Jammerland Bugt - Ansøgning om geotekniske forundersøgelser

Underwater noise prognosis for geotechnical investigations

Jammerland Bay Nearshore A/S

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Contents

1 Introduction

This note describes the underwater noise prognosis conducted by NIRAS for geotechnical investigations planned by Jammerland Bay Nearshore A/S for the project "Jammerland Bugt kystnær havmøllepark", hereafter referred to as Jammerland.

2 Project description

The project site is about 6.7 km southwest of Sjælland's coast (see Figure 2.1). The export cable corridor runs from the site to the landing area on Sjælland's coast, south of Kalundborg. Geotechnical activities are divided into three work packages (WP):

- "WP GT1: Main array" outlines activities at individual wind turbine generator (WTG) locations, depicted as red dots in Figure 2.1.
- "WP GT2: Cables" outlines activities along inter-array cables (IAC) represented by blue dots within the purple area in Figure 2.1, and along the export cable corridor (ECC), shown by blue dots within the red area in Figure 2.1.
- "WP GT3: Nearshore / Onshore" outlines activities near the shore, represented by green dots in the red area in Figure 2.1 and onshore, depicted as yellow dots inside the blue area in Figure 2.1.

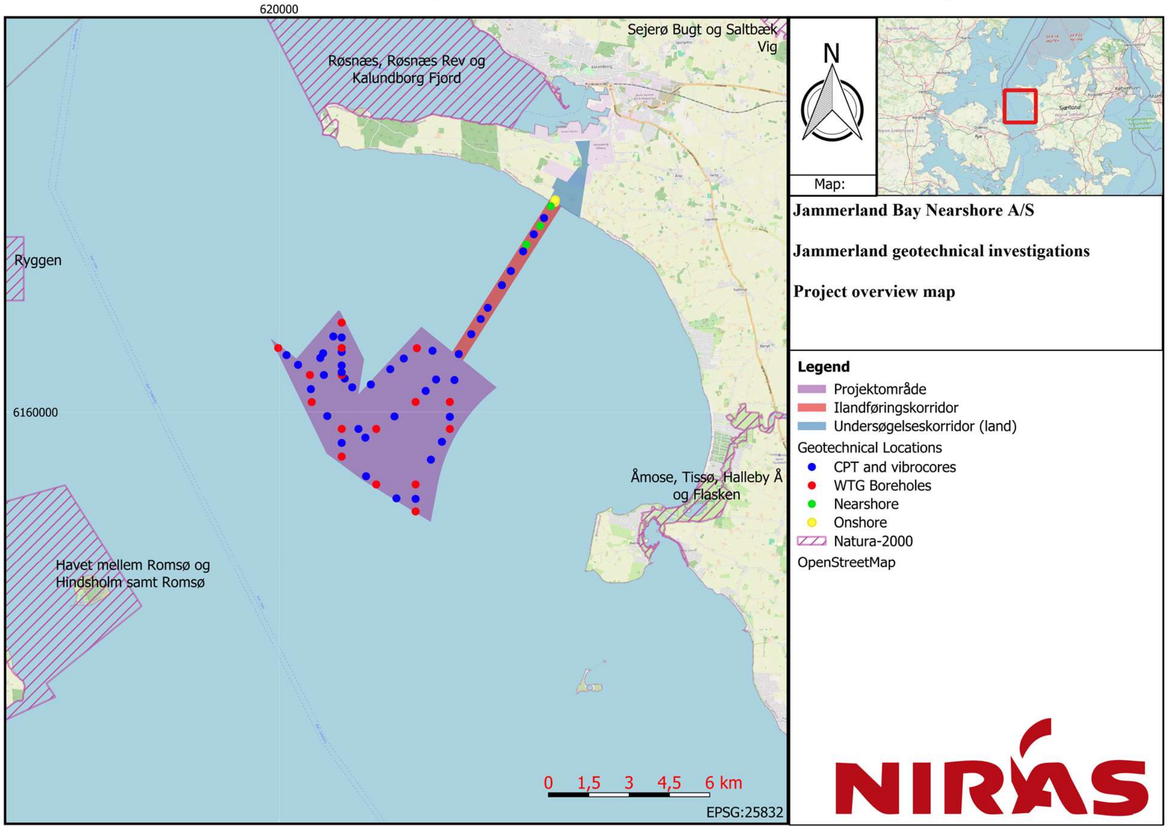

Figure 2.1: Overview map of Jammerland geotechnical investigations, split into the three subareas "WP GT1: Main array" (red dots), "WP GT2: Cables", interarray (blue dots in purple area) and export (blue dots in red area), "WP GT3: Nearshore / Onshore", nearshore (green dots in red area) and onshore (yellow dots in blue area).

The geotechnical investigations program is briefly outlined in the following, with focus on activities that potentially has an impact on relevant marine mammals and fish, as a result of underwater noise emission.

- WP GT1: Main array activities include 16 boreholes (drilling) at the location of the WTGs, with a target depth of 40 m below seabed. This includes PS logging, sampling and Cone Penetration Testing (CPT). Rock coring can occur if needed. Activities are set to take place during Q2-Q3 2025 for up to 54 days (active survey time). Activities will be undertaken from a jack-up vessel.

- WP GT2: Cables activities include 40 CPT and vibrocore tests to a depth of up to 6 m below seabed. Activities are set to take place during Q2-Q3 2025 for up to 18 days (active survey time). Activities will be undertaken from a mobile survey vessel.

- WP GT3: Nearshore / Onshore activities include 3 nearshore and 2 onshore boreholes to 40 m target depth. Activities are set to take place during Q2-Q3 2025 for up to 10 days (nearshore) + 33 days (onshore). Nearshore activities are undertaken from a small jack-up vessel, while onshore activities are undertaken by a mobile drilling rig.

