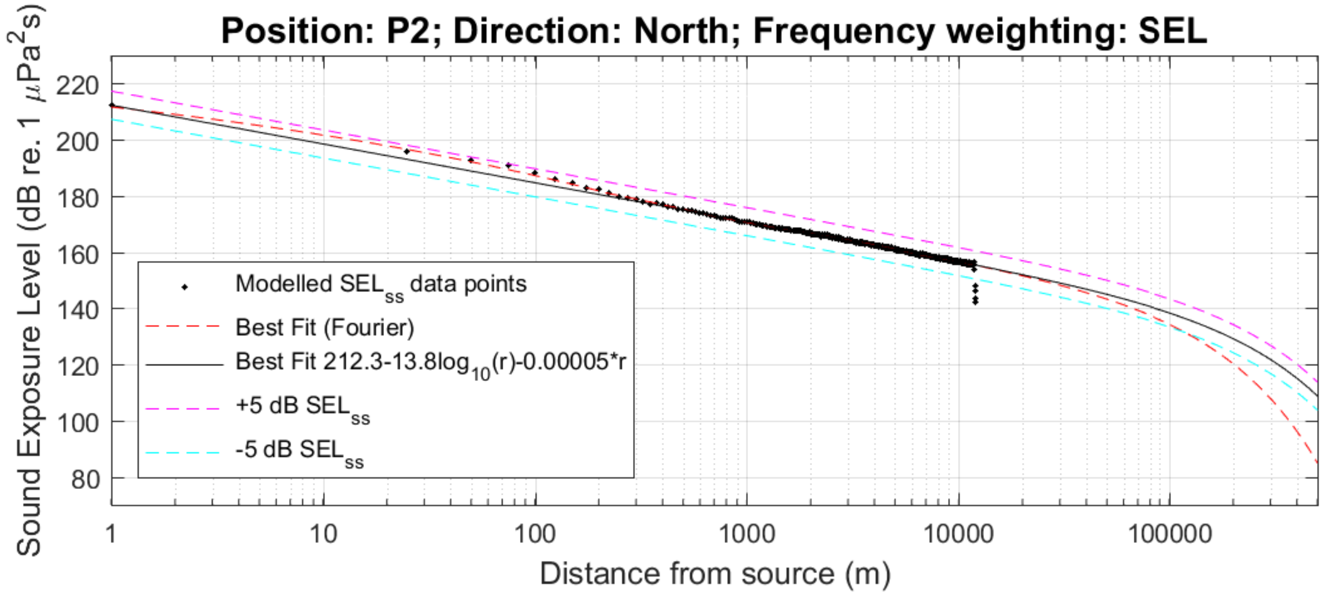

Figure 4.21: Sound propagation model curve fits and data points for the worst-case position in the worst-case direction for jacket foundation installation without mitigation, unweighted. Fourier curve fit (red) is used for determining impact ranges, while logR curve fit (black) is the reference curve fit used for describing overall sound propagation properties.

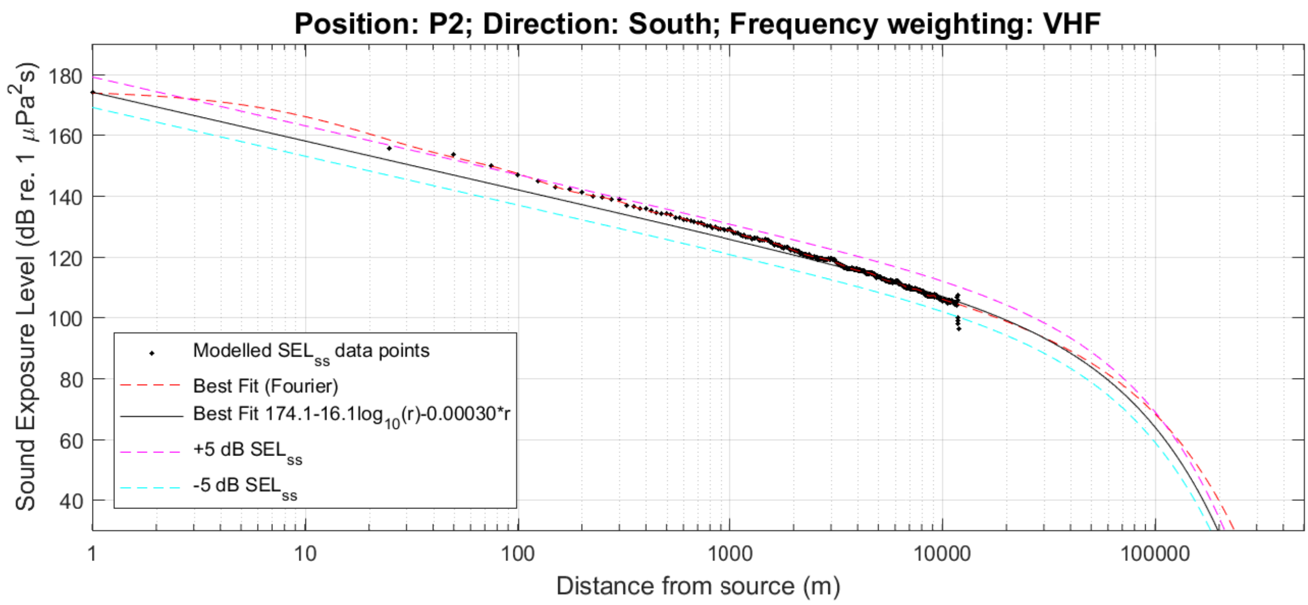

Figure 4.22: Sound propagation model curve fits and data points for the worst-case position in the worst-case direction for jacket foundation installation without mitigation, VHF weighted. Fourier curve fit (red) is used for determining impact ranges, while logR curve fit (black) is the reference curve fit used for describing overall sound propagation properties.

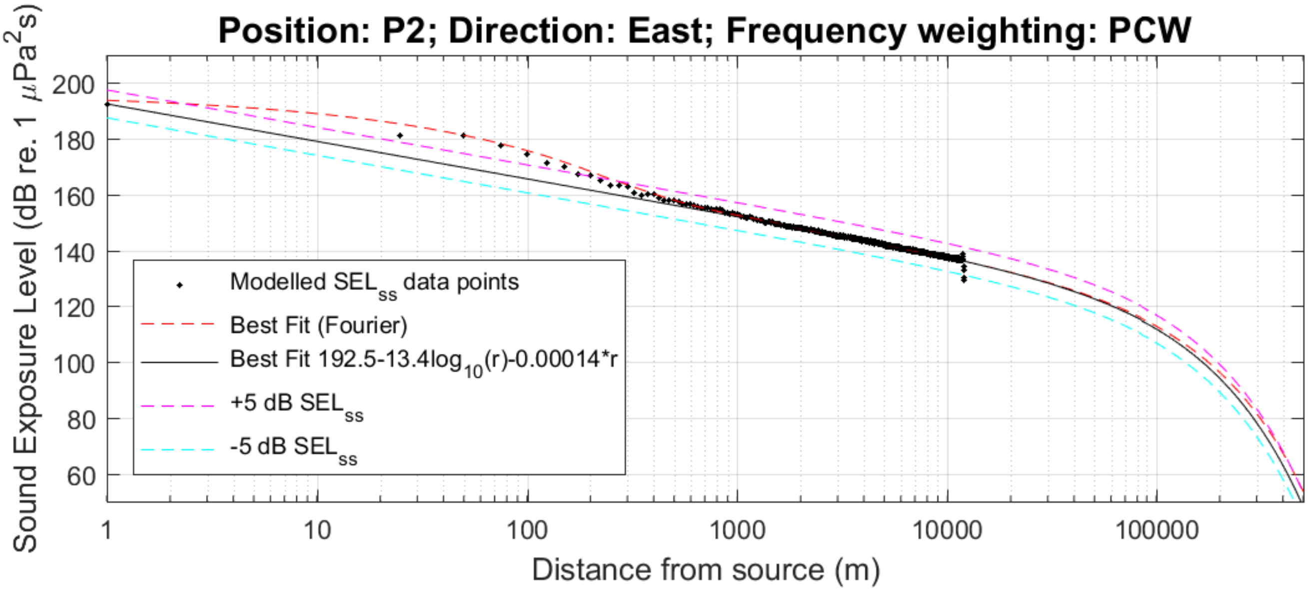

Figure 4.23: Sound propagation model curve fits and data points for the worst-case position in the worst-case direction for jacket foundation installation without mitigation, PCW weighted. Fourier curve fit (red) is used for determining impact ranges, while logR curve fit (black) is the reference curve fit used for describing overall sound propagation properties.

4.4.2. Distance-to-Threshold for unmitigated pile driving

Based on the Fourier curve fits shown in the previous section, and in Appendix 2 , the following impact ranges for PTS, TTS and avoidance behaviour were calculated for the unmitigated scenarios. Note that distances for TTS and avoidance behaviour are generally extrapolated from the curve fits as these extend beyond the sound propagation model range of 12 km.

4.4.2.1. Scenario 1: 10 m monopile foundation

Table 4.8: Resulting threshold impact distances for fish, unmitigated monopile foundation (scenario 1).

Position	Distance-to-threshold (km)								
	Injury (r_{injury})					TTS (r_{TTS})			
	Stationary	Juvenile Cod	Adult Cod	Herring	Larvae and eggs	Stationary	Juvenile Cod	Adult Cod	Herring
1	15.6 km	13.3 km	10.7 km	10.0 km	10.6 km	73.0 km	70.8 km	67.9 km	67.1 km
2	13.8 km	11.8 km	9.1 km	8.4 km	9.2 km	84.8 km	82.9 km	79.9 km	79.1 km
3	15.7 km	13.5 km	11.0 km	10.3 km	10.2 km	91.9 km	89.9 km	87.0 km	86.3 km
4	11.8 km	9.7 km	7.2 km	6.5 km	8.2 km	70.3 km	68.3 km	65.4 km	64.7 km

Table 4.9: Resulting threshold impact distances for marine mammals, unmitigated monopile foundation (scenario 1).

Position	Distance-to-threshold				
	PTS (r_{PTS})		TTS (r_{TTS})		Avoidance (r_{behav})
	Porpoise (VHF)	Seal (PCW)	Porpoise (VHF)	Seal (PCW)	Porpoise (VHF)
1	475 m	3.15 km	14.1 km	48.5 km	37.6 km
2	475 m	2.00 km	15.0 km	45.3 km	41.0 km
3	500 m	2.85 km	16.7 km	49.3 km	46.6 km
4	450 m	1.25 km	14.1 km	40.3 km	37.8 km

4.4.2.2. Scenario 2: Jacket foundation with 4x 2.5 m pin piles

Table 4.10: Resulting threshold impact distances for fish, unmitigated jacket foundation (scenario 2).

Position	Distance-to-threshold (km)								
	Injury (r_{injury})					TTS (r_{TTS})			
	Stationary	Juvenile Cod	Adult Cod	Herring	Larvae and eggs	Stationary	Juvenile Cod	Adult Cod	Herring
S	5.4 km	975 m	< 200 m	< 200 m	3.3 km	51 km	44.9 km	37.2 km	35.5 km

Table 4.11: Resulting threshold impact distances for marine mammals, unmitigated jacket foundation (scenario 2).

Position	Distance-to-threshold				
	PTS (r_{PTS})		TTS (r_{TTS})		Avoidance (r_{behav})
	Porpoise (VHF)	Seal (PCW)	Porpoise (VHF)	Seal (PCW)	Porpoise (VHF)
S	< 200 m	< 200 m	7.4 km	18.3 km	27.7 km

4.4.3. Mitigation requirements

In line with Danish guidelines (Energistyrelsen, 2022), r_{PTS}, as explained in section 3.2.1, is not allowed to exceed 200 m for any marine mammal species. For the WTG monopile foundation scenario, 200 m is exceeded for both harbour porpoise (VHF) and seal (PCW). In Table 4.12, the mitigation requirement, ΔL_{xx}, calculated in accordance with guideline specifications, is provided for each of the marine mammal species in each modelled source position and for each foundation scenario. From Table 4.12, it should be noted, that while the mitigation requirement for the sub-station is 0 dB for both harbour porpoise and seal, the impact ranges in terms of behaviour reaction in harbour porpoise, Table 4.11, and TTS for fish, Table 4.10, are very large.

