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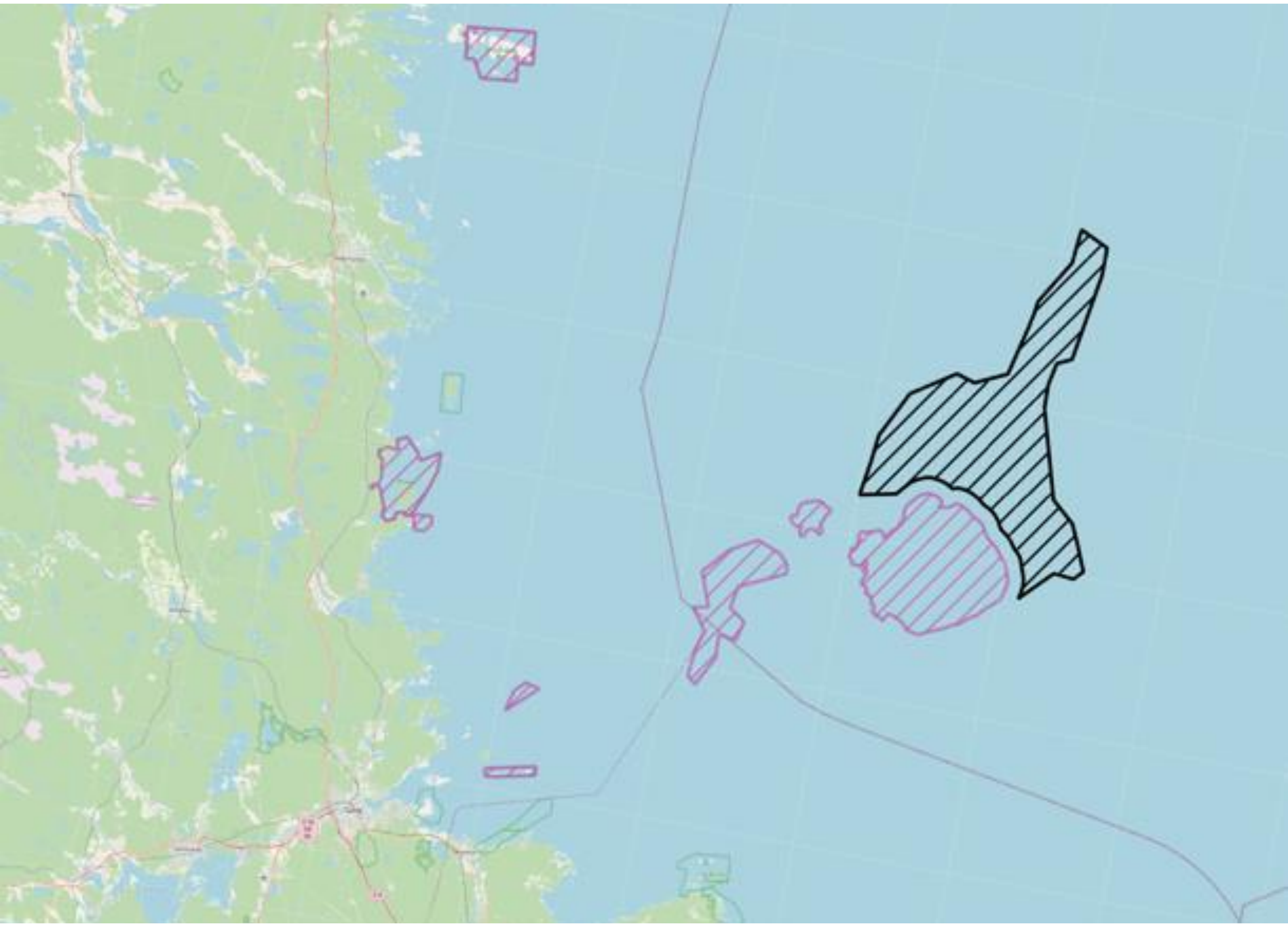
Bilaga M13: Underwater noise prognosis



Fyrskeppet offshore wind farm

Underwater noise prognosis: construction, operation, and geotechnical survey

Fyrskeppet Offshore AB

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Contents

Summary

This report documents the underwater sound prognosis in connection with the environmental impact assessment for Fyrskeppet Offshore Wind Farm (OWF). The prognosis contains three elements.

1. Underwater sound propagation modelling of foundation installation in the OWF site.
2. Underwater sound propagation modelling for geotechnical and geophysical survey activities in the OWF site.
3. Literature review of underwater noise from operational wind turbines.

For the prognosis of underwater noise related to the installation phase, two foundation types were considered: a 15 m diameter monopile, and a jacket foundation with 12 x 5.5 m pin piles. The worst case scenario, from an underwater noise impact perspective, was evaluated to be the 15 m monopile. Underwater sound propagation was calculated for this foundation type in 7 positions distributed throughout the OWF site.

For the prognosis of underwater noise related to geotechnical and geophysical surveys within the OWF site, sound propagation was evaluated for the activities:

1. Multibeam Echosounder (MBES),
2. Side scan sonar (SSS),
3. Sub-bottom profiler (SBP),
4. Cone penetration test (CPT), and
5. Drilling.

For activity 3 (SBP), sound propagation modelling was carried out, while the rest of the activities were evaluated based on literature.

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. Using advanced underwater sound propagation algorithms, normal modes (NM) and ray tracing, the sound propagation was calculated in 36 directions (10° resolution) from each source in a 50 m x 0.5 m grid (range x depth). This model was used for both geotechnical survey and installation of foundations.

The modelling of foundation installation was conducted with underwater noise mitigation effect active, equivalent to reported frequency based effectiveness of a Double Big Bubble Curtain (DBBC). Modelling was carried out for 7 positions, in 2 different months, a worst case for the entire year represented by the month of April, as well as a worst case for the period June – October, represented by the month of June.

For geotechnical survey modelling, 2 representative positions were modelled for the worst case scenario of April.

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 earless seals in order to prevent Permanent Threshold Shift (PTS) and Temporary Threshold Shift (TTS), based on threshold levels in (NOAA, 2018).

For the installation phase, DTT for TTS and injury threshold criteria for Cod and Herring, as well as Injury for larvae and eggs were also calculated, see Table 1.1. DTT for earless seal thresholds are shown in Table 1.2.

For geotechnical and geophysical surveys, results are listed in Table 1.3.

Table 1.1: Resulting threshold impact distances for fish using DBBC mitigation effect on a 15 m monopile.

Position	Distance-to-threshold [meters]						
	TTS (r_{TTS})			Injury (r_{injury})			
	Juvenile Cod	Adult Cod	Herring	Juvenile Cod	Adult Cod	Herring	Larvae & Eggs
Worst case for January - December (**Month of April**)							
1	9900	6000	5200	25	25	25	575
2	7600	4150	3400	25	25	25	475
3	8800	5600	4900	25	25	25	600
4	8100	4850	4100	25	25	25	500
5	11900	8100	7200	25	25	25	600
6	9600	6000	5100	25	25	25	625
7	10600	6800	6000	25	25	25	625
Worst case for June - October (**Month of June**)							
1	9600	5700	4850	25	25	25	575
2	7000	3750	3000	25	25	25	500
3	8200	5100	4450	25	25	25	625
4	7400	4250	3550	25	25	25	475
5	11300	7500	6600	25	25	25	600
6	8700	5200	4300	25	25	25	600
7	10100	6400	5500	25	25	25	625

Table 1.2: Resulting threshold impact distances for earless seals using DBBC mitigation effect on a 15 m monopile.

Position	Distance-to-threshold for earless seal [meters]			
	Worst case for January - December (**Month of April**)		Worst case for June - October (**Month of June**)	
	PTS (r_{PTS})	TTS (r_{TTS})	PTS (r_{PTS})	TTS (r_{TTS})
1	25	25	25	25
2	25	25	25	25
3	25	25	25	25
4	25	25	25	25
5	25	25	25	25
6	25	25	25	25
7	25	25	25	25

Threshold distances for PTS and TTS describe the minimum distance from the source a seal 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.

Table 1.3: Distance-to-threshold in meters for seismic survey activities for individual equipment types. PTS and TTS distances show, at which range, from the survey vessel (SBP), CPT or drilling activity a marine mammal must at least be at the onset of full survey activities to avoid the respective impact.

Geotechnical/geophysical survey method	Position	Impact range (m from activity)	
		$L_{E,cum,24h,PCW}$	
		TTS	PTS
Innomar Medium 100 (SBP)	3	< 25 m	< 25 m
	5	< 25 m	< 25 m
Drilling	Literature	< 25 m	< 25 m
Cone Penetration Test (CPT)	Literature	N/A*	N/A*

*: It was not possible to determine impact ranges, but impact range is assessed to be less than that of the survey vessel.

List of abbreviations

Full name	Abbreviation	Symbol
Sound Exposure Level	SEL	$L_{E,p}$
Cumulative Sound Exposure Level	$SEL_{cum,24h}$	$L_{E,p,cum,24h}$
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	
Side Scan Sonar	SSS	
Sub Bottom Profiler	SBP	
Multi Beam Echo Sounder	MBES	
World Ocean Atlas 2023	WOA23	
Normal modes	NM	
Parabolic Equation	PE	
Distance-To-Threshold	DTT	
Propagation loss	PL	N_{PL}
Sound Exposure Propagation loss	EPL	$N_{PL,E}$
National Marine Fisheries Service	NMFS	

1. Introduction

This report documents the underwater sound propagation prognosis in connection with the environmental impact assessment for the installation and operation of wind turbine foundations at Fyrskeppet Offshore Wind Farm (OWF), as well as for on-site geotechnical and geophysical surveys.

Fyrskeppet OWF site is located in the Swedish region of the Gulf of Bothnia, about 75 km northeast of the Swedish city "Gävle" and 54 km east of the nearest shore. The project area is approximately 488 km^2. In Figure 1.1, the OWF area is shown along with the maritime boundary "Finland-Sweden".

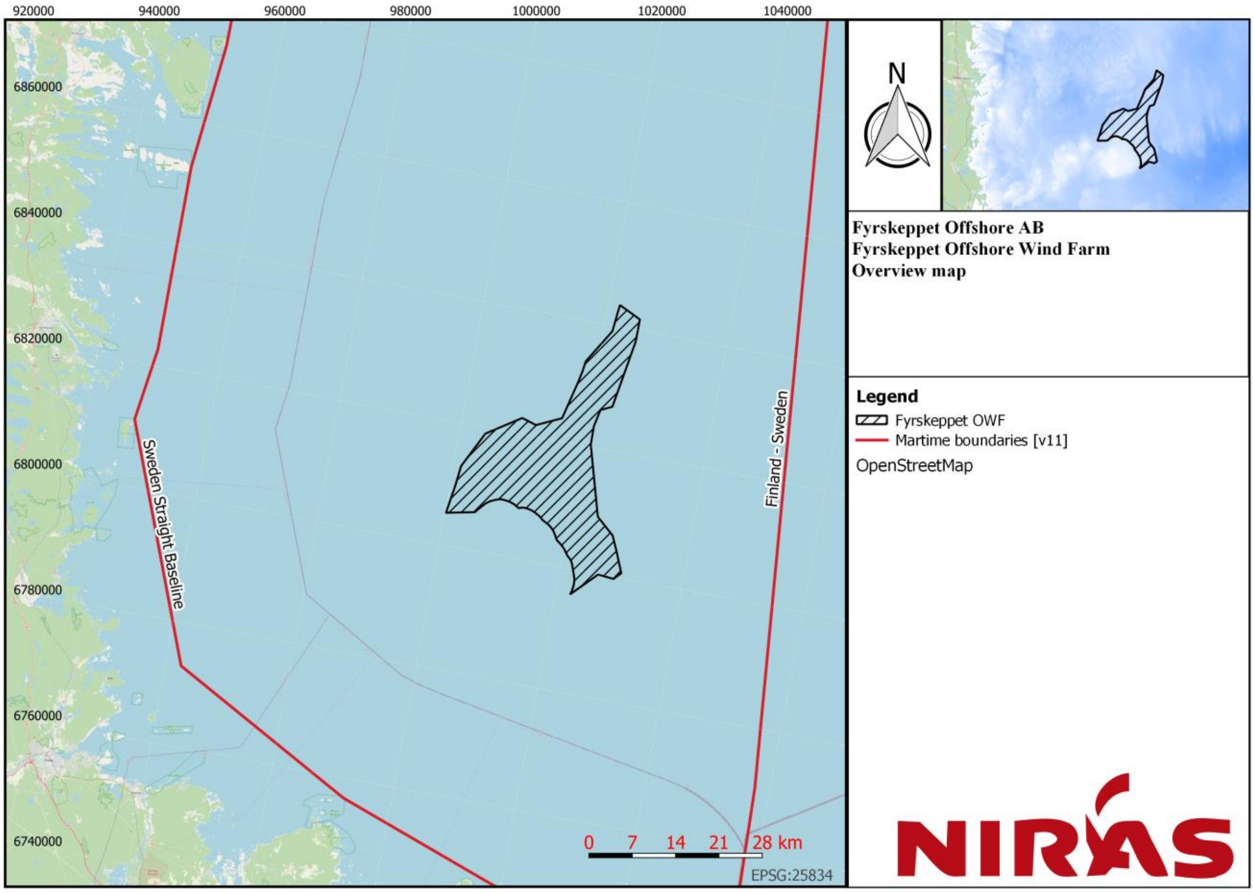


Figure 1.1: Overview of Fyrskeppet offshore wind farm site (black) and surrounding area.

The project includes installation of up to 187 wind turbines within the project area. Foundation types for the turbines have not been decided, however a number of options are considered possible. Monopile foundations up to 15 m diameter, 3- or 4-legged jacket foundations with up to 3 pin piles per leg, each up to 5.5 m diameter. Sound propagation modelling is only carried out for the worst case scenario with regards to underwater noise emission. The different foundation types are evaluated in section 6.1, with identification of the worst case scenario.

The report documents impact ranges for all relevant threshold levels for the impact on earless seals and fish.

2. Purpose

The purpose of this report is to provide an underwater noise emission prognosis from the construction and operation of Fyrskeppet OWF, as well as from on-site geophysical and geotechnical survey activities, to inform marine mammal and fish impact assessments.

3. Underwater sound definitions

In the following, the reader is introduced to the acoustic metrics used throughout the report for quantifying the sound levels.

3.1. 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 root-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 $1\ \mu\mathrm{Pa}^2\ \mathrm{m}^2\ \mathrm{s}$.

3.2. Sound Pressure Level

In underwater noise modelling, the Sound Pressure Level (SPL), $\mathrm{L_p}$, is commonly used to quantify the noise level at a specific position, and in impact assessments, is increasingly used for assessing the behavioural response of marine mammals as a result of noise emitting activities. The definition for SPL is shown in Equation 1 (Erbe, 2011):

$$\mathrm{L_p} = 20 * \log_{10}\left(\sqrt{\left(\frac{1}{\mathrm{T}}\right)\int_0^T \mathrm{p(t)}^2}\right) \quad [\mathrm{dB\ re.\ 1\mu Pa}] \qquad \text{Equation 1}$$

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.

In order to evaluate the behavioural response of the marine mammal a time window must be specified. 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).

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

Equation 2

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

3.3. Sound Exposure Level

The Sound Exposure Level (SEL) 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.

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

Equation 3

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

The relationship between SPL in Equation 1 and SEL, in Equation 3, is given in Equation 4 (Erbe, 2011).

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

Equation 4

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

Marine mammals and fish 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 metric to assess the risk of hearing impairment as a result of noisy activities. (Martin, et al., 2019).

3.4. 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 ($L_{E,cum,t}$) is used to describe the total noise dose received by marine mammals and fish as a result of an underwater noise emitting activity.

3.4.1. Stationary source (pile driving)

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. A method for implementing such conditions in the calculation of cumulative SEL has been proposed by (Energistyrelsen, 2022), for the Danish guidelines for pile driving activities, as given by Equation 5. Here, the duration is fixed to 24 hours (24h) to represent the daily cumulative SEL, $L_{E,cum,24h}$. If multiple foundations are installed in the same 24h window, all must be included in the calculation.

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

Equation 5

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 should be based on realistic worst-case assumptions and can be achieved through a site-specific drivability analysis. The relationship between hammer energy level and pile strike number is referred to as the hammer curve.

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

The calculation model presented in Equation 5, is used throughout the report for all calculations of cumulative SEL. Furthermore, the Danish approach of including all installations occurring within a 24h period is adopted, and $L_{E,cum,24h}$ is therefore used for the remainder of this report.

3.4.2. Moving sources (survey vessels)

For moving sources in combination with moving receivers, the $L_{E,cum,t}$ is proposed to be calculated using the approach presented in (Tougaard, 2016). Here the source vessel speed, and its direction relative to a moving receiver is used to calculate the $L_{E,cum,t}$ for a given receiver. In Equation 6, the distance between the source and receiver at the ith pulse, r_i, of a specific piece of survey equipment, given a starting position of the marine mammal relative to the source defined by the on-axis distance, l_0, corresponding to the transect line, and the off-axis distance, d_0, corresponding to the perpendicular distance from the transect line. Here, Δt_i is the time in seconds between the first pulse and the ith , while v_{ship} and $v_{receiver}$ is the ship and receiver moving speed respectively, in m/s.

$$r_i = \sqrt{\left(l_0 - ((i-1)\cdot\Delta t_i)\cdot v_{ship}\right)^2 + (d_0 + ((i-1)\cdot\Delta t_i)\cdot v_{receiver})^2} \qquad \text{Equation 6}$$

By summing the pulses from the entire survey, within a 24h window, given the propagation loss for the survey area, Equation 7 gives the resulting $L_{E,cum,24h}$.

$$L_{E,cum,24h} = 10 * \log_{10}\left(\sum_{i=1}^{N} 10^{\left(\frac{L_{S,E} - X*\log_{10}(r_i) - A*(r_i)}{10}\right)}\right) \qquad \text{Equation 7}$$

Where N is the total number of pulses for that piece of survey equipment, $L_{S,E}$ is the source level at 1 m distance, X and A describe the sound exposure propagation losses (EPL), $N_{PL,E}$, for the specific project site. In the original equation by (Tougaard, 2016), it is assumed that the marine mammal moves in a straight line at constant speed directly perpendicular to the transect line (source vessel direction). In NIRAS' adaptation to the (Tougaard, 2016) model, it is however assumed that the marine mammal moves in a straight line directly away from the source. For surveys using multiple equipment types, the contribution from each source is first normalized into 1 sec. SEL based on firing frequency, and then added.

