Sand dreading operations in Baltic

Modeling of underwater noise emissions during sand dreading works

Oldenburg, 18.10.2022

Version 3

Contracting body: WSP
Linnés Allé 2
2630 Taastrup
Denmark

Execution: Patrick Remmers, B. Eng.
Stephan Gerlach, M. Sc.

itap GmbH
Institute for Technical and Applied Physics GmbH
Marie-Curie-Straße 8
D – 26129 Oldenburg

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INSTITUT FÜR TECHNISCHE UND ANGEWANDTE PHYSIK GMBH

Sitz
itap GmbH
Marie-Curie-Straße 8
26129 Oldenburg

Amtsgericht Oldenburg
HRB: 12 06 97

Kontakt
Telefon (0441) 570 61-0
Fax (0441) 570 61-10
Mail info@itap.de

Geschäftsführer
Dr. Michael A. Bellmann

Bankverbindung
Raiffeisenbank Oldenburg
IBAN:
DE80 2806 0228 0080 0880 00
BIC: GENO DEF1 OL2

Commerzbank AG
IBAN:
DE70 2804 0046 0405 6552 00
BIC: COBA DEFF XXX

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Revision table

Version	Date	Comment
1	27.06.2022	First draft.
2	14.09.2022	Textual changes
3	18.10.2022	Changed values in Table 4

The latest version replaces all previous versions.

Units:

μm/s - micrometer per second

μPa - micropascal

dB - decibel

Pa - pascal

Metrics:

pH - Power of hydrogen

TL - Transmission Loss

α - absorption coefficient

λ - wave length

ρ - density of a medium

E_{cum} - cumulative sound exposure

SEL - single strike Sound Exposure Level

SPL - (energy-) equivalent continuous Sound Pressure Level

SPL_{SS} - single strike (energy) equivalent Sound Pressure Level

T - averaging time

Z - acoustic characteristic impedance

c - sound velocity

f_g - cut off frequency

k - propagation term

p - sound pressure

$p(t)$ - time variant sound pressure

$p0$ - reference sound pressure

v - particle velocity

Abbreviations:

HF - high-frequency

LF - low-frequency

PCW - phocid pinnipeds

pH - Power of hydrogen

PTS - Permanent threshold shift

rms - root mean square

TSHD - Trailing suction hopper dredger

VHF - very-high-frequency

1. Executive summary

In 2022, a new guideline for underwater noise was published by the Danish Energy Agency (Energistyrelsen 2022), which defines different threshold values for different species. In order to assess how the marine fauns may be affected by sand dreading works in the Danish Baltic Sea, *itap – Institute for Technical and Applied Physics GmbH* was commissioned to carry out the modeling of the underwater noise during sand dreading and draining in the Baltic Sea exemplary for water depths of 20 m and 15 m.

For sand dreading operations, trailling hopper suction dredgers (TSHD) are used, which can vary greatly in noise depending on the vessel. Differences of more than 15 dB can be found in the literature (by comparison of 10 different TSHD). For this reason, the source spectrum of the loudest THSD with comparable dimensions (< 80 m long), for which measurement data is available, was used as the basis for this model.

The operations for this vessel are divided in dreading and draining. For both operations the impact distances for the PTS and TTS thresholds according to Energistyrelsen (2022) are below 50 m. The assumed geometric propagation functions describe a sound field in which the direct sound is superimposed with reflections from the water surface and the sediment. This is only the case at a distance of a few metres. For this reason, a 1 m accurate representation of impact ranges below 50 m distances is omitted in this report.

For distances up to 2.915 km in 20 m water depth and 2.49 km in 15 m water depth behavioral disturbances of very-high frequency cetaceans (e. g. harbour porpoise, *Phocena phocena*) are expected (Energistyrelsen 2022), using the tresholds for behavioral disburbances from Tougaard (2021). For phocid seals the disturbance ranges are up to 4.307 km in 20 m water depth and 3.52 km in 15 m water depth according to Tougaard (2021).

Oldenburg, 18.10.2022

Patrick Remmers, B. Eng.

itap GMBH
Marie-Curie-Str. 8
26129 Oldenburg

Stephan Gerlach, M. Sc.