Table 4.12: Mitigation requirements according to Danish guidelines (Energistyrelsen, 2022), for each marine mammal species and for both foundation scenarios. Mitigation requirement stated as ΔL_{xx} $[dB]$, where "xx" refers to the marine mammal hearing group frequency weighting. For any given position, all species specific mitigation requirements must be ensured by the mitigation solution. Worst-case mitigation requirements for each species are shown in **bold**.

Position	Mitigation requirement $\Delta \boldsymbol{L_{xx}}$ $[\boldsymbol{dB}]$			
	Monopile WTG foundation (scenario 1)		Sub Station Jacket foundation (scenario 2)	
	Porpoise (VHF)	Seal (PCW)	Porpoise (VHF)	Seal (PCW)
1	2.3	3.8	-	-
2	2.1	2.6	-	-
3	**2.5**	**4.3**	-	-
4	2.1	2.1	-	-
5	-	-	0	0

4.5. Mitigation measures

This section provides a brief description of different noise mitigation measures. The systems can be either on-pile systems (actively reducing the source level) or near-pile which reduces the noise emission after it has entered the water column.

4.5.1. Big bubble curtains (BBC, DBBC)

A frequently applied technique uses either a single big bubble curtain (BBC), or double (DBBC). Bubble curtains consist of a series of perforated pipes or hoses that release a continuous stream of air bubbles into the water column, thereby creating a barrier made of air, which effectively traps the acoustic energy inside the barrier. While bubble curtains are effective at reducing underwater noise, they have some limitations. The effectiveness of the curtain depends on the depth of the water, the size of the bubbles, and the distance between the noise source and the curtain. Additionally, the installation and operation of the curtains can be expensive, and the use of air compressors to generate the bubbles requires a lot of energy. The DBBC is shown in Figure 4.24.

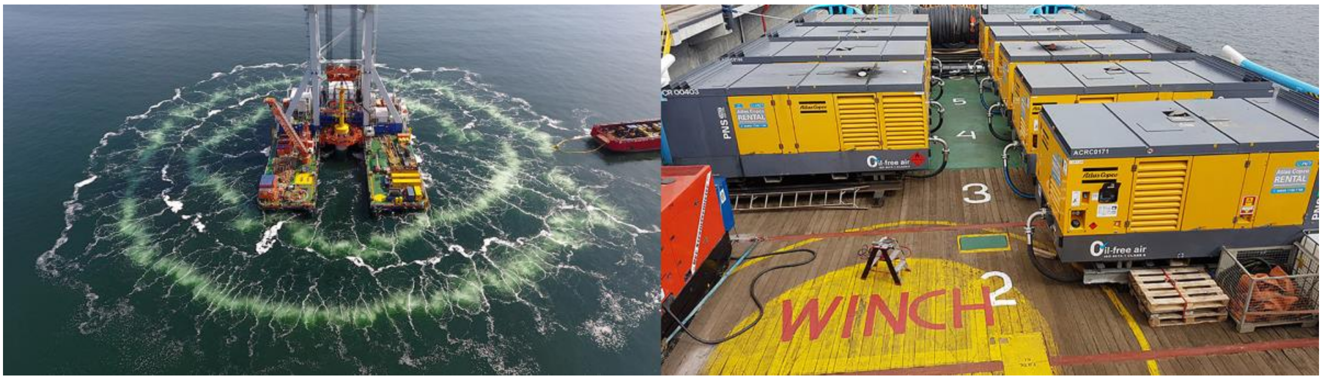

Figure 4.24: Illustration of a DBBC mitigation system (Left: in effect; Right: compressors for creating the air pressure) (Source: hydrotechnik-luebeck.de).

The curtains are typically positioned at 50 – 200 m radius around the pile. Due to the change in impedance in the water-air-water bubble interface, a significant part of the outgoing noise is reflected backwards and kept near the pile, just like the water surface prevents underwater sound from being transmitted into the air. Noise energy going through the bubble curtain is greatly attenuated (Tsouvalas, 2020). The success depends on three parameters: size of holes in the hosepipe (determines bubble sizes), spacing of holes (determines density of bubble curtain) and the amount of air used (air pressure). The best configuration was found to be with relatively small holes, a small spacing and using a substantial air pressure (Diederichs, et al., 2014).

Part of the noise emission from pile driving occurs through the pile striking the sediment. The sound moves through the sediment and is then partially reintroduced to the water column further from the pile. The distances to which sound reintroduced to the water column is of significant amplitude depends on the seabed characteristics at and near the pile site. The further from the pile the bubble curtain(s) are located, the more of the reintroduced sound can be captured. It is however in most cases considered impossible to avoid reintroduced sound from the sediment solely by use of bubble curtains given the typical bubble curtain radius of up to 200 m. The upper limit to the effectiveness of bubble curtains is therefore often dependent on the sediment.

4.5.2. Pile sleeves

A pile sleeve is an on-pile mitigation system forming a physical wall around the pile. One such system is the Noise Mitigation Screen from IHC (IHC-NMS) where a double walled steel sleeve with an air-filled cavity is positioned over the pile (Figure 4.25). This system utilises the impedance difference in the water-steel-air-steel-water interfaces to reduce the sound transmission. This system has been used for example at the German wind park Riffgat. Noise mitigation was assessed to be around 16-18 dB (Verfuß, 2014).

Figure 4.25: Illustration of IHC-NMS system (source: iqip.com)

Often, a pile sleeve is applied in combination with a bubble curtain solution to increase the overall mitigation effect. The pile sleeve however has an important limitation when it comes to future installations, as the weight of the system is significant. With increasing pile sizes, the pile sleeve also increases in size, and thereby weight. It is uncertain whether this system is applicable for large future monopiles. For jacket foundations, the applicability is also uncertain, as the pin piles are often installed into a template, thus preventing a seal towards the seabed.

Cofferdams are a special type of pile sleeve. They also surround the pile, however in comparison to the IHC-NMS, the water in between the pile and the sleeve is extracted, so that the interface from pile to water becomes air-steel-water. These sleeves are deemed to reduce noise by around 20 dB, as demonstrated in Aarhus Bay (Verfuß, 2014). However, tests further offshore and in connection with the construction of wind parks have yet to be carried out (Verfuß, 2014). An inherent challenge with this solution is that it can be difficult to keep the water out of the cofferdam, as local sediment conditions can prevent a perfect water-tight seal with the seabed.

4.5.3. Hydro Sound Dampers

Hydro Sound Damper (HSD) systems are in many ways similar to the bubble curtain, however instead of using hoses with air, the curtain consists of fixed position air-filled balloons or foam-balls. The size, spacing and density of the foam balls or air-filled balloons then dictate the achievable noise mitigation. The HSD system makes it possible to "tune" the system to work optimally at specific frequencies, thus allowing for project specific optimal solutions.

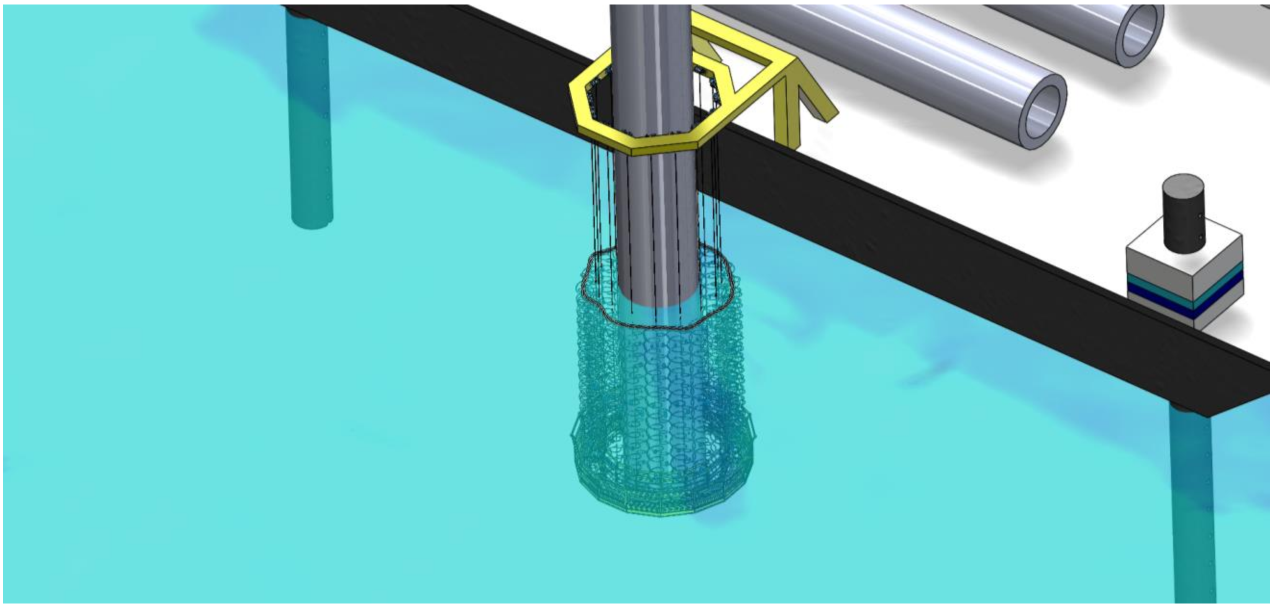

Figure 4.26: Illustration of the HSD system deployed around a monopile. (source: https://www.offnoise-solutions.com/).

4.5.4. Effectiveness of mitigation measures

For commercially available and proven mitigation systems, a summary of achieved mitigation levels throughout completed installations is given in (Bellmann, et al., 2020), and shown in Figure 4.27, for different configurations of bubble curtains, and in Figure 4.28 for HSD, IHC-NMS and combinations of different types of mitigation systems.

No.	**Noise Abatement System resp. combination of Noise Abatement Systems** (applied air volume for the (D)BBC; water depth)	**Insertion loss ΔSEL [dB]** (min. / average / max.)	**Number of piles**
1	Single Big Bubble Curtain – BBC (> 0.3 m^3/(min·m), water depth < 25 m)	11 ≤ 14 ≤ 15	> 150
2	Double Big Bubble Curtain – DBBC (> 0.3 m^3/(min·m), water depth < 25 m)	14 ≤ 17 ≤ 18	> 150
3	Single Big Bubble Curtain – BBC (> 0.3 m^3/(min·m), water depth ~ 30 m)	8 ≤ 11 ≤ 14	< 20
4	Single Big Bubble Curtain – BBC (> 0.3 m^3/(min·m), water depth ~ 40 m)	7 ≤ 9 ≤ 11	30
5	Double Big Bubble Curtain – DBBC (> 0.3 m^3/(min·m), water depth ~ 40 m)	8 ≤ 11 ≤ 13	8
6	Double Big Bubble Curtain – DBBC (> 0.4 m^3/(min·m), water depth ~ 40 m)	12 ≤ 15 ≤ 18	3
7	Double Big Bubble Curtain - DBBC (> 0.5 m^3/(min·m), water depth > 40 m)	~ 15 – 16	1

Figure 4.27: Achieved unweighted broadband mitigation for different configurations of bubble curtain systems. Note: unoptimized configurations yielded significantly lower mitigation effect. (Bellmann, et al., 2020)

No.	**Noise Abatement System resp. combination of Noise Abatement Systems** (applied air volume for the (D)BBC; water depth)	**Insertion loss ΔSEL [dB]** (minimum / average / maximum)	**Number of foundations**
1	IHC-NMS (different designs) (water depth up to 40 m)	13 ≤ 15 ≤ 17 dB IHC-NMS8000 15 ≤ 16 ≤ 17 dB	> 450 > 65
2	HSD (water depth up to 40 m)	10 ≤ 11 ≤ 12 dB	> 340
3	optimized double BBC[*1] (> 0,5 m^3/(min m), water depth ~ 40 m)	15 – 16	1
4	combination IHC-NMS + optimized BBC (> 0,3 m^3/(min m), water depth < 25 m)	17 ≤ 19 ≤ 23	> 100
5	combination IHC-NMS + optimized BBC (> 0,4 m^3/(min m), water depth ~ 40 m)	17 – 18	> 10
6	combination IHC-NMS + optimized DBBC (> 0,5 m^3/(min m), water depth ~ 40 m)	19 ≤ 21 ≤ 22	> 65
7	combination HSD + optimized BBC (> 0,4 m^3/(min m), water depth ~ 30 m)	15 ≤ 16 ≤ 20	> 30
8	combination HSD + optimized DBBC (> 0,5 m^3/(min m), water depth ~ 40 m)	18 – 19	> 30
9	GABC skirt-piles[*2] (water depth bis ~ 40 m)	~ 2 – 3	< 20
10	GABC main-piles[*3] (water depth bis ~ 30 m)	< 7	< 10
11	„noise-optimized“ pile-driving procedure (additional additive, primary noise mitigation measure; chapter 5.2.2)	~ 2 - 3 dB per halving of the blow energy	

Figure 4.28: Achieved source mitigation effects at completed projects using different noise abatement systems, (Bellmann, et al., 2020).