The parameters in Equation 6 and Equation 7 related to the source level, firing frequency, movement speed and source direction must be based on realistic assumptions and can be achieved through a site-specific survey setup. The EPL parameters (X and A) must be determined through an advanced sound propagation model, in which all relevant site-specific environmental parameters are considered.

4. Underwater noise impact criteria

Guidance or threshold values for regulating underwater noise during construction of OWFs (pile driving), and from geotechnical surveys have been developed by several different countries and international organizations. There are different approaches in the different countries when it comes to assessing impacts from pile driving on marine mammals and fish. The project area is located in the Swedish Exclusive Economic Zone (EEZ), and Sweden does not have established guidelines for underwater noise from impact pile driving. On the reasoning for the modelled threshold values, the reader is referred to the respective impact assessments for fish and marine mammals.

4.1. Applied threshold for fish

Threshold levels for when fish begin to experience hearing loss depending on their hearing capabilities, begins at around 186 dB $\mathrm{L}_{\mathrm{E,cum,24h}}$ for fish least tolerant to noise (Table 4.1). Conservatively, the noise level where irreversible hearing loss and permanent injuries leading to mortality is set at 204 dB for all fish, and at 207 dB $\mathrm{L}_{\mathrm{E,cum,24h}}$ for fish larvae and eggs.

Assessment of the noise impact on fish, larvae and eggs are all based on frequency unweighted threshold levels using the metric $\mathrm{L}_{\mathrm{E,cum,24h}}$, and are presented in Table 4.1. The threshold is adopted from (Andersson, et al., 2016) and (Popper, et al., 2014).

Table 4.1: Unweighted threshold criteria for fish (Andersson, et al., 2016), (Popper, et al., 2014).

Species	Swim speed [m/s]	Species specific unweighted thresholds (Impulsive)	
		$\mathrm{L}_{\mathrm{E,cum,24h}}$	
		TTS [dB]	Injury [dB]
Juvenile Cod	0.38	186	204
Adult Cod	0.9	186	204
Herring	1.04	186	204
Larvae and eggs	-	-	207

4.2. Applied threshold for marine mammals

Based on the newest scientific literature, it is recommended that the $\mathrm{L}_{\mathrm{E,cum,24h}}$ and frequency weighting is used to assess TTS and PTS. Threshold levels for TTS and PTS are primarily based on a large study from the American National Oceanographic and Atmospheric Administration (NOAA), (NOAA, 2018), where species specific frequency weighting is proposed, accounting 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, only the latter is relevant. More details about the hearing groups and their frequency sensitivities are given in section 4.4. The hearing group weighted threshold criteria can be seen in Table 4.2.

Table 4.2: Species specific weighted threshold criteria for earless seals. This is a revised version of Table AE-1 in (NOAA, 2018) to highlight the important species in the project area including behaviour response. "xx" indicates the weighting function.

Species	Species specific weighted thresholds (non-impulsive)		Species specific weighted thresholds (Impulsive)	
	$L_{E,cum,24h,xx}$		$L_{E,cum,24h,xx}$	
	TTS [dB]	PTS [dB]	TTS [dB]	PTS [dB]
Seal (PCW)	181	201	170	185

Thresholds listed as "non-impulsive", apply for continuous noise (e.g., ship noise, drilling) 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, explosives and airguns, stricter threshold levels apply as listed in Table 4.2. 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. For those sources where their source characteristic is impulsive in nature, only the impulsive criteria will be considered. For sources that are continuous in nature, only the non-impulsive criteria will be used. For sources where the characteristics can be debated, both criteria will be considered.

4.3. Distance-To-Threshold

The impact criteria, as presented in section 4.1 and 4.2, 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 and fish must be deterred to, prior to onset of the noise producing activity in order to avoid the respective impact. It does therefore not represent a specific measurable sound level, but rather a starting distance.

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.

4.4. Frequency weighting functions

As described in previous sections, the impact assessment for underwater noise includes frequency weighted threshold levels. 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, for the human auditory system it is called A-weighting. For marine mammals the same principle applies through the weighting function, $W(f)$, defined through Equation 8.

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

Equation 8

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 4.1.

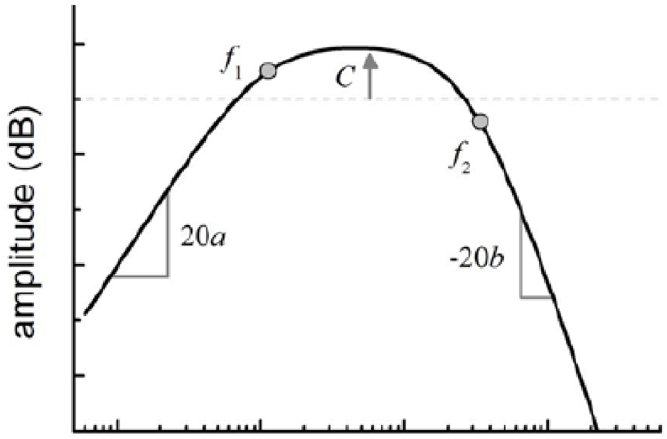


Figure 4.1: Illustration of the 5 parameters in the weighting function (NOAA, 2018).

The parameters in Equation 8 are defined for the relevant hearing groups and the values are presented in Table 4.3.

Table 4.3: Parameters for the weighting function for the relevant hearing groups (NOAA, 2018).

Hearing Group	a	b	f_1 [kHz]	f_2 [kHz]	C [dB]
Phocid Pinniped (PCW) (Underwater)	1.0	2	1.9	30	0.75

By inserting the values from Table 4.3 into Equation 8, the following spectra is obtained for the PCW hearing group (grey and ringed seals).

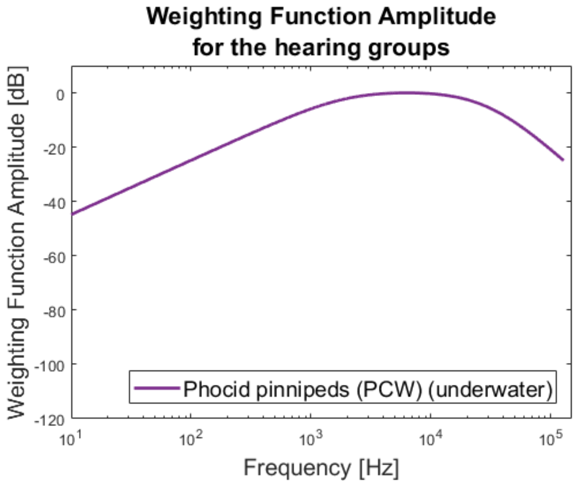


Figure 4.2: The weighting functions for the different hearing groups.

5. Underwater Sound Propagation Modelling

Underwater sound propagation modelling for this prognosis is done through numerical modelling, whereby mathematical propagation models, using environmental and source model inputs, predict the underwater sound propagation through the environment. The approach is used for both foundation installation noise prognosis and for the prognosis of geotechnical survey activities.

Such models include as detailed information as available for the environmental parameters of importance, most notable the bathymetry, seabed sediments, as well as salinity, temperature, and sound speed profiles. Underwater sound propagation concepts as well as the project specific environmental parameters implemented are discussed in the following.

5.1. 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 9.

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

Equation 9

Where:

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

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.

In 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 relationship 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 Gulf and Bay of Bothnia, where ice cover is present during winter and spring. After the thaw, in April/May a gradual shift in sound speed profile from near-iso speed and/or upward refracting in the winter, to downward refracting takes place. This is observed based on temperature and salinity readings throughout the year. The readings come from the NOAAs World Ocean Atlas database (WOA23), freely available from the "National Oceanic and Atmospheric Administration" (NOAA) (Locarnini, et al., 2023) (Reagan, et al., 2023).

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 seas 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 10 (Jensen, et al., 2011):

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

Where $\mathbf{f}$ is the frequency of the wave in kHz. This infers that increasing frequency leads to increased absorption.

5.2. 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 5.1, an overview of the application range of the different sound propagation models is shown.

Table 5.1: 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 NM 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 $\mathbf{c}$ is the speed of sound in [m/s] and $\mathbf{d}$ 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.

5.3. 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 NIRAS' software package NiFlee, where distances to relevant thresholds are calculated. For this project, the dBSea settings listed in Table 5.2 were used.

Table 5.2: dBSea Settings

Technical Specification		
Octave bands		1/3
Calculation range (radius)		20 km
Grid resolution (Range step, depth)		50 m x 0.5 m
Number of transects		36 (10°)
Sound Propagation Model Settings (Pile driving)		
Model	Start frequency band	End frequency band
dBSeaModes (Normal Modes)	31 Hz	250 Hz
dBSeaRay (Ray tracing)	315 Hz	32 kHz
Sound Propagation Model Settings (Geotechnical surveys)		
dBSeaRay (Ray tracing)	31 Hz	128 kHz

5.4. Environmental model

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

5.4.1. Bathymetry

dBSea incorporates range-dependent bathymetry modelling and supports raster and vector bathymetry import. Figure 5.1 shows the bathymetry for the wind farm site and surroundings, (EMODnet, 2022), where the bathymetry is provided in a 57 x 115 m resolution. In this area, the bathymetry ranges from a depth of 150 m, indicated by the darker colours, to a depth of 0 m, indicated by the lighter colours.

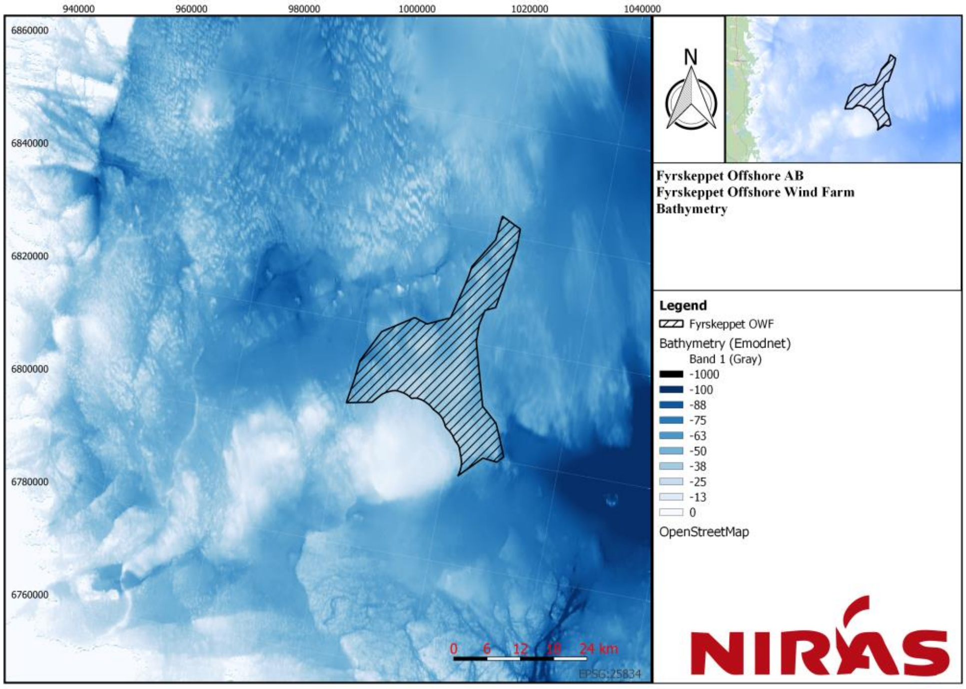


Figure 5.1: Bathymetry map for the project area and surroundings.

5.4.2. 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 through literature research in combination with available site-specific survey findings.

Seabed substrate maps were supplied by the client to build the sediment model. For this project, no geological profiles from survey transects or other literature were found near the project site. Therefore no information on local layer thickness were available. To calculate the worst case sound propagation it was decided to have a thin overlay of 1 m of the top sediment before reaching bedrock. This is considered to be a very conservative profile for the OWF area, however aims to ensure that sound propagation is not underestimated. The top layer (seabed substrate) inside the OWF was obtained through Figure 5.2, while the top layer information for the area outside the OWF was obtained through "Sveriges geologiska undersökning" (SGU) data, Figure 5.3, which was also provided by the client.

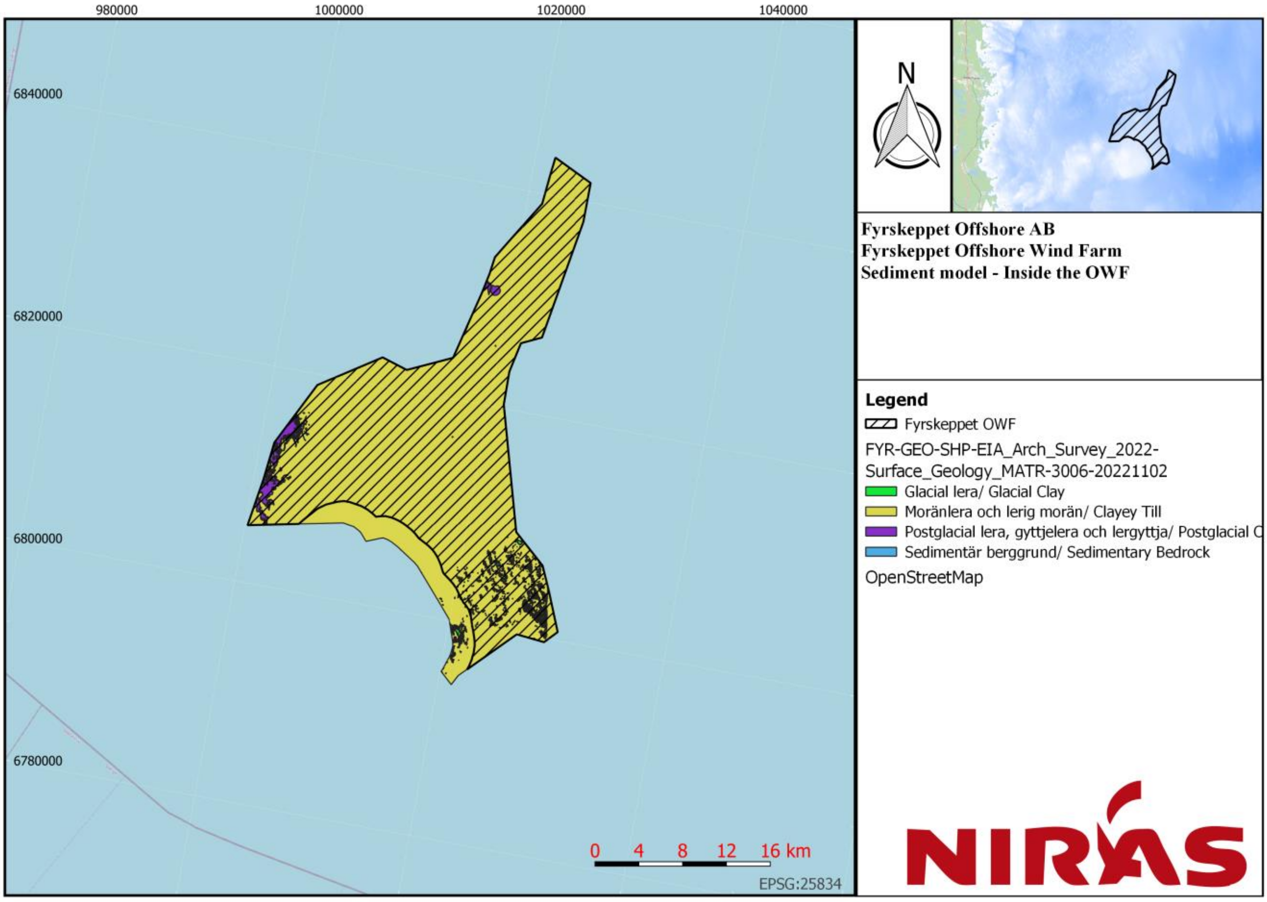


Figure 5.2: Seabed substrate map, used for areas inside the OWF, which was provided by the client.

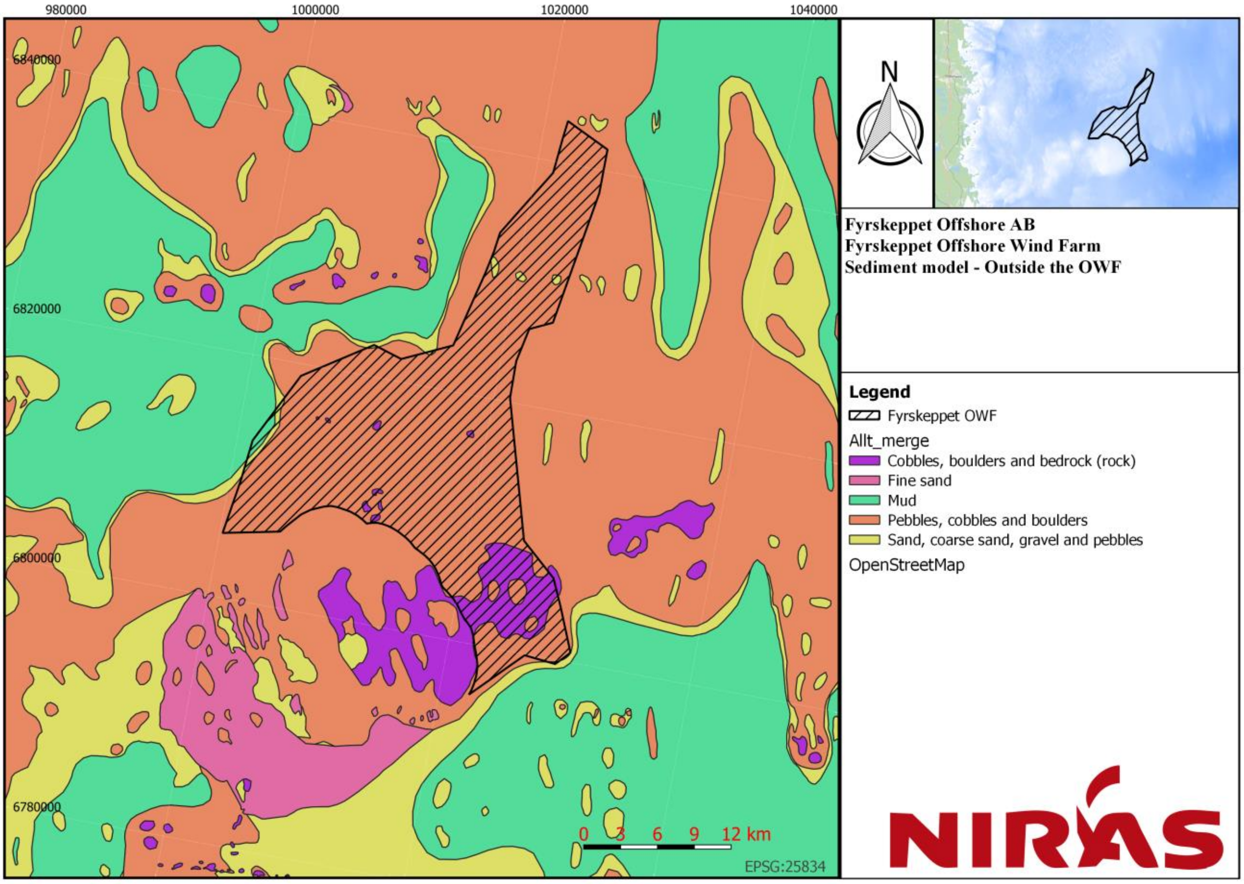


Figure 5.3: Seabed substrate map, used for the area outside the OWF, which was provided by the client.