2. Introduction and definition of tasks

Acoustic pollution of seas and rivers has increased significantly in the recent years due to anthropogenic sound inputs, such as maritime shipping and the expansion of renewable energy sources at sea. However, the use of water bodies must go hand in hand with an awareness of sustainability issues, especially the protection of nature and marine ecosystems. Various studies show that sound inputs to water can have potentially harmful effects on marine life; e.g., Southall et al. (2019) and Tougaard et al. (2015).

Based on the Marine Strategy Framework Directive (MSRL 2008), "good environmental status" is to be defined and ensured for European waters on a national, as well as regional basis for the respective flagship species. Descriptor 11 of the MSFD covers the topic of energy input into the water/underwater noise and subdivides this into (11.1) impulsive noise input, e.g. during foundation work on offshore foundations (pile driving) / blasting and (11.2) continuous noise, e.g. maritime shipping, use of echo sounders, etc.

In the course of this, this study will calculate and assess the sound input during sand dreading operations in the Baltic Sea based on the Danish Guidelines for underwater noise (Energistyrelsen 2022) (Tougaard 2021).

The *itap – Institute for Technical and Applied Physics GmbH* was commissioned to carry out the modeling of the underwater noise during sand dreading and draining in the Baltic Sea exemplary for water depths above and below 15 m.

3. Acoustic basics

Sound is a rapid, often periodic variation of pressure, which additively overlays the ambient pressure (in water the hydrostatic pressure). This involves a reciprocating motion of water particles, which is usually described by particle velocity v. Particle velocity means the alternating velocity of a particle oscillating about its rest position in a medium. Particle velocity is not to be confused with sound velocity c_{water}, thus, the propagation velocity of sound in a medium, which generally is c_{water} = 1,500 m/s in water. Particle velocity v is considerably less than sound velocity c.

Sound pressure p and particle velocity v are associated by the acoustic characteristic impedance Z, which characterizes the wave impedance of a medium as follows:

$$Z = \frac{p}{v}$$

Equation 1

In the far field, that means in a distance[1] of some wavelengths (frequency-dependent) from the source of sound, the impedance is:

$$Z = \rho c$$

Equation 2

with ρ – density of a medium and c – sound velocity.

For instance, when the sound pressure amplitude is 1 Pa (with a sinusoidal signal, it is equivalent to a Sound Pressure Level of 117 dB re 1 µPa or a zero-to-peak Sound Pressure Level of 120 dB re 1 µPa), a particle velocity in water of approximately 0.7 µm/s is obtained.

[1] The boundary between near and far field in hydro sound is not exactly defined or measured. It is a frequency-dependent value. In airborne sound, a value of ≥ 2λ is assumed. For underwater noise, values of ≥ 5λ can be found in literature.

In acoustics, the intensity of sounds is generally not described by the measurand sound pressure (or particle velocity), but by the level in dB (decibel), known from the telecommunication engineering. There are different sound levels defined in the (ISO 18405 2017) and in (Energistyrelsen 2022):

- (energy-) equivalent continuous Sound Pressure Level – SPL ,
- Cumulative Sound Exposure Level – SEL_{cum}

The SPL and SEL_{cum} can be specified independent of frequency, which means as broadband single values, as well as frequency-resolved, for example, in one-third octave bands (third spectrum).

In the following, the level values mentioned above are briefly described.

(Energy-) equivalent continuous Sound Pressure Level (SPL)

The SPL is the most common measurand in acoustics and is defined as:

$$SPL = 10\ \log_{10}\left(\frac{1}{T}\int_0^T \frac{p(t)^2}{p_0^2}\,\mathrm{d}t\right)\ [\mathrm{dB}]$$

Equation 3

with

$p(t)$ - time-variant sound pressure,

p_0 - reference sound pressure (in underwater noise 1 µPa),

T - averaging time.

