Jammerland Bay
Near Shore Wind Farm

INSTITUT FÜR TECHNISCHE UND ANGEWANDTE PHYSIK GMBH

Modeling of underwater noise emissions during construction pile-driving work

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
Oldenburger Volksbank
IBAN:
DE95 2806 1822 0080 0880 00
BIC: GENO DEF1 EDEB

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

USt.-ID.-Nr. DE 181 295 042

Oldenburg, 15.02.2024

Version 11

Contracting body: WSP
Linnés Allé 2
2630 Taastrup
Denmark

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

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

Scope of report: 62 pages

Table of contents

Revision table

Version	Date	Comment
1	21.12.2021	First draft.
2	20.01.2022	Revised Version
3	28.02.2022	Rename model scenarios
4	03.03.2022	Textual changes
5	05.05.2023	Textual changes
6	20.06.2023	New project design added
7	23.06.2023	Revised Version
8	30.06.2023	Revised Version
9	04.07.2023	Revised Version
10	29.09.2023	TTS ranges included
11	15.02.2024	Textual changes and SELcum in 200 m distance added

The latest version replaces all previous versions.

Units:

µm/s - micrometer per second

µPa - micropascal

bar - 100 kPa

cm - centimeter

dB - decibel

Hz - hertz

kg - kilogram

kHz - kilohertz

kn - knot

kPa - kilopascal

m/s - meter per second

min - minute

Pa - pascal

s - second

Metrics:

TL - Transmission Loss

α - absorption coefficient

λ - wave length

ρ - density of a medium

τ_{90} - interval length in seconds including 90 % of the sound energy of one blow

E - sound exposure

E_{cum} - cumulative sound exposure

F - 10 $\log_{10}$(f *[kHz]*)

L_{hg} - background noise level

$L_{p,pk}$ - zero-to-peak Sound Pressure Level

$L_{pk,pk}$ - peak-to-peak Sound Pressure Level

SEL - single strike Sound Exposure Level

SEL_{05} - 5 % exceedance 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 - frequency

f_g - cut off frequency

k - propagation term

n - count

p - sound pressure

$p(t)$ - time variant sound pressure

$p0$ - reference sound pressure

p_{pk} - maximum sound pressure

v - particle velocity

Abbreviations:

BBC - Big Bubble Curtain

BfN - Federal Agency for Nature Conservation

DBBC - Double Big Bubble Curtain, Double Big Bubble Curtain

EEZ - Exclusive Economic Zone

FAD - free air delivery

IIg - zone classification according to Thiele & Schellstede

NAS - Noise Abatement System

OWF - offshore wind farm

PCW - phocid pinnipeds

PTS - Permanent threshold shift

rms - root mean square

SRD - Soil Resistance Value

UXO - unexploded ordnance

VHF - very-high-frequency

WTG - Wind Turbine Generator

1. Executive summary

The *Jammerland Bay Near Shore Wind Farm* site is located in the inner Danish Waters (The Great Belt) at the west coast of Sjæland. The water depth in the project area is between 6 m and 27 m. The preferred site layout includes 16 Wind Turbine Generators (WTG). Since the final design has not been determined at this time, 2 alternative WTG layouts are still being considered. For alternative 1, the foundation dimensions are identical to the preferred project design, but the layout contains 2 WTG more. For alternative 2 a site layout with 21 WTG is planned for *Jammerland Bay Near Shore Wind Farm.* All three project alternatives (the preferred layout and alternative 1 and 2) envisage installing the WTGs on monopile foundations by using impact pile-driving.

The construction of *Jammerland Bay Near Shore Wind Farm* includes activities that emit noise levels that could potentially harm marine mammals and fish in the area (Energistyrelsen (2022), Southall et al. (2019), Tougaard et al. (2015), Andersson, et al. (2016) and Popper AN (2014)). Installation of monopile foundations into the seabed by means of impact pile driving is regarded the most significant noise source during construction.

The *itap – Institute for Technical and Applied Physics GmbH* was commissioned to carry out the modeling of the underwater pile-driving noise during the construction of the WTGs within the *Jammerland Bay Near Shore Wind Farm* offshore wind farm.

Modeling scenarios, including pile diameter, hammer type and WTG locations, were defined to reflect the current project status to the highest extent possible with the objective to determine the expected noise levels, allowing an accurate assessment of the environmental impact of the pile-driving activities. Modeling included both cumulative and single strike Sound Exposure Levels as well as zero-to-peak Sound Pressure Levels. In addition to unweighted noise levels, hearing sensitivities of relevant species were taken into account for the underwater noise prognosis according to Energistyrelsen (2022) and Southall et al. (2019).

A comparison with various sensation levels from the literature for relevant species of marine mammals and fish (Southall et al. (2019), Tougaard et al. (2015), Andersson, et al. (2016) and Popper et al. (2014)) according to the “Guideline for underwater noise - Installation of impact or vibratory driven piles“ (Energistyrelsen 2022) showed that all limit values for a permanent threshold shift can be met by using a standard noise mitigation system.

Oldenburg, 15.02.2024

Patrick Remmers, B. Eng.

itap GMBH
Marie-Curie-Str. 8
26129 Oldenburg

Aenne Euhus, B. Eng.