From the available source, a multipoint sediment model was made for the relevant project area and surroundings reflecting the seabed substrate. For each point in the model, the sediment layer types were translated into geoacoustic parameters, utilizing information from (Jensen, et al., 2011), (Hamilton, 1980).

Table 5.3: Geoacoustic properties of sediment 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

5.4.3. Sound speed profile, salinity, and temperature

The sound propagation also depends on the season and location specific 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.

NIRAS used NOAAs WOA23, freely available from the "National Oceanic and Atmospheric Administration" (NOAA) (Locarnini, et al., 2023) (Reagan, et al., 2023), 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.

5.4.3.1. Sound speed profile

Figure 5.4 shows the extracted sound speed profiles at the available positions. Note that the gridded layout of the sound speed profiles indicates their respective position geographically. Examining Figure 5.4, this would indicate April as the worst-case month of the entire year, and June as the worst case for the time span June – October, indicated as a period of specific interest by the client. Sound propagation models for both April and June were included in the prognosis.

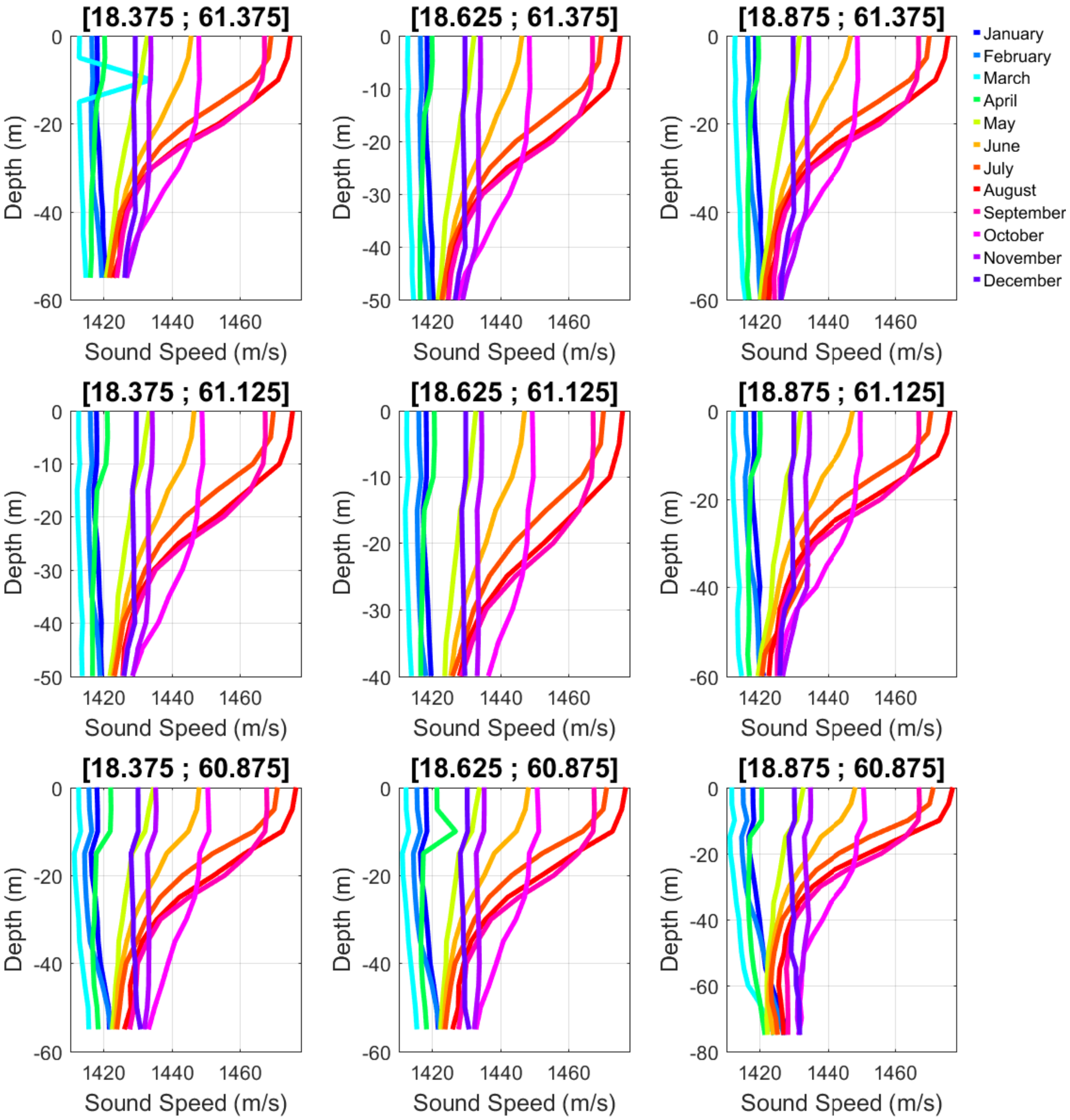


Figure 5.4: Sound speed profiles for the project area and surroundings.

5.4.3.2. *Salinity profile*

Figure 5.5 shows the extracted salinity profiles at the available positions. It is observed that the salinity profiles do not vary to any significant degree over the year as a function of depth. The average salinity used for the model is therefore 5 ppt.

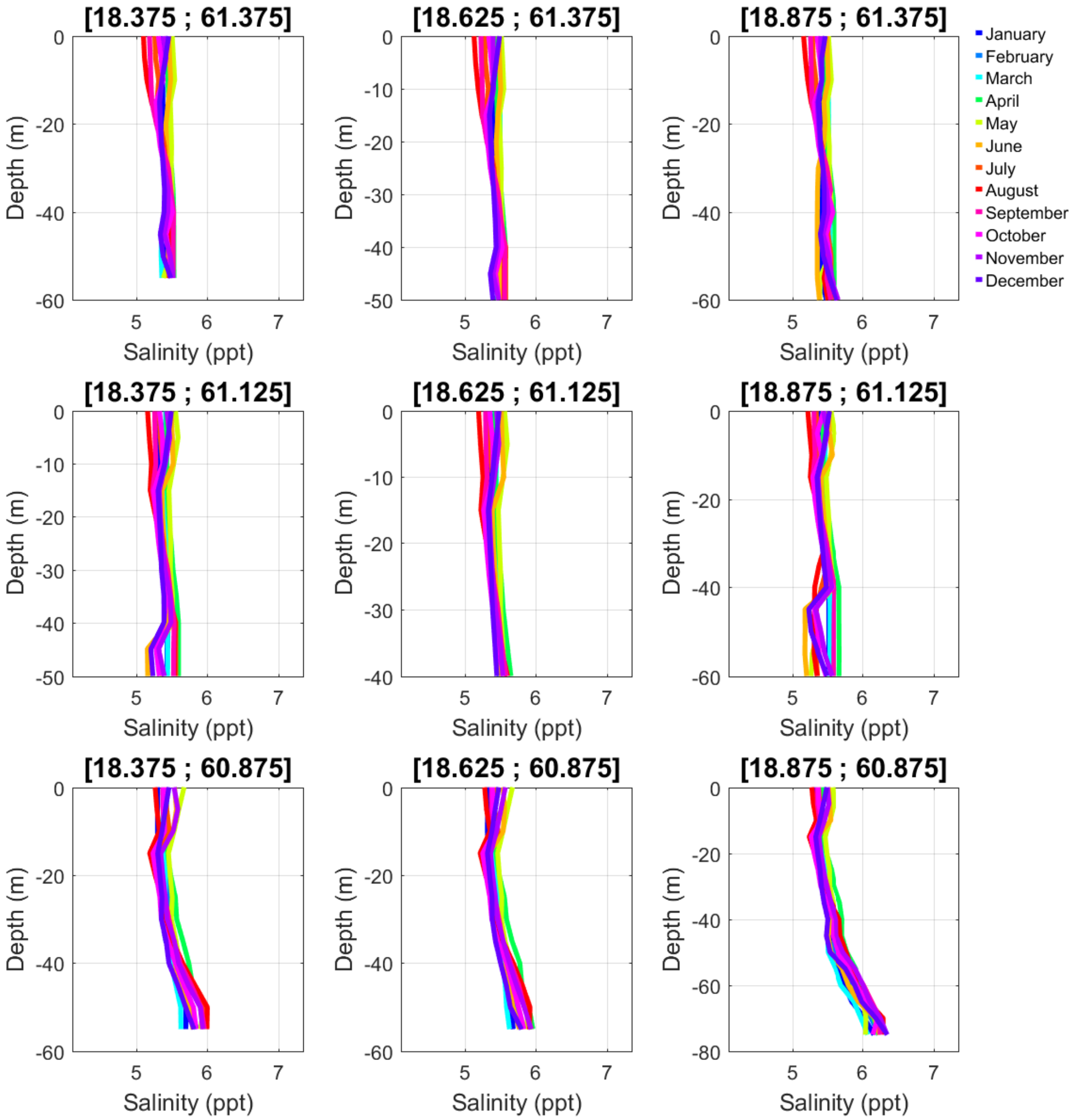


Figure 5.5: Salinity profiles for the project area and surroundings.

5.4.3.3. *Temperature profile*

Figure 5.6 shows the extracted temperature profiles at the available positions. With the salinity profiles being stable over the year, the sound speed profile differences are purely driven by the temperature profiles which show significant variation both temporally, and over depth. The average temperatures implemented in the model are 2°C for April, and 5°C for June.

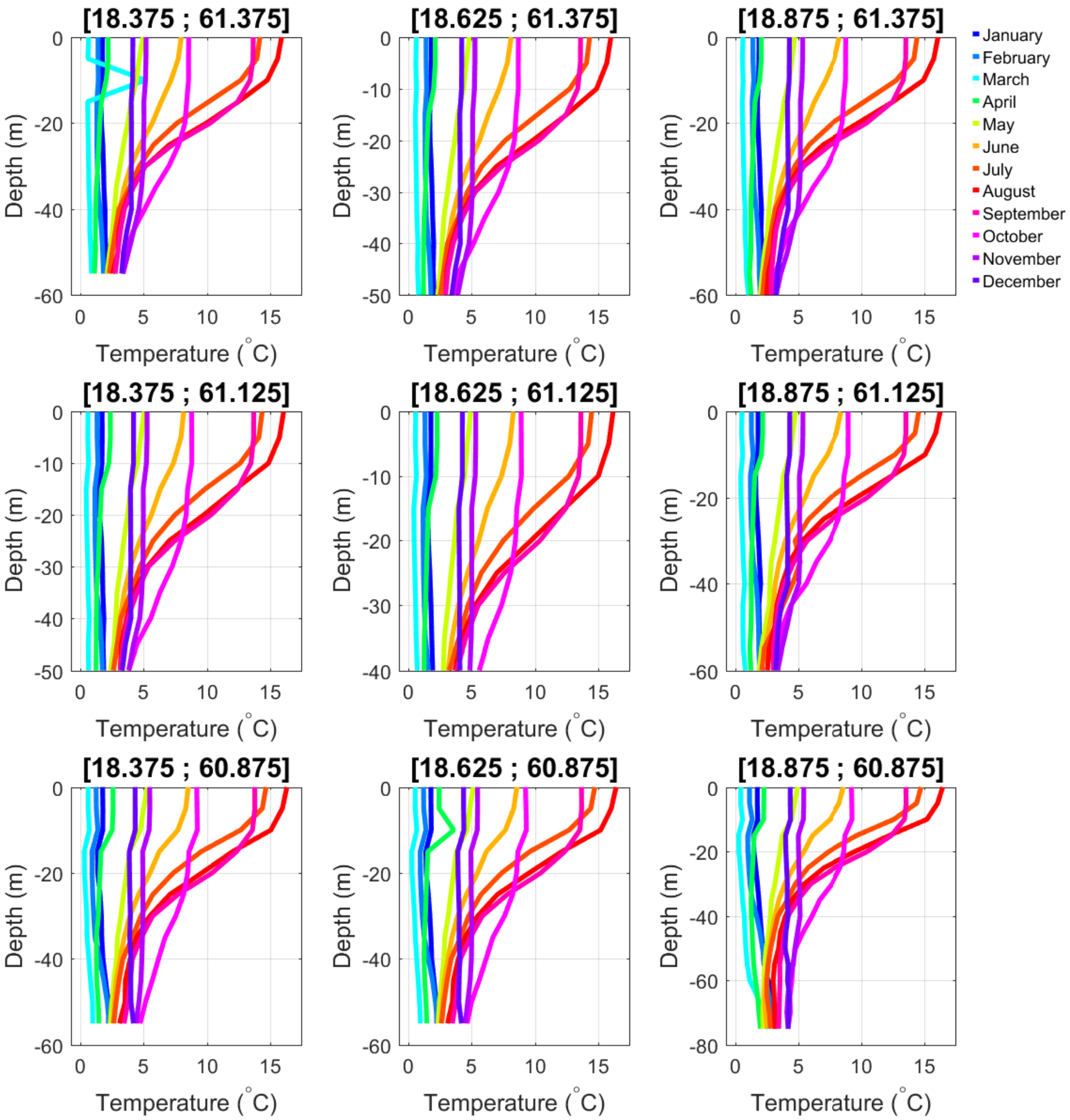


Figure 5.6: Temperature profiles for the project area and surroundings.

6. Underwater noise prognosis for pile driving activities

This chapter describes the underwater noise prognosis for the installation phase where impact pile driving of wind turbine foundations is the source of noise. Noise from supporting activities, such as vessels, is not included as it is considered to have lower overall impact acoustically. In section 6.1, the source model and implementation thereof are described in further detail, with results being presented in section 6.2.

6.1. Source Model

It is not yet decided which foundation types will be used for the actual installation. It may be a single foundation type, or a mix of different foundation types. For the wind turbines, foundation types could include steel monopiles up to 15 m diameter, jacket, or tripod foundations with pin piles up to 5.5 m diameter. The latter would also be used for offshore substations.

Gravitation and suction bucket foundation types have not been ruled out, but since they are the foundation types with the lowest underwater noise emissions, and are considered negligible from an underwater noise impact perspective, they are not considered further in this report.

It is therefore assessed that the worst-case scenarios for the construction phase will be either monopiles of 15 m diameter, or jacket foundations with up to 12 x 5.5 m pin piles. Due to differences in the frequency spectrum and number of piles for the different foundation types, both are evaluated in section 6.1.5 to identify the worst case with regards to relevant threshold criteria. Source models for the two scenarios are described further in section 6.1.4.

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 4 pin piles per 24 hours for jacket foundations.

The technical source model parameters are provided in Table 6.1 for the monopile foundation scenario, and in Table 6.2 for the jacket foundation scenario. Number of pile strikes, hammer energy and time interval between each pile strike as well as duration and number of pile strikes at each hammer intensity level were chosen by NIRAS as conservative values, as foundation design is not yet carried out. It is therefore important, that at the point in time when the finalized design is available, and pile drivability studies have been carried out, a revised underwater sound prognosis is carried out. The prognosis provided in this report serves only as input for a conservative evaluation of environmental impact provided the currently available information.

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 6.1: Technical specifications and pile driving procedure for scenario 1: 15 m monopile foundation

<table>
<tr><th colspan="4">Technical specification for scenario 1</th></tr>
<tr><td colspan="2">Foundation type</td><td colspan="2">Monopile</td></tr>
<tr><td colspan="2">Impact hammer energy</td><td colspan="2">5500 kJ</td></tr>
<tr><td colspan="2">Pile Diameter</td><td colspan="2">15 m</td></tr>
<tr><td colspan="2">Total number of strikes pr. pile</td><td colspan="2">9 600</td></tr>
<tr><td colspan="2">Number of piles per foundation</td><td colspan="2">1</td></tr>
<tr><th colspan="4">Pile driving procedure</th></tr>
<tr><td>Name</td><td>Number of strikes</td><td>% of maximum hammer energy</td><td>Time interval between strikes [s]</td></tr>
<tr><td>Soft start</td><td>1200</td><td>10</td><td>1.5</td></tr>
<tr><td>Ramp-up</td><td>300 300 300 300</td><td>20 40 60 80</td><td>1.5</td></tr>
<tr><td>Full power</td><td>7 200</td><td>100</td><td>1.5</td></tr>
</table>

Table 6.2: Technical specifications and pile driving procedure for scenario 2: Jacket foundation with 4x5.5m pin piles.

<table>
<tr><th colspan="4">Technical specification for scenario 2</th></tr>
<tr><td colspan="2">Foundation type</td><td colspan="2">Jacket</td></tr>
<tr><td colspan="2">Impact hammer energy</td><td colspan="2">3000 kJ</td></tr>
<tr><td colspan="2">Pile Diameter</td><td colspan="2">5.5 m</td></tr>
<tr><td colspan="2">Total number of strikes pr. pile</td><td colspan="2">9 600</td></tr>
<tr><td colspan="2">Number of piles installed within a 24 hour time frame</td><td colspan="2">4</td></tr>
<tr><th colspan="4">Pile driving procedure</th></tr>
<tr><td>Name</td><td>Number of strikes</td><td>% of maximum hammer energy</td><td>Time interval between strikes [s]</td></tr>
<tr><td>Soft start</td><td>1200</td><td>10</td><td>1.5</td></tr>
<tr><td>Ramp-up</td><td>300 300 300 300</td><td>20 40 60 80</td><td>1.5</td></tr>
<tr><td>Full power</td><td>7 200</td><td>100</td><td>1.5</td></tr>
</table>

6.1.1. Source model concept

The source model must represent the actual underwater sound source as accurately as possible, with regards to both source level, frequency content, as well as the temporal aspects of the activity. Any mitigation measures intended must also be included. These parameters are described in detail in the following sections.