The prognosis assesses the impact of underwater noise from activities such as drilling, vibrocore, CPT, and PS logging on marine mammals and fish. It also includes noise emissions from the jack-up vessel, survey vessel, and tug boat. Onshore drilling rig noise is excluded as it does not affect underwater environments. Vessel positioning will not use acoustic systems like USBL.

3 Definitions

Acoustic metrics and relevant terms used in the report are defined in this chapter. Terminology follows ISO standard 18405 (DS/ISO 18405, 2017), however with a few exceptions as outlined in the following.

3.1 Frequency weighting functions

In underwater noise assessments, frequency weighting is often used to reflect the underwater noise impact more accurately on specific marine mammal species.

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 1 (NOAA, 2018).

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

Equation 1

Where:

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

For an illustration of the parameters see Figure 3.1.

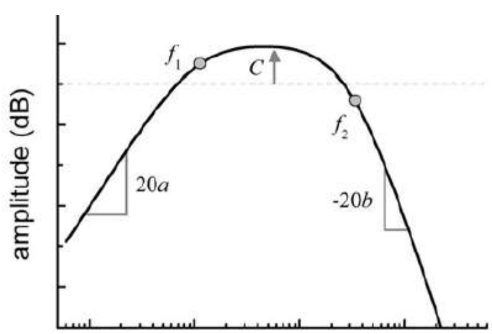

Figure 3.1: Illustration of the 5 parameters in the weighting function (NOAA, 2018).

Marine mammals are divided into four hearing groups, 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 Carnivores in Water (**PCW**) (NOAA, 2018; Southall B. , et al., 2019). The parameters in Equation *1* are defined for the hearing groups and the values are presented in Table 3.1.

Table 3.1: Parameters for the weighting function for the relevant hearing groups (NOAA, 2018).

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

The weighting function amplitude for the four hearing groups is achieved by inserting the values from Table 3.1 into Equation 1. The resulting spectra for the four hearing groups are shown in Figure 3.2.

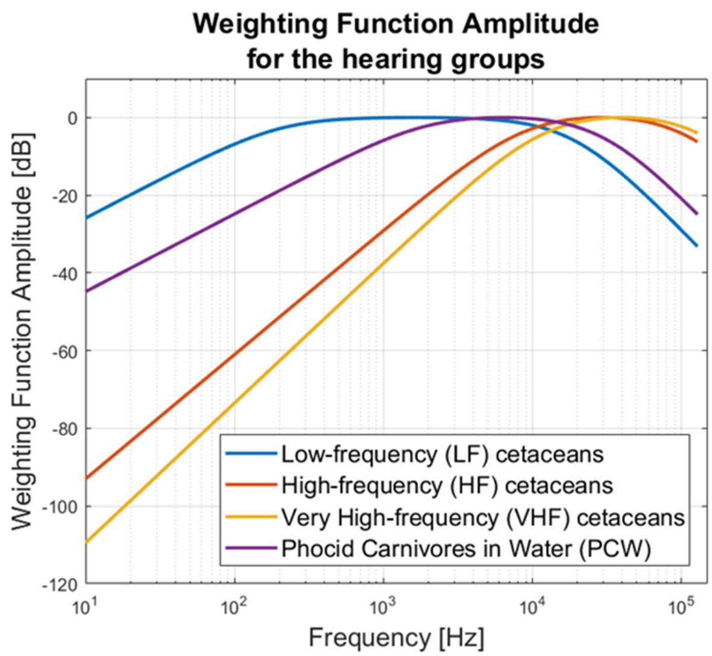

Figure 3.2: The weighting functions for the different hearing groups.

For this project, relevant species only include harbour porpoise (classified as a Very High Frequency Cetacean (VHF)) and seals (PCW).

3.2 Sound Pressure Level

The Sound Pressure Level (SPL), L_p, is used to describe the noise level. The definition for SPL is shown in Equation 2 (Erbe C. , 2011):

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

Equation 2

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

For ambient underwater noise and for operational underwater noise, L_p is the preferred metric.

To evaluate the behavioural response of the marine mammal a time window is needed. Often, a fixed time window of 125 ms. is used due to the integration time of the ear of mammals (Tougaard & Beedholm, Practical implementation of auditory time and frequency weighting in marine bioacoustics, 2018). The metric is then referred to as $L_{p,125ms}$ and the definition is shown in Equation 3 (Tougaard, Thresholds for behavioural responses to noise in marine mammals. Background note to revision of guidelines from the Danish Energy., 2021).

$$L_{p,125ms} = L_{E,p} - 10 * \log_{10}(0.125) = L_{E,p} + 9 \text{ dB} \quad [\text{dB re. } 1\mu\text{Pa}]$$ Equation 3

Where $L_{E,p}$ is the sound exposure level, which are explained in the next section. When considering the threshold for specific marine mammal species, the terminology is $L_{p,125ms,w}$, where "w" denotes the species-specific weighting.

3.3 Sound Exposure Level

The Sound Exposure Level (SEL), $L_{E,p}$, describes the total energy of a noise event (Jacobsen & Juhl, 2013). A noise event can for instance be the duration of an entire survey from start to end, or it can be a single noise event like an airgun pulse. The SEL is normalized to 1 second and is defined in (Martin, Morris, & O'Neill, 2019) through Equation 4.

$$L_{E,p} = 10 * \log_{10}\left(\frac{1}{T_0 p_0^2}\int_0^T p^2(t)\right) \quad [\text{dB re. } 1\mu\text{Pa}^2\text{s}]$$ Equation 4

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 μPa.