2. Introduction and definition of tasks

The *Jammerland Bay Near Shore Wind Farm* site is located in the inner Danish Waters (The Great Belt) at the west coast of Sjæland. The water depth in the project area is between 6 m and 27 m. The preferred site layout includes 16 Wind Turbine Generators (WTG) (Figure 1). Since the final design has not been determined at this time, 2 alternative WTG layouts are still being considered. For alternative 1, the foundation dimensions are identical to the preferred project design, but the layout contains 2 WTG more. For alternative 2 a site layout with 21 WTG is planned for *Jammerland Bay Near Shore Wind Farm* (Table 1 and Figure 2 and Figure 3). Of the three different WTG types two different combinations of diameter and hammer size will be modeled based on a driverability analysis. All three project alternatives (the preferred layout and alternative 1 and 2) envisage installing the WTGs on monopile foundations by using impact pile-driving.

The construction of *Jammerland Bay Near Shore Wind Farm* includes activities that emit noise levels that could potentially harm marine mammals and fish in the area (Energistyrelsen (2022), Southall et al. (2019), Tougaard et al. (2015), Andersson, et al. (2016) and Popper et al. (2014)). Installation of monopile foundations into the seabed by means of impact pile driving is regarded the most significant noise source during construction.

The *itap – Institute for Technical and Applied Physics GmbH* was commissioned to carry out the modeling of the underwater pile-driving noise during the construction of the WTG within the OWF *Jammerland Bay Near Shore Wind Farm*.

Since the wind farm layout and the final pile design have not yet been determined, the focus of this report is to determine the maximum noise emission that can be expected and to what extent this can be reduced with a double Big Bubble Curtain (DBBC). The largest of the possible WTGs are to be erected on monopile foundations with 8.00 m in diameter (the preferred layout and alternative 1). In altervative 2, piles with a diameter of 7 m are provided. As part of a feasibility study, a pile driving analysis was performed for different locations based on different drilling samples within the construction field. For the underwater noise modeling a piling sequence of 3,424 blows with a constant blow energy of 4,000 kJ and a constant blow rate of 30 blows/minute without interruptions will be considered for the for the preferred project and alternative 1, whereas a piling sequence of 2,840 blows with a constant blow energy of 3,500 kJ at a constant blow rate and 30 blows/minute is considered for alternative 2. When calculating the cumulative Sound Exposure Level (SEL_{cum}) for a moving receiver, this leads to slightly higher values compared to real piling sequences, since a soft start and a ramp-up procedure with lower energies and interruptions usually takes place. It is to be expected that the actual pile-driving consequences will differ at the individual locations.

However, the pile-driving analyses included in this forecast are based on the borehole investigations and are exemplary for the immediate borehole environment.

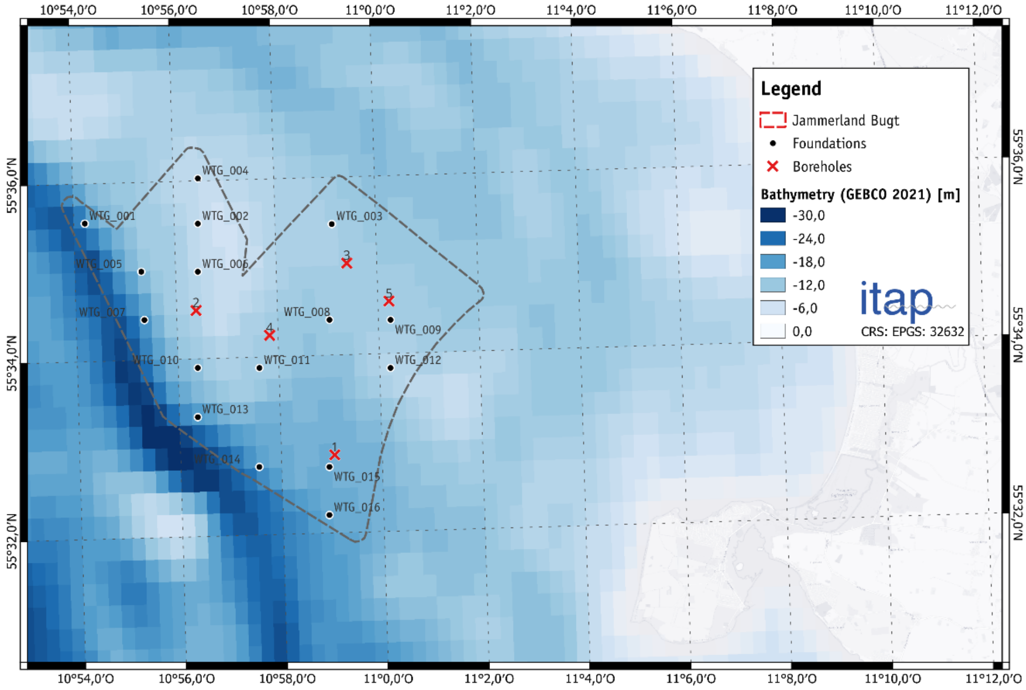


Figure 1: *Possible Site layout of the OWF Jammerland Bay Near Shore Wind Farm according to the preferred project design with bathymetry (GEBCO 2021).*