Sometimes in literature, the label SPL is used for a Sound Pressure Level without time averaging. According to this definition, the continuous Sound Pressure Level over an interval is than labeled as SPL_{rms} with the index rms for root mean square. In this report, the terminology according to the (ISO 18406 2017) is used and the index rms is omitted, since a definition according to Equation 3 already implies averaging. In some nations, the rms value of the Sound Pressure Level (SPL_{SS}) of each single strike shall be determined. Therefore, the duration of each single strike shall be considered.

Cumulative Sound Exposure Level (SEL_{cum})

A value for the noise dose is the cumulative Sound Exposure Level (SEL_{cum}) and is defined as follows:

$$SEL_{cum} = 10 \ \log_{10}\left(\frac{E_{cum}}{E_{ref}}\right) \ [\mathrm{dB}]$$

Equation 4

With the cumulative sound exposure E_{cum} for N transient sound events with the frequency unweighted sound exposure E_n

$$E_{cum} = \sum_{n=1}^{N} E_n$$

Equation 5

and the reference exposure $E_{ref} = p_{ref}^2 \cdot T_{ref}$, in which p_{ref} is the reference sound pressure 1 µPa and T_{ref} the reference duration 1 s.

4. Underwater noise mitigation values

The emission of underwater noise during sand dreading is a human intervention in the marine environment which can have negative effects on the marine fauna. High sound pressure has the potential to harm marine mammals potentially leading to behavioral disturbance and permanent hearing damage (PTS, Permanent Threshold Shift) (cf. Table 1).

To assess the impact from underwater noise on marine mammals, the threshold levels according to the Guidelines for underwater noise (Energistyrelsen 2022) and the Thresholds for behavioural responses to noise in marine mammals (Tougaard 2021) presented in Table 1 were modelled. Pertaining to threshold levels for auditory injury of marine mammals, frequency weighted threshold levels are modelled. The frequency weighting functions are based on the audiograms for generalized hearing groups according to the recommendations by Southall et al. (2019). By means of hearing group specific weighting functions, frequencies outside the optimal hearing range are given less weight than frequencies within the hearing range. Figure 1 shows the weighting functions provided by by Southall et al. (2019) for very-high-frequency cetaceans (VHF) (e. g. harbour porpoise, *Phocena phocena*), high-frequency cetaceans (HF) (e. g. White-beaked dolphin, *Lagenorhynchus albirostris*), low-frequency cetaceans (LF))(e. g. Minke whale, *Balaenoptera acutorostrata*) and phocid pinnipeds (PCW) (e. g. harbour seal, *Phoca vitulina*). For modeling of cumulative Sound Exposure Levels (SEL_{cum}), an accumulation period of 24 hours as recommend by the Southall et al. (2019) is applied.

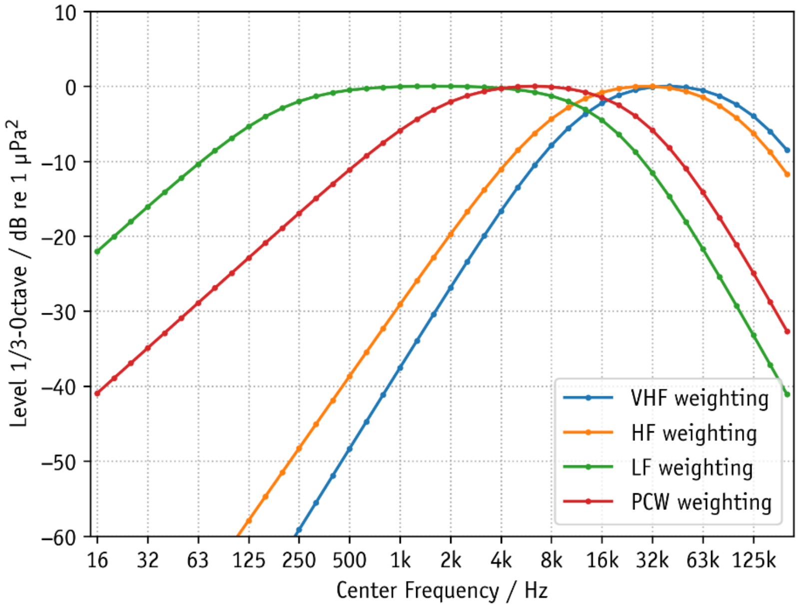

Figure 1: Weighting functions for very-high-, high-, and low-frequency cetaceans VHF, HF, LF and phocid seals according to Southall et al. (2019).