The relationship between SPL, Equation 2, and SEL, Equation *4*, is given by Equation *5* (Erbe C. , 2011).

$$L_{E,p} = L_p + 10 * \log_{10}(T)$$ Equation 5

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 can incur hearing loss, either temporarily or permanently because of exposure to high noise levels. The level of injury depends on both the intensity and duration of noise exposure. SEL is therefore a commonly used metric to assess the risk of hearing impairment because of noisy activities (Martin, Morris, & O'Neill, 2019).

3.4 Cumulative Sound Exposure level

For moving sources in combination with moving receivers, the $L_{E,cum,t}$ is calculated using the approach presented in (Tougaard, Input to revision of guidelines regarding underwater noise from oil and gas activities - effects on marine mammals and mitigation measures., 2016). The survey 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 i^{th} pulse, r_i, is given for a specific piece of survey equipment. This is based on 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. Δt_i is the time in seconds between the first pulse and the i^{th} while v_{ship} and $v_{receiver}$ is the ship and receiver moving speed respectively, in ms^{-1}.

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

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 $L_{E,cum,24h}$.

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

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. 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. For stationary vessels, the vessel movement speed is set to $0\ ms^{-1}$

To differentiate between different marine species, and differences in swim speed, the species specific received cumulative SEL in this report is denoted $L_{E,cum,t,v_f,w}$ where "w" is the frequency weighting, currently only relevant for marine mammals, see section 3.1.

The parameters used in Equation 6 and Equation 7, related to the source level, firing frequency, movement speed and source direction must be based on best available knowledge. The EPL parameters (X and A) must be determined through advanced sound propagation modelling, in which all relevant site-specific environmental parameters are considered.

3.5 Source level

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

SL is defined for a continuous source as the SPL_{rms} at 1 m from the source with a reference value of $1\ \mu Pa \cdot m$. The metric is used primarily for non-impulsive source types, such as vessels.

ESL is used to describe a transient sound source and is defined as the SEL at 1 m from the source with a reference value of $1\ \mu Pa^2\ m^2$ s. This is the standard metric used to describe the source level of impulsive noise sources.

4 Evaluation criteria

Underwater noise emission is evaluated against the marine mammal threshold criteria. Marine mammal species included are: harbour porpoise and seal (harbour and grey seal). Thresholds include Temporary Threshold Shift (TTS), Permanent Threshold Shift (PTS) and behavioural disturbance for both harbour porpoise and seals. For PTS and TTS impact ranges, avoidance behaviour is included assuming a constant swim speed of $1.5\ ms^{-1}$ directly away from the activity. For fish, threshold criteria for injury and TTS are included, based on non-avoidance behaviour. Threshold criteria for marine mammals are given in Table 4.1 and for fish in Table 4.2.

Table 4.1: Species specific thresholds for harbour porpoise and seal (harbour and grey seal), based on Southall, et al (2019), Tougaard (2021) and Andersson et al (2025). Avoidance behaviour is assumed for both species to be $v_f = 1.5\ ms^{-1}$.

Species	Frequency weighting (w)	Species specific weighted threshold criteria				
		PTS $L_{E,cum,24h,v_f,w}$ $[dB\ re. 1\mu Pa^2 s]$		TTS $L_{E,cum,24h,v_f,w}$ $[dB\ re. 1\mu Pa^2 s]$		Behaviour $L_{p,125ms,w}$ $[dB\ re. 1\mu Pa]$
		Impulsive	Non-impulsive	Impulsive	Non-impulsive	Impulsive
Harbour porpoise	Very high frequency Cetacean (VHF)	155 dB	173 dB	140 dB	153 dB	103 dB
Harbour seal and Grey seal	Phocid Carnivores (PCW)	185 dB	201 dB	170 dB	181 dB	120 – 138* dB

*: There is currently no single threshold value for the avoidance behaviour of seals, and a range is instead considered. The upper and lower criteria are based on observed reactions from different studies, converted into $L_{p,125ms,PCW}$ (Andersson, Carlsson, Thörn, & Östberg, 2025).

Table 4.2: Threshold criteria for fish, based on Popper et al (2014). All fish are assumed stationary (non-avoidance).

Category	Unweighted threshold criteria	
	Injury, $L_{E,cum,24h}$ $[dB\ re. 1\mu Pa^2 s]$	TTS, $L_{E,cum,24h}$ $[dB\ re. 1\mu Pa^2 s]$
Stationary fish	203	186
Larvae and eggs	207	-

Threshold criteria for both marine mammals and fish are based on cumulative Sound Exposure Level (SEL) over a 24-hour period of activities. Where the SEL describes the total acoustic energy of a single noise event, the cumulative SEL represents the sum of energy of multiple events (here over a 24 hour period). The cumulative SEL is used to reflect the impact of prolonged noise exposure on the marine mammal and fish auditory systems.

For marine mammals, thresholds are divided into non-impulsive and impulsive threshold criteria, while only impulsive threshold criteria exist for fish.

Impulsive noise sources have short durations, high peak sound pressure, a fast rise time and has a acoustic energy over a broad frequency spectrum. Examples of impulsive sources are explosives, airguns, and pile driving. Non-impulsive noise sources on the other hand may exhibit some, but not all of the characteristics of impulsive sources. Examples of non-impulsive sources are vessel noise, sonars, and drilling.

Non-impulsive noise is less harmful for the auditory system compared to impulsive noise, as indicated by the higher tolerance/threshold level of non-impulsive noise. For each of the proposed activities, it is evaluated whether impulsive or non-impulsive criteria should apply. For fish, impulsive criteria are used regardless of the source characteristics, as there are no non-impulsive criteria available, however it should be noted that the impact ranges for non-impulsive sources are likely to be overly conservative.