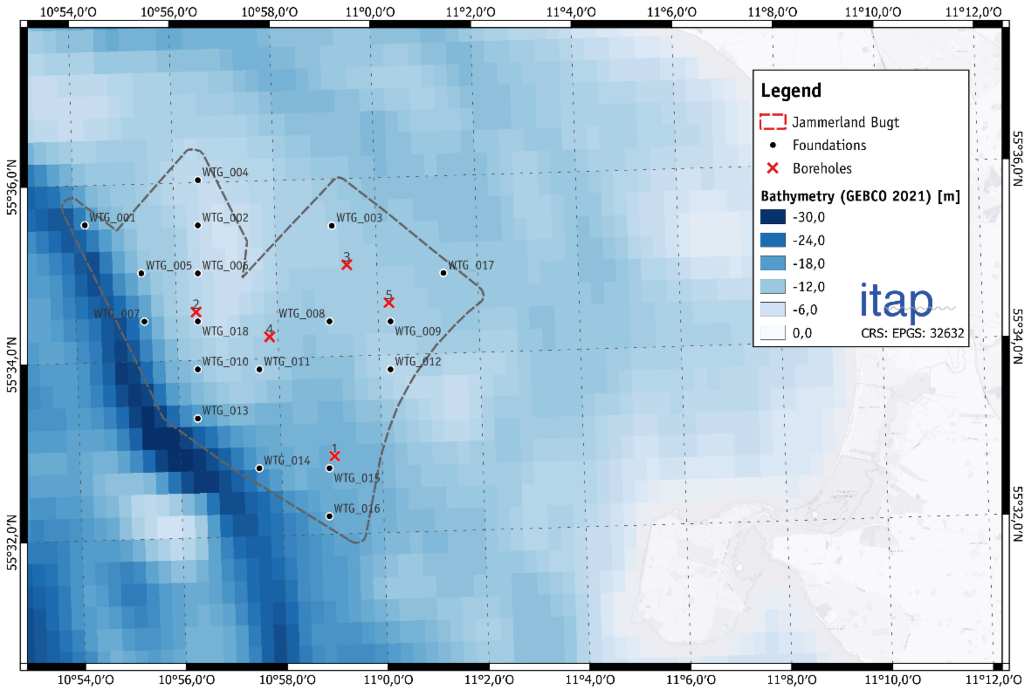


Figure 2: *Possible Site layout of the OWF Jammerland Bay Near Shore Wind Farm according to alternative 1 with bathymetry (GEBCO 2021).*

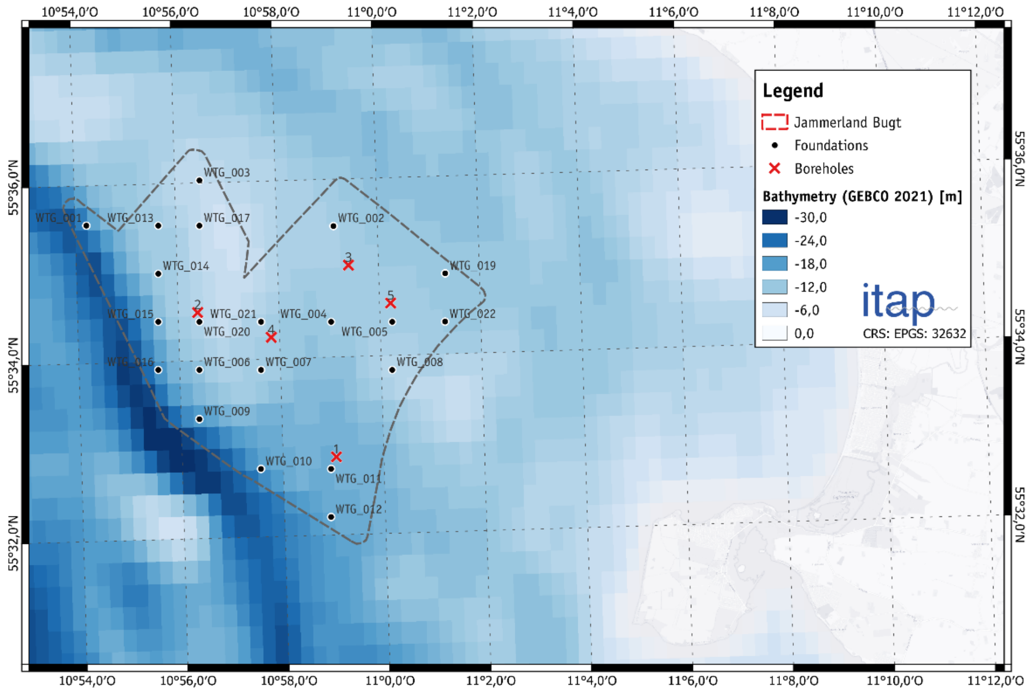


Figure 3: Possible Site layout of the OWF Jammerland Bay Near Shore Wind Farm according to alternative 2 with bathymetry (GEBCO 2021).

Table 1: Modelling and Windfarm-layout scenarios for OWF Jammerland Bay Near Shore Wind Farm including foundation diameter, the expected max. blow energy and total number of blows specified for the representive borehole according to the pile driving analyses and the closest location used for modelling.

Scenario	Diameter [m]	Max. blow energy [kJ]	Total blows	Borehole	Model Location	Water depth at location [m]*
Preferred project design	8.0	4,000	3,424	2	WTG06	- 9
Alternative 1	8.0	4,000	3,424	2	WTG18	- 10
Alternative 2	7.0	3,500	2,840	2	WTG20	- 10

* Sea floor height (above mean sea level) according to the GEBCO 2021 bathymetry grid, used for modeling.