Table 1: *Noise modeling threshold criteria and considered fleeing speeds for different animals according to the Guidelines for underwater noise (Energistyrelsen 2022) and the Thresholds for behavioural responses to noise in marine mammals (Tougaard 2021). PTS: Permanent Threshold Shift; TTS: Temporary Threshold Shift; BD Behavioral Disturbance.*

Receptor	Impact type	metric	Fleeing speed [m/s]	Criteria [dB]
VHF	PTS	$SEL_{\mathrm{cum,\ VHF}}$	1.5	173
	TTS	$SEL_{\mathrm{cum,\ VHF}}$	1.5	153
	BD	$SPL_{\mathrm{VHF,\ 125ms}}$		103
PCW	PTS	$SEL_{\mathrm{cum,\ HF}}$	1.5	201
	TTS	$SEL_{\mathrm{cum,\ HF}}$	1.5	181
	BD	$SPL_{\mathrm{VHF,\ 125ms}}$		120

5. Model approaches

5.1 Sound propagation in shallow waters

Impact of the distance

For approximate calculations, it can be assumed, that the sound pressure decreases with the distance according to a basic power law. The level in dB is reduced about:

$$TL = k \cdot \log_{10}\left(\frac{r_1}{r_2}\right) \text{ [dB]}$$

Equation 6

with

r_1 and r_2 - the distance to the source of sound increases from r_1 to r_2,

TL - Transmission Loss,

k - absolute term (in shallow waters, an often used value is k = 15, for spherical propagation, k = 20).

Often, the transmission loss is indicated for the distance r_1 = 1 m (fictitious distance to an assumed point source). This is used to calculate the sound power of the pile-driving in a distance of 1 m; often, this is called source level. Equation 6 then reduces to: $TL = -k \log_{10}(r)$. Additionally, it has to be considered, that the equation above is only valid for the far field of an acoustic signal, meaning in some distance (frequency-dependent) to the source.

Additionally, the absorption in water becomes more apparent in distances of several kilometers and leads to a further reduction of the sound pressure. This is taken into account with a constant α proportional to the distance. Equation 6 expands to:

$$TL = -k \log_{10}(r) + \alpha r \text{ [dB]}$$

Equation 7

Based on empirical values from various hydro-sound measurements in the North Sea and the Baltic Sea (unpublished data from itap GmbH) two k values are assumed for the model depending on the water depth (k = 16.4 for water depth above 15 m and k = 17.5 for water depth below 15 m). By modeling the transmission loss via such a propagation function, a plain wave in water is assumed. This is only the case for distances from the pile larger than the water depth, when the directly emitted sound from the pile is superimposed with the first reflections from the water surface and the sediment. Below 50 m from the pile, no plain wave field has formed within the water column and the noise level will be below the level calculated with Equation 7. In the model results, the noise level will be constant over the first 50 m from the pile.

The absorption constant α is determined according to Francois & Garrison (1982) as a function of frequency, salinity, water depth, temperature and pH. This results in an absorption shown in Figure 2 for different salinities at a water depth of 15 m, a temperature of 7°C and a pH-value of 8.1.