5 Underwater noise prognosis

The underwater noise prognosis includes a detailed description of the individual activities, and the underwater noise emission is evaluated based on best-available knowledge. For activities where potentially harmful underwater noise emission cannot be ruled out, impact ranges are calculated for relevant marine mammal and fish threshold criteria (based on threshold criteria in section 4). Summarized from section 2, the following activities, and thereto related underwater noise sources are evaluated for their potential to emit harmful levels of underwater noise to the marine environment:

- Geotechnical drilling (jack-up vessel)
- Vibrocore (mobile survey vessel)
- Cone Penetration Testing (CPT) (mobile survey vessel & jack-up vessel)
- PS-logging (jack-up vessel)
- Vessel transit and positioning (mobile survey vessel & tug boat)

Vessel positioning will not require the use of acoustic positioning systems (USBL), as per client specifications.

5.1 Geotechnical drilling

There are few measurements of underwater noise from geotechnical drilling activities, but studies where underwater noise from geotechnical drilling activities has been measured (Erbe & McPherson, 2017), 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 measured frequency spectrum in Figure 5.1. Source levels were computed by assuming spherical spreading, meaning 20 dB/decade propagation loss (Erbe & McPherson, 2017). A jack-up vessel was used to undertake the geotechnical drilling activity, as will be the case for this project.

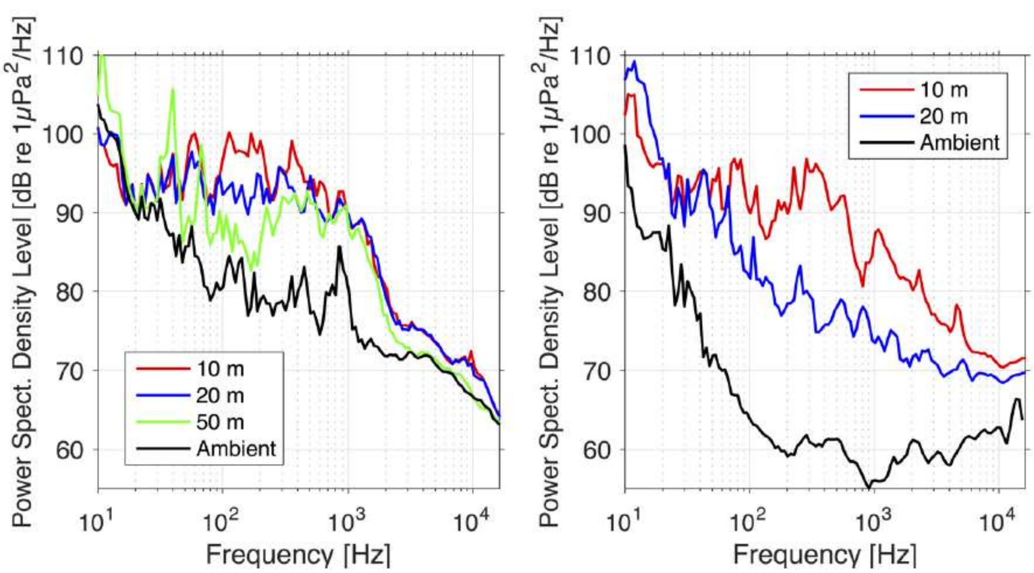

Fig. 2. (Color online) Power spectral density levels of drilling received at various ranges from the drill string at Geraldton (left) and James Price Point (right), compared to ambient noise at both sites—averaged over 10 min.

Figure 5.1: Frequency spectrum from underwater noise measurements of drilling (Erbe & McPherson, 2017).

The measured underwater noise levels were not reported in octave or 1/3-octave bands, which complicates the conversion to species-specific frequency-weighted levels (Southall B. L., et al., 2019) necessary for assessing the impact on harbour porpoises and seals. Given the low frequency content, it is assessed that the audibility for harbour porpoise will be orders of magnitude lower than the reported levels, as this species is not very sensitive to low frequency sounds (see section 3.1). The same applies for seals, however to a lesser degree. Given a reported broadband unweighted source level of $SPL_{RMS} = 145\ dB\ re. 1\ \mu Pa\ @\ 1m$, it is considered likely that the frequency weighted source levels for harbour porpoise and seal, would not exceed $SPL_{RMS,VHF} = 120\ dB\ re. 1\ \mu Pa\ @\ 1m$ $SPL_{RMS,PCW} = 130\ dB\ re. 1\ \mu Pa\ @\ 1m$ respectively.

Drilling is considered a continuous (non-impulsive) noise source. No duration per drilling site was provided, however conservatively, the duration of a single drilling activity has been assumed to be 24 hours a day. Since drilling is a non-impulsive noise source, the corresponding non-impulsive threshold criteria are used for marine mammals. For fish, where no non-impulsive threshold criteria are available, impulsive criteria are used as a conservative approach, noting the likelihood of overestimating the impact. Impact ranges are calculated for harbour porpoise and seal (Table 5.1) and fish (Table 5.2).

Table 5.1: Marine mammal impact ranges resulting from geotechnical drilling activity.

Species	Frequency weighting ($\boldsymbol{w}$)	Impact range [meters from activity]		
		PTS $L_{E,cum,24h,v_f,w}\ [dB\ re. 1\mu Pa^2 s]$	TTS $L_{E,cum,24h,v_f,w}\ [dB\ re. 1\mu Pa^2 s]$	Behaviour* $L_{p,125ms,w}\ [dB\ re. 1\mu Pa]$
Harbour porpoise	Very high frequency Cetacean (VHF)	< 1 m	< 1 m	10 m
Harbour seal and Grey seal	Phocid Carnivores (PCW)	< 1 m	< 1 m	< 1 m (138 dB) 5 m (120 dB)
*: The behaviour criterion is based on impulsive noise sources and highly likely overestimating the impact when used for non-impulsive sources, such as drilling.				