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.

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):

- (energy-) equivalent continuous Sound Pressure Level – SPL ,
- single strike Sound Exposure Level – SEL,
- zero-to-peak Sound Pressure Level $L_{p,pk}$.

[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.

The SPL and SEL 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.

Sound Exposure Level (SEL)

For the characterization of pile-driving sounds, the SPL solely is an insufficient measure, since it does not only depend on the strength of the pile-driving blows, but also on the averaging time and the breaks between the pile-driving blows. The sound exposure – E or rather the resulting Sound Exposure Level – SEL is more appropriate. Both values are defined as follows:

$$E = \frac{1}{T_0}\int_{T_1}^{T_2}\frac{p(t)^2}{p_0^2}\,\mathrm{d}t$$

Equation 4

$$SEL = 10\ \log_{10}\left(\frac{1}{T_0}\int_{T_1}^{T_2}\frac{p(t)^2}{p_0^2}\ \mathrm{d}t\right)\ [\mathrm{dB}]$$

Equation 5

with

T_1 and T_2 - starting and ending time of the averaging (should be determined, so that the sound event is between T_1 and T_2),

T_0 - reference 1 second.

Therefore, the Sound Exposure Level of a sound impulse (pile-driving blow) is the (SPL) level of a continuous sound of 1 s duration and the same acoustic energy as the impulse.

The Sound Exposure Level (SEL) and the Sound Pressure Level (SPL) can be converted into each other:

$$SEL = 10\ \log_{10}\left(10^{\frac{SPL}{10}} - 10^{\frac{L_{hg}}{10}}\right) - 10\ \log_{10}\left(\frac{nT_0}{T}\right)\ [\mathrm{dB}]$$

Equation 6

with

n - number of sound events, thus the pile-driving blows, within the time T,

T_0 - 1 s,

L_{hg} - noise and background level between the single pile-driving blows.

Thus, Equation 6 provides the average Sound Exposure Level (SEL) of n sound events (pile-driving blows) from just one Sound Pressure Level (SPL) measurement. In case, that the background level between the pile-driving blows is significantly minor to the pile-driving noise (for instance > 10 dB), it can be calculated with a simplification of Equation 6 and a sufficient degree of accuracy as follows:

$$SEL \approx SPL - 10\ \log_{10}\left(\frac{nT_0}{T}\right)\ [\mathrm{dB}]$$

Equation 7

Cumulative Sound Exposure Level (SEL_{cum})

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

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

Equation 8

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 9

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.

Zero-to-peak Sound Pressure Level ($L_{p,pk}$)

This parameter is a measure for sound pressure peaks. Compared to the Sound Pressure Level (SPL) and the Sound Exposure Level (SEL), there is no average determination:

$$L_{p,pk} = 20\ \log_{10}\left(\frac{|p_{pk}|}{p_0}\right)\ [\mathrm{dB}]$$

Equation 10

with
$|p_{pk}|$ - maximum determined Sound Pressure.

Figure 4 depicts an example. The zero-to-peak Sound Pressure Level ($L_{p,pk}$) is always higher than the Sound Exposure Level (SEL). Generally, the difference between $L_{p,pk}$ and SEL during pile-driving work is 20 dB to 25 dB. Some authors prefer the peak-to-peak value ($L_{pk,\ pk}$) instead of $L_{p,pk}$. A visual definition of this parameter is given in Figure 4, but this metric is not defined in the international standard (ISO 18406 2017). This factor does not describe the maximum achieved (absolute) Sound Pressure Level, but the difference between the maximum negative and the maximum positive amplitude of an impulse. This value is maximum 6 dB higher than the zero-to-peak Sound Pressure Level $L_{p,pk}$.