6.1.1.1. Pile driving source level

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 graphic summary of measured sound levels at 750 m distance as a function of pile size. This is shown in Figure 6.1. The measurements are all normalized to 750 m distance from the pile.

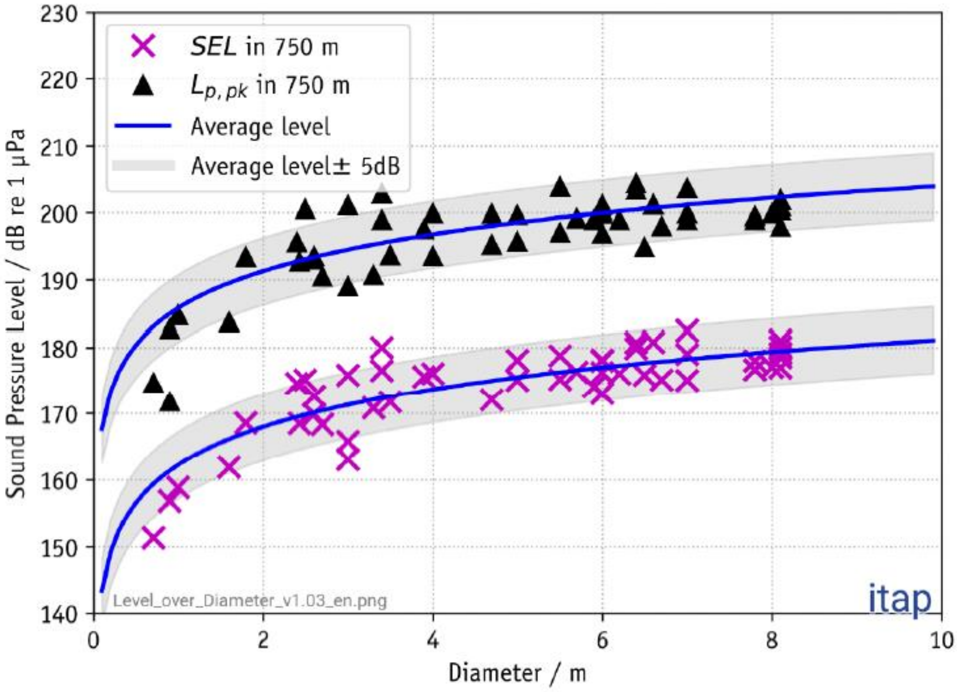


Figure 6.1: Relationship between measured SPL and SEL levels, measured at 750 m distance, and pile size (Bellmann, et al., 2020).

Examining Figure 6.1, 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 ESL 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 6.1 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.

6.1.1.1.1. Source level influencing factors

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, in shallow water, can also influence the noise emission. As the water depth decreases, the cut-off frequency increases, which can be seen in Figure 6.2. Frequency content of the noise source, below the cut-off frequency, has difficulty propagating through the water column, and will be attenuated at an increased rate, compared to frequency content above the cut-off frequency (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.

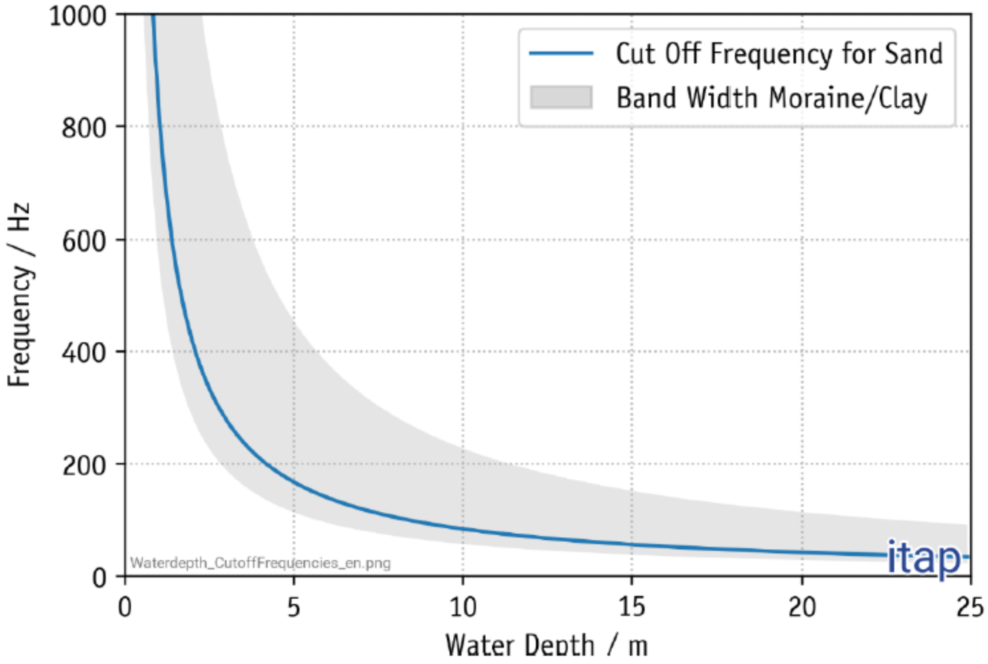


Figure 6.2: Cut off frequency and its dependency on sediment type and water depth (Bellmann, et al., 2020).

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 6.3, 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).

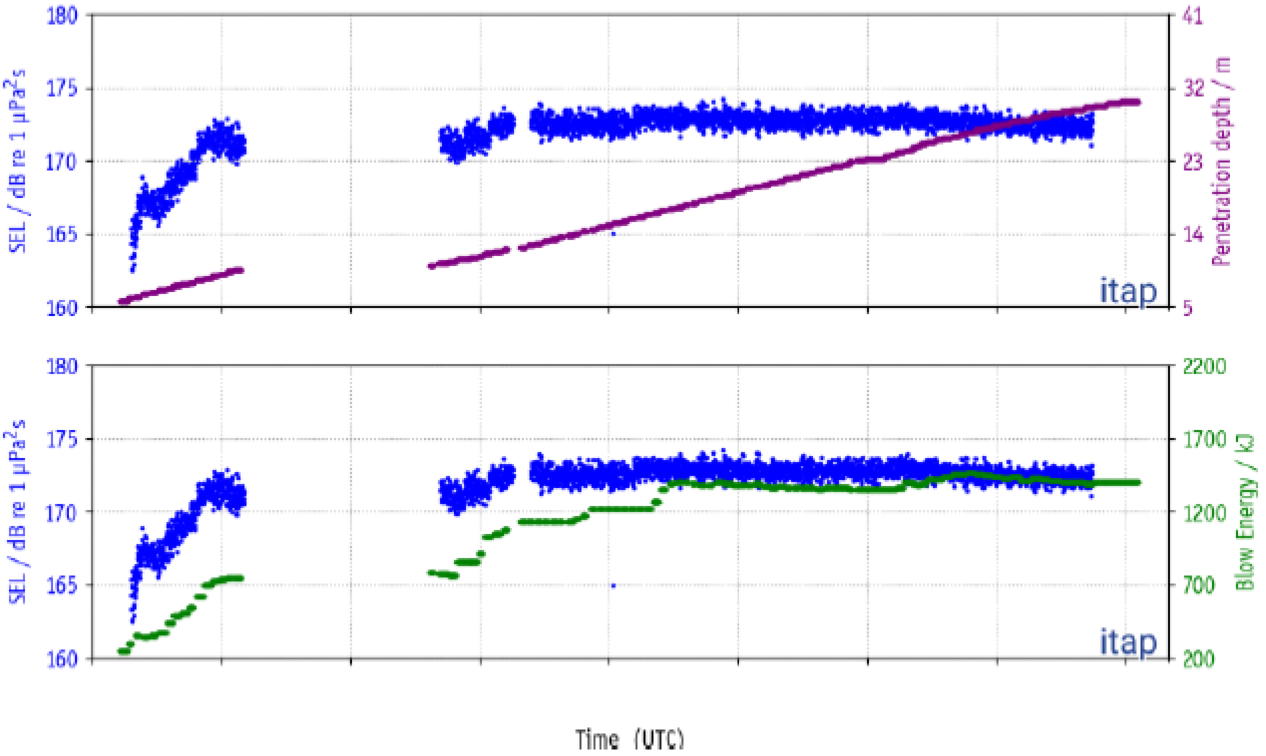


Figure 6.3: Relationship between SEL versus penetration depths and blow energy (Bellmann, et al., 2020).

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).

Summary of uncertainties

A number of factors influencing the source level of a pile installation were described in general terms. For this project, the foundation parameters greatly exceed those currently in existence. Neither impact hammer, monopile or jacket foundations of the proposed dimensions exist, and it is therefore unknown at this time how the different uncertainties will affect the source level. In order to carry out the prognosis, the average relationship between pile size and sound levels, Figure 6.1, will be used to determine the source level. The uncertainty, is assessed to be $\pm 5\ dB$.

6.1.1.2. *Pile driving frequency spectrum*

Due to the natural variations of measured frequency content, Figure 6.4 (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).

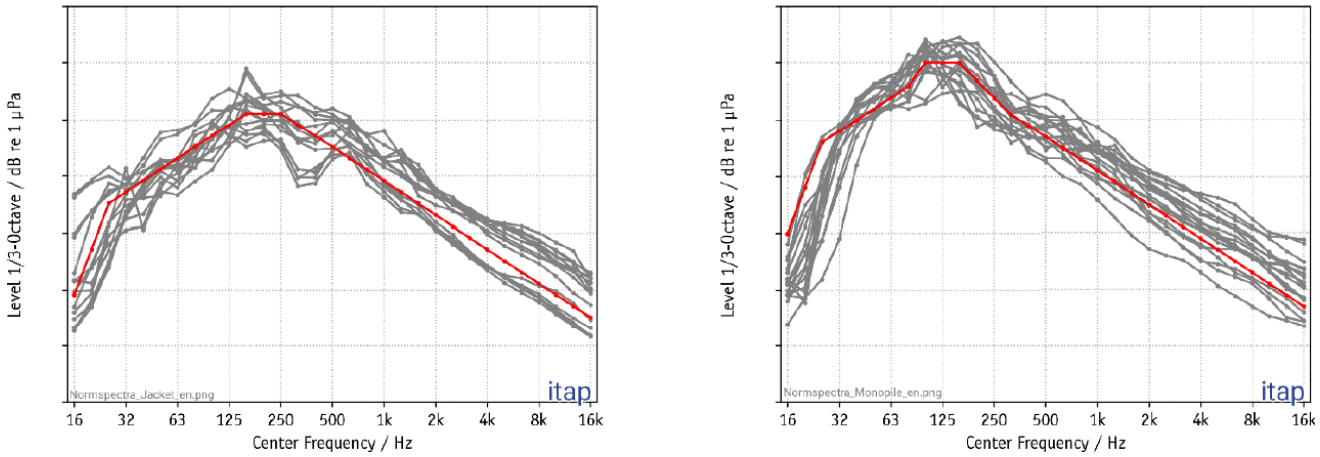


Figure 6.4: Measured pile driving frequency spectrum (grey lines) at 750m, with the averaged spectrum shown as the red line (Bellmann, et al., 2020). The spectrum ranges from 110-180 dB.

The spectrum shown to the left in Figure 6.4 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 6.4 illustrates 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.

6.1.2. Pile driving mitigation measures

As foundation structures become larger and more knowledge come to light about marine mammal hearing, the more unlikely it is that the projects can comply with local regulation without mitigation measures.

This section provides a brief description of different Noise Abatement Systems (NAS), used as a general descriptor for measures taken that reduce the underwater noise emitted. Such systems can be either on-pile systems, actively reducing the source noise output or near-pile which reduces the noise emission after it has entered the water column.

6.1.2.1. Noise abatement system types

6.1.2.1.1. Big bubble curtains

The most frequently applied technique uses a big bubble curtain (BBC). Air is pumped into a hose system positioned around the pile installation at the bottom of the sea, at a distance of 50 – 200 m. The hoses are perforated and air bubbles leak and rise towards the surface as air is pressured to the hose via compressors on a surface vessel. This forms an air curtain through the entire water column from seabed to sea surface. Due to the change in sound speed in the water-air-water bubble interface, a significant part of the outgoing noise is reflected backwards and kept near the pile, while the remaining noise energy going through the bubble curtain is greatly attenuated (Tsouvalas, 2020). Part of the noise emission from pile driving occurs through the sediment, which is then reintroduced to the water column further from the pile. It is important, that bubble curtains are not placed too close to the pile, as this would reduce their effectiveness on noise transmitted through the soil. By placing the bubble curtain further from the pile, it can mitigate some of this noise as it enters the water column. Bubble curtains usually surround the construction site completely leaving no gaps where noise is emitted unattenuated.

Currents can cause a drift in bubbles, but this difficulty can be overcome if the bubble curtain is installed in an oval rather than a circle. This system was used for example in Borkum West II, where a noise reduction of on average 11 dB (unweighted broadband) was achieved with the best configuration. This project tested different configurations. The success depended 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).

The effect of bubble curtains can be increased further if a second bubble curtain is installed even further from the installation, referred to as a Double Big Bubble Curtain (DBBC). The effect is greatest if the distance between the hosepipes is at least three times the water depth (Koschinski S et al., 2013).

6.1.2.1.2. 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, thus using 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). Often, a pile sleeve NAS is applied in combination with a bubble curtain solution to increase the overall mitigation effect. The pile sleeve NAS however has an important limitation to consider for 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.

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.

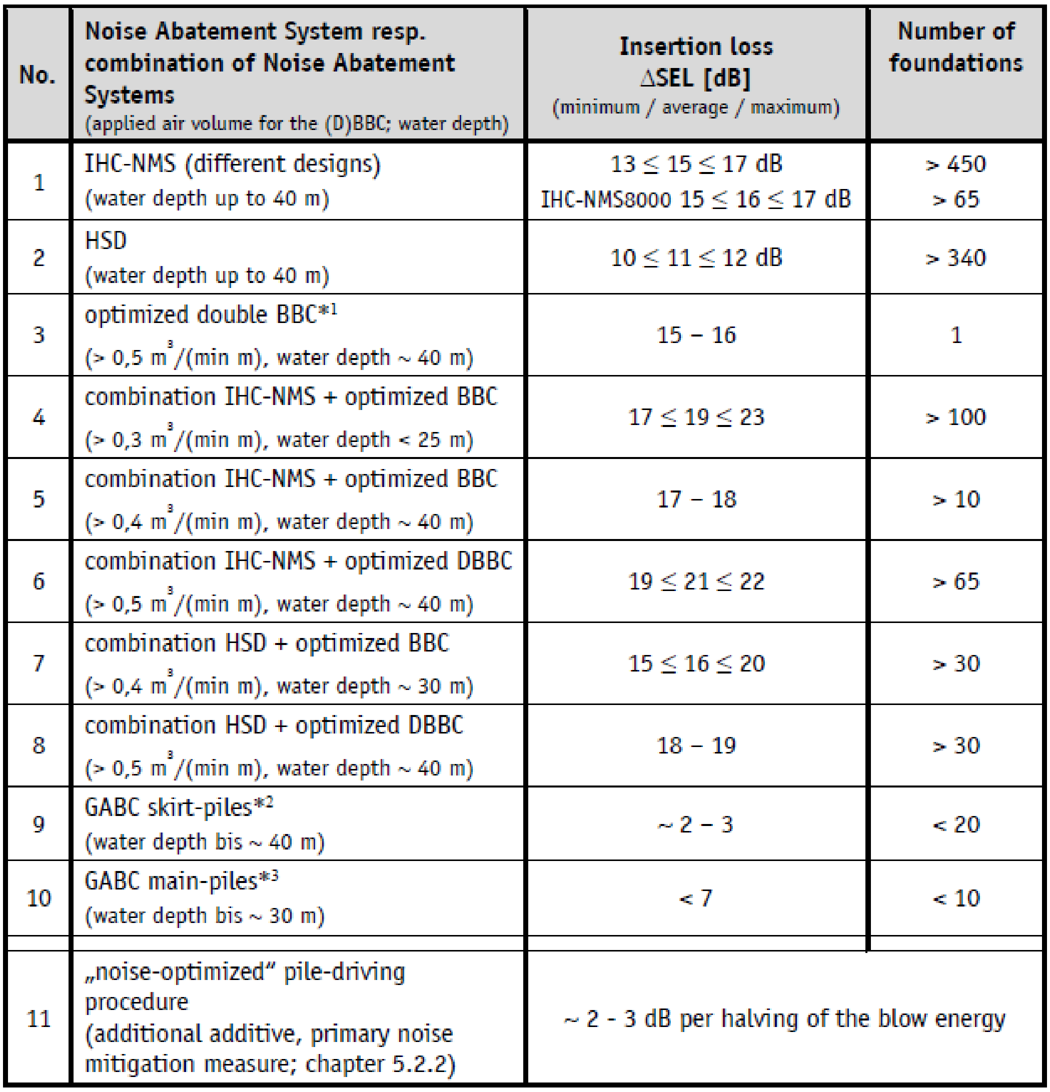
6.1.2.1.3. Hydro-sound-dampers

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. With the HSD system, it is possible to "tune" the NAS to work optimally at specific frequencies, thus allowing for project specific optimal solutions. For the same reason however, the system is typically less effective at other frequencies.

6.1.2.2. Noise abatement system effectiveness

For commercially available and proven NAS, a summary of achieved mitigation levels throughout completed installations is given in (Bellmann, et al., 2020), as shown in Figure 6.5. 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. That is, the source level reduction achievable for a source with equal acoustic energy in all octave bands, also called pink noise. Pile driving spectra however, as described in section 6.1.1.2, are far from a flat octave band 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 6.6, the broadband flat spectrum attenuation achieved with the different NAS, are instead given in 1/3 octave bands, thus showing the achieved mitigation per frequency band.

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



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)	$13 \leq 15 \leq 17$ dB IHC-NMS8000 $15 \leq 16 \leq 17$ dB	> 450 > 65
2	HSD (water depth up to 40 m)	$10 \leq 11 \leq 12$ 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)	$17 \leq 19 \leq 23$	> 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)	$19 \leq 21 \leq 22$	> 65
7	combination HSD + optimized BBC (> 0,4 m^3/(min m), water depth ~ 30 m)	$15 \leq 16 \leq 20$	> 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 6.5: Achieved source mitigation effects at completed projects using different NAS, (Bellmann, et al., 2020).