Table 5.2: Fish impact ranges resulting from geotechnical drilling activity

Category	Impact range [meters from activity]	
	Injury $L_{E,cum,24h}\ [dB\ re. 1\mu Pa^2 s]$	TTS $L_{E,cum,24h}\ [dB\ re. 1\mu Pa^2 s]$
Stationary fish	< 1 m	5 m
Larvae and eggs	< 1 m	-
*: Injury and TTS criteria are based on impulsive noise sources and highly likely overestimating the impact when used for non-impulsive sources, such as drilling.		

5.2 Vibrocore

Vibrocore equipment may be used to gather core samples of the seabed sediments. A vibrocorer functions by means of a vibrotory hammer driving a hollow steel cylinder into the seabed soil until a target depth is reached, after which the cylinder and vibrotory hammer is pulled back up from the seabed and the core can be extracted from within the cylinder.

Measurements of underwater sound emissions from vibrocore equipment with a simultaneously active DP system was investigated in Reiser et al (2011). Figure 5.2 shows 1/3-octave band values of the measured sound pressure for the two measurement distances of 207 m (left side plot) and 74 m (right side plot). The broadband unweighted source level $SPL_{RMS} = 187.4\ dB\ re. 1\ \mu Pa\ @\ 1m$ was back-calculated from the measurements, assuming 14.9 dB/decade propagation loss (Reiser, Funk, Rodrigues, & Hannay, 2011).

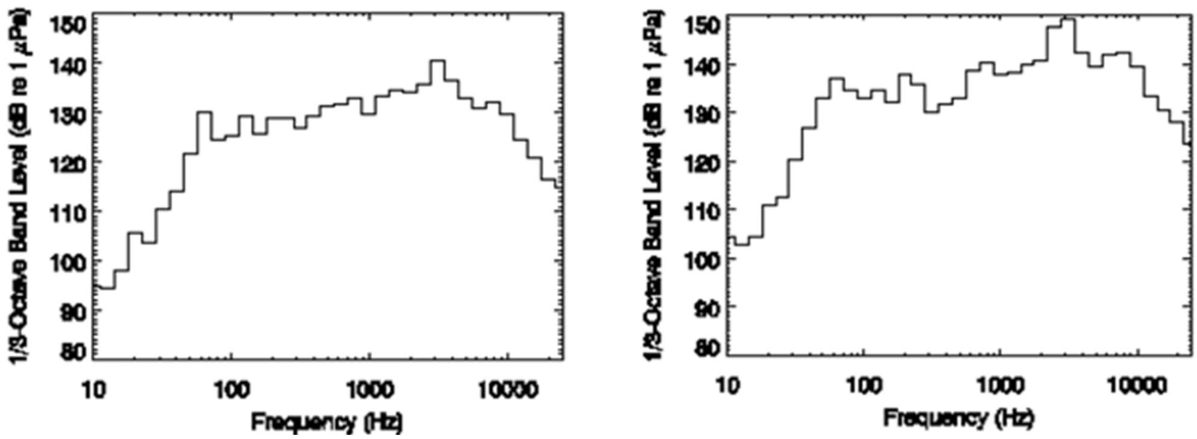

Figure 5.2: Frequency spectrum in 1/3 octave bands representing the 30-s average SPL measured during vibrocore operation at 207 m distance (left) and 74 m (right), (Reiser, Funk, Rodrigues, & Hannay, 2011).

Based on the reported noise levels in 1/3-octave bands, species specific frequency weighted levels (section 3.1) are calculated below. For the 1 m distance (source) level, it was back-calculated using the reported 14.9 dB/decade propagation loss from the 74 m distance measured 1/3-octave band spectrum:

- VHF-weighted broadband:
  - $@207m\ distance: L_{p,VHF} \approx 130\ dB\ re\ 1\mu Pa$
  - $@74m\ distance: L_{p,VHF} \approx 139\ dB\ re\ 1\mu Pa$
  - Frequency weighted loss over distance (based on measurements): 20.2 dB/decade.
- PCW-weighted broadband:
  - $@207m\ distance: L_{p,PCW} \approx 144\ dB\ re\ 1\mu Pa$
  - $@74m\ distance: L_{p,PCW} \approx 152\ dB\ re\ 1\mu Pa$
  - Frequency weighted loss over distance (based on measurements): 17.9 dB/decade.

The duration of the vibrocore activity for this project was not provided, however literature (GEO, 2009), (BOEM, 2023), states typical durations of 5 – 10 minutes per test. In Reiser et al (2011), the duration was approximately 200 seconds (Figure 5.3), illustrating a gradual increase in noise levels for the first minute, followed by high noise levels and a gradual decrease towards the end of the test.

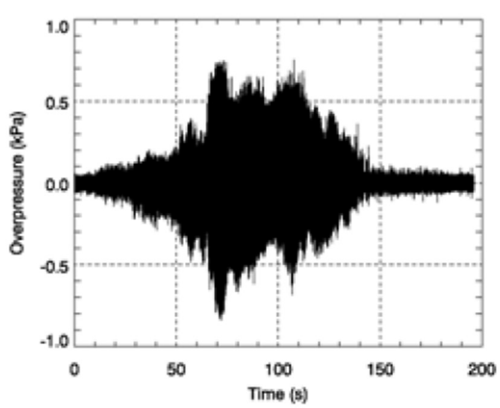

Figure 5.3: Time series of vibrocore deployment from water entry to operational stop. Measured at 74 m distance. Source: (Reiser, Funk, Rodrigues, & Hannay, 2011).