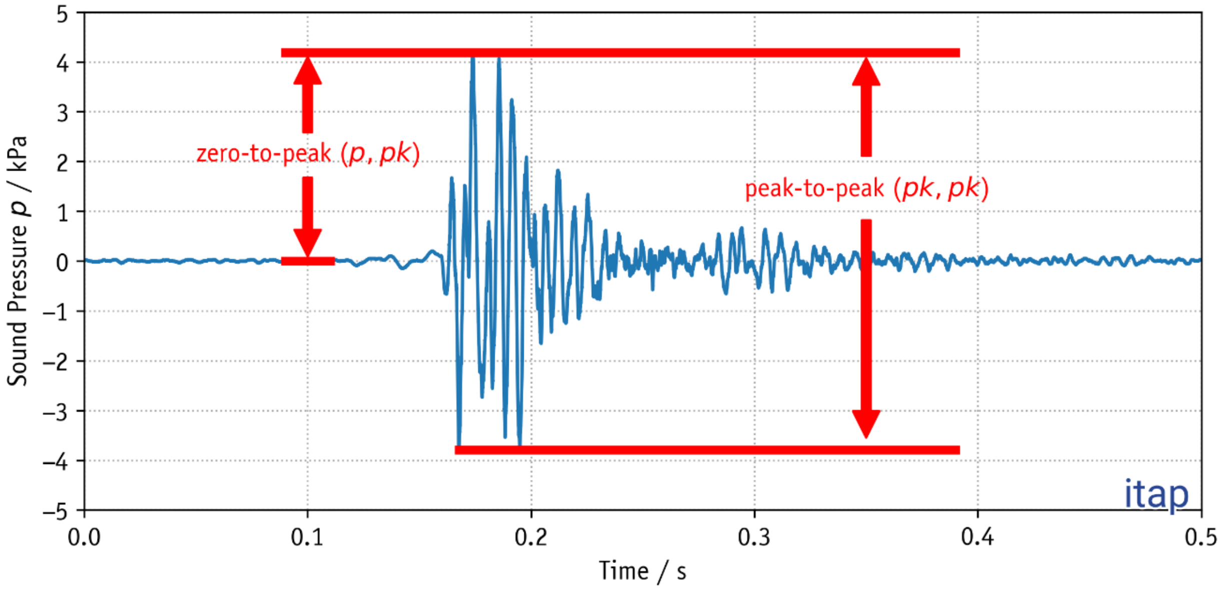


Figure 4: Typical measured time signal of underwater noise due to pile-driving in a distance of several 100 m.

4. Underwater noise mitigation values

The emission of underwater noise during seismic surveys 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 2).

To assess the impact from underwater noise on marine mammals and fish, the threshold levels according to Energistyrelsen (2022) presented in Table 2 were modelled. For further details of the threshold levels, the reader is encouraged to consult the respective references provided in Table 2. 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 5 shows the weighting functions provided by Southall et al. (2019) for very-high-frequency cetaceans (VHF) (e. g. harbour porpoise, *Phocena phocena*) 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 in line with Energistyrelsen (2022).

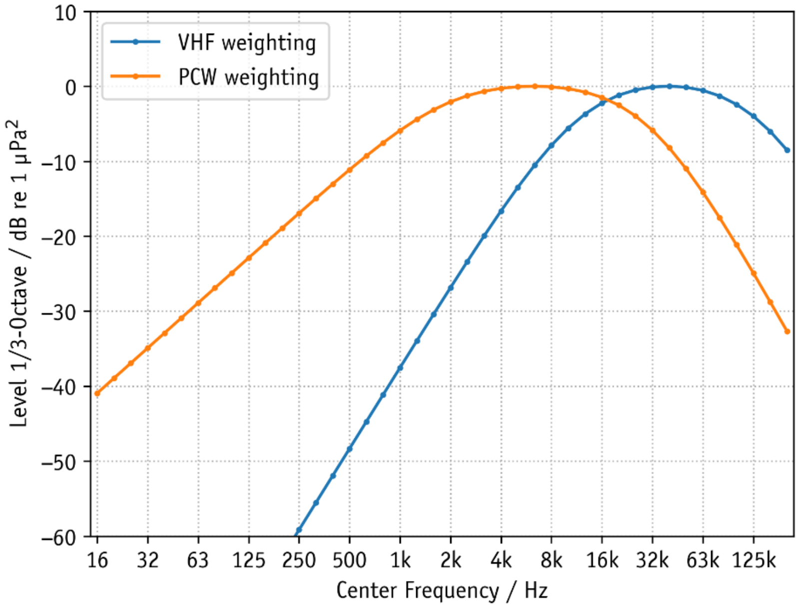


Figure 5: *Weighting functions for high- and mid-frequency cetaceans HF and MF and phocid seals according to Southall et al. (2019).*

Table 2: *Noise modeling threshold criteria and considered fleeing speeds for different animals according to Energistyrelsen (2022). PTS: Permanent Threshold Shift; TTS: Temporary Threshold Shift.*

Receptor	**Impact type**	**metric**	**Fleeing speed [m/s]**	**Criteria [dB]**
VHF	PTS	$SEL_{\text{cum, VHF}}$	1.5	155
VHF	TTS	$SEL_{\text{cum, VHF}}$	1.5	140
VHF	Avoidance reaction	$SPL_{\text{VHF, 125ms}}$	0	103
PCW	PTS	$SEL_{\text{cum, PCW}}$	1.5	185
PCW	TTS	$SEL_{\text{cum, PCW}}$	1.5	170
Fish	Mortal injury	SEL_{cum}	Herring: 1.04 Adult Cod: 0.9 Juveline Cod: 0.38	204
Fish	recoverabel injury	SEL_{cum}	Herring: 1.04 Adult Cod: 0.9 Juveline Cod: 0.38	203
Fish larves	Mortal injury	SEL_{cum}	0	207

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 11

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 11 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 11 expands to:

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

Equation 12

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 6. 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.