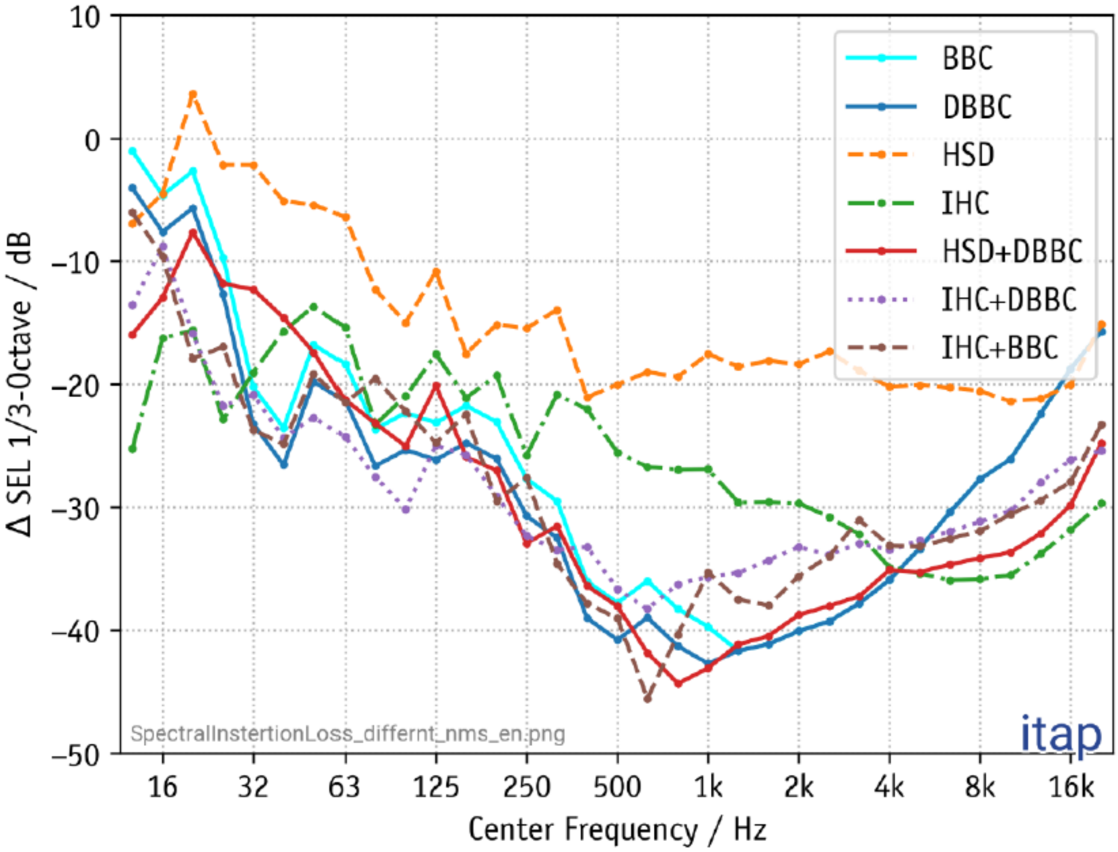


Figure 6.6: Frequency dependent noise reduction for NAS, (Bellmann, et al., 2020).

In Figure 6.6 the mitigation effect is provided as the noise level relative to installation without any active NAS, so the more negative the value, the better the mitigation effect. In numeric form, the mitigation effect in the different frequency bands is provided in Table 6.3.

Table 6.3: Mitigation effect of different Noise Abatement Systems (NAS) (Bellmann, et al., 2020). Values are indicated by frequency band specific mitigation effects. The more negative the value, the better the mitigation effect.

Frequency	Mitigation effect of NAS [dB]		
	BBC	DBBC	HSD-DBBC
12.5	-1	-4	-10
16	-5	-8	-13
20	-3	-6	-8
25	-10	-13	-12
31.5	-20	-23	-13
40	-23	-26	-14
50	-16	-20	-17
63	-18	-21	-22
80	-23	-27	-23
100	-22	-26	-25
125	-23	-27	-20
160	-22	-25	-26
200	-23	-26	-27
250	-28	-31	-33
315	-29	-32	-32
400	-37	-39	-36
500	-38	-41	-38
630	-36	-39	-42
800	-38	-41	-44
1k	-40	-43	-43
1.2k	-42	-42	-41
1.6k	-41	-41	-41
2k	-40	-40	-39
2.5k	-39	-39	-38
3.2k	-38	-38	-37
4k	-36	-36	-35
5k	-33	-33	-35
6.3k	-30	-30	-34
8k	-28	-28	-34
10k	-27	-27	-33
12.5k	-23	-23	-32
16k	-19	-19	-30
20k	-16	-16	-25
25k	-13	-13	-20

It should be noted from Table 6.3, that the HSD-DBBC mitigation effect is less than that of the DBBC system at individual frequencies in the low and mid frequency region. This would imply, that the mitigation effect is worse for a NAS consisting of an HSD and a DBBC system, compared to a DBBC system alone.

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 current conditions. It is not clear from the report, when and where each NAS effect was measured, and it is therefore not possible to determine what would contribute to the achieved effects.

As the measurement results originate from German OWFs, it is however worth noting the measurement procedure for installations including NAS, where one pile is measured without any NAS active, one pile is measured with each individual NAS (such as BBC or IHC-NMS) and the rest of the piles are measured with all NAS active (such as IHC-NMS+DBBC).
It is also worth emphasizing that the mitigation effect presented is the average of achieved mitigation, and given the continuous development of NAS 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 NAS technologies and installation methods emerge in the coming years, however until such methods exist, it is not possible to include in a prognosis.

In summary, prediction of achievable mitigation effect for any system, based on past implementations, 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 NAS is likely to be necessary for the current project, based on typical frequency specific mitigation effects.

If the purpose is to limit broadband noise output, an NAS 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 when choosing NAS. As an example, the DBBC NAS 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 would provide significantly better protection. It is therefore recommended to always carry out detailed site and pile specific underwater sound emission modelling with incorporation of NAS available to the contractor, based on the project specific mitigation purpose.

6.1.3. Source positions

Sound propagation modelling for pile driving activities is carried out for seven positions shown in Figure 6.7. The source positions were chosen due to their location relative to maximum expected sound propagation, and for maximum overlap with the nearby Natura 2000 area, see Figure 6.8.

- Position 1 is located at the north-eastern part of the OWF area. The water depth at the source position is 48 m, and topsoil sediments are mainly clayey till.

- Position 2 is located in the westernmost part of the OWF area, at ~62 km distance east of the Swedish coastline, and ~8 km from the natura 2000 area "Finngrundet-Östra banken". The water depth at the source position is 47 m, and topsoil sediments are mainly postglacial till.

- Position 3 is located in the middle of the OWF area on the southern border, immediately north of the Natura 2000 area "Finngrundet-Östra banken". The water depth at the source position is 38 m, sediment conditions are mainly clayey till. This position is expected to have the furthest impact towards the Natura 2000 area "Finngrundet-Östra banken".

- Position 4 is located at the southeasternmost corner of the OWF area, at ~10 km distance from the natura 2000 area "Finngrundet-Östra banken". The water depth at the source position is 44 m, and sediment conditions are a mix of clay and till. This position is considered representative worst case in regard to sound propagation in direction of the Finland-Sweden maritime border.

- Position 5 is located in the middle of the OWF area and will aim to describe the general sound propagation inside the OWF area. The water depth at the source position is 45 m and is at a distance of 10 km to the Natura 2000 area "Finngrundet-Östra banken". Sediment conditions are a mix of clay and till.

- Position 6 is located in the south-eastern part of the OWF area on the western border towards the Natura 2000 area "Finngrundet-Östra banken". The depth is 38 m and sediment conditions are a mix of clay and till.

- Position 7 is located in the middle of the OWF area in between position 3 and 5. The water depth at the source position is 40 m and is at a distance of 6.3 km to the Natura 2000 area "Finngrundet-Östra banken". Sediment conditions are a mix of clay and till.

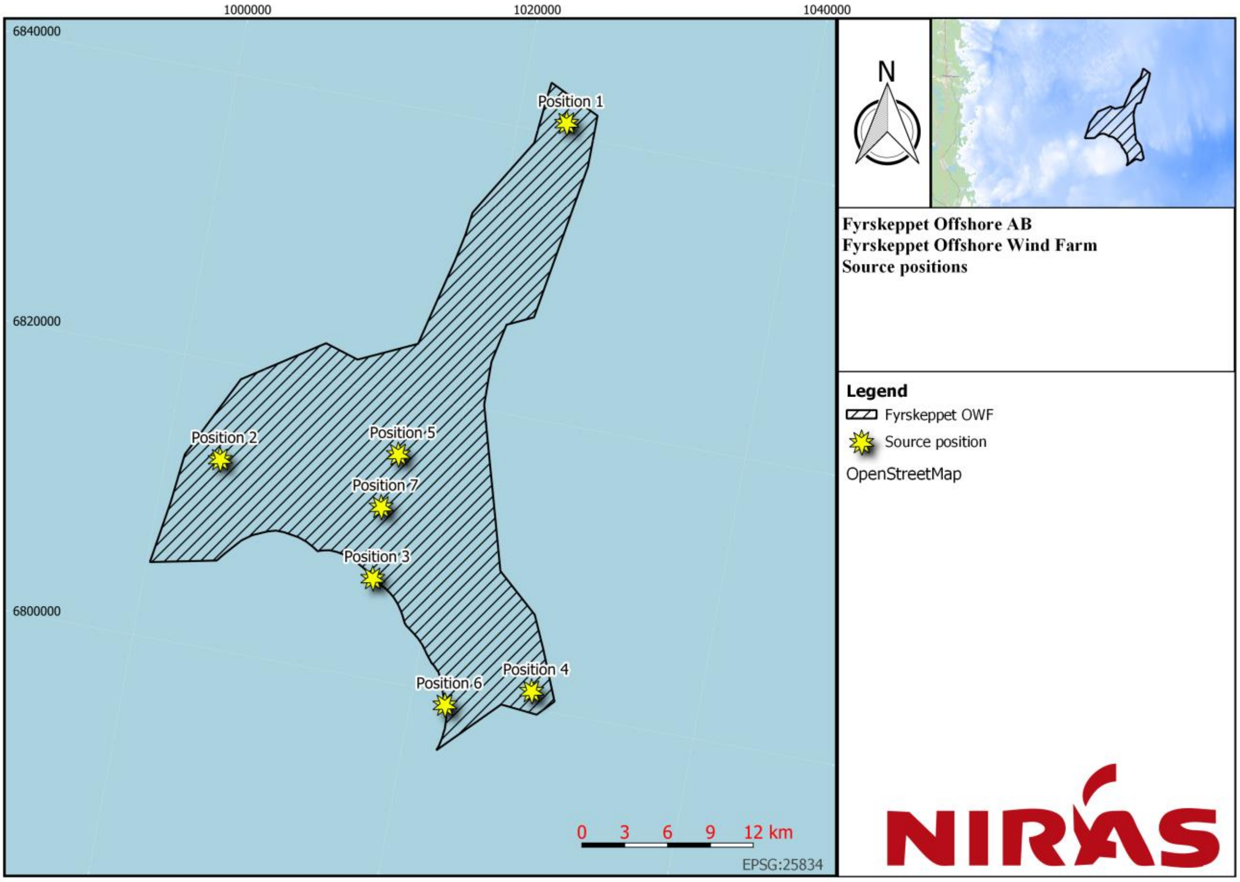


Figure 6.7: Source positions chosen for sound propagation modelling.

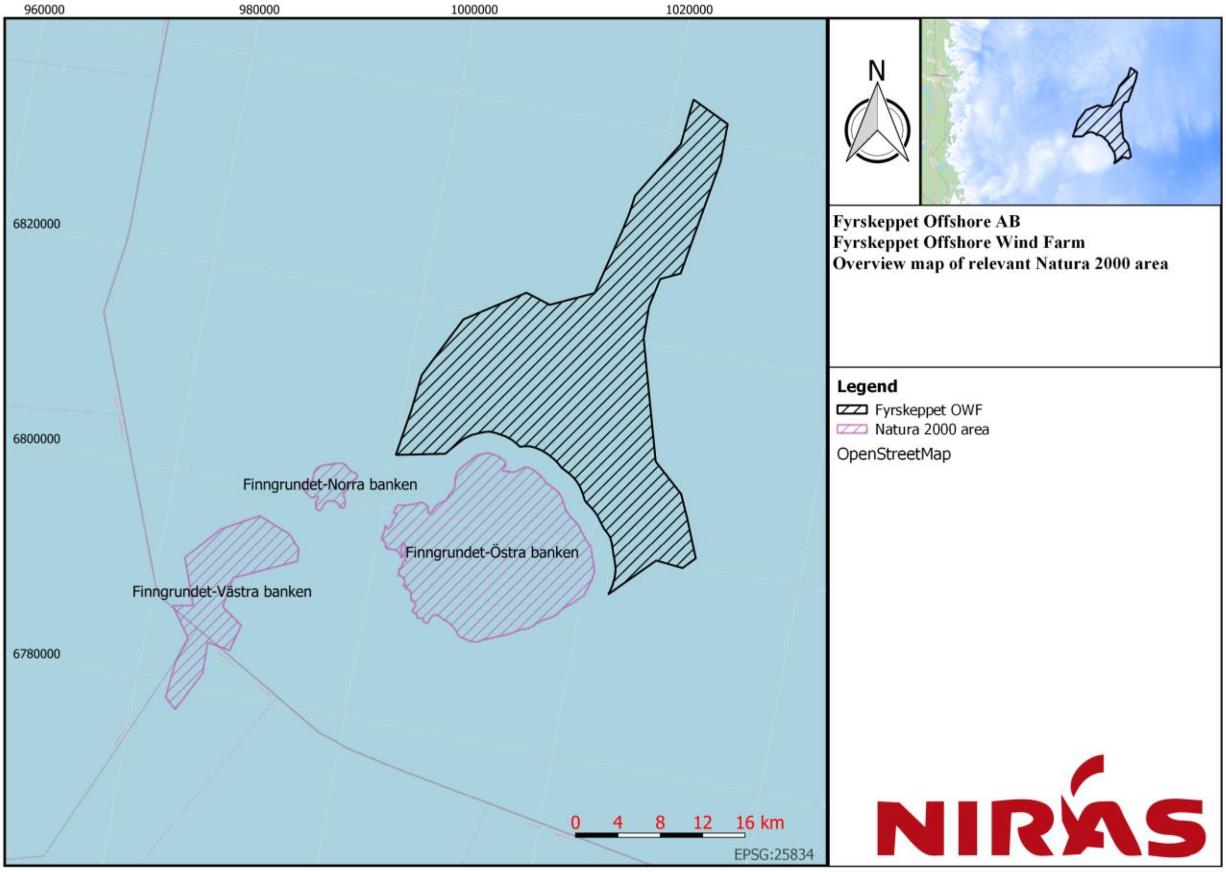


Figure 6.8: Overview of nearby Natura 2000 areas.

6.1.4. Source model implementation

Following the methodology presented in the section 6.1.1, source levels and frequency spectrum for the two foundation types are defined in the following subsections.

6.1.4.1. Foundation scenario 1: 15 m diameter monopile

For the monopile foundation scenario, the unmitigated and unweighted SEL at 750 m was derived to be: $\mathrm{SEL}_{@750\mathrm{m}} = 185.1\ \mathrm{dB\ re.\ 1\ \mu Pa^2 s}$. Backcalculating this level to 1 m, results in $L_{S,E} = 228.3\ \mathrm{dB\ re.\ 1\ \mu Pa^2\ m^2\ s}$. The source level is presented in all relevant metrics, with and without frequency weighting, see Table 6.4.

Table 6.4: Broadband source level for monopile foundation scenario, with and without frequency weighting.

Frequency weighting	Source level $(\mathbf{L_{S,E}})[\mathbf{dB\ re.\ 1\mu Pa^2 m^2 s}]$
Unweighted	228.3
Phocid Carnivores in water (PCW)	206.8

The unweighted ESL frequency spectrum for this foundation scenario is provided in Table 9.1, Appendix 1.

As previously mentioned, due to the unlikeliness of an unmitigated installation scenario being allowed, the source model includes the application of a noise mitigation system. For the monopile foundation scenario the DBBC system is applied. See mitigated source levels in Table 6.5. It should be noticed, that the high mitigation effect relies on the spectral insertion loss data presented in (Bellmann, et al., 2020), and a product specific prognosis should be carried out by the contractor when the specific installation method, pile size and mitigation technique is chosen.

Table 6.5: Broadband source level for monopile foundation scenario, with and without frequency weighting.

Frequency weighting	Mitigated source level (with DBBC) $(\mathbf{L_{S,E}})[\mathbf{dB\ re.\ 1\mu Pa^2m^2s}]$
Unweighted	203.4
Phocid Carnivores in water (PCW)	179.7

6.1.4.2. *Foundation scenario 2: Jacket foundation with 4x 5.5m pin piles*

For the jacket foundation scenario, the unmitigated and unweighted SEL at 750 m was derived to be: $\mathrm{SEL}_{@750\mathrm{m}} = 177.3\ \ \mathrm{dB\ re.}\ 1\ \mu\mathrm{Pa}^2\mathrm{s}$. Backcalculating this level to 1 m, results in $L_{S,E} = 219.2\ \mathrm{dB\ re.}\ 1\ \mu\mathrm{Pa}^2\ \mathrm{m}^2\ \mathrm{s}$. The source level is presented in all relevant metrics, with and without frequency weighting, see Table 6.6.

Table 6.6: Broadband source level for jacket foundation scenario, with and without frequency weighting.

Frequency weighting	Source level $(\mathbf{L_{S,E}})[\mathbf{dB\ re.\ 1\mu Pa^2m^2s}]$
Unweighted	219.2
Phocid Carnivores in water (PCW)	201.8

The unweighted ESL frequency spectrum for this foundation scenario is provided in Table 9.2, Appendix 1.

Like the monopile foundation scenario, the DBBC system is considered. See mitigated source levels in Table 6.7. It should be noticed, that the high mitigation effect relies on the spectral insertion loss data presented in (Bellmann, et al., 2020), and a product specific prognosis should be carried out by the contractor when the specific installation method, pile size and mitigation technique is chosen.

Table 6.7: Broadband source level for jacket foundation scenario, with and without frequency weighting.