Due to the spatial distance between test locations (see Figure 2.1), the impact is evaluated per test site. As a conservative approach, a test duration of 10 minutes is considered, including a 1-minute ramp up from 0 – 100% followed by 9 minutes at maximum noise level. The scaling used for the ramp up is 3 dB/doubling of energy. The frequency weighted propagation loss is used to extrapolate the impact ranges. The impact ranges calculated for the use of vibrocore, are summarized in Table 5.3 for harbour porpoise and seal, and in Table 5.4 for fish. It should be noted, that the vibrocore activity is a non-impulsive continuous noise activity, and behaviour thresholds are only considered representative for impulsive noise sources. Impact ranges for harbour porpoise and seal behaviour are therefore considered highly conservative.

Table 5.3: Marine mammal impact ranges resulting from vibrocoring with a simultaneously active DP system.

Species	Frequency weighting ($\boldsymbol{w}$)	Impact range [meters from activity]		
		PTS $L_{E,cum,24h,v_f,w}$ $[dB\ re. 1\mu Pa^2 s]$	TTS $L_{E,cum,24h,v_f,w}$ $[dB\ re. 1\mu Pa^2 s]$	Behaviour* $L_{p,125ms,w}$ $[dB\ re. 1\mu Pa]$
Harbour porpoise	Very high frequency Cetacean (VHF)	< 1 m	77 m	4450 m
Harbour seal and Grey seal	Phocid Carnivores (PCW)	< 1 m	< 1 m	450 m (138 dB) 4560 m (120 dB)
*: The behaviour criterion is based on impulsive noise sources and highly likely overestimating the impact when used for non-impulsive sources, such as vibrocoring.				

Table 5.4: Fish impact ranges resulting from geotechnical vibrocoring with a simultaneously active DP system.

Category	Impact range [meters from activity]	
	Injury $L_{E,cum,24h}$ $[dB\ re. 1\mu Pa^2 s]$	TTS $L_{E,cum,24h}$ $[dB\ re. 1\mu Pa^2 s]$
Stationary fish	9 m	90 m
Larvae and eggs	< 1 m	-
*: Injury and TTS criteria are based on impulsive noise sources and highly likely overestimating the impact when used for non-impulsive sources, such as vibrocoring.		

5.3 Cone penetration testing (CPT)

For cone penetration testing (CPT), the CPT-cone is pushed into the seabed, or inside a borehole, and through sensors mounted in/on the cone, the vibration through the sediment is registered, and provides data on the composition and characteristics of the sediment. With seismic CPT, in addition to the CPT cone, an excitation pulse is generated by a device placed on the seabed nearby, which 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.

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. It must however be emphasized, that the above assessment relies only on the supplier's description of the equipment operation, and a qualified guess on the impact.

There are no public available data on 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 conducted. It is therefore not possible to compare noise levels to any thresholds. A study using a mini-CPT was however found (Erbe & McPherson, 2017), wherein the noise from the CPT system itself was not possible to measure over the noise from the survey vessel. This is due to the use of a Dynamic Positioning (DP) system on the survey vessel, which maintains vessel position, using thrusters, while the tests are conducted. This is discussed further in section 5.5.1.

Based on Erbe & McPherson (2017) The CPT and seismic CPT are assessed to cause underwater noise levels at low levels in relation to the marine mammal and fish hearing abilities, however while the CPT systems themselves do not produce significant noise, an active survey vessel DP system is likely to cause measurable noise levels.

5.4 PS-logging

PS-logging, or P-S logging, is a geotechnical survey method used to measure in-situ stress and deformation properties of the seabed sediment. This technique involves the use of sensors to record the response of the sediment to stress waves, providing valuable data on the mechanical properties of the subsurface. PS-logging does not generate underwater noise, making it an ideal choice for conducting surveys in sensitive marine environments where noise pollution must be minimized. The absence of noise emission is due to the passive nature of the logging process, which relies on the natural stress waves within the sediment rather than creating artificial pulses or vibrations. PS-logging will occur from the jack-up vessel and thus will not require the use of a DP system.

5.5 Vessel noise

5.5.1 Mobile survey vessel (with active DP)

Mobile survey vessels rely on a Dynamic Positioning (DP) system to hold its position against environmental forces such as currents and waves during tests. The DP system controls the thrusters and propellers to make continuous adjustments to the vessel's position, ensuring stability during the survey operations. This process generates underwater noise, which varies depending on the vessel's design, the positioning methodology of the DP system, and the local environmental conditions.

A sound source verification study in the Baltic Sea from 2023 (unpublished), measurements included a survey vessel with active DP system. PTS and TTS impact ranges were not directly calculated for the DP test, however unweighted as well as species specific frequency weighted curve fits for harbour porpoise and seal were provided. The calculated curve fits in the form: $L_{p,125ms,w}(r) = L_{S,w} - X_w \cdot log_{10}(r) - A_w \cdot r \ \ [dB]$ were:

- Unweighted: $L_{p,125ms}(r) = 165 - \ 11 \cdot log_{10}(r) - 0.0001 \cdot r \ \ [dB\ re\ 1\mu Pa]$
- Harbour porpoise: $L_{p,125ms,VHF}(r) = 134 - \ 13 \cdot log_{10}(r) - 0.0001 \cdot r \ \ [dB\ re\ 1\mu Pa]$
- Harbour seal/grey seal: $L_{p,125ms,PCW}(r) = 155 - \ 12 \cdot log_{10}(r) - 0.0001 \cdot r \ \ [dB\ re\ 1\mu Pa]$

Based on the curve fits reported in the study, PTS, TTS, and avoidance behaviour was calculated for harbour porpoise and seal, and injury and TTS for fish, larvae and eggs. In the calculation of injury, PTS, and TTS, the duration of the activity was assumed to be 2 hour per sample location. The impact ranges are shown in Table 5.5 for harbour porpoise and seal, and in Table 5.6 for fish.