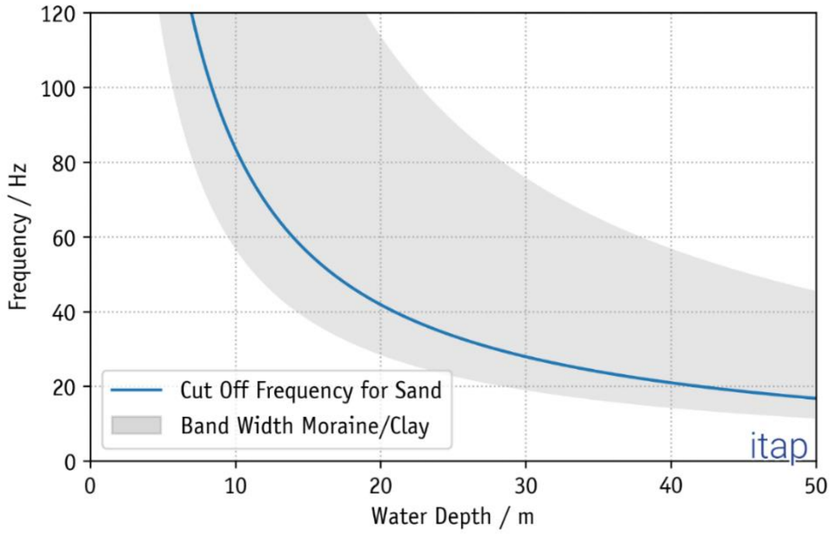


Figure 6: *Theoretical, lower (limit) frequency (f_g) for an undisturbed sound propagation in water as a function of the water depth for different soil stratifications (example adapted from (Urick 1983) and (Jensen et al., 2010); the example shows the possible range caused by different layers; the layer does not correspond to the layers in the construction field).*

5.2 Model description

The model of the *itap GmbH* for source level estimation is an empirical model in accordance with Energistyrelsen (2022), i. e, it is based on measured Sound Exposure Levels (SEL) and on zero-to-peak Sound Pressure Levels ($L_{p,pk}$) of previous projects. Therefore, this sort of model is an “adaptive” model, which becomes more “precise” with increasing input data.

The emitted sound level depends on many different factors, such as wall thickness, blow energy, diameter and soil composition (soil resistance) and water depth. But since all parameters mentioned might interact with each other, it is not possible to make exact statements on the impact of a single parameter. In a first step, only one parameter, the “pile diameter”, is considered.

Figure 7 shows noise levels measured during pile-driving construction work at a number of offshore sites plotted over the input parameter “pile diameter”. The bigger the sound emitting surface in the water, the bigger the sound entry. This means, the evaluation-relevant level values rise with increasing pile surface, thus the diameter of the pile. It should also be noted, that the relationship is not linear.

The model uncertainty is ± 5 dB, just taking into account the input parameter „pile diameter", and is based on the scatter of the actual existing measuring results from Figure 7, which is probably due to further influencing factors, such as blow energy and reflecting pile skin surface.

Technical note: Over the last years, monopile designs occurred with various diameters between the pile bottom and top. For the upcoming underwater noise prognosis, only the maximum pile diameter will be considered, since this diameter mostly covered the pile design within the full water column and thus reflects the sound-emitting pile surface.

The following comparison between the predicted values and the actually measured level values was covered adequately in any case by the specified model uncertainty (± 5 dB). In most cases, the model slightly overestimated the level value in 750 m distance (unpublished data). Therefore, an application in the present case is possible from a practical point of view. Therefore, the model is likely to be conservative.

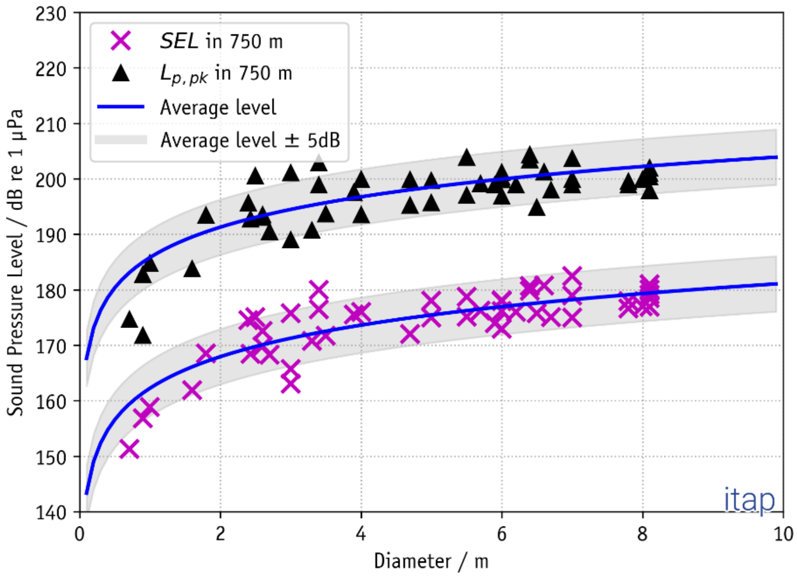


Figure 7: Measured zero-to-peak Sound Pressure Level ($L_{p,pk}$) and broadband 5 % exceedance Sound Exposure Levels (SEL_{05}) at pile-driving construction works in 750 m distance at a number of OWFs as function of the pile diameter.

Moreover, in this model, additions resp. deductions for very high and very low maximum blow energies are used in a second step. Considering the actually applied maximum blow energy resp. the maximum blow energy estimated in the model, normally, differences between the model and the real measuring values of about 2 dB were obtained. In the majority of cases, the model slightly overestimated the level value at a distance of 750 m with the input data "pile diameter" and "maximum blow energy".

It was established, that the impact of the blow energy used is on average about 2.5 dB per duplication of the blow energy (Gündert 2014).This finding resulted from investigations at different foundations, at which the variations of the blow energy during pile-driving (penetration depth) were statistically compared to corresponding level changes (each from soft-start to maximum blow energy).