Frequency weighting	Mitigated source level (with DBBC) $(\mathbf{L_{S,E}})[\mathbf{dB\ re.\ 1\mu Pa^2m^2s}]$
Unweighted	193.4
Phocid Carnivores in water (PCW)	172.4

6.1.5. Identification of worst-case foundation type

In the previous sections, the two foundation installation scenarios are described in terms of source characteristics both unweighted and with regards to phocid pinnipeds (seals). A direct comparison of the source levels both unweighted and PCW-weighted, reveal that the monopile has the highest source level. Impact ranges for single pile strikes are therefore guaranteed to be longer for monopiles than for the jacket foundations.

For evaluation of PTS, TTS and injury criteria using the cumulative SEL metric, the number of pile strikes over a 24h duration however has an influence on the impact ranges. For monopiles, this includes up to 9600 pile strikes, while for jacket foundations the assumed number of pile strikes is 4 times higher due to multiple piles being installed within a 24h window.

A comparative calculation was therefore carried out for position 5, where PTS, TTS and injury criteria were calculated for both the monopile and jacket foundation scenarios. The calculations show the impact ranges in Table 6.8. Similar calculations were carried out for seal TTS and PTS, however were found to both be below the lowest reported threshold of 25 m. A difference in impact is therefore not observable for seals between the two foundation types.

Table 6.8: Comparison of monopile and jacket foundation impact ranges for evaluation of worst-case foundation type, using threshold criteria for fish. Impact ranges are in meters.

Foundation	Distance-to-threshold [meters]						
	TTS (r_{TTS})			Injury (r_{injury})			
	Juvenile Cod	Adult Cod	Herring	Juvenile Cod	Adult Cod	Herring	Larvae & Eggs
Monopile	11 900	8 100	7 200	25	25	25	600
Jacket	1 900	25	25	25	25	25	250

The results show a significantly longer impact range for monopile installation compared to jacket foundations. Sound propagation prognosis will therefore only consider monopile installation for the remainder of this report.

6.1.6. Installation of two foundations within a 24h period

If two foundations were to be installed within a 24h period, sound propagation and foundation type considered equal, it is assumed that the noise emission from each is similar. Differentiation between simultaneous/partially overlapping and sequential installation is important, and the consequence of each scenario is discussed in the following.

6.1.6.1. Installation of two foundations simultaneously

If the 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 emission relative to the swim speed of the marine mammal and fish.

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 can occur, where a marine mammal and fish would swim away from 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 kind of $L_{E,cum,24h}$, the marine mammal and fish would receive over the span of the installations.

Inversely, the closer the foundations, the lower the risk of trapping, but also the closer to 2x single foundation threshold distances 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 and fish are able to create distance between themselves and the pile installation(s), before both piling activities are active.

Another aspect of concurrent installations is that it can potentially result in increased behaviour distances if the pile strikes are synchronized. The likelihood of synchronization would however be low as the behaviour criteria is based on the noise dose within a 125 ms time window.

There is however also a secondary effect, where the noise emission from one pile installation would cause positive and destructive interference with the noise emission from the second pile installation, resulting in local variations of ±3 dB, and thereby potentially increasing the impact distance for behaviour significantly. Installation of two foundation simultaneously is therefore not recommended.

6.1.6.2. Installation of two foundations sequentially

If installation of two foundations is carried out sequentially, where the second pile installation is started as soon as the former is completed, the effects on underwater noise exposure become significantly less uncertain. 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 on marine mammals and fish.

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 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.

Thus, it is assessed that the installation of two foundations (positioned close to each other) sequentially will not increase the impact ranges for behavioural avoidance responses nor the TTS and PTS impact ranges. A theoretical scenario where sequential installation is used with 2 piles installed per day, will prolong (double) the daily time period where pile driving is taking place, however reduce (half) the number of days with piling noise emission. Under the assumption, that installation will occur every day, the effective installation period for pile driving activities would be reduced (halved).

6.1.7. Uncertainties

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

The prognosis assumes a worst case scenario of a 15 m diameter monopile, while the projects may be completed using monopiles of a smaller diameter. An uncertainty of absolute source level is therefore present in the model. As explained in detail in section 6.1.1.1.1, 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. Due to the significant extrapolation with regards to the monopile diameter, it can however not be ruled out, that deviations from this might occur.

Uncertainties in the environmental parameters primarily relate to the topsoil 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 this study was not evaluated 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 DBBC equivalent mitigation effect were applied 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.

6.2. Pile driving underwater sound propagation results

Underwater sound propagation modelling was carried out for the 15 m monopile scenario in seven positions distributed throughout the OWF area. The source model included the use of a DBBC equivalent mitigation effect. The alternative foundation type of jacket foundations using up to 12 x 5.5 m pin piles per foundation was found to result in overall lower impact ranges, and was not included in the sound propagation modelling, which focused solely on worst case.

DTT for PTS, TTS and Injury describe the minimum distance from the source, a marine mammal or fish must at least be deterred to, 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 at which distance from the pile driving activities the individual should be, to avoid the respective impact.

Section 6.2.1 and section 6.2.2 shows the calculated DTT for fish and earless seals respectively.

6.2.1. Mitigated threshold distances for fish

For calculating the DTT for TTS and Injury in regard to fish, Table 6.9, the cumulative 24h modelling was used. This is represented by the thresholds:

- $\mathrm{L}_{\mathrm{E,cum,24h,unweighted}} = 186\ \mathrm{dB\ re\ 1\ \mu Pa^2 s}$ for TTS,
- $\mathrm{L}_{\mathrm{E,cum,24h,unweighted}} = 204\ \mathrm{dB\ re\ 1\ \mu Pa^2 s}$ for injury,
- $\mathrm{L}_{\mathrm{E,cum,24h,unweighted}} = 207\ \mathrm{dB\ re\ 1\ \mu Pa^2 s}$. for injury in Larvae and eggs.

Table 6.9: Resulting threshold impact distances for fish using DBBC mitigation effect on a 15 m monopile, April and June.

Position	Distance-to-threshold [meters]						
	TTS (r_{TTS})			Injury (r_{injury})			
	Juvenile Cod	Adult Cod	Herring	Juvenile Cod	Adult Cod	Herring	Larvae & Eggs
Worst case for January - December (Month of April)							
1	9900	6000	5200	25	25	25	575
2	7600	4150	3400	25	25	25	475
3	8800	5600	4900	25	25	25	600
4	8100	4850	4100	25	25	25	500
5	11900	8100	7200	25	25	25	600
6	9600	6000	5100	25	25	25	625
7	10600	6800	6000	25	25	25	625
Worst case for June - October (Month of June)							
1	9600	5700	4850	25	25	25	575
2	7000	3750	3000	25	25	25	500
3	8200	5100	4450	25	25	25	625
4	7400	4250	3550	25	25	25	475
5	11300	7500	6600	25	25	25	600
6	8700	5200	4300	25	25	25	600
7	10100	6400	5500	25	25	25	625

6.2.2. Mitigated threshold distances for marine mammals

For calculating the DTT for TTS and PTS in regard to earless seals, Table 6.10, the cumulative 24h modelling was used. The following thresholds apply:

- $L_{E,cum,24h,PCW} = 170 \text{ dB re } 1 \, \mu Pa^2 s$ for TTS,
- $L_{E,cum,24h,PCW} = 185 \text{ dB re } 1 \, \mu Pa^2 s$ for PTS.

Table 6.10: Resulting threshold impact distances for earless seals using DBBC mitigation effect on a 15 m monopile, for April and June.

Position	Distance-to-threshold [meters]			
	Worst case for January - December (Month of April)		Worst case for June - October (Month of June)	
	PTS (r_{PTS})	TTS (r_{TTS})	PTS (r_{PTS})	TTS (r_{TTS})
1	25	25	25	25
2	25	25	25	25
3	25	25	25	25
4	25	25	25	25
5	25	25	25	25
6	25	25	25	25
7	25	25	25	25

6.2.3. Mitigated area of effect for herring TTS criteria

In addition to the DTT values, the total area affected for the TTS impact criteria for herring is calculated, Table 6.11. The affected area represents the zone within which, herring, present at the onset of pile driving, is likely to be exposed to a cumulative noise dose above the TTS threshold criteria.

Table 6.11: Area affected for TTS impact threshold criteria for herring, for April and June.

Position	Affected area (TTS in herring) [km^2]	
	Worst case for January - December (Month of April)	Worst case for June - October (Month of June)
1	48 km^2	41 km^2
2	14 km^2	10 km^2
3	39 km^2	32 km^2
4	22 km^2	15 km^2
5	62 km^2	51 km^2
6	32 km^2	23 km^2
7	60 km^2	49 km^2

6.2.4. Underwater noise contour map for herring TTS threshold criteria

Underwater noise contour maps for herring TTS criteria are shown in Figure 6.9 - Figure 6.15. Affected area is also illustrated in the figures. It should be noted, that TTS impact ranges are extremely sensitive to long range propagation losses as fleeing behaviour is included. Therefore, large variations in impact range are likely to occur where steep changes in bathymetry take place. This is noticeable in especially position 1, 2 and 4.

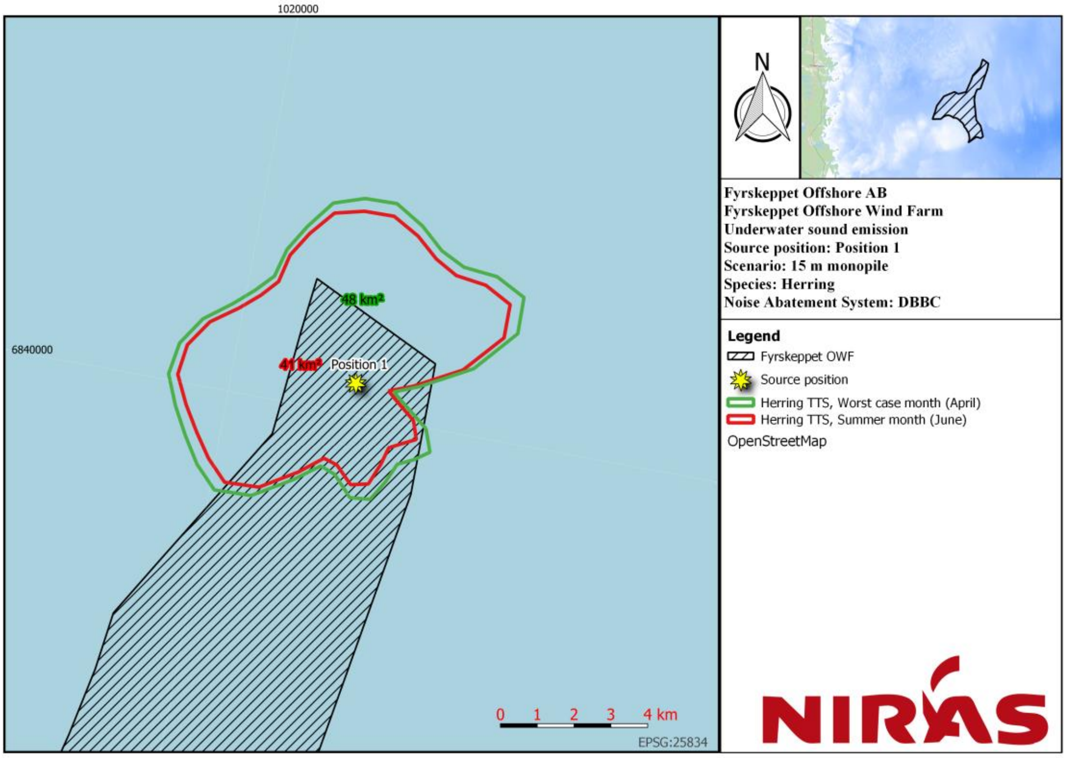


Figure 6.9: Noise contour map for herring TTS criteria, for 15 m monopile with DBBC mitigation effect at position 1.

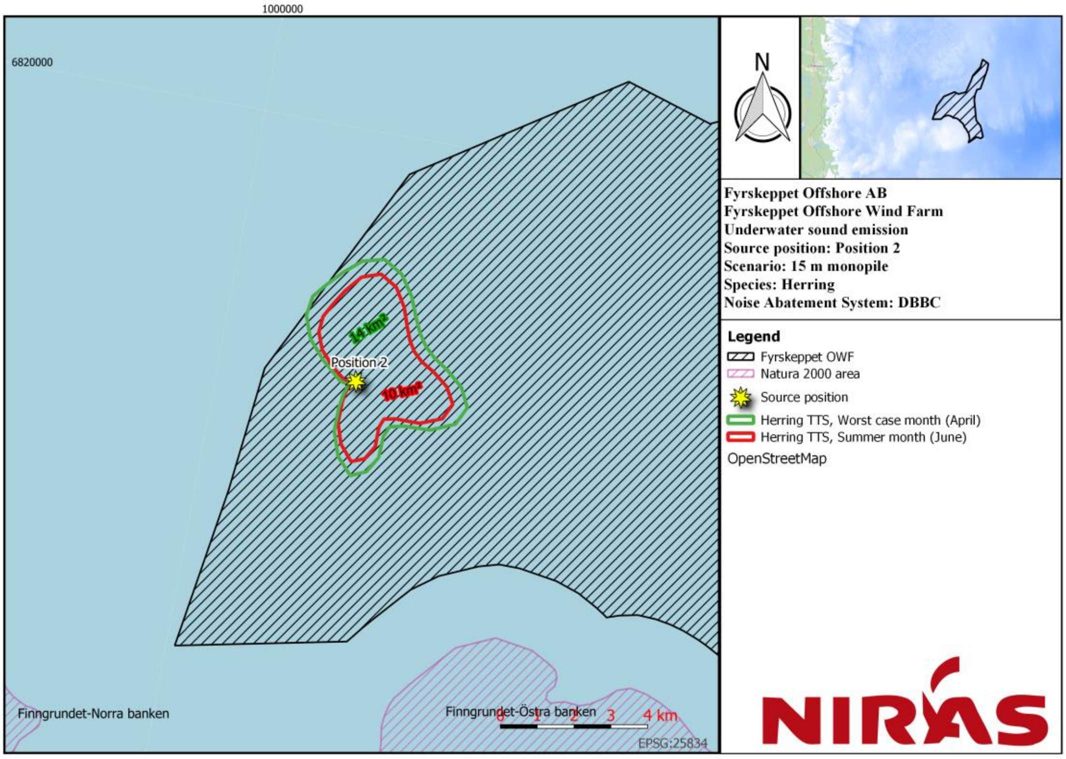


Figure 6.10: Noise contour map for herring TTS criteria, for 15 m monopile with DBBC mitigation effect at position 2.

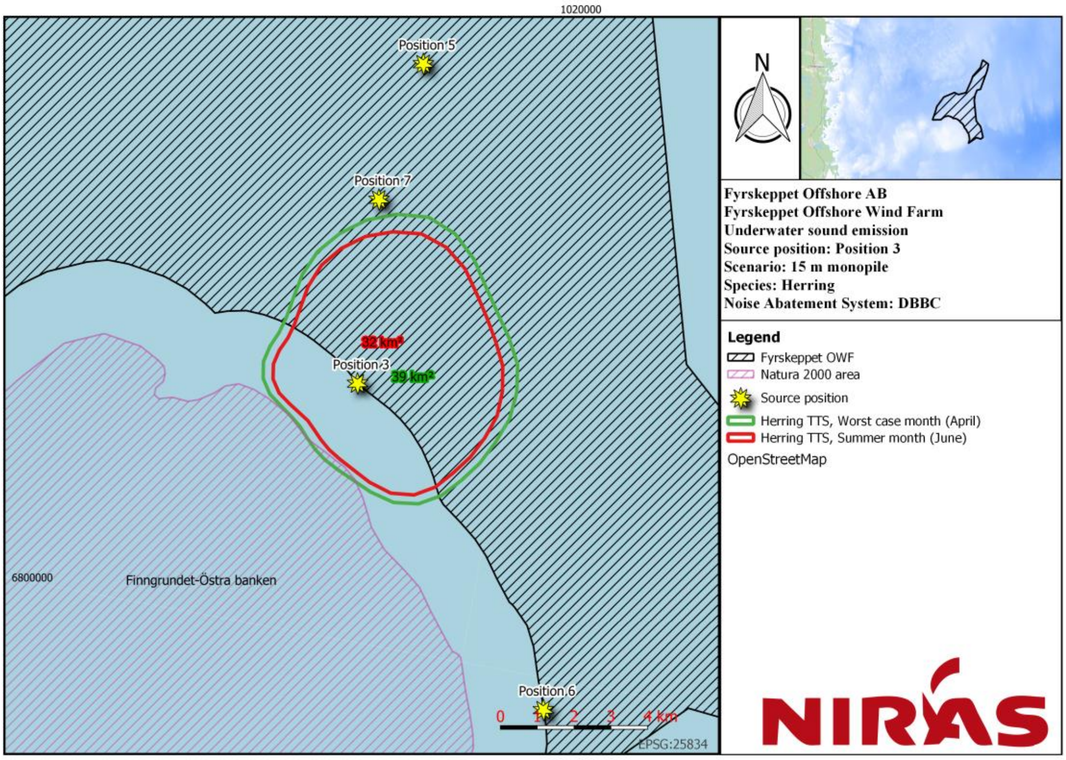


Figure 6.11: Noise contour map for herring TTS criteria, for 15 m monopile with DBBC mitigation effect at position 3.

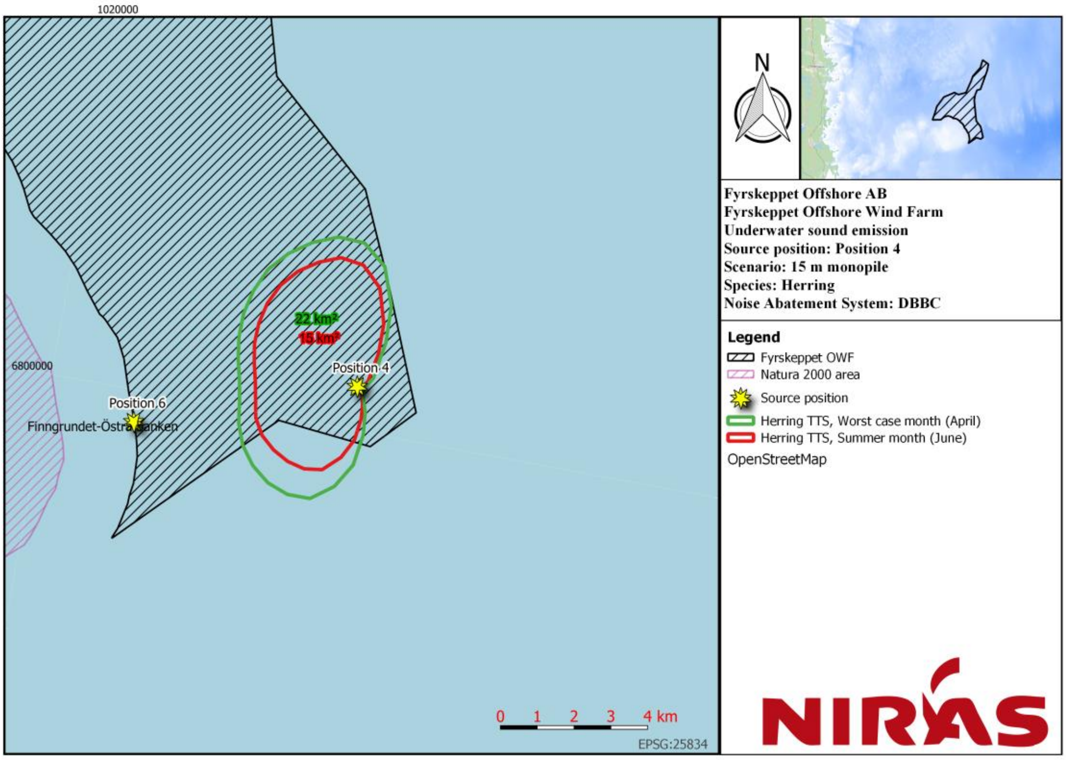


Figure 6.12: Noise contour map for herring TTS criteria, for 15 m monopile with DBBC mitigation effect at position 4.