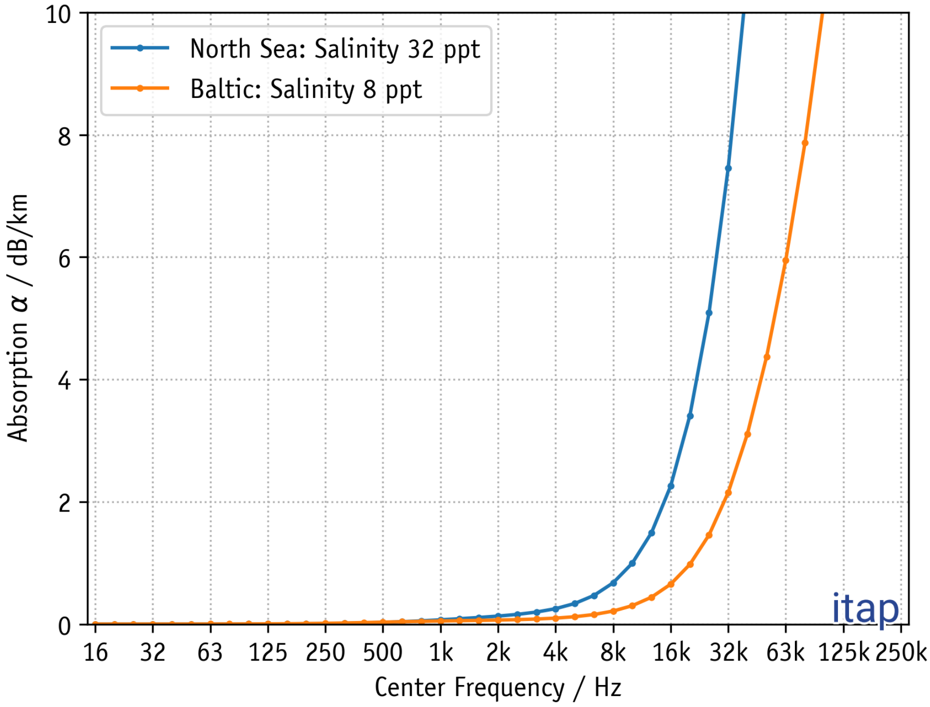

Figure 2: Frequency dependent absorption according to Francois & Garrison (1982) for the Baltic- and North Sea with different salinities at a water depth of 15 m, a temperature of 7°C and a pH-value of 8.1.

Impact of water depth

Sound propagation in the ocean is also influenced by water depth. Below a certain cut-off frequency (f_g), a continuous sound propagation is impossible. The shallower the water, the higher this cut-off frequency. The cut-off frequency (f_g) also depends on the type of sediment. The lower limit frequency for predominantly arenaceous soil as a function of water depth is depicted in Figure 3. Moreover, the band widths of the lower cut-off frequency (f_g) at different soil layers, e. g. clay and chalk (till or moraine), are illustrated in grey (Jensen, et al. 2011). Sound around the cut-off frequency (f_g) is reduced or damped to a larger extent with an increasing distance to the sound source.

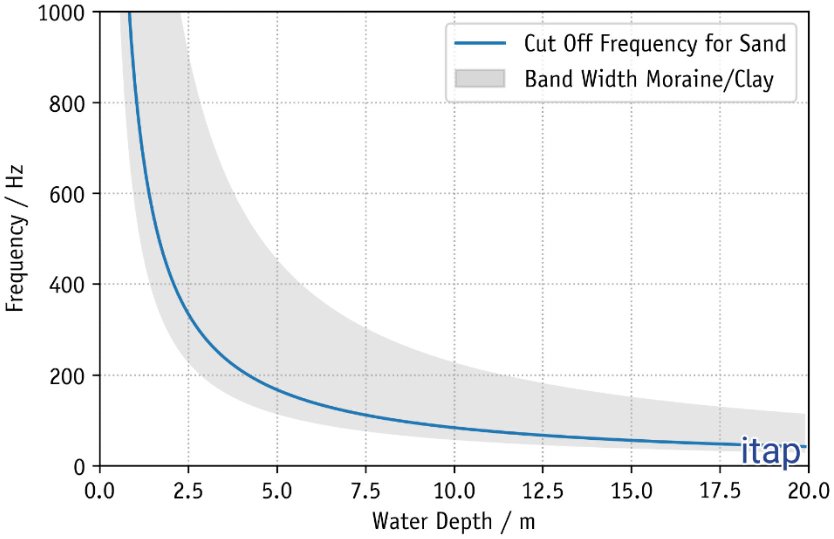

Figure 3: Theoretical, lower (limit) frequency (f_g) for an undisturbed sound propagation in water as a function of the water depth for different soil stratifications (example adapted from (Urick 1983) and (Jensen et al., 2010); the example shows the possible range caused by different layers; the layer does not correspond to the layers in the construction field).