Therefore, this additional module for the existing model of the *itap GmbH* is able to predict the evaluation-relevant level values for each single blow with given courses of blow energy. The model uncertainty of this statistic model (*itap GmbH* basic model + extension) is verifiably ± 2 dB; a slight overestimation of this model could be proven as well.

Gündert (2014) shows, that the blow energies used and the penetration depth considerably influence the resulting sound pollution with a significant correlation of penetration depth and applied blow energy. Considering the influencing factors "pile diameter", "maximum blow energy" and "penetration depth", a model uncertainty of ± 2 dB in the range of measurement inaccuracy could be achieved. The biggest amount of the measured variances could thus be traced back to the three influencing factors mentioned above.

Since an exact modeling of the blow energy to be applied over the entire penetration depth (per blow) is not possible without further "uncertainties", additions and deductions for the maximum blow energy are considered.

Based on experiences of the last few years and the findings from the master's thesis, it can be assumed, that the model uncertainty can be minimized significantly in due consideration of the above mentioned additions and deductions.

5.3 Determination of the source and propagation level

The Sound Exposure Level (SEL) varies in the course of a pile-driving and depends on, as mentioned before, several parameters (e. g. reflecting pile skin surface, blow energy, soil conditions, wall thickness, etc.). The applied model just considers the pile diameter as influencing parameter in a first step. To get a statistically valid result of the loudest expected blows, the empirical model for this model is based on the 5 % exceedance of the Sound Exposure Level (SEL_{05}) during one pile installation.

5.3.1 Blow energy

The level values (SEL, SPL, and $L_{p,pk}$) rise with increasing blow energy. Based on the experiences of previous construction projects, a starting point for the determination of the influence parameter “blow energy” is assumed. Assuming this, additions resp. deductions of 2.5 dB per doubling/halving for higher resp. lower maximum blow energies are estimated in the model.

5.3.2 Hydraulic hammer

Currently, the influence of different hydraulic hammer types is not taken into account, since too many influencing parameters and factors exist, e. g. anvil design, contact area between hammer and pile, pile gripper or pile-guiding frame. Theoretical studies point out, that the influence of different hammer types could be in a range of 0 dB to max. 3 dB. Additionally, no valid empirical data regarding different hammer types currently exist. Therefore, the *itap* model is focusing on the worst case (loudest possible) scenario. In case new and statistically valid results for the influencing factor hammer type will be available within the project duration, these findings will be taken into account.

5.3.3 Ground couplings

The influence of different ground conditions is currently still subject to research. However, it can be assumed, that the used blow energy will also increase with growing soil resistance (SRD-value) of a soil layer. As in the construction field there is a sandy underground mixed with small quartzite cobbles/gravel and the measurement data shown in chapter 5.2 Figure 7 were largely determined on sandy and medium-tight, argillaceous underground, it can be assumed, that the sound emissions to be expected are the same as the regression line shown in Figure 7. For this reason, in the model, a frequency-independent safety margin for the soil conditions (ground coupling) is not necessary.

5.3.4 Spectrum of piling noise

The estimations of the broadband Sound Exposure Level (SEL) and the zero-to-peak Sound Pressure Level ($L_{p,pk}$)-value shown in the chapters below are based on the broadband measuring data of different studies (Figure 7). However, sound propagation in the sea is highly frequency-dependent. For this reason, estimations of the frequency composition of the respective source levels[2] have to be made for the calculations.

Figure 8 shows the spectral distribution of the Sound Exposure Levels (SEL), which have been determined during pile-driving works at different piles (gray lines). The spectra determined at different distances as well as at different blow energies and pile diameters run similarly. The frequency spectrum shows a maximum within the range of 60 to 250 Hz. At frequencies above approx. 250 Hz, the levels decrease gradually, while for frequencies lower than approx. 60 Hz, a steep decrease in levels is observed. The cut-off frequency for the steeply fall-off at low frequencies depends on the water depth. The deeper the water, the lower the cut-off frequency. For the water depths in the project area between 6 m and 27 m, the cut-off frequency will be within 139 Hz and 31 Hz.

From measurements collected over the last two years, it has become apparent, that the hydraulic hammer type, as well as the pile diameter can have an influence on the piling noise spectrum to be expected. By trend, the local maximum shifts in case of larger pile hammer types and larger pile diameters to lower frequencies. At present, however, these influencing factors cannot be estimated with statistical validity.

In detail, the spectral course of a piling noise event is not exactly predictable according to the present state of knowledge. Thus, for the modeling, an idealized model spectrum for the Sound Exposure Level will be extracted from the measured data of comparable construction projects. Figure 8 shows the shape of this idealized 1/3-octave-spectrum in red color. The frequency-dependent amplitudes are normalized in a way, that the sum level of this spectrum in 750 m distance corresponds to the source levels determined before. Since 2016, the model of the *itap GmbH* calculates the evaluation-relevant level values on the measured Sound Exposure Level (5 % percentile level, SEL_{05}) and the measured zero-to-peak Sound Pressure Level ($L_{p,pk}$).

[2] "Source level" means the Sound Exposure Level (SEL) or zero-to-peak Sound Pressure Level ($L_{p,pk}$) at a fictive distance of 750 m to an imagined point sound source.