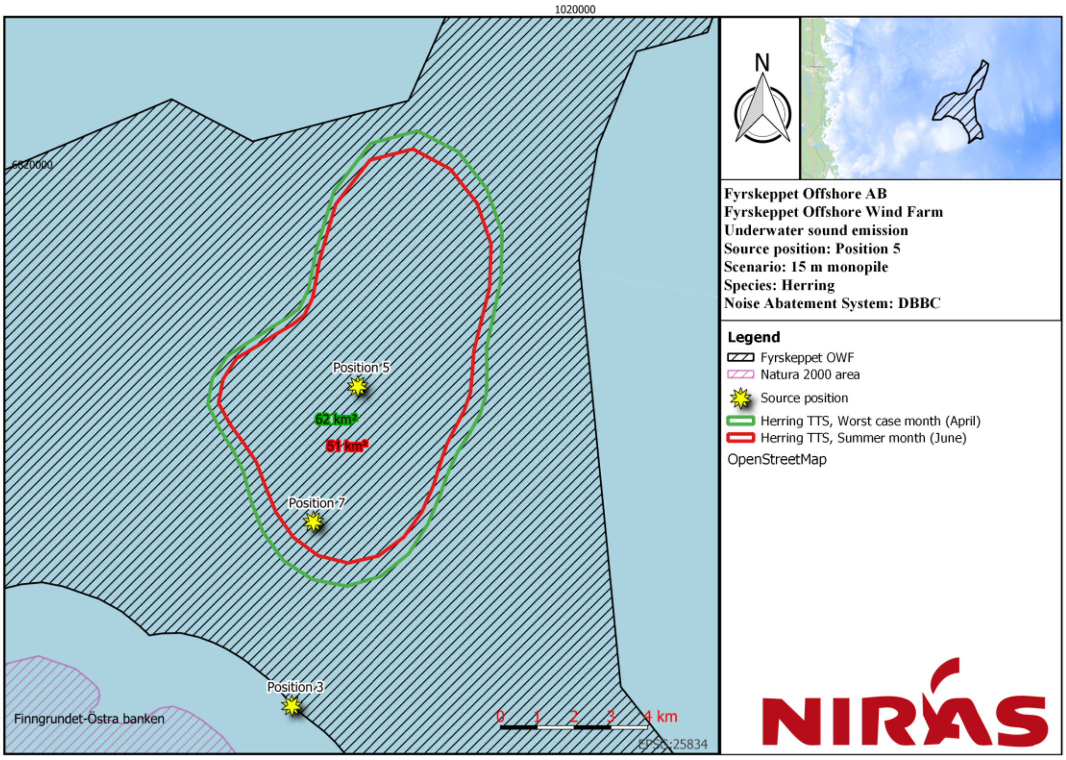


Figure 6.13: Noise contour map for herring TTS criteria, for 15 m monopile with DBBC mitigation effect at position 5.

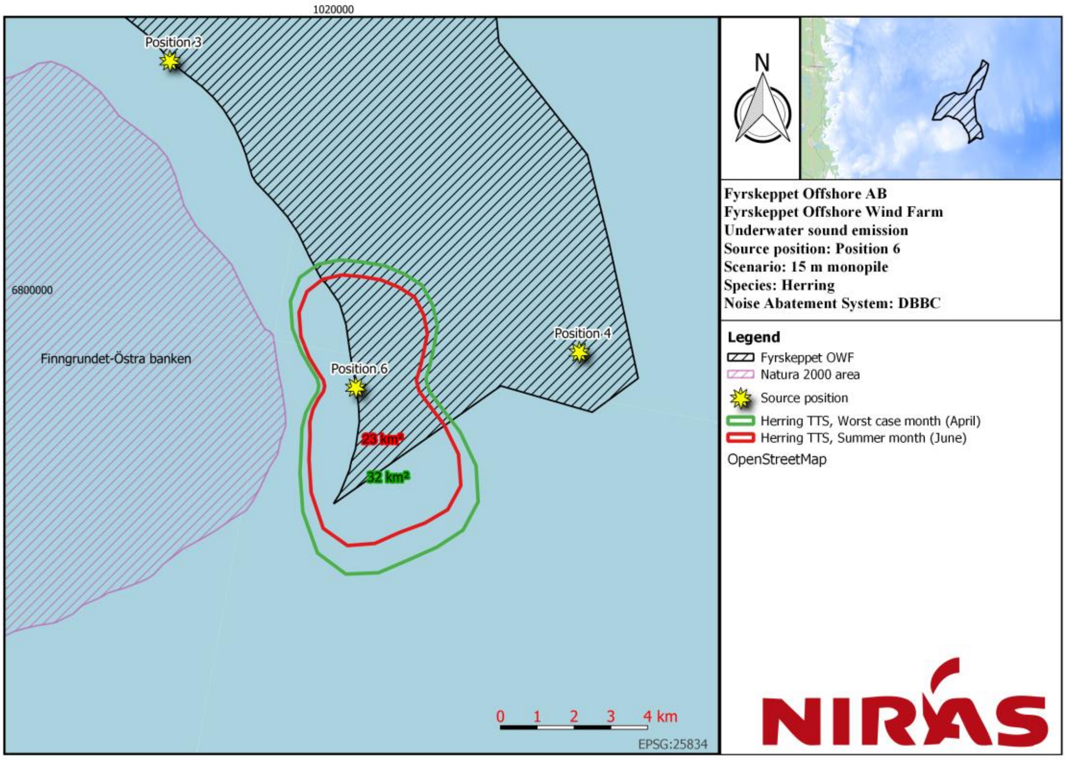


Figure 6.14: Noise contour map for herring TTS criteria, for 15 m monopile with DBBC mitigation effect at position 6.

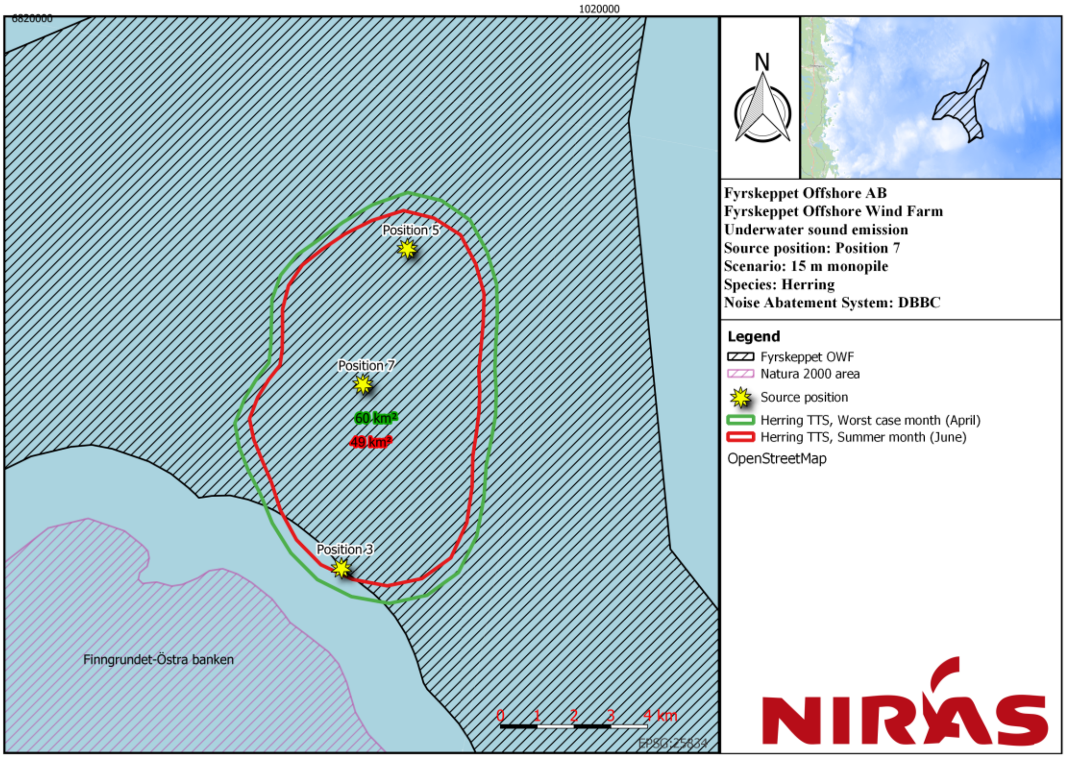


Figure 6.15: Noise contour map for herring TTS criteria, for 15 m monopile with DBBC mitigation effect at position 7.

7. Underwater noise prognosis for geotechnical survey

Fyrskeppet Offshore AB has requested an underwater noise prognosis for geotechnical and geophysical survey activities that may be required in connection with detailed foundation design. The activities would have the purpose of obtaining detailed knowledge of the sediment layers for the locations where foundations are to be installed.

7.1. Description of activities

The client has provided a list of activities and equipment which can potentially be used. These include:

- Geotechnical survey: Multibeam echosounder (MBES), side scan sonar (SSS), sub-bottom profiler (SBP)
- Geophysical survey: Cone Penetration Test (CPT), Geo-technical drilling

No timeline has been proposed for the activities, and worst case with regards to sound propagation is therefore assumed.

MBES and SSS systems both have acoustic emission, however for geotechnical survey activities, typical models have their frequency content located outside any marine mammal and fish hearing range (>200 kHz), and therefore without any negative auditory impact. It should be noted, that if frequency content below 200 kHz is present in the final equipment models, a re-evaluation might be required. MBES and SSS are not covered any further in this report.

Details on specific equipment models for the rest of the investigations and/or operational parameters have not been made available for the prognosis, and it is therefore based on typical equipment models used for such investigations. In Table 7.1, representative survey equipment and operational parameters are listed based on previous surveys.

Table 7.1: Survey equipment models and operational parameters. Note that actual equipment models to be used have not yet been selected, and the listed models and operation parameters are used as representative equipment, based on previous surveys.

Type	Equipment model	Source Level, $\mathbf{L_s}$ $[\mathbf{dB\ re\ 1\ \mu Pa \cdot m}]$	Primary Frequency Range (Hz)	Pulse Length	Beam Width	Sound exposure source level, $\mathbf{L_{S,E}}$ $[\mathbf{dB\ re\ 1\ \mu Pa^2 m^2 s}]$	Duty cycle over a 24 hour period
Sub-bottom profiler (SBP)	Innomar Medium 100 or similar	247 dB	1k – 150k	0.07 – 2 ms	2°	213 dB	40 Hz
Cone Penetration Test (CPT)	-	-	-	-	-	-	-
Drilling	-	145 dB	0 – 2 kHz	continuous	omnidirectional	145 dB	continuous

7.1.1. Sub Bottom Profiler (SBP) – Innomar Medium 100

SBPs are a generic descriptor for survey equipment that has the purpose of creating a profile of the sub bottom seabed layers. They come in many different variations, each with their own acoustic profile. Examples are airguns, sparkers, boomers and parametric SBPs. For shallow water investigations where only the uppermost 10-20 m are of interest, it is typically sufficient to use an Innomar system, which is a parametric SBP.

For the Innomar, the purpose is typically to create a very detailed profile of the uppermost part of the seabed, typically the first 20 m below the seabed. For this, an Innomar Medium-100 is typically used.
The Innomar system emits two high frequency pulses, called the primary frequencies, typically in the frequency range of 100 – 120 kHz. The frequency separation between the two pulses dictates the secondary frequency as the difference between the two primary frequencies: $f_{sec} = f_{pri2} - f_{pri1}\ [Hz]$. The source level (SL) of the Innomar Medium-100 is listed as $SL\ =\ 247\ dB\ re.1\mu Pa\ @1m$.

The Innomar system is a complex sound source as the sound emission is heavily focused towards the seabed. The horizontal emission of underwater noise is therefore limited, compared to the emission directly downward into the seabed. The frequency composition in combination with high source level, however warrants an assessment of the impact on marine mammals. It can be discussed whether the Innomar system, operating at a 40 Hz ping rate is to be considered an impulsive source, or a non-impulsive source, however to err on the side of caution, the stricter thresholds, for impulsive sources is considered.

7.1.2. Cone Penetration Test (CPT)

Cone Penetration Tests are carried out by a mechanism lowered onto the seafloor pushing a cone into the seabed, and through sensors mounted in/on the cone, the vibration through the sediment is registered, and provides data on the sediment. A variation of this test is called seismic CPT, where, in addition to the CPT cone, an excitation pulse is generated by a device placed on the seabed nearby. This creates a motion and transfers it into the seabed for further data input. There are different designs, one of which consist of a frame-mounted, cylinder-encapsuled, spring loaded weight that, on release, is accelerated against an end-cap. This creates an impact pulse. The pulse is then structurally transferred through the frame into the seabed. The noise source in this action consists of the noise from the impact itself, as well as from the vibration of the frame.

It has not been possible to acquire underwater noise measurements for this type of equipment, and according to GEO (one of the companies providing such services), no noise measurements have yet been carried out. In an environmental assessment report from Massachusetts (BOEM, 2012), the noise sources from CPT investigations are characterized as that of the survey vessel, indicating that the CPT in itself is not a significant noise source.

For the seismic source used in seismic CPT tests, noise emission is considered to have two potential sources. The impact of the weight against the endcap, and the vibration of the frame. The impact of the weight against the endcap, occurs inside a closed metallic cylinder, and it is therefore assessed to be effectively attenuated, and insignificant relative to any impact on marine mammals. While the vibration of the frame occurs in direct contact with the water, it is not expected to result in a significant noise emission, rather a low amplitude "ringing" effect. It is not expected to cause any negative impact on marine mammals at any distance.

Based on the above, CPT as a general survey method, is considered without negative acoustic impact on marine mammals and fish and the acoustic impact ranges are considered negligible.

7.1.3. Drilling

There are few measurements of underwater noise from drilling activities (Erbe & McPherson, 2017), but studies where underwater noise from geotechnical drilling activities has been measured, show that the noise is limited to the low-frequency range. Reported source levels are between $SL = 142 - 145\ dB\ re. 1\ \mu Pa\ @\ 1m$, with primary frequency content located between 30 Hz – 2 kHz (Erbe & McPherson, 2017), see frequency spectrum as measured in Figure 7.1.

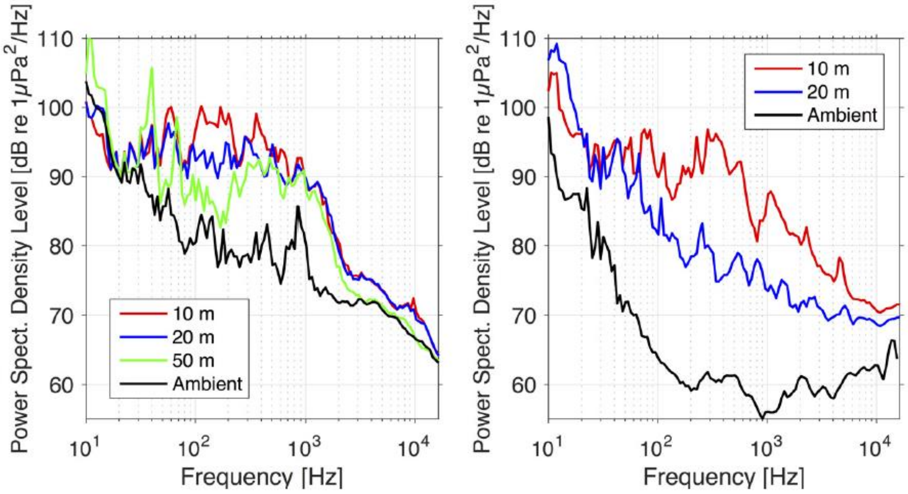


Fig. 2. (Color online) Power spectral density levels of drilling received at various ranges from the drill string at Geraldton (left) and James Price Point (right), compared to ambient noise at both sites—averaged over 10 min.

Figure 7.1: Frequency spectrum from underwater noise measurements of drilling (Erbe & McPherson, 2017).

To understand the potential underwater noise emission in metrics relevant for the marine mammals of interest, the frequency spectrum shown in Figure 7.1, was frequency weighted (filtered) with the PCW-weighting curve (NMFS, 2018), (Southall, et al., 2019). The weighted noise levels should more accurately represent what seals hear. Given an unweighted source level of $SPL_{RMS} = 145\ dB\ re. 1\ \mu Pa\ @\ 1m$, the corresponding PCW-weighted source level was assessed to be $SPL_{RMS(PCW)} \sim 140\ dB\ re. 1\ \mu Pa\ @\ 1m$.

Drilling is considered a continuous noise source. No duration per drilling site was provided, however conservatively, the duration of a single drilling activity has been assumed to be no more than 12 hours. Evaluating the potential impact of this activity against the listed thresholds for continuous noise sources, impact ranges are calculated (Table 7.2).

Table 7.2: Impact range for drilling activity, assessment based on literature.

Hearing group	Impact range (m from activity)	
	$L_{E,cum,24h,PCW}$	
	TTS	PTS
Phocid Carnivores in water (PCW) - seals	< 25 m	< 25 m

7.2. Source model

As described in section 7.1, sound propagation modelling is proposed for the activities involving Innomar equipment, while impact ranges for CPT and drilling activities were assessed based on literature.