Table 5.5: Marine mammal impact ranges for vessel noise with active dynamic positioning (DP).

Species	Frequency weighting (w)	Impact range [meters from activity]		
		PTS $L_{E,cum,24h,v_f,w}$ $[dB\ re. 1\mu Pa^2 s]$	TTS $L_{E,cum,24h,v_f,w}$ $[dB\ re. 1\mu Pa^2 s]$	Behaviour* $L_{p,125ms,w}$ $[dB\ re. 1\mu Pa]$
Harbour porpoise	Very high frequency Cetacean (VHF)	< 1 m	< 1 m	241 m
Harbour seal and Grey seal	Phocid Carnivores (PCW)	< 1 m	< 1 m	27 m (138 dB) 812 m (120 dB)

*: The behaviour criterion is based on impulsive noise sources and highly likely overestimating the impact when used for non-impulsive sources, such as vessel noise with active DP.

Table 5.6: Fish impact ranges for vessel noise with active dynamic positioning (DP).

Category	Impact range [meters from activity]	
	Injury $L_{E,cum,24h}$ $[dB\ re. 1\mu Pa^2 s]$	TTS $L_{E,cum,24h}$ $[dB\ re. 1\mu Pa^2 s]$
Stationary fish	< 1 m	48 m
Larvae and eggs	< 1 m	-

*: Injury and TTS criteria are based on impulsive noise sources and highly likely overestimating the impact when used for non-impulsive sources, such as vessel noise with active DP.

It should be noted that vessel noise during DP is considered non-impulsive continuous, and the behaviour threshold criteria impact ranges for both harbour porpoise and seals are likely overly conservative.

5.5.2 Vessel transit

Prior to and following the execution of geotechnical activities, as well as during the transition between sampling locations, the survey vessel must navigate to its designated positions. The underwater noise generated during transit is primarily produced by the vessel's propulsion system, which encompasses engines, propellers, and thrusters. Noise levels during this phase can vary significantly based on factors such as the vessel's size, speed, design, and operational condition. Generally, larger vessels and those traveling at higher speeds emit greater levels of noise.

A review by Jimenez-Arranz et al (2020), included measurement data from six different survey vessels listing back-calculated source levels ranging from $L_{S,RMS} = 150.5 - 181.3\ dB\ re\ 1\mu Pa$ for vessels of different size, gross tonnage (GT) and with varying vessel speed. For this project, a 54 m long vessel (SUSANNE A) with a GT of 469 has been proposed as the mobile survey vessel. Jimenez-Arranz et al (2020) listed a survey vessel with a length of 56.7 m and 496 GT, along with measured noise levels at 400 m distance of $L_{p,RMS} = 118 - 132\ \ dB\ re\ 1\mu Pa$, with the higher noise levels representing measurements at 12.6 knots, and the lower noise levels representing measurements at 4.6 knots. For the maximum vessel speed (12.6 knots) the back-calculated source level is $L_{S,RMS} = 158.6\ dB\ re\ 1\mu Pa$. These are unweighted levels, with the primary acoustic energy concentrated at frequencies below 1 kHz (Jiménez-Arranz, Banda, & Cook, 2020). Frequency weighted source levels for species such as harbour porpoises and seals are likely to be substantially lower. Assuming the same frequency distribution as for vessel positioning with active DP (section 5.5.1), and assuming a source level 6.4 dB lower during transit, impact ranges are calculated for a transit between two neighbouring sampling locations (500 m distance, 12.6 knots ≈ 1.5 minutes transit time).

Table 5.7: Marine mammal impact ranges for vessel noise during transit.

Species	Frequency weighting (w)	Impact range [meters from activity]		
		PTS $L_{E,cum,24h,v_f,w}$ $[dB\ re.1\mu Pa^2 s]$	TTS $L_{E,cum,24h,v_f,w}$ $[dB\ re.1\mu Pa^2 s]$	Behaviour* $L_{p,125ms,w}$ $[dB\ re.1\mu Pa]$
Harbour porpoise	Very high frequency Cetacean (VHF)	< 1 m	< 1 m	78 m
Harbour seal and Grey seal	Phocid Carnivores (PCW)	< 1 m	< 1 m	8 m (138 dB) 240 m (120 dB)
*: The behaviour criterion is based on impulsive noise sources and highly likely overestimating the impact when used for non-impulsive sources, such as vessel noise.				

Table 5.8: Fish impact ranges for vessel noise during transit.

Category	Impact range [meters from activity]	
	Injury $L_{E,cum,24h}$ $[dB\ re.1\mu Pa^2 s]$	TTS $L_{E,cum,24h}$ $[dB\ re.1\mu Pa^2 s]$
Stationary fish	< 1 m	< 1 m
Larvae and eggs	< 1 m	-
*: Injury and TTS criteria are based on impulsive noise sources and highly likely overestimating the impact when used for non-impulsive sources, such as vessel noise.		

5.5.3 Jack-up vessel

Jack-up vessels are commonly used in geotechnical surveys due to their stability and ability to maintain a fixed position during operations. Unlike mobile survey vessels that rely on Dynamic Positioning (DP) systems to hold their location, jack-up vessels use spuds - large legs that anchor the vessel to the seabed. This method eliminates the need for thrusters or propellers, significantly reducing noise emissions during stationary operations.

During transit, jack-up vessels are typically towed to the destination by a tug boat. The underwater noise generated during transit is primarily due to the tub boats propulsion system. This noise can vary depending on the vessel's size, speed, and design. Typically, the noise levels during transit are higher than when the vessel is stationary, but they are comparable to other types of survey vessels.