5.2 Model description

For dreading and draining operations Trailing suction hopper dredgers (TSHD) with a length below 80 m are to be used.

In 2011, itap GmbH surveyed a TSHD, the Thor R, with a comparable size of 79 m during operation close off the coast of Sylt which is used for modelling (unpublished measurement data of itap). During the pumping and dredging operations a broadband Sound Pressure Level (SPL) of 150 dB was measured during dredging and 149 dB during draining (see Figure 4). An extrapolation to a distance of 1 m with $15 \log_{10} R$, as is often found in the literature, results in a source level of 187 dB for both variants.

In comparison Robinson et al. (2011), made measurements on 7 TSHD between 72 m and 120 m in length and compared with other literature values. Differences in source level of 14 dB were recorded for the 7 suction hopper dredgers between 176 dB and 189 dB. Similar source level, between 172 dB and 188 dB were recorded for the literature values presented by Robinson et al. (2011) The variations in the source level can be attributed not only to differences in design, but also to differences in sediment. For example, the suction noise of sand is a few dB quieter than that of gravel.

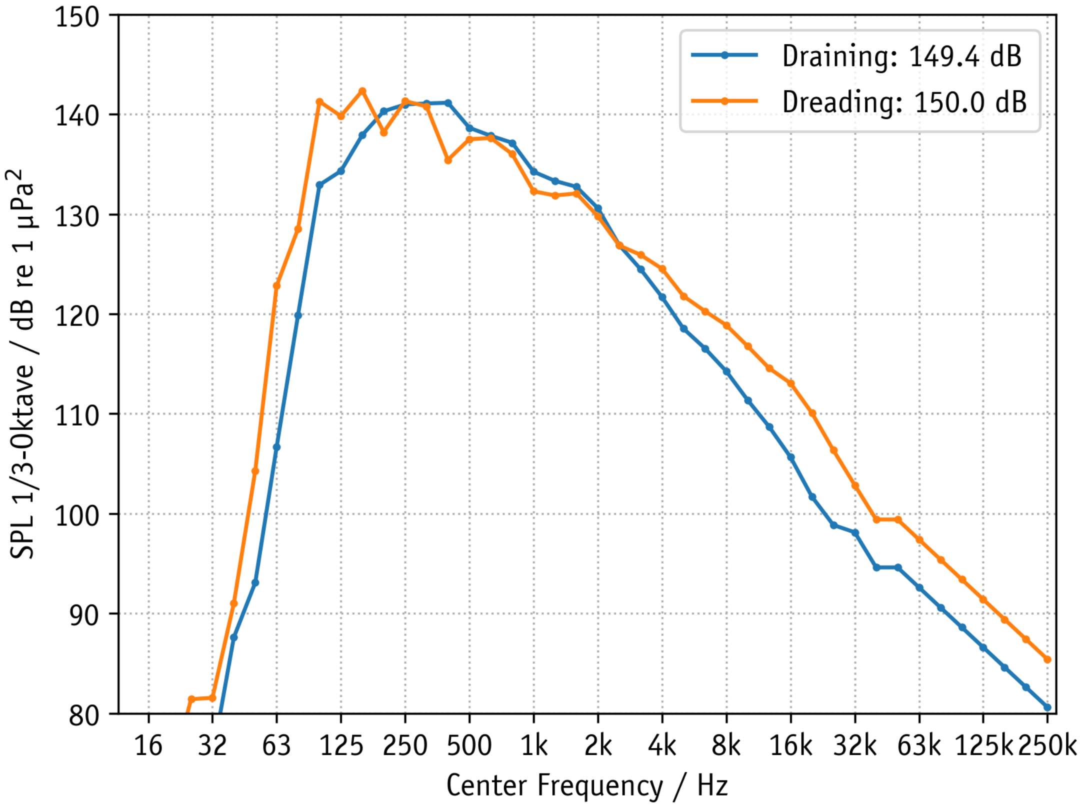

Figure 4: Measured Sound Pressure Level in 300 m distance as 1/3 octave spectra for Draining and Dreading operations, form a measurement of the TSHD Thor R in 2011, unpublished data of itap GmbH.