The listed broadband mitigation, ΔSEL represents a flat frequency spectrum, in order to compare the efficiency of the different mitigation systems on different pile installations. Pile driving spectra however, as described in section 4.1.3, are far from a flat frequency spectrum, and the effective noise mitigation achieved in terms of sound level measured with and without the system in use at a specific installation, will therefore differ from the listed mitigation. In Figure 4.29, the broadband flat spectrum attenuation achieved, with the different mitigation systems, are instead given in 1/3 octave bands, thus showing the achieved mitigation per frequency band.

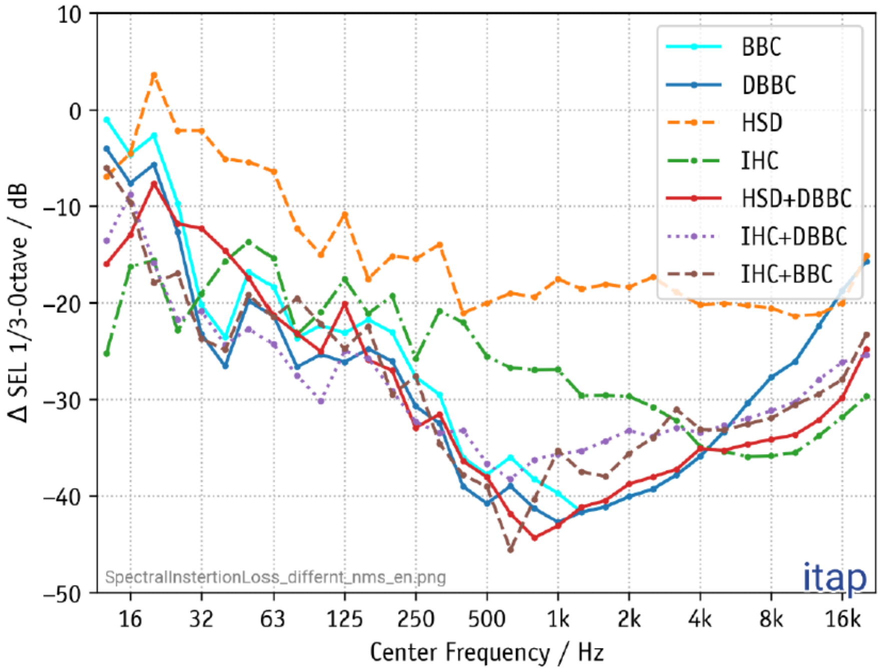

Figure 4.29: Frequency dependent noise reduction for noise abatement systems, (Bellmann, et al., 2020).

Lastly, it is important to recognize, that development of new and improved noise mitigation systems is an ongoing process, and new knowledge and often better solutions become available every year.

In Figure 4.29 the mitigation effect is provided as the noise level relative to installation without any active mitigation measures, so the more negative the value, the better the mitigation effect.

It should be noted from Figure 4.29, that the HSD+DBBC mitigation effect (red curve) is less than that of the DBBC system (dark blue curve) at several frequencies in the low and mid frequency region. This would imply, that the low- and mid-frequency mitigation effect decreases by adding an HSD system to a DBBC system. While the measurements would indeed indicate such an effect, it must be noted, that the representation method in (Bellmann, et al., 2020) does not represent the effect of a single fixed system used in different projects, but rather the average of a number of different systems, across different pile installations, across different project areas and environmental conditions. It is not clear from the report, when and where each mitigation system effect was measured, and it is therefore not possible to determine the direct contributors of any variation in effect.

As the measurement results originate from German OWFs, it is however worth noting the measurement procedure for installations including mitigation measures, where one pile is measured without any mitigation active, one pile is measured with each individual mitigation system (such as BBC or IHC-NMS) and the rest of the piles are measured with all mitigation systems active (such as IHC-NMS+DBBC).

It is also worth emphasizing that the mitigation effect presented is the average of achieved mitigation over a number of years, and given the continuous development of mitigation system technology, it is considered likely that performance would typically improve over time. Utilizing the reported average mitigation effect is therefore considered conservative. It should furthermore be expected, that entirely new and more effective mitigation systems and installation methods emerge in the coming years, however until such methods exist, it is not considered feasible to include in a prognosis.

In summary, prediction of achievable mitigation effect for any system, based on past installations, must be considered cautiously, and it should be expected that variations will occur between projects. The previously achieved mitigation effects can however be used more broadly to identify which type(s) of mitigation systems are likely to be useful for the current project, based on typical frequency specific mitigation effects.

If the purpose is to limit broadband noise output, a system with a high broadband mitigation effect could be a good choice. However if the purpose is to reduce the impact on a specific group of marine mammal or fish, the frequency specific mitigation effect should be considered. As an example, DBBC is very effective at reducing the broadband noise level, however for species such as porpoise (VHF) and dolphin (HF), which both have high frequency hearing above 10 kHz, a combination of HSD with DBBC could provide better protection, as indicated by the HSD+DBBC curve in Figure 4.29, for frequencies above 4 kHz. It is therefore recommended to always carry out detailed site and pile specific underwater sound emission modelling with incorporation of mitigation, based on the project specific mitigation purpose. It must also be emphasized, that any mitigation effect included in the prognosis is based on historical data, and not a suppliers guaranteed noise mitigation effect of a specific system. Such guarantee must be procured when final pile design is available, based on the actual installation scenario.

4.5.5. Uncertainties in determining mitigation effectiveness

A large uncertainty in the source model is the mitigation system effectiveness. While a large review (Bellmann, et al., 2020) contains data on mitigation technique effectiveness, it is reported in a statistical way, not documenting individually measured effectiveness, but averages. It is therefore not possible, from the review, to pin point and thereby model, the effectiveness of a specific solution individually. Using the average 1/3 octave band values is considered the best available method, however the uncertainty connected with this approach must be recognized.

Another limitation is the ambient noise level during the measurements. From (Bellmann, et al., 2020), it is noted that especially for the higher frequencies, the measured levels with active mitigation are often not distinguishable from the ambient noise. The actual effectiveness of the mitigation system can therefore not be determined with sufficient accuracy. Provided that the analysis in (Bellmann, et al., 2020) is conservative with regards to high frequency mitigation effect, it is more likely than not, that the implementation of the reported values will lead to a conservative estimate for species sensitive to high frequencies.

From (Bellmann, et al., 2020), it is also noted, that the reported mitigation effectiveness is a result of measurements acquired over a large time span, and with different iterations and variations of the same technology; this development is expected to continue. For prognosis in early stage development, where mitigation effectiveness is based on historical averages, it is likely that future innovation will allow for better mitigation than is currently available.

A large source of uncertainty pertains to the local environmental conditions. For bubble curtains, strong currents have the potential to “blow the bubbles away” and disturb the intended air flow and thereby the acoustic barrier effect. Seabed characteristics can also affect sound emission from the pile, in the sense that harder sediments can lead to increased sound transmission through the sediment, thereby potentially bypassing the mitigation system.

4.6. Source model with mitigation measures

The species specific mitigation requirements presented in section 4.4.3 were examined with respect to the available literature on achievable mitigation effects from different systems, as covered in section 4.5.

For the monopile foundation scenario, the BBC system is proposed for compliance with regulation as its reported mitigation effect is sufficient for all species specific mitigation requirements. In Table 4.13, the mitigation requirements, mitigation effect of BBC, and mitigated broadband source levels, are shown. To ensure a conservative prognosis, a 5 dB reduction in reported mitigation effectiveness of the system, compared to the values reported in (Bellmann, et al., 2020) (Figure 4.29), was used.

Table 4.13: Broadband source level for monopile foundation scenario, with and without frequency weighting, as well as mitigation effect of BBC.

Frequency weighting	Mitigation requirement $(\mathbf{L_{xx}})[\mathbf{dB}]$	Mitigation effect: BBC $(\mathbf{L_{xx}})[\mathbf{dB}]$	Mitigated source level $(\mathbf{L_{S,E}})[\mathbf{dB\ re.\ 1\mu Pa^2 m^2 s}]$
Unweighted	-	12.4 dB	212.4 dB
VHF Cetaceans	2.5 dB	11.4 dB	168.1 dB
Phocid Carnivores in water (PCW)	4.3 dB	18.7 dB	184.4 dB

For the jacket foundation scenario, no mitigation system is required for compliance with the authority guidelines, however due to TTS impact ranges for fish > 40 km and avoidance behaviour impact range for harbour porpoise of > 25 km, it was chosen to also calculate impact ranges for the jacket foundation with an active BBC mitigation effect. In Table 4.14, the mitigation requirements, mitigation effect of BBC, and mitigated broadband source levels, are shown. As for the monopile foundations, a conservative approach was taken, assuming a mitigation effect 5 dB below the values reported in (Bellmann, et al., 2020) (Figure 4.29).

Table 4.14: Broadband source level for jacket foundation scenario, with and without frequency weighting, as well as mitigation effect of BBC.

Frequency weighting	Mitigation requirement $(\mathbf{L_{xx}})[\mathbf{dB}]$	Mitigation effect: BBC $(\mathbf{L_{xx}})[\mathbf{dB}]$	Mitigated source level $(\mathbf{L_{S,E}})[\mathbf{dB\ re.\ 1\mu Pa^2 m^2 s}]$
Unweighted	-	14 dB	198.3 dB
VHF Cetaceans	0 dB	8.1 dB	166 dB
Phocid Carnivores in water (PCW)	0 dB	19.4 dB	174.1 dB

The source level in 1/3 octave bands with mitigation applied is provided for both foundation scenarios in Table 6.3, Appendix 1.

4.7. Mitigated underwater noise emission results

The sound propagation model was rerun in dBSea for all positions for foundation scenario 1 and 2 with their respective mitigation effects active. For foundation scenario 1, this was a 10 m diameter monopile with an active "BBC" mitigation effect, and for scenario 2; Jacket foundation with 4x 2.5 m diameter pin piles with an active BBC mitigation effect.

4.7.1. Distance-to-Threshold for mitigated pile driving

The following impact ranges for PTS, TTS and avoidance behaviour were calculated for the mitigated scenarios.

4.7.1.1. Scenario 1: 10 m monopile foundation with active BBC mitigation effect

Table 4.15: Resulting threshold impact distances for fish, mitigated monopile foundation (scenario 1).

Position	Distance-to-threshold (km)								
	Injury (r_{injury})					TTS (r_{TTS})			
	Stationary	Juvenile Cod	Adult Cod	Herring	Larvae and eggs	Stationary	Juvenile Cod	Adult Cod	Herring
1	1500 m	120 m	< 100 m	< 100 m	900 m	17.6 km	15.4 km	12.7 km	12.0 km
2	1300 m	< 100 m	< 100 m	< 100 m	800 m	15.9 km	13.7 km	11.2 km	10.4 km
3	1550 m	110 m	< 100 m	< 100 m	925 m	18.4 km	16.2 km	13.5 km	12.8 km
4	1250 m	< 100 m	< 100 m	< 100 m	750 m	13.4 km	11.4 km	8.8 km	8.1 km

Table 4.16: Resulting threshold impact distances for marine mammals, mitigated monopile foundation (scenario 1).