Very few measurements exist, documenting the underwater sound emission, and/or source characteristics in the horizontal plane, from Innomar survey activities. In connection with recent seismic survey activities for the Danish Energy Island in the North Sea, a source characterization study took place (Pace, et al., 2021), carrying out underwater sound measurements from an active Innomar medium-100.

The environmental conditions in the North Sea, where the measurements were obtained, are however vastly different from those in the project area with regards to both bathymetry, salinity, temperature and sediment composition, and the results from the North Sea study can therefore not be used directly.
NIRAS has previously made a calibration model based on the North Sea measurements, where the actual environment during the measurements was recreated in dBSea, after which the measurements were replicated by adjusting the source characteristics. Through the calibration model, an equivalent source model was derived for the Innomar medium-100. While it must be recognized that the approach is considered an approximation of the actual source, it is considered the best available data.

The detailed sound source level (SL), species-specific frequency weighted for Phocid Pinniped (PCW) was included in the dBSea sound propagation modelling. Further specifications regarding the dBSea source propagation model are listed in Table 7.3.

Table 7.3: Technical specifications of source and receiver behaviour for the survey activities.

Technical specification		Note
Vessel speed	0 knots for Innomar	
Time duration of the survey	24 h for Innomar	
Fleeing behaviour	Included with 1.5 m/s swim speed	Fleeing behaviour considered is "negative phonotaxy" (Tougaard, 2016)
Number of transects	36 (10° resolution)	
Survey vessel route	Final routes not decided.	

7.2.1. Source position

No specific survey positions were provided, as the survey has not yet been planned. Two representative positions were therefore selected as examples. The positions were chosen by NIRAS based on the environmental parameters for the project area. The positions are shown in Figure 7.2.

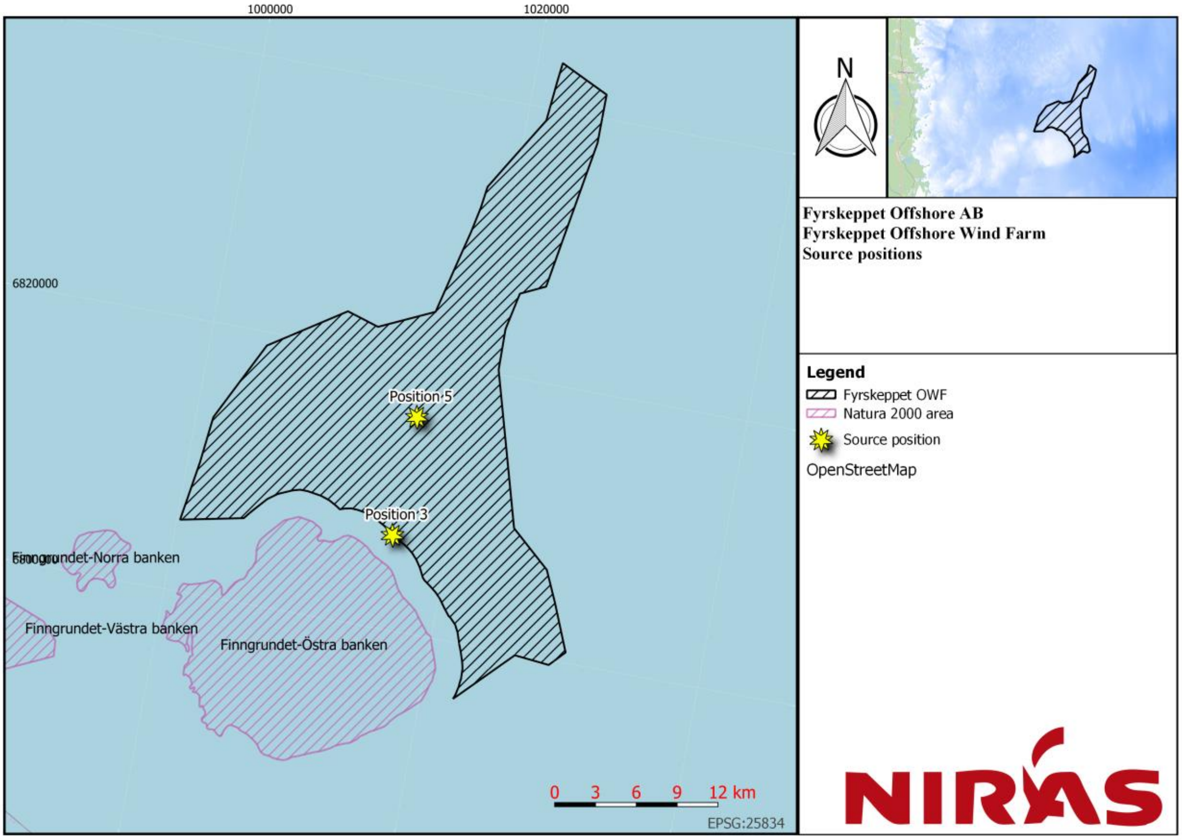


Figure 7.2: Source positions used for the sound propagation modelling of Innomar.

7.3. Sound Propagation Results

Sound propagation modelling using the approach and inputs described in this note, was carried out for two source positions, for the SBP equipment type. The resulting distances to relevant threshold levels are listed in Table 7.4.

Table 7.4: Distance-to-threshold in meters for seismic survey activities for individual equipment types. PTS and TTS distances show, at which range, from the survey vessel (SBP) a marine mammal must at least be at the onset of full survey activities to avoid the respective impact criteria (impulsive).

Hearing group	Position	Impact range (m from activity)	
		$L_{E,cum,24h,PCW}$	
		TTS	PTS
Phocid Carnivores in water (PCW) - seals	3	< 25 m	< 25 m
	5	< 25 m	< 25 m

Impact ranges for PTS and TTS criteria indicate, at which distance, in meters, from the survey vessel, a marine mammal must at least be at the onset of full survey activities in order to avoid each of the given impacts. The results can be used to define the minimum distance, a marine mammal must be deterred to, relative to the survey vessel at the onset of full activities, in order to avoid the respective impact.

7.4. Result summary

In the following, the resulting impact ranges for each of the proposed activities are summarized. For drilling and CPT activity, the assessed impact ranges were based on literature, while impact ranges for Innomar (SBP) are based on numerical sound propagation modelling in dBSea. Impact ranges for the CPT were not possible to determine based on literature, and impact ranges are therefore denoted “N/A”. It is however, as previously described, assessed that impact ranges would be less than that from the survey vessel.

Table 7.5: Distance-to-threshold in meters for survey activities for individual equipment types. PTS and TTS distances show, at which range, from the survey vessel (SBP), CPT or drilling activity a marine mammal must at least be at the onset of full survey activities to avoid the respective impact.

Geotechnical/geophysical survey type	Position	Impact range (m from activity)	
		$L_{E,cum,24h,PCW}$	
		TTS	PTS
Innomar Medium 100 (SBP)	3	< 25 m	< 25 m
	5	< 25 m	< 25 m
Drilling	Literature	< 25 m	< 25 m
Cone Penetration Test (CPT)	Literature	N/A*	N/A*

*: It was not possible to determine impact ranges, but impact range is assessed to be less than survey vessel.

7.5. Uncertainties

The sound propagation prognosis was carried out based on best-available knowledge, however certain limitations and uncertainties to the approach must be recognized.

For drilling and CPT, the impact ranges are based on literature. Impact ranges for drilling are very short (up to 25 m) and an overestimation is therefore not of any concern. For CPT, no impact range was possible to determine, however it is considered to be less than that of the survey vessel.

For the Innomar Medium 100, the source model is based on measurements in the North Sea, and NIRAS internal calibration model thereof. Uncertainties to this source model are assessed to be that it is conservative in nature, and any deviation from the model is expected to be in terms of shorter than predicted impact ranges.

As previously mentioned, source data was selected based on previous experience from similar studies and literature, based on most likely equipment types. If actual equipment models for the activities differ from those assumed in this prognosis, impact ranges could be affected.

8. Underwater noise during 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. In a review by Tougaard (2020) individual measurements from many different turbine types and sizes and at different wind speeds and distances from the foundation were examined. All measurements show that sound levels radiated from turbine foundations are relatively low, but with an increasing trend with increasing turbine size (Figure 8.1). 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.

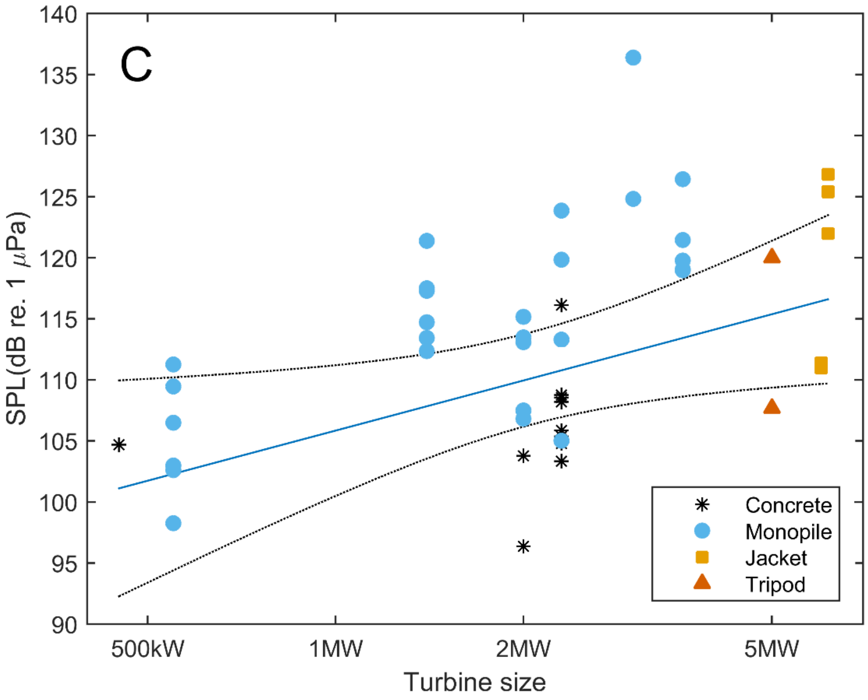


Figure 8.1: Relationship between measured broadband noise and turbine size compiled from available literature. Measurements have been normalized to a distance of 100 m from the turbine foundation and a wind speed of 10 m/s. From (Tougaard, et al., 2020).

There is a strong dependency between wind speeds and radiated noise levels (Figure 8.2). 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.

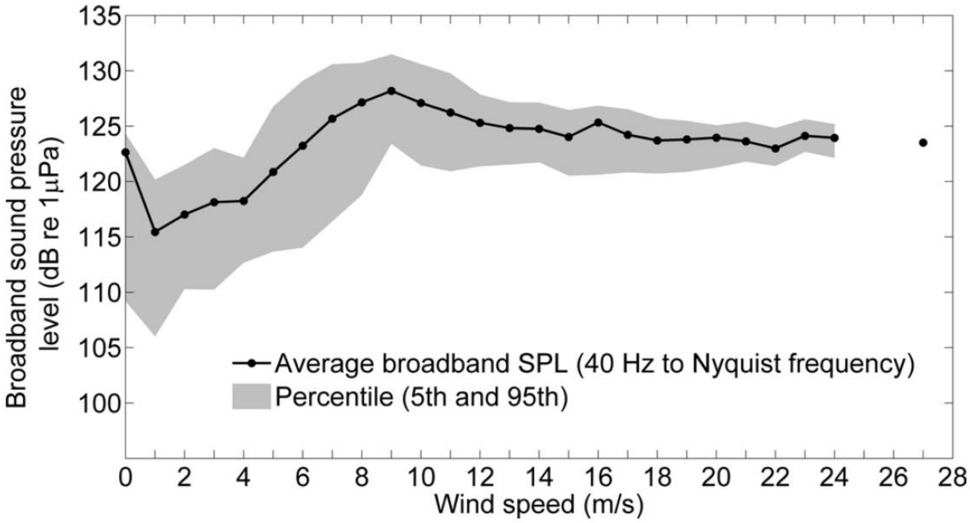


Figure 8.2: Relationship between wind speed and broadband noise level, measured about 50 m from the turbine (3.6 MW Siemens turbine at Sheringham Shoal). Maximum production of the turbine is reached at about 10 m/s, above which the production is constant. Figure from (Pangerc, et al., 2016).

All measurements of turbine noise show 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 8.3, where pronounced peaks are visible in the spectrum in the 160 Hz and 320 Hz, 10 Hz bands. Ambient noise spectrum was not available for the current project; however measurements thereof could be used to compare the theoretical turbine noise to the ambient noise to derive at which distances, the turbine noise would be dominant over other sources such as shipping noise.

Despite the inherent uncertainties with respect to type and size of turbines to be used in the future Fyrskeppet project it is considered likely that the turbine noise will be comparable to what has been measured from other turbines. There is a size dependency, with source level increasing by a factor of 14 dB per factor 10 in turbine nominal capacity (Tougaard, et al., 2020) and turbines for Fyrskeppet are expected to be larger than the largest turbine from which measurements are available (6.15 MW). If measurement data becomes available for larger turbine sizes, it is recommended to re-evaluate whether this assumption still applies. 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. The limited data suggests that noise levels from the direct drive turbine are more broadband in nature than from types with gear box.

Within the radius where the noise from the turbines exceeds ambient noise, the turbine noise is likely to be audible to seals and possibly also fish (Madsen, et al., 2006).

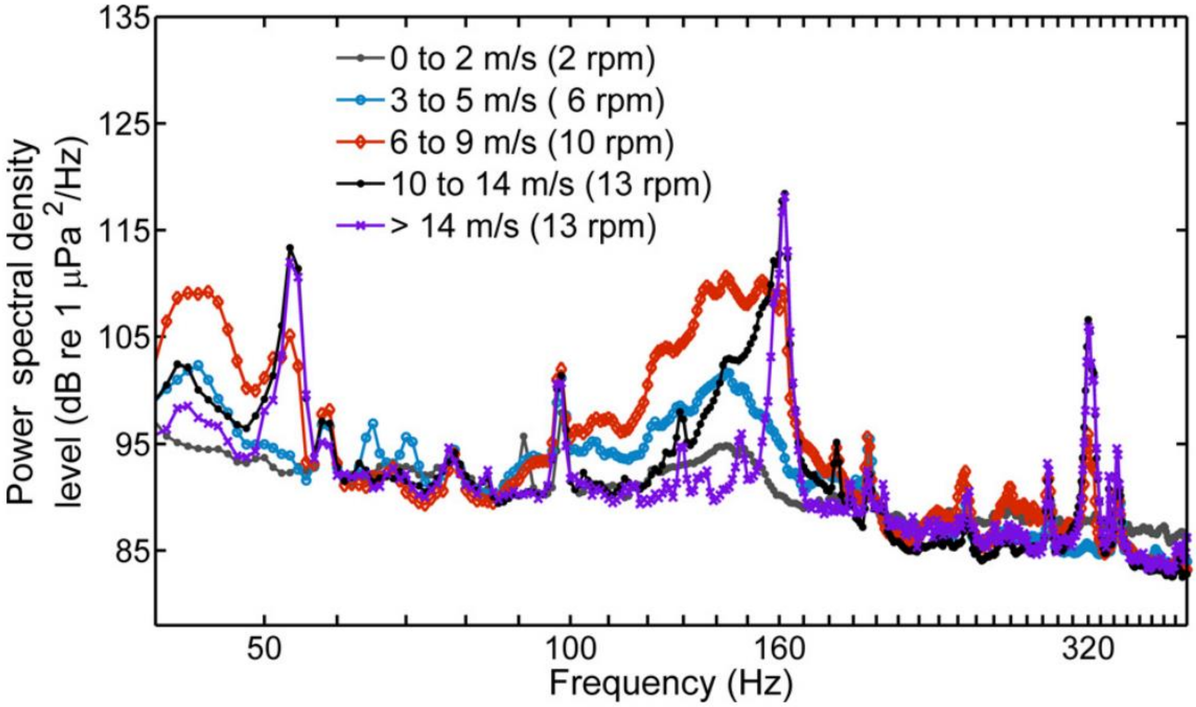


Figure 8.3: Example of frequency spectra from a medium sized turbine (3.6 MW, Gunfleet Sands) at different wind speeds. Levels are given in 10 Hz intervals. Measurements were obtained about 50 m from the turbine. Measurements from (Pangerc, et al., 2016).

8.1. Noise from service boats

In addition to the noise from the turbines themselves, the service boats within wind farms are likely to be a significant 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. It is well known that harbour porpoises will react negatively to ship noise, in particular the part of the noise above 2 kHz (Dyndo, et al., 2015) (Wisniewska, et al., 2018). On the other hand, it has also been documented that harbour porpoises are continuously present around active and noisy oil and gas production platforms (Clausen, et al., 2021) (Todd, et al., 2009). Without dedicated studies it is therefore not possible to quantify the contribution of service boats to the noise in the wind farm and the role of the noise in disturbance of marine mammals.

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Appendix 1

Detailed source levels in 1/3 octave bands

Table 9.1: Unweighted source level in 1/3 octave bands, for unweighted and unmitigated monopile foundation of 15 m diameter. Note that a 5 dB gain has been added to the 32 kHz band to compensate for the limitation on frequency range.

Frequency [Hz]	ESL [dB]
31.5	209.1
40	213.2
50	216.2
63	217.1
80	218.3
100	222.1
125	221.2
160	220.4
200	216.6
250	213.6
315	208.1
400	206.1
500	203.3
630	197.7
800	197.6
1k	196.3
1.2k	194.6
1.6k	193.3
2k	192
2.5k	190
3.2k	186.1
4k	186.1
5k	184.2
6.3k	182.5
8k	180.5
10k	178.7
12.5k	177.1
16k	175.8
20k	174.7
25k	174.1
32k	179.2

Table 9.2: Source level in 1/3 octave bands, for the unmitigated and unweighted jacket foundation with 5.5 m pin piles. Note that a 5 dB gain has been added to the 32 kHz band to compensate for the limitation on frequency range.

Frequency [Hz]	ESL [dB]
31.5	197.6
40	201.7
50	204.2
63	205.6
80	206.8
100	208.6
125	209.7
160	211.4
200	210.6
250	210.6
315	205.6
400	203.6
500	200.8
630	195.2
800	195.1
1k	193.8
1.2k	192.1
1.6k	190.8
2k	189.5
2.5k	187.5
3.2k	183.6
4k	183.6
5k	181.7
6.3k	180
8k	178
10k	176.2
12.5k	174.6
16k	173.3
20k	172.2
25k	171.6
32k	176.7