5.3 Calculation procedure

In the following subsections, the different calculation procedures/steps and sub-model runs are described in detail.

5.3.1 Step 1: Sound Pressure Level at different distances

In the first step of this underwater sound prediction, the instantaneous Sound Pressure Levels SPL (stationary sound source) are calculated according to the international standard (ISO 18406) for different types of noise that may occur during dreading and draining. The calculations were performed as a function of the distance to the source, independent of the exact location and the operating time.

5.3.2 Step 2: Cumulative SEL

The cumulative Sound Exposure level (SEL_{cum}) is a value for the noise dose, a marine mammal (e. g. a harbor porpoise) is exposed to. This value is the sum of the energy from one event a marine mammal is exposed to within 24 hours (Southall, et al. 2019), moving with a constant speed, increasing its distance with e. g. 1.5 m/s (Energistyrelsen 2022). In order to determine the impact ranges for certain sensation level values, the cumulative Sound Exposure Level (SEL_{cum}) will be calculated as a function over the start distance.

5.3.3 Step 3: Impact ranges

For the threshold levels listed in Table 1 chapter 4 impact ranges will be calculated where these levels are reached. All calculations will be done in 1/3 octave frequency resolution, considering the acoustic filters (Southall, et al. 2019) in frequency domain (see chapter 4) the cumulative Exposure Level (SEL_{cum}) represents do not a distance. The impact distances refer to the distance from the source at which the animal risks e. g. PTS when moving at a constant speed of 1.5 m/s away from the source.

5.4 Acoustically relevant input data

For a generel model for underwater noise prognosis of the dreading and draining operations in the Baltic, the following input data and model assumptions are applied:

Input parameter:	15 m water depth	20 m water depth
- Source Vessel	Thor R (dredging and pumping)	Thor R (dredging and pumping)
- Transmission loss	$17.5\ \log_{10} R$	$16.14\ \log_{10} R$
- Salinity	8 ppt	8 ppt
- Temperature	7°C	7°C
- pH	8.1	8.1
- Cutoff Frequency by water depth	55	42

6. Model results

Considering the model approaches in chapter 5 the following levels are expected in different distances (Table 2 to Table 4).

Table 2: *Calculated level of the Sound Pressure Level (SPL) in 15 m water depth and different distances for different weightings.*

MNFS weighting	SPL in 750 m distance	SPL in 1,500 m distance	SPL in 3,000 m distance
Dreading			
No	143	138	132
High frequency cetaceans	113	107	101
Phocid seals	131	126	121
Draining			
No	142	137	132
High frequency cetaceans	109	103	98
Phocid seals	132	127	121

Table 3: *Calculated level of the Sound Pressure Level (SPL) in 20 m water depth and different distances for different weightings.*

MNFS weighting	SPL in 750 m distance	SPL in 1,500 m distance	SPL in 3,000 m distance
Dreading			
No	143	139	134
High frequency cetaceans	113	108	103
Phocid seals	132	127	122
Draining			
No	143	138	133
High frequency cetaceans	109	104	99
Phocid seals	132	128	123

Table 4. *The cumulative Sound Exposure Level (SEL_{cum}) in 15 m and 20 m water depth for different receptors for 24 h working interval and a reference time of 1 s.*

Receptor	weighting	Deterrence distance [m]	Fleeing speed [m/s]	SEL_{cum}
Dreading				
High-frequency cetaceans	VHF	200	1.5	145 / 145
Phocid seals	PCW	200	1.5	164 / 164
Draining				
High-frequency cetaceans	VHF	200	1.5	141 / 141
Phocid seals	PCW	200	1.5	164 / 164

Figure 5 shows the calculated Sound Pressure Level (SPL) for dreading in 15 m water depth as a function over the distance.