Once the jack-up vessel reaches its designated survey location, the spuds are lowered to anchor the vessel to the seabed. This process is relatively quiet compared to the vessel noise with active DP by mobile survey vessels. The lack of continuous thruster use means that underwater noise levels are significantly reduced during the operation phase. Noise contributions from the tug boat, and from geotechnical activities are therefore considered the primary noise sources when using a jack-up vessel.

6 Summary

The underwater noise prognosis for geotechnical activities at the Jammerland project comprised geotechnical investigations within three work packages. Below is a summary of the impact for each work package (Table 6.1), followed by a short explanation of the results.

Table 6.1: Impact ranges from geotechnical survey activities, summarized. A "-" indicates threshold criteria not relevant for that species. Values in bold indicate impulsive threshold criteria were used to evaluate non-impulsive noise sources and should therefore be considered with caution.

Work package	Activity	Species	Impact range [meters from activity]			
			Injury	PTS	TTS	Behaviour
GT1	Geotechnical drilling from jack-up vessel	Harbour porpoise	-	< 1 m	< 1 m	**10 m**
		Seal	-	< 1 m	< 1 m	**1 m (138 dB) – 5 m (120 dB)**
		Fish	**< 1 m**	-	**5 m**	-
		Larvae and eggs	**< 1 m**	-	-	-
	Cone penetration testing (CPT) and PS-logging	All species	Negligible	Negligible	Negligible	Negligible
	Vessel transit (tug boat)	Harbour porpoise	-	< 1 m	< 1 m	**78 m**
		Seal	-	< 1 m	< 1 m	**8 m (138 dB) – 240 m (120 dB)**
		Fish	**< 1 m**	-	**< 1 m**	-
		Larvae and eggs	**< 1 m**	-	-	-
GT2	Vibrocorer	Harbour porpoise	-	< 1 m	77 m	**4450 m**
		Seal	-	< 1 m	< 1 m	**450 m (138 dB) - 4560 m (120 dB)**
		Fish	**9 m**	-	**90 m**	-
		Larvae and eggs	**< 1 m**	-	-	-
	Cone penetration testing (CPT)	All species	Negligible	Negligible	Negligible	Negligible
	Vessel noise with active Dynamic Positioning (DP)	Harbour porpoise	-	< 1 m	< 1 m	**241 m**
		Seal	-	< 1 m	< 1 m	**27 m (138 dB) - 812 m (120 dB)**
		Fish	**< 1 m**	-	**48 m**	-
		Larvae and eggs	**< 1 m**	-	-	-
	Vessel transit	Harbour porpoise	-	< 1 m	< 1 m	**78 m**
		Seal	-	< 1 m	< 1 m	**8 m (138 dB) - 240 m (120 dB)**
		Fish	**< 1 m**	-	**< 1 m**	-
		Larvae and eggs	**< 1 m**	-	-	-
GT3	Geotechnical drilling from jack-up vessel	Harbour porpoise	-	< 1 m	< 1 m	**10 m**
		Seal	-	< 1 m	< 1 m	**1 m (138 dB) – 5 m (120 dB)**
		Fish	**< 1 m**	-	**5 m**	-
		Larvae and eggs	**< 1 m**	-	-	-
	Vessel transit (tug boat)	Harbour porpoise	-	< 1 m	< 1 m	**78 m**
		Seal	-	< 1 m	< 1 m	**8 m (138 dB) – 240 m (120 dB)**
		Fish	**< 1 m**	-	**< 1 m**	-
		Larvae and eggs	**< 1 m**	-	-	-

For all species, PTS, TTS, and injury impact ranges determine the distance from the activity at which an animal may be affected by these impacts if it is within that range when the activity starts. Animals outside this distance at activity start will not be affected. For fish, it is reiterated that TTS and injury criteria are only available for impulsive sources, while all the sources in this study were non-impulsive. TTS and injury impact ranges for fish are therefore likely overestimating the impact.

Behavioural impact ranges for harbour porpoise and seal are constant impact ranges throughout the activity timeframe. For seals, there is no single value for behavioural impact, however a range is specified. Impact ranges are calculated for both, however caution is warranted, until a better supported threshold criterion is available. Furthermore, behavioural thresholds for both harbour porpoise and seals are based on impulsive noise sources, while all the sources in this study were non-impulsive. Behavioural impact ranges are therefore likely overestimating the impact.

For work package GT1 and GT3, there is no risk of PTS nor TTS effects for harbour porpoises and seals beyond the immediate vicinity (>1 m) of the activities. For fish, injury ranges are also limited to 1 m from the activity, while TTS effects can occur up to 5 m from the activity.

Calculations show exceedance of the behavioural threshold value at distances up to 78 m for harbour porpoise. For seals, between 8 – 240 m behavioural impact range was calculated. It is reiterated that these threshold criteria are to be considered cautiously, as previously explained.

For work package GT2, PTS effects are unlikely to occur beyond 1 m from all activities for both harbour porpoise and seals. Calculations show TTS impact ranges at distances up to 77 m during active vibrocore activities, and up to 1 m from all other activities. For seals, TTS impact ranges are 1 m for all activities. For fish, calculations show injury ranges up to 9 m, and TTS effects up to 90 m from the vibrocoring activity and up to 48 m during active vessel positioning. It is reiterated that impulsive threshold values are used, while the activities are non-impulsive, and the impact is therefore likely overestimated.

Behavioural effects are calculated to be likely at distances up to 4.45 km for harbour porpoise and between 450 m – 4.56 km for seals, again noting the limitations of the threshold values for non-impulsive sources.

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