Position	Distance-to-threshold				
	PTS (r_{PTS})		TTS (r_{TTS})		Avoidance (r_{behav})
	Porpoise (VHF)	Seal (PCW)	Porpoise (VHF)	Seal (PCW)	Porpoise (VHF)
1	< 100 m	< 50 m	575 m	275 m	6.3 km
2	< 100 m	< 50 m	550 m	100 m	6.4 km
3	< 100 m	< 50 m	550 m	275 m	6.4 km
4	< 100 m	< 50 m	600 m	< 100 m	6.2 km

4.7.1.2. Scenario 2: Jacket foundation with 4x 2.5 m pin piles with active BBC mitigation effect

Table 4.17: Resulting threshold impact distances for fish, mitigated jacket foundation (scenario 2).

Position	Distance-to-threshold (km)								
	Injury (r_{injury})					TTS (r_{TTS})			
	Stationary	Juvenile Cod	Adult Cod	Herring	Larvae and eggs	Stationary	Juvenile Cod	Adult Cod	Herring
S	525 m	< 100 m	< 100 m	< 100 m	375 m	5.8 km	1.4 km	<200 m	<200 m

Table 4.18: Resulting threshold impact distances for marine mammals, mitigated jacket foundation (scenario 2).

Position	Distance-to-threshold				
	PTS (r_{PTS})		TTS (r_{TTS})		Avoidance (r_{behav})
	Porpoise (VHF)	Seal (PCW)	Porpoise (VHF)	Seal (PCW)	Porpoise (VHF)
S	< 100 m	< 50 m	225 m	< 100 m	4.3 km

4.8. Uncertainties

In this section, a discussion of the prognosis uncertainties is provided, divided into the categories: Source characteristics, environmental parameters and mitigation effect.

4.8.1. Uncertainties in the source model

The prognosis assumes a worst case scenario of a 10 m diameter monopile, while the project may be completed using monopiles of a smaller diameter. An uncertainty of absolute source level is therefore present in the model. As explained in details in section 4.1.2, even for the 10 m monopile, literature reviews of previous installations show significant variations in not only source level, but also in frequency spectrum. An unweighted uncertainty of up to ±5dB is indicated in (Bellmann, et al., 2020), however with largest uncertainties for small pile diameters, and lower deviations from the average for larger pile sizes. Following this pattern, a ±5dB uncertainty appears conservative for the monopile scenario.

Uncertainties in the environmental parameters primarily relate to the top soil sediment properties, and changes in the bathymetry from what is included in the model. Also the actual sound speed profile, temperature and salinity during installation will be a contributing factor. The prognosis has assumed worst-case conditions for environmental parameters, and it is therefore considered more likely than not, that the environmental conditions in the model result in a conservative prognosis. Furthermore, the sound propagation model assumes calm waters, meaning very little backscatter from the air-water interface, thus understating the losses when the sea state is higher.

Mitigation effects used in these calculations are based on a literature review by Bellmann et al. (2020), which is the largest publicly available collection of mitigation effectiveness of noise mitigation systems to date. It must however be noted, that mitigation effectiveness in the review by (Bellmann, et al., 2020) was not reported on a project-by-project basis, detailing the specific environmental and source conditions for each dataset, but rather with focus on the mitigation effect of different types of mitigation systems. The resulting mitigation effectiveness of such systems should therefore be considered with a degree of caution, and prone to deviations for any future application. For bubble curtain systems, differences in air pressure, hole size, distance from pile, sediment vibration transmission properties and sea currents will also play a role in mitigation effect achievable for any given project and pile installation.

While a BBC was found sufficient in this prognosis, it should be noted, that a detailed calculation should be made for the actual mitigation solution to be used, for the actual pile installation to be performed. To ensure a conservative prognosis, the mitigation effect used for both monopile and jacket foundation, was reduced by 5 dB in comparison to reported effectiveness by (Bellmann, et al., 2020), Figure 4.29.

4.9. Conclusion

Underwater sound propagation modelling was undertaken for a 10 m diameter monopile scenario, representing Wind Turbine Generator (WTG) foundations, as well as for a jacket foundation used for a sub-station, within the THOR Offshore Wind Farm (OWF).

Calculations were completed in line with authority guideline requirements (Energistyrelsen, 2022), and the results show compliance, through use of a Big Bubble Curtain (BBC) mitigation effect for the monopiles. For the jacket foundation, no mitigation was required as per Danish guidelines, however due to long impact ranges, a BBC mitigation effect was proposed and included in the calculations.

Conclusions for each of the foundation types are provided below.

4.9.1. Pile driving of 10 m monopile

The prognosis showed mitigation requirements of $\mathbf{L_{VHF}} = 2.5\ dB$ and $\mathbf{L_{PCW}} = 4.3\ dB$ for the monopile foundations. It was chosen to use literature based mitigation values to ensure compliance, corresponding to a BBC, however conservatively applying a 5 dB reduction in mitigation effectiveness.

Calculations with mitigation effect active, showed Permanent Threshold Shift (PTS) is unlikely to occur for harbour porpoise and seals located further than 100 m and 50 m respectively, from the source at the onset of piling activities. Temporary Threshold shift (TTS) is unlikely to occur for harbour porpoise located further than 600 m from the source at onset of piling, while it is 275 m for seals.

Avoidance behaviour impact range for harbour porpoise was calculated to be up to 6.4 km radius from the source for the part of the installation where 100% hammer energy is applied. For lower hammer energies, such as during soft start and ramp up, shorter behaviour impact distances are observed.

For fish, impact distances between 8.1 km – 18.4 km for TTS were found, with the stationary (non-fleeing) fish experiencing the longest impact range, and herring the shortest. Injury distances are found to be up to 1550 m for stationary fish, up to 120 m for juvenile cod, and below 100 m for adult cod and herring. For larvae and eggs the injury distances were calculated up to 925 m.

4.9.2. Pile driving of 4x 2.5 m pin piles for sub-station jacket foundation

The prognosis showed mitigation requirements of $\mathbf{L_{VHF}} = 0\ dB$ and $\mathbf{L_{PCW}} = 0\ dB$ for the jacket foundation, thereby being in compliance with Danish guidelines without any mitigation measures applied. As previously mentioned, a BBC mitigation effect was however included due to far reaching consequences for fish and harbour porpoise behaviour, which are effects not covered in the guideline evaluation criteria. A 5 dB reduction in mitigation effectiveness was applied to ensure a conservative prognosis.

Calculations with mitigation effect active, showed Permanent Threshold Shift (PTS) is unlikely to occur for harbour porpoise and seals located further than 100 m and 50 m respectively, from the source at the onset of piling activities. Temporary Threshold shift (TTS) is unlikely to occur for harbour porpoise located further than 225 m from the source at onset of piling, while it is below 100 m for seals.

Avoidance behaviour impact range for harbour porpoise was calculated to be up to 4.3 km radius of the pile for the part of the installation where 100% hammer energy is applied. For lower hammer energies, such as during soft start and ramp up, shorter behaviour impact distances are observed.

For fish, impact distances between 200 m – 5.8 km for TTS were found, with the stationary (non-fleeing) fish experiencing the longest impact range, and herring the shortest. Injury distances are found to be up to 525 m for stationary fish, and below 100 m for all cod and herring. For larvae and eggs the injury distances were calculated up to 375 m.

4.10. Discussion on cumulative impact from multiple concurrent installations

If more than one foundation is installed at the same time, the cumulative aspects for sound propagation must be considered. Two scenarios are considered; Simultaneous/partially overlapping and sequential installation.

4.10.1. Installation of two foundations simultaneously

If two foundations were to be installed at the same time, this would likely result in increased PTS and TTS impact distances (up to a factor 2 increase), as these thresholds are based on the time-dependent noise dose received by a marine mammal or fish. For certain species, this would depend on their swim speed.

The further apart the two foundations, the lower the difference in PTS/TTS relative to the single foundation scenario. However, with larger spacing, a trapping effect could potentially occur, whereby a marine mammal or fish would swim away from the underwater noise caused by one foundation, only to get closer to the installation of the second foundation, thus not achieving a linear decrease in received SEL with time. In this scenario, it is difficult to predict what $L_{E,cum,24h}$, the marine mammal or fish would receive over the span of the installations. Inversely, the closer the foundations, the lower the risk of trapping, but also the longer the threshold distances for PTS and TTS would be expected.

One method for reducing the increase in impact distances for concurrent installations, would be to add a time-delay to the installation of the second foundation, such that the marine mammals are able to create distance between themselves and the pile installation(s), before both piling activities are active. It is assessed that the increase in PTS/TTS distances could be up to a factor 2 of the single installation, however with a time-delayed approach, it is unlikely that the increase would exceed a factor 1.5.

Another aspect of concurrent installations is that it can potentially result in increased behaviour distances. The interaction between wave fronts from two pile installations will however be a complex mix of positive and destructive interference patterns as the wave fronts collide. The resulting sound field would be impossible to predict but it is expected that avoidance behaviour could occur at increased distances, compared to those of a single pile installation. The joint behaviour impact area of the individual installations would however be larger than that of the individual installation, depending on the distance between the piles. In a worst-case scenario, where the piles are separated by the sum of the individual behaviour radius, the joint behaviour impact area would correspond to the sum of the individual behaviour impact areas, and if synchronized in time, potentially up to a 20-25% larger area near the wavefront intersection.

4.10.2. Installation of two foundations sequentially

Installation of two foundations sequentially, where the second pile installation is started as soon as the former is completed, would result in more predictable effects on the underwater soundscape. In a closely spaced scenario, the marine mammals and fish that would be affected by the second pile installation, would already have had significant time to vacate the underwater noise impacted area, thereby limiting the increase in impact.

For behaviour, the impact distance would not be affected by interference patterns (which will be the case if installation of two pile installations occurs at the same time), nor would it equate the sum of impact areas for both installations, rather it would shift from one location to the next. For PTS and TTS, the impact distances would likely not increase, as the marine mammals and fish are already assumed far from both installation sites and therefore receiving minimal additional impact from the installation of the second installation. It is however important that the second installation is not delayed significantly in time after the completion of the first, as this would allow for marine mammals and fish to return to the area.

5. Underwater noise evaluation for operation phase

Underwater noise from offshore wind turbines comes primarily from two sources: mechanical vibrations in the nacelle (gearbox etc.), which are transmitted through the tower and radiated into the surrounding water; and underwater radiated noise from the service boats in the wind farm. Comparatively few, good measurements of underwater noise from operating offshore wind turbines are available. All available measurements were reviewed by (Tougaard, et al., 2020). The individual measurements were obtained from different turbine types and sizes and at different wind speeds and distances from the foundation. All measurements show that sound levels radiated from turbine foundations are relatively low, but with an increasing trend with increasing turbine size (Figure 5.1). It is likely that there are differences between noise levels from different types of foundations and between turbine technologies (direct drive vs. gear box), but the limited data does not allow for such differences to be resolved.

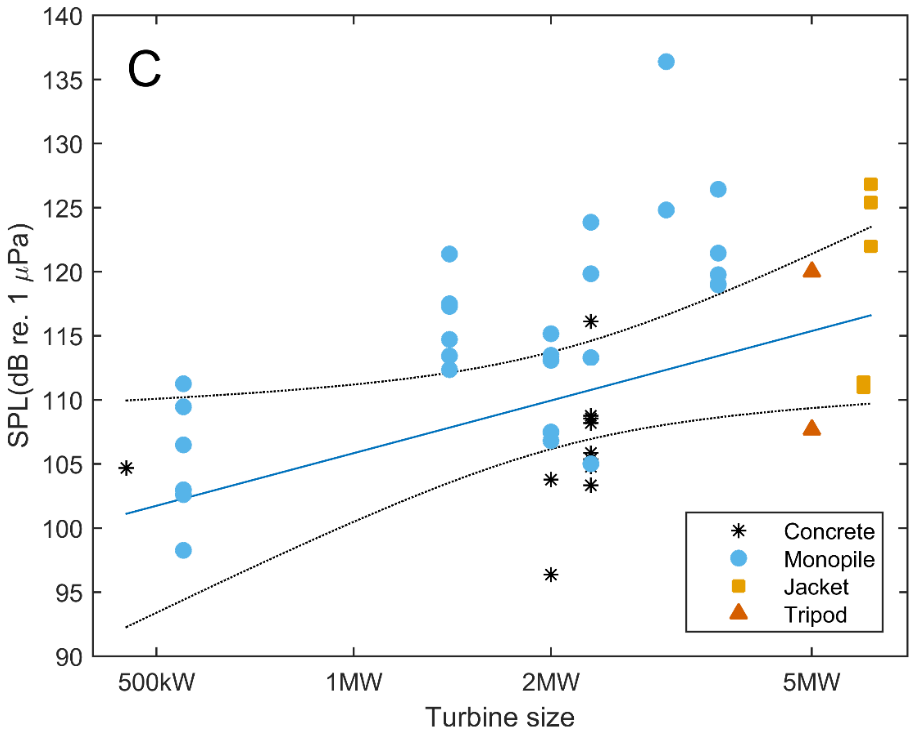

Figure 5.1: Relationship between measured broadband noise and turbine size compiled from available literature sources. Measurements have been normalized to a distance of 100 m from the turbine foundation and a wind speed of 10 m/s. From (Tougaard, et al., 2020).