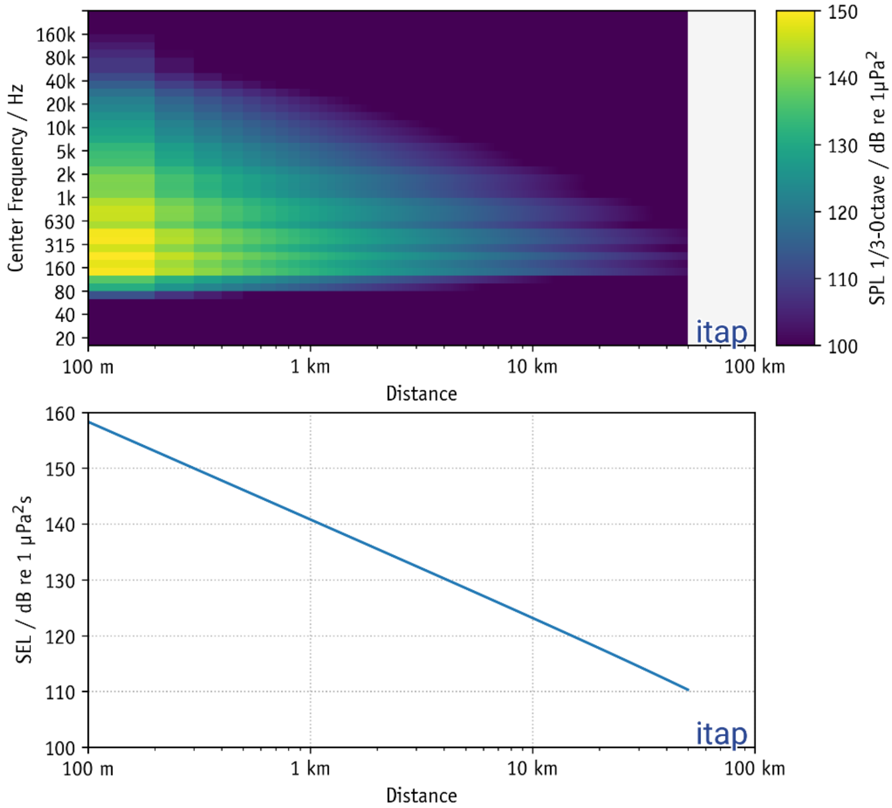

Figure 5: *Predicted SPL (unweighted) during sand dreading in 15 m water depth over the distance. The spectrogram on top shows the SPL divided in 1/3-octave components. On the y-axis the frequency is listed and on the x-axis the distance is shown. The value of the unweighted SPL in every 1/3 octave band is marked by different colors, yellow for high levels and blue for low levels. The diagram below shows the broad-band values SPL.*

For the threshold levels in chapter 4, the following impact ranges are expected in which these values are reached (Table 5). The assumed geometric propagation function describe a sound field in which the direct sound is superimposed with reflections from the water surface and the sediment. This is only the case at a distance of a few metres. For this reason, a 1 m accurate representation of impact ranges below 50 m distances is omitted in this report.

Marine Mammals:

Table 5: *Distances to thresholds for marine mammals for 15 m / 20 m water depth.*

Receptor	Impact type	metric	Fleeing speed [m/s]	Criteria [dB]	Range [km] No NMS
Dreading					
High-frequency cetaceans	PTS	$SEL_{\text{cum, VHF}}$	1.5	173	< 50 m
	TTS	$SEL_{\text{cum, VHF}}$	1.5	153	< 50 m
	BD	SPL_{VHF}	0	103	2.490/ 2.915
Phocid seals	PTS	$SEL_{\text{cum, PCW}}$	1.5	201	< 50 m
	TTS	$SEL_{\text{cum, PCW}}$	1.5	181	< 50 m
	BD	SPL_{PCW}	0	120	3.248 / 3.948
Draining					
High-frequency cetaceans	PTS	$SEL_{\text{cum, VHF}}$	1.5	173	< 50 m
	TTS	$SEL_{\text{cum, VHF}}$	1.5	153	< 50 m
	BD	SPL_{VHF}	0	103	1.546 / 1.762
Phocid seals	PTS	$SEL_{\text{cum, PCW}}$	1.5	201	< 50 m
	TTS	$SEL_{\text{cum, PCW}}$	1.5	181	< 50 m
	BD	SPL_{PCW}	0	120	3.520 / 4.307

7. References

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