There is a strong dependency between wind speeds and radiated noise levels (Figure 5.2). At the lowest wind speeds, below the cut-in, there is no noise from the turbine. Above cut-in, there is a pronounced increase in the noise level with increasing wind speed, until the noise peaks when nominal capacity is reached in output from the turbine. Above this point, there is no further increase with wind speed and perhaps even a slight decrease.

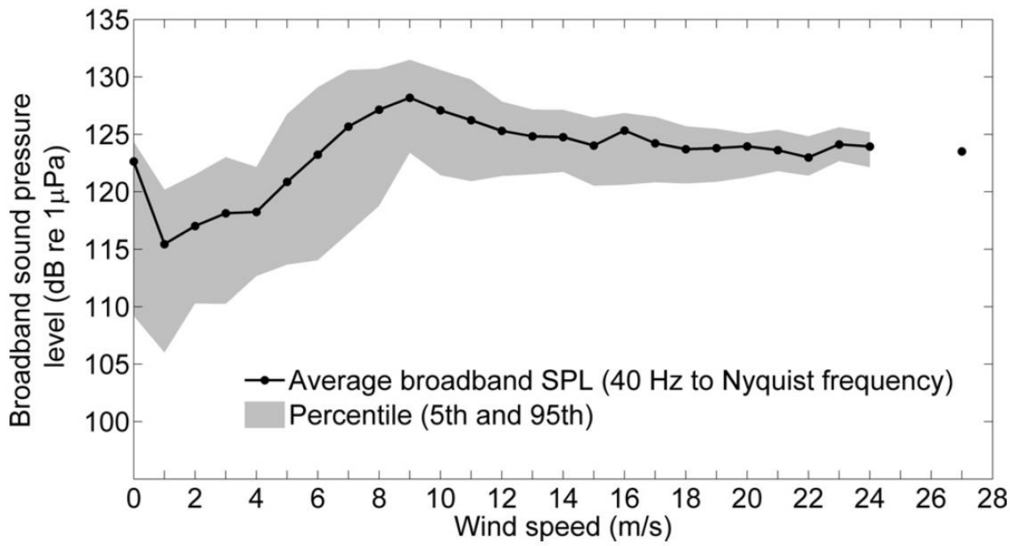

Figure 5.2: Relationship between wind speed and broadband noise level, measured about 50 m from the turbine (3.6 MW Siemens turbine at Sheringham Shoal). Maximum production of the turbine is reached at about 10 m/s, above which the production is constant. Figure from (Pangerc, et al., 2016).

All measurements of turbine noise shows the noise to be entirely confined to low frequencies, below a few kHz and with peak energy in the low hundreds of Hz. One spectrum of a typical mid-sized turbine is shown in Figure 5.3, where pronounced peaks are visible in the spectrum in the 160 Hz and 320 Hz, 10 Hz bands.

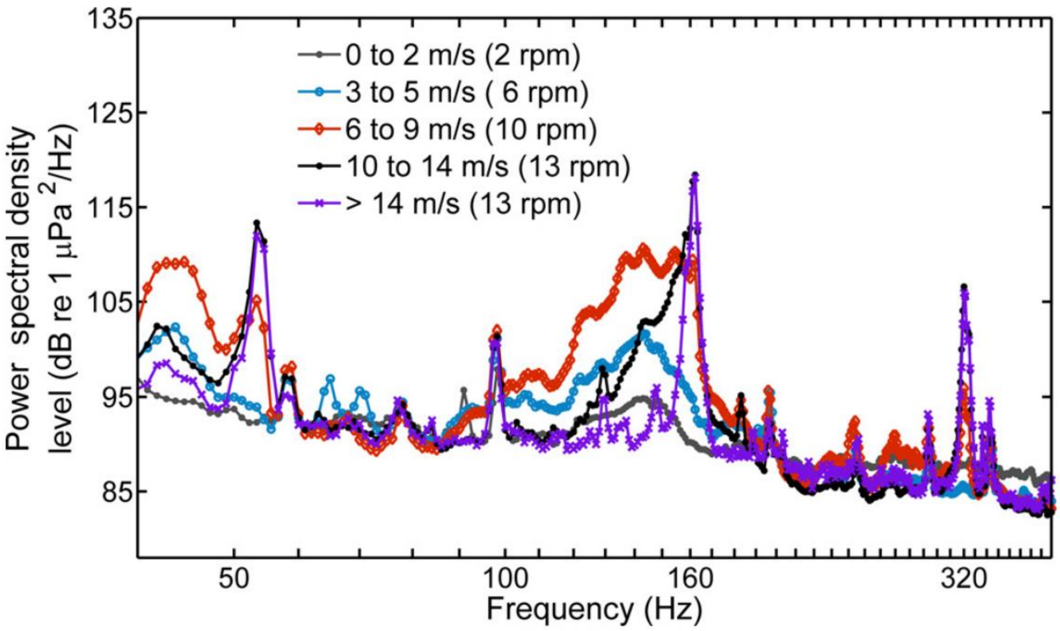

Figure 5.3: Example of frequency spectra from a medium sized turbine (3.6 MW, Gunfleet Sands) at different wind speeds. Levels are given in 10 Hz intervals. Measurements were obtained about 50 m from the turbine. Measurements from (Pangerc, et al., 2016).

While the type and size of turbines to be used for the project, no data is available on underwater noise emission. It is considered likely that the turbine noise will be comparable to what has been measured from other turbines. However, it should be considered with caution. Based on the data in Figure 5.1, a number of observations should be mentioned. First and foremost, significant variation in measured sound levels for individual turbine sizes on same foundation type, up to 20 dB is noticed. Second, the trendline (blue) representing the best fit of all data points, is not assessed to provide an accurate fit for any given turbine size. This presents a challenge in terms of reliably predicting source levels within the covered turbine size range in Figure 5.1 (0.4 MW – 6.15 MW), and to an even greater extent for turbine sizes outside this range. For Thor OWF, turbine will have an individual capacity of 14 MW (with possibility for boost). This would represent a 5 fold increase compared to the available empirical data for monopiles. Given the uncertainties present in the empirical data, any extrapolation of such magnitude is considered to be provide a very uncertain source level prediction.

An additional source of uncertainty in prediction is the type of turbine. All but one of the turbines, from which measurements are available, are types with gearbox, a main source of the radiated noise. Only one measurement is available for a turbine with a direct drive (Haliade 150, 6 MW) (Elliott, et al., 2019), which is a type increasingly being installed in new projects, and which is also the type to be used for Thor OWF. The limited data suggests that noise levels from the direct drive turbines are more broadband in nature than from types with gear box.

For comparison, in a review by Bellmann et. al (2020), a study of underwater noise emission from pile driving activities of different pile sizes was presented, see Figure 4.1. The relationship between measured sound level at 750 m and the foundation pile diameter, for piles 1 m – 8 m diameter, showed a clear trendline (blue). This was used in the pile driving prognosis to extrapolate the source level of the 10 m diameter monopile foundation, as well as interpolate it for the 2.5 m pin piles for the jacket foundation.

For the monopiles, this corresponded to an extrapolation factor 1.2, for the available empirical data, and for the 2.5 m pin piles, this was covered within the available data range. Examining the lower half of the empirical data however reveals a significant variation in measured levels. Had a trendline been established for the data points spanning 0.5 – 4 m pile diameter, an extrapolation to 10 m diameter monopiles would have been connected with a significant degree of uncertainty, and would likely have indicated a steeper trendline, resulting in a higher extrapolated source level estimate for larger pile sizes.

It is assessed to be highly likely, that this is currently the case for operational underwater noise. The data set used to establish a trend, is very limited, and will potentially result in significant errors that scale in size, with the degree of extrapolation.

Despite all of the above mentioned uncertainties, a calculation for PTS, TTS and behaviour reaction threshold criteria is carried out below, based on the blue trendline in Figure 5.1 as well as the scaling and frequency considerations presented in (Tougaard, et al., 2020). It should be kept in mind, that there are significant uncertainties with the estimated impact range due to the lack of scientific data supporting such a calculation.

For a 15 MW turbine, the sound level at 100 m, would be $SPL_{rms} = 122\ dB\ re\ 1\mu Pa$, based on the extrapolation of the blue trendline. The primary frequency would be ~160 Hz, with secondary frequency at 320 Hz, approximately 10 dB below the primary (Tougaard, et al., 2020).

A conservative approach would set the unweighted 160 Hz level to $SPL_{rms} = 122\ dB\ re\ 1\mu Pa$ and for 320 Hz, $SPL_{rms} = 112\ dB\ re\ 1\mu Pa$.

Seals and harbor porpoise however are not equally good at hearing all frequencies. As described in further detail in section 3.3.4, frequency weighting functions are used to more accurately predict impact ranges for the individual species. For seal, the frequency weighting for Phocid Carnivores in Water (PCW) is used, and for harbor porpoise, Very High Frequency Cetacean (VHF). In Figure 3.2, the frequency dependent correction values are listed, from which the following correction values (number of dB to be subtracted from unweighted levels) can be observed for seal and harbor porpoise.

- For seal:
  - -20 dB at 160 Hz, and
  - -15 dB at 320 Hz.
- For harbor porpoise:
  - -65 dB at 160 Hz, and
  - -55 dB at 320 Hz.

The sound levels, as experienced by seal and harbor porpoise, from a single turbine in operation would therefore amount to:

- For seal:
  - @160Hz, 100 m distance: $SPL_{rms,PW} = 102\ dB\ re\ 1\mu Pa$
  - @320Hz, 100 m distance: $SPL_{rms,PW} = 97\ dB\ re\ 1\mu Pa$
  - "Broadband", 100 m distance: $SPL_{rms,PW} = 103\ dB\ re\ 1\mu Pa$
- For harbor porpoise
  - @160Hz, 100 m distance: $SPL_{rms,VHF} = 57\ dB\ re\ 1\mu Pa$
  - @320Hz, 100 m distance: $SPL_{rms,VHF} = 57\ dB\ re\ 1\mu Pa$
  - "Broadband", 100 m distance: $SPL_{rms,VHF} = 60\ dB\ re\ 1\mu Pa$

For seal, no behaviour threshold is currently supported by literature, and it is therefore not possible to compare the sound level at 100 m with a behavioral threshold. For harbor porpoise, a behavioural threshold criteria of $SPL_{rms,125ms,VHF} = 103\ dB\ re\ 1\mu Pa$, is however provided in (Tougaard, 2021). Noticing, that the single turbine level at 100 m is 43 dB below the behavioural threshold value, it is unlikely that the harbor porpoise will react to the noise from one operating turbine. Even when summing the contributions of all nearby turbines, assuming a conservative 15 dB/decade sound propagation loss, the nearest 9 turbines would add less than 5 dB in any position to this level, and further turbines, even less. A cautious total of 10 dB addition to the sound field, from all turbines combined, will still mean that the sound level is 33 dB below the behavioural threshold value. It is therefore assessed that even for the conservative scenario, behavioural reaction is considered unlikely.

Adding 10 dB (to include noise from nearby turbines) would bring the broadband sound levels at 100 m up to $SPL_{rms,PCW} = 113\ dB\ re\ 1\mu Pa$ for seal, and $SPL_{rms,VHF} = 70\ dB\ re\ 1\mu Pa$ for harbor porpoise. Calculating the cumulative noise dose for a seal located at a constant distance of 100 m from a turbine foundation within the wind farm area, over a 24 hour period, would result in cumulative sound exposure level, $SEL_{cum,24h,PCW} = 113 + 10 \cdot log_{10}(86400) \cong 152\ dB\ re.1\mu Pa^2 s$. Given a threshold criteria for onset of TTS in seal for continuous noise of $SEL_{cum,24h,PW} = 183\ dB\ re.1\mu Pa^2 s$, the impact over a 24 hour duration is 31 dB lower than the TTS onset criteria. With a 31 dB margin to the TTS threshold criteria, auditory injures are unlikely to occur.

For harbor porpoise, the calculation gives an $SEL_{cum,24h,VHF} = 70 + 10 \cdot log_{10}(86400) \cong 119\ dB\ re.1\mu Pa^2 s$. This is 34 dB below the threshold criteria for TTS. With a 34 dB margin to the TTS threshold criteria, auditory injures are unlikely to occur.

Most fish detect sound from the infrasonic frequency range (<20 Hz) up to a few hundred Hz (e.g. salmon, dab and cod) whereas other fish species with gas-filled structures in connection with the inner ear (e.g. herring) detect sounds up to a few kHz. The main frequency hearing range for fish is therefore overlapping with the frequencies, produced by operational wind turbines (below a few hundred Hz). There are no studies defining fish behavioural response threshold for continuous noise sources, and the scientific data addressing TTS from such noise sources is very limited. The only studies providing a TTS threshold value for fish is from experiments with goldfish. Goldfish is a freshwater hearing specialist with the most sensitive hearing in any fish species. In the project area for Thor OWF, the most common fish species are flatfish (plaice, dab and solenette), cod as well as herring and European sprat (Rambøll, 2021). All of these species have a less sensitive hearing compared to the goldfish (Popper, et al., 2014), and using threshold for goldfish will lead to an overestimation of the impact. Empirical data for several of the fish species without a connection between the inner ear and the gas-filled swim bladder showed no TTS in responses to long term continuous noise exposure (Popper, et al., 2014). In a study by Wysocki et al. (2007), rainbow trout exposed to increased continuous noise (up to 150 dB re 1 μPa rms) for nine months in an aquaculture facility, showed no hearing loss nor any negative health effect. Therefore, it is assessed that TTS is unlikely to occur as a result of an operational offshore wind farm.

In summary, the underwater noise emission from operational wind turbines, depends on the turbine size, wind speed and whether it has a gear-box or is gearless (direct drive). While available literature indicates a correlation between turbine size and underwater noise levels, the available dataset is limited to 6.15 MW turbines, and shows significant variance in reported noise levels for the same turbine size. Extrapolation of the reported trend, to be used in assessing the underwater noise emission from future turbines of 15 MW and larger, should therefore be used with caution.

5.1. Noise from service boats

In addition to the noise from the turbines themselves, the service boats within wind farms are likely to be a source of underwater noise during the operational phase of the wind farm. However, the levels and temporal statistics of this noise source has not yet been sufficiently quantified or described. Without dedicated studies it is therefore not possible to quantify the contribution of service boats to the noise in the wind farm.

It is expected that both small and fast boats as well as larger, slower moving vessels will be used. Underwater noise from smaller boats has a noise level ranging 130-160 dB re 1 µPa@1meter (Erbe, 2013; Erbe, et al., 2016), while the underwater noise levels from larger vessels is up to 200 dB re 1 µPa@1 meter (Erbe & Farmer, 2000; Simard, et al., 2016; Gassmann, et al., 2017). Source levels may vary by 20-40 dB within a ship class due to variability in design, maintenance, and operation parameters such as speed (Simard, et al., 2016; Erbe, et al., 2019). Furthermore the underwater noise levels increase when the ship is maneuvered, such as when the ship goes astern, or thrusters are used to hold the ship at a certain position (Thiele, 1988). Ship noise contributes to the ambient underwater noise level from frequencies as low as 10 Hz to as high as several kHz, depending on ship size and speed (Haver, et al., 2021).

The Thor OWF area is located in an area with heavy ship traffic and near a major shipping route (Jomopans, 2021; Rambøll, 2022) and the area is therefore expected already to be dominated by low-frequency ship noise.

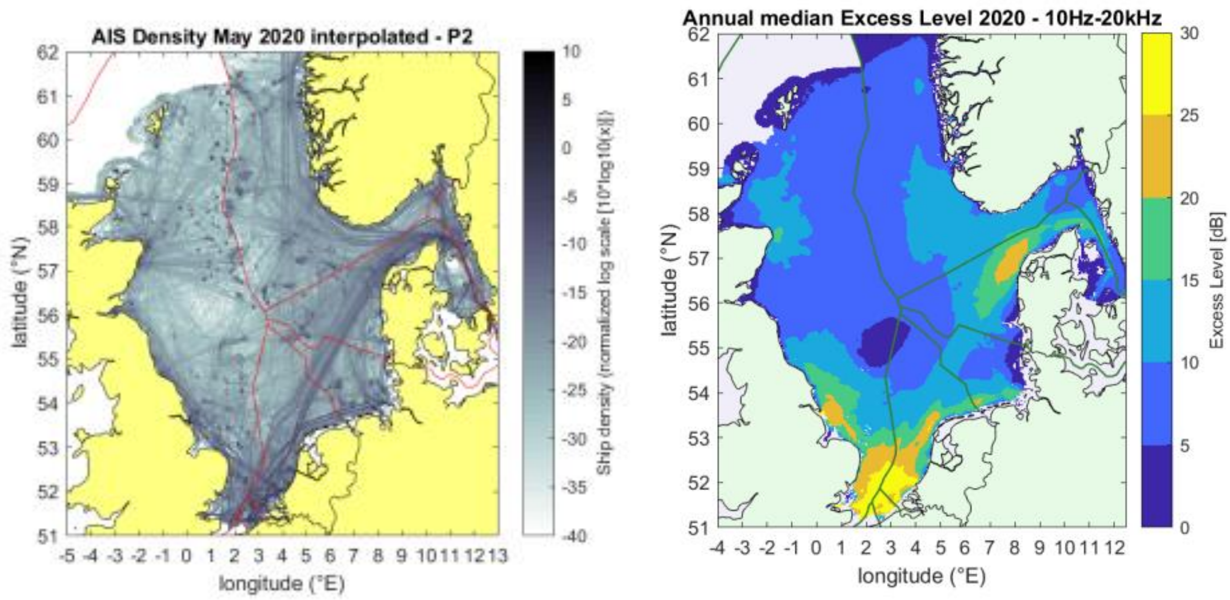

Figure 5.4: AIS density plots for May 2020 dB shown as interpolated AIS recordings (left) and annual median (50th percentile) broadband excess level (in dB) in the North Sea region in 2020 (right), where shipping noise dominates over wind noise (Jomopans, 2021).

Based on data from the JOMOPANS-project, the ambient underwater noise level is already dominated by ship noise (Figure 5.4), and it is considered unlikely, that the vessel traffic added by the operation of the wind farm, will result in broad increases to the current underwater soundscape.

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Appendix 1

Source frequency spectrums, 1/3 octave band values

Table 6.1: Source level in 1/3 octave bands, for the unmitigated and unweighted foundation scenario 1: 10 m diameter monopile. Note that a 5 dB gain has been added to the 32 kHz band to compensate for the limitation in frequency range.

Frequency [Hz]	ESL [dB]
12.5	202.7
16	198.2
20	199.5
25	210.9
31.5	205.4
40	209.5
50	212.5
63	213.4
80	214.6
100	218.4
125	217.5
160	216.7
200	212.9
250	209.9
315	204.4
400	202.4
500	199.6
630	194
800	193.9
1k	192.6
1.2k	190.9
1.6k	189.6
2k	188.3
2.5k	186.3
3.2k	182.4
4k	182.4
5k	180.5
6.3k	178.8
8k	176.8
10k	175
12.5k	173.4
16k	172.1
20k	171
25k	170.4
32k	170.5

Table 6.2: Source level in 1/3 octave bands, for the unmitigated and unweighted foundation scenario 2: Jacket foundation with 4x 2.5 m diameter pin piles. Note that a 5 dB gain has been added to the 32 kHz band to compensate for the limitation in frequency range.

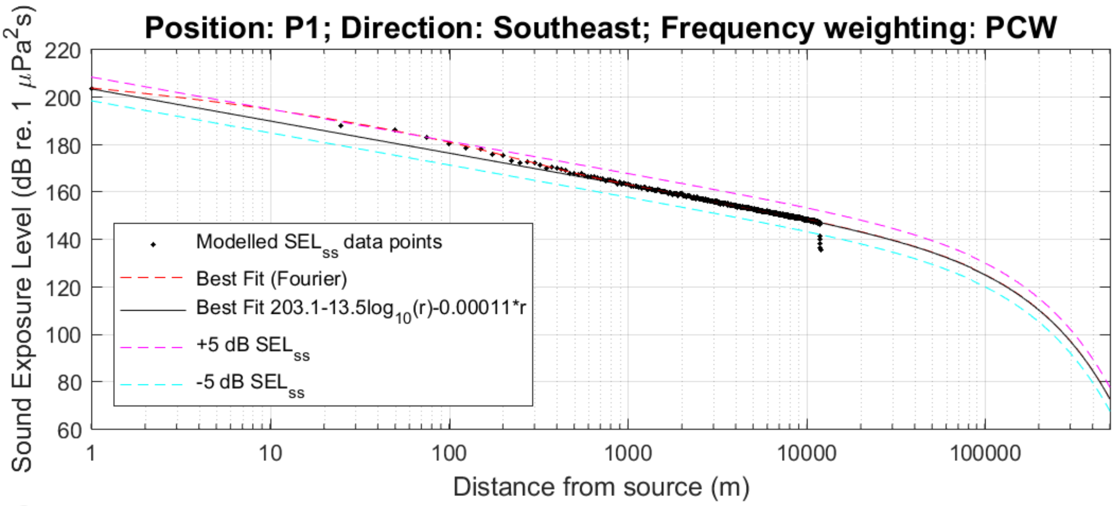
Frequency [Hz]	ESL [dB]
12.5	187.3
16	184.3
20	185.1
25	197.5
31.5	191
40	195.1
50	197.6
63	199
80	200.2
100	202
125	203.1
160	204.8
200	204
250	204
315	199
400	197
500	194.2
630	188.6
800	188.5
1k	187.2
1.2k	185.5
1.6k	184.2
2k	182.9
2.5k	180.9
3.2k	177
4k	177
5k	175.1
6.3k	173.4
8k	171.4
10k	169.6
12.5k	168
16k	166.7
20k	165.6
25k	165
32k	170.1

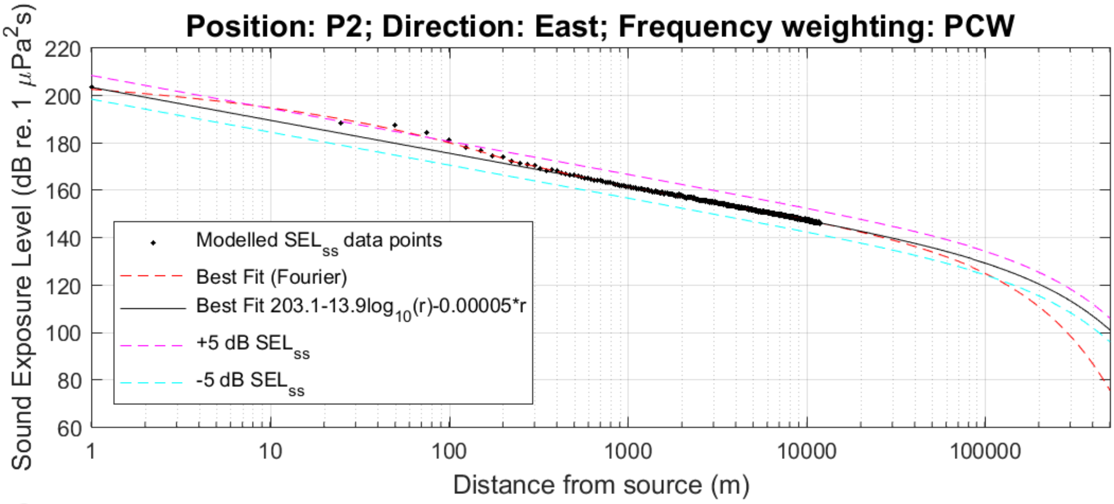
Table 6.3: Source level in 1/3 octave bands, for the mitigated foundation scenarios. Note: A) a 5 dB gain has been added to the 32 kHz band to compensate for the limitation on frequency range. B) a 5 dB reduction in assumed mitigation effectiveness has been used.

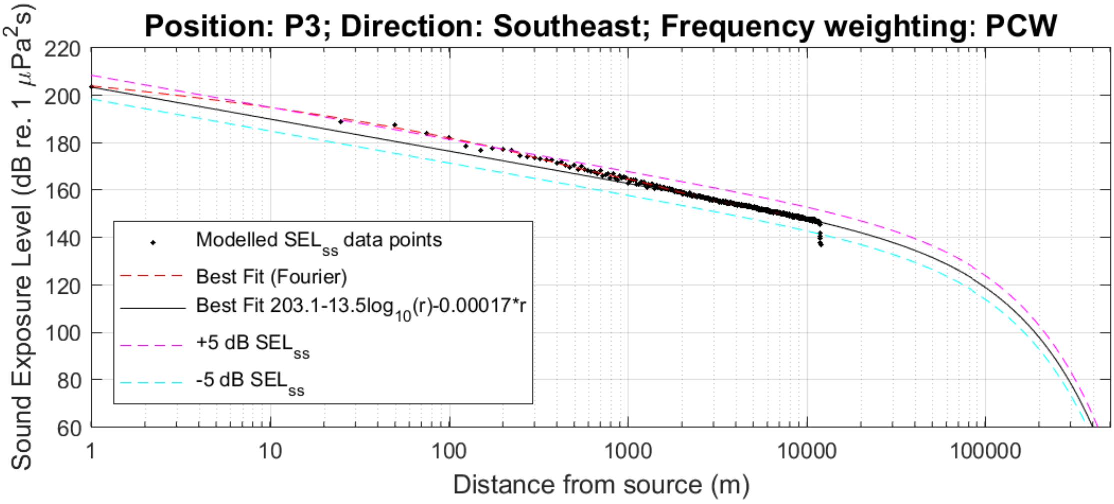
Frequency [Hz]	ESL (mitigated) [dB]	
	Monopile foundation (scenario 1) + BBC	Jacket foundation (scenario 2) + BBC
12.5	206.7	191.3
16	198.2	184.3
20	201.5	187.1
25	205.9	192.5
31.5	190.4	176
40	191.5	177.1
50	201.5	186.6
63	200.4	186
80	196.6	182.2
100	201.4	185
125	199.5	185.1
160	199.7	187.8
200	194.9	186
250	186.9	181
315	180.4	175
400	170.4	165
500	166.6	161.2
630	163	157.6
800	160.9	155.5
1k	157.6	152.2
1.2k	153.9	148.5
1.6k	153.6	148.2
2k	153.3	147.9
2.5k	152.3	146.9
3.2k	149.4	144
4k	151.4	146
5k	152.5	147.1
6.3k	153.8	148.4
8k	153.8	148.4
10k	153	147.6
12.5k	155.4	150
16k	158.1	152.7
20k	160	154.6
25k	162.4	157
32k	165.5	165.1

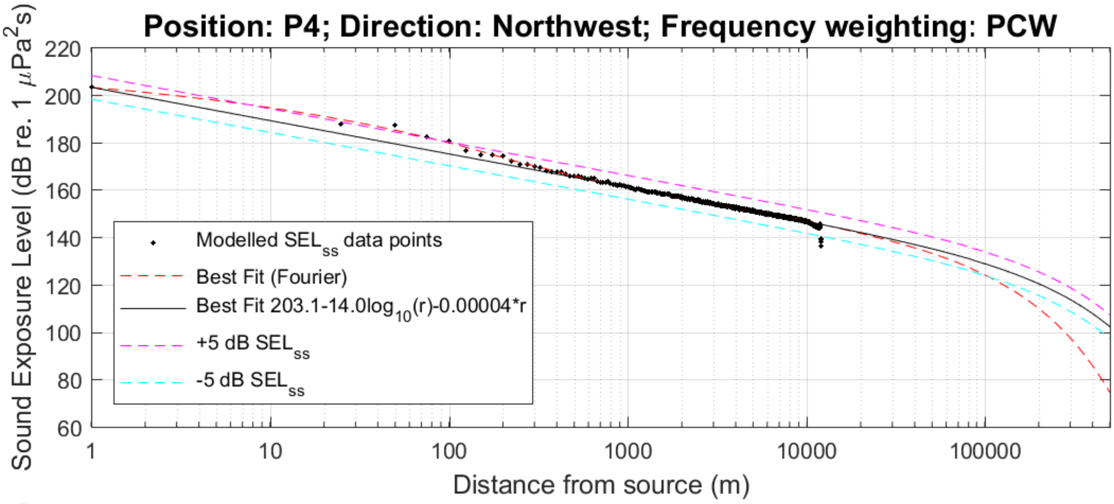
Appendix 2

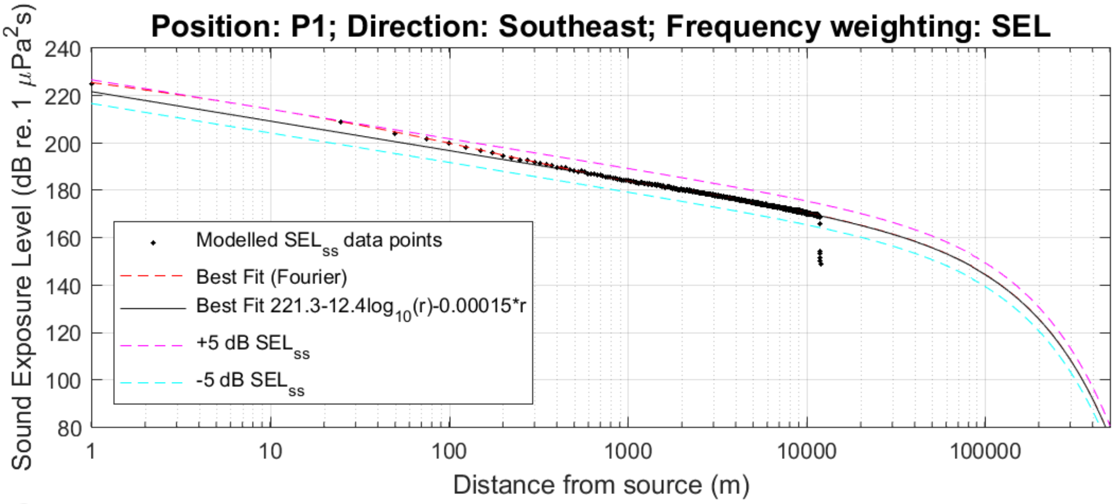
Foundation scenario 1: Monopile curve fits, unmitigated

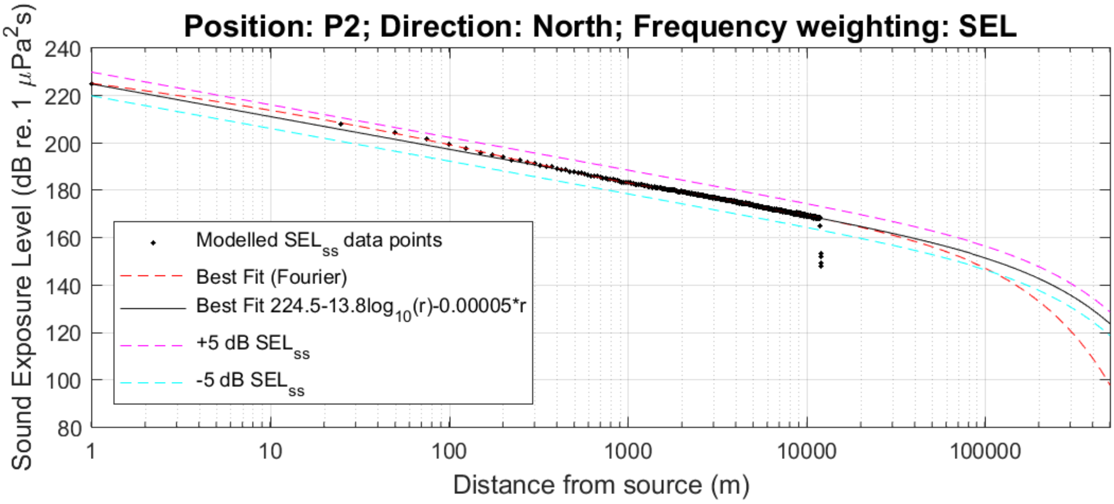

Position: P1; Direction: Southeast; Frequency weighting: PCW
Sound Exposure Level (dB re. 1 μPa²s)
220
200
180
160
140
120
100
80
60
1
10
100
1000
10000
100000
Distance from source (m)
Modelled SEL_ss data points
Best Fit (Fourier)
Best Fit 203.1-13.5log_10(r)-0.00011*r
+5 dB SEL_ss
-5 dB SEL_ss

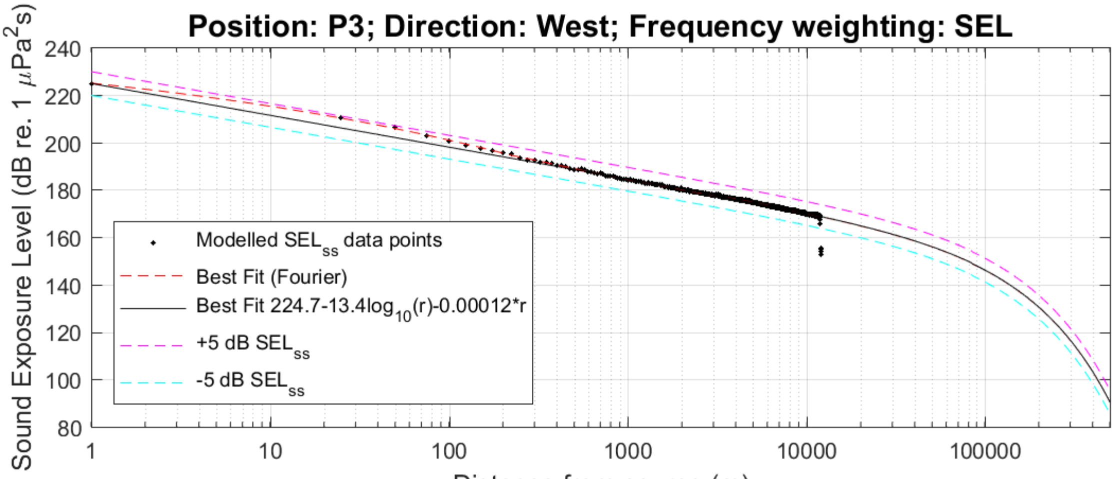

Position: P2; Direction: East; Frequency weighting: PCW
Sound Exposure Level (dB re. 1 μPa²s)
220
200
180
160
140
120
100
80
60
1
10
100
1000
10000
100000
Distance from source (m)
Modelled SEL_ss data points
Best Fit (Fourier)
Best Fit 203.1-13.9log_10(r)-0.00005*r
+5 dB SEL_ss
-5 dB SEL_ss

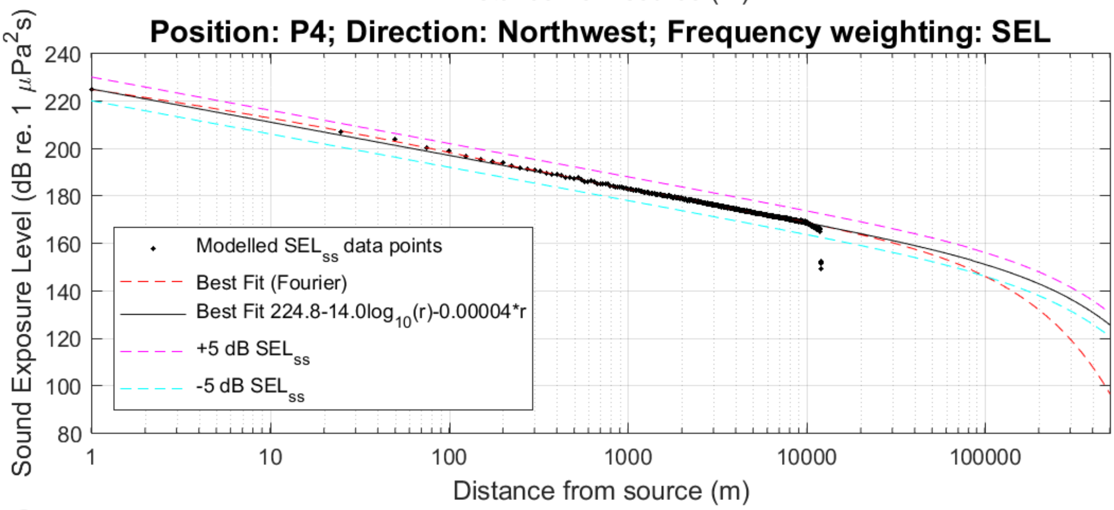

Position: P3; Direction: Southeast; Frequency weighting: PCW
Sound Exposure Level (dB re. 1 μPa²s)
220
200
180
160
140
120
100
80
60
1
10
100
1000
10000
100000
Distance from source (m)
Modelled SEL_ss data points
Best Fit (Fourier)
Best Fit 203.1-13.5log_10(r)-0.00017*r
+5 dB SEL_ss
-5 dB SEL_ss

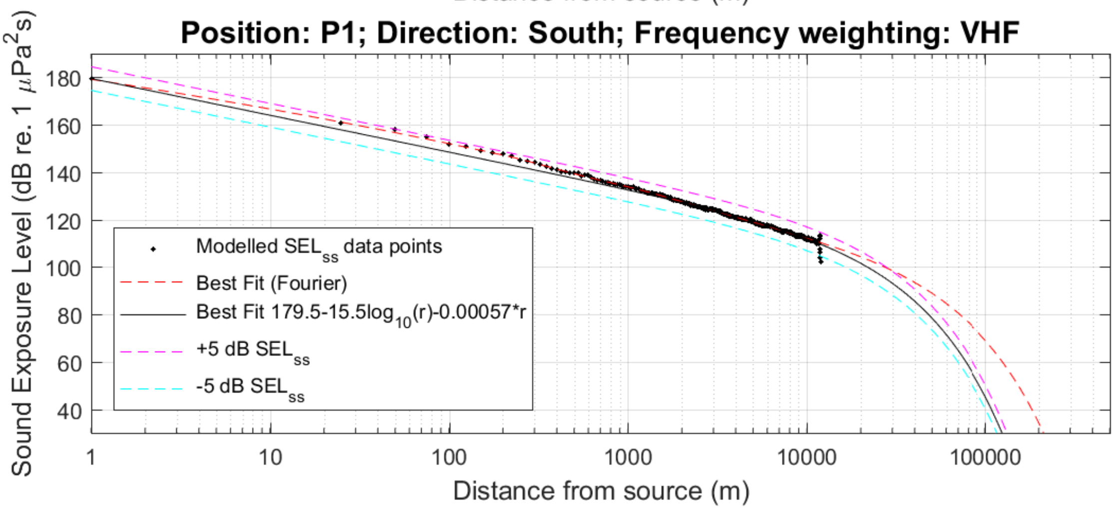

Position: P4; Direction: Northwest; Frequency weighting: PCW
Sound Exposure Level (dB re. 1 μPa^{2}s)
Distance from source (m)
Modelled SEL_{ss} data points
Best Fit (Fourier)
Best Fit 203.1-14.0log$_{10}$(r)-0.00004*r
+5 dB SEL_{ss}
-5 dB SEL_{ss}


Position: P1; Direction: Southeast; Frequency weighting: SEL
Sound Exposure Level (dB re. 1 μPa^{2}s)
Distance from source (m)
Modelled SEL_{ss} data points
Best Fit (Fourier)
Best Fit 221.3-12.4log$_{10}$(r)-0.00015*r
+5 dB SEL_{ss}
-5 dB SEL_{ss}


Position: P2; Direction: North; Frequency weighting: SEL
Sound Exposure Level (dB re. 1 μPa^{2}s)
Distance from source (m)
Modelled SEL_{ss} data points
Best Fit (Fourier)
Best Fit 224.5-13.8log$_{10}$(r)-0.00005*r
+5 dB SEL_{ss}
-5 dB SEL_{ss}


Position: P3; Direction: West; Frequency weighting: SEL
Sound Exposure Level (dB re. 1 μPa²s)
240
220
200
180
160
140
120
100
80
1
10
100
1000
10000
100000
Distance from source (m)
Modelled SEL$_{ss}$ data points
Best Fit (Fourier)
Best Fit 224.7-13.4log$_{10}$(r)-0.00012*r
+5 dB SEL$_{ss}$
-5 dB SEL$_{ss}$


Position: P4; Direction: Northwest; Frequency weighting: SEL
Sound Exposure Level (dB re. 1 μPa²s)
240
220
200
180
160
140
120
100
80
1
10
100
1000
10000
100000
Distance from source (m)
Modelled SEL$_{ss}$ data points
Best Fit (Fourier)
Best Fit 224.8-14.0log$_{10}$(r)-0.00004*r
+5 dB SEL$_{ss}$
-5 dB SEL$_{ss}$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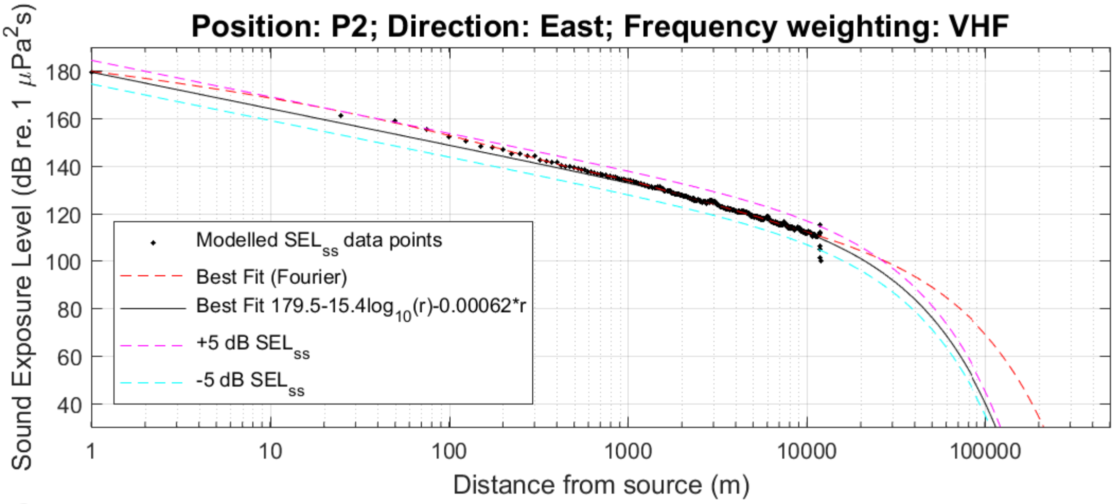
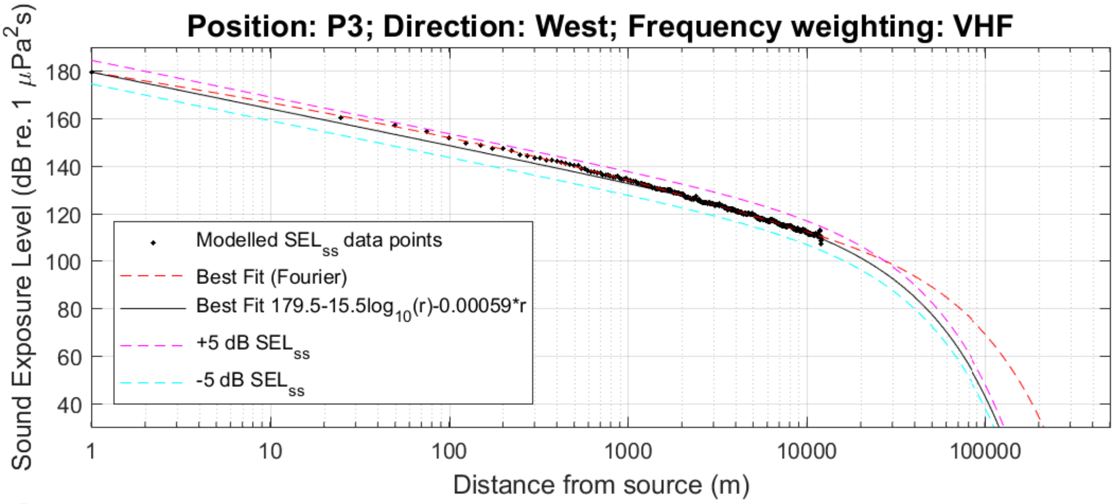
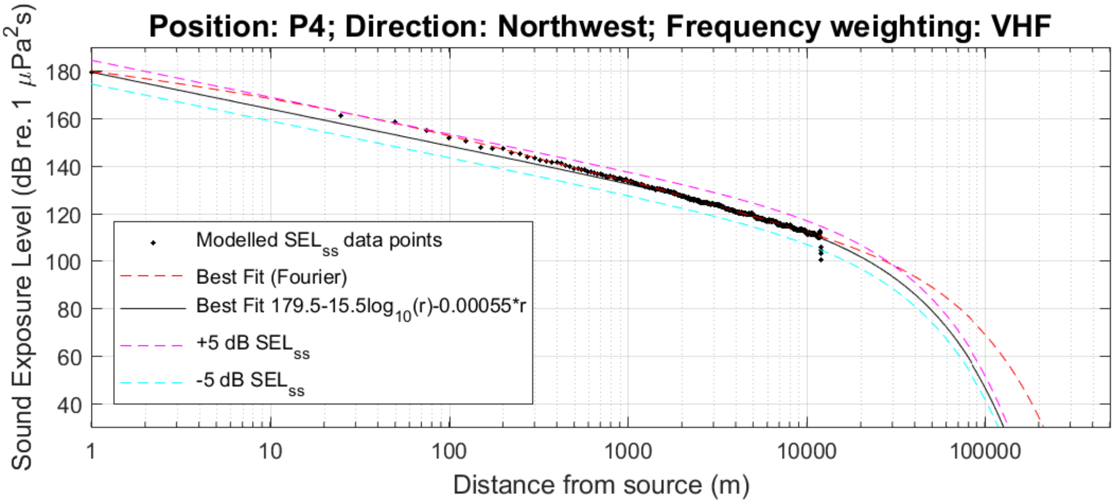
Sound Exposure Level (dB re. 1 μPa²s)
180
160
140
120
100
80
60
40
1
10
100
1000
10000
100000
Distance from source (m)
Modelled SEL$_{ss}$ data points
Best Fit (Fourier)
Best Fit 179.5-15.5log$_{10}$(r)-0.00057*r
+5 dB SEL$_{ss}$
-5 dB SEL$_{ss}$


Position: P2; Direction: East; Frequency weighting: VHF
Sound Exposure Level (dB re. 1 μPa²s)
Distance from source (m)
Modelled SELss data points
Best Fit (Fourier)
Best Fit 179.5-15.4log10(r)-0.00062*r
+5 dB SELss
-5 dB SELss


Position: P3; Direction: West; Frequency weighting: VHF
Sound Exposure Level (dB re. 1 μPa²s)
Distance from source (m)
Modelled SELss data points
Best Fit (Fourier)
Best Fit 179.5-15.5log10(r)-0.00059*r
+5 dB SELss
-5 dB SELss


Position: P4; Direction: Northwest; Frequency weighting: VHF
Sound Exposure Level (dB re. 1 μPa²s)
Distance from source (m)
Modelled SELss data points
Best Fit (Fourier)
Best Fit 179.5-15.5log10(r)-0.00055*r
+5 dB SELss
-5 dB SELss