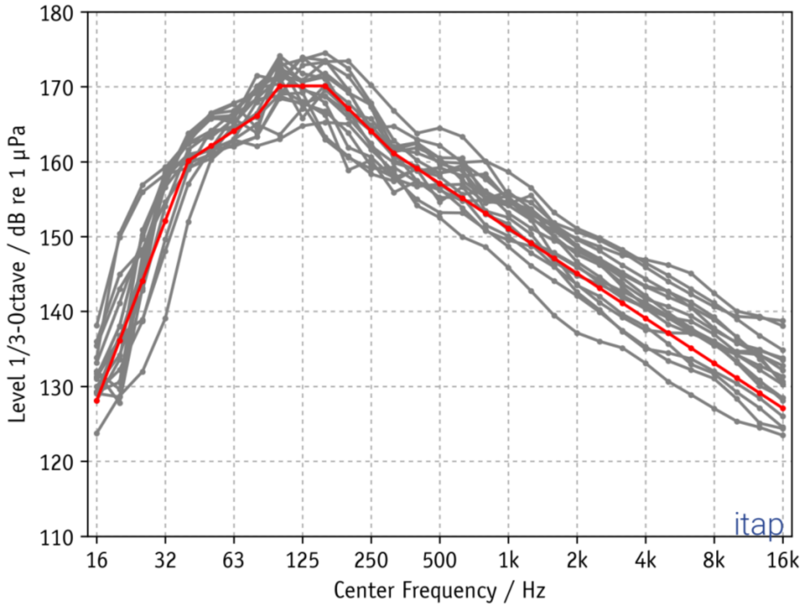


Figure 8: The model spectrum (red, blue) estimated for piling noise, based on different measuring data (grey: measuring data) for monopiles.

5.3.5 Water depth

The water depth also influences the sound propagation in the water. Below a certain cut-off frequency, however, a continuous sound propagation in shallow water is not possible. The shallower the water, the higher this frequency is. Figure 6 in chapter 5.1 shows the cut-off frequencies for an undisturbed sound propagation. For the modeling, all frequencies below this cut-off frequency will decrease with 12 dB/octave. Decisive is the minimum water depth between source and receiver. The water depth in the project area is between 6 m and 27 m. This results in cut-off frequencies of 139 Hz for 6 m and 31 Hz for 27 m. For higher frequencies, the sound propagation of shallow water will be used.

5.3.6 Transmission loss

For the modeling Equation 12 is considered. To adapt the propagation term k and the absorption coefficient α to the local conditions, the transmission loss was estimated for the expected worst case tansect in 165° direction from the source based on the maximum water depth. The transmission loss was estimated by using the Range-dependent Acoustic Model (RAM) according to Micheal D Collins (1995) and the Bathymetry from GEBCO 2020 of a 20 km x 20 km grid quantized in 2 m steps (Annex 2). The pile is modelled with three point sources at different water depths for each octave band between 20 Hz and 120 kHz. For Frequencies from 10 kHz only distances up to 20.000 wavelengths were considered. From the numerical results the propagation term k and the absorption coefficient α are estimated using the ordinary least squared curve fitting. The resulting propagation term k and the absorption coefficient α are listed in Annex 1.

5.3.7 Model requirements

The empirical pile-driving model fulfills the national guidelines from the regulators in Denmark (Energistyrelsen 2022) for impact pile-driving noise predictions. Additionally, the *itap GmbH* is accredited for underwater noise predictions and measurements in accordance with the DIN 17025 (2018). International guidelines or standards for underwater pile-driving noise predictions do not exist today. Other nations also have no fixed guidance for the predictions; typically, the requirements on the predictions will be defined separately for each construction project. This model has already been applied in countries like Germany, Denmark, the Netherlands, the United Kingdom, Belgium, France, the USA, Australia and Taiwan.

Due to the location close to the coast and the shallow water depths, unhindered sound propagation over many kilometers is not possible. For this reason, the transmission loss is only determined for an exemplary direction of 165°, in deviation from the "Guideline for underwater noise - Installation of impact or vibratory driven piles" (Energistyrelsen 2022). Unhindered sound propagation is possible in this direction and the lowest propagation attenuation for low frequencies is expected due to the water depths.

5.4 Calculation procedure

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

5.4.1 Step 1: Determination of the SEL and the SPL at 750 m distance to the source

The *itap* model predicts the Sound Exposure Level (SEL) and the zero-to-peak Sound Pressure Level ($L_{p,pk}$) based on the empirical data base in a specified distance of 750 m to the source in accordance to the requirements of the German measurement guidance (BSH 2011)and the international standard (ISO 18406). The model results depend on the following parameters:

(i) the pile diameter,
(ii) the maximum blow energy (worst-case-scenario),
(iii) the water depth and
(iv) the safety margins for e. g. soil conditions.

To calculate the Sound Pressure Level (SPL) the pile-driving duration of each single strike is mandatory. The longer the pile-driving duration, the lower the resulting SPL value, because the sound energy of the blow is distributed over a longer period. Figure 9 shows examples for the single strike duration τ_{90} (interval length in seconds including 90 % of the sound energy of one single strike in accordance to the Dutch measurement guideline (De Jong, Ainslie and Blacquière 2011) for three different monopile installations. The measured pile-driving duration of a single strike shows large variances due to the fact that this parameter significantly depends on many influencing factors. For the prognosis, an average single strike duration of 0.1 s is assumed and the Sound Pressure Level will be calculated by applying the predicted Sound Exposure Level and the averaged single strike duration (Equation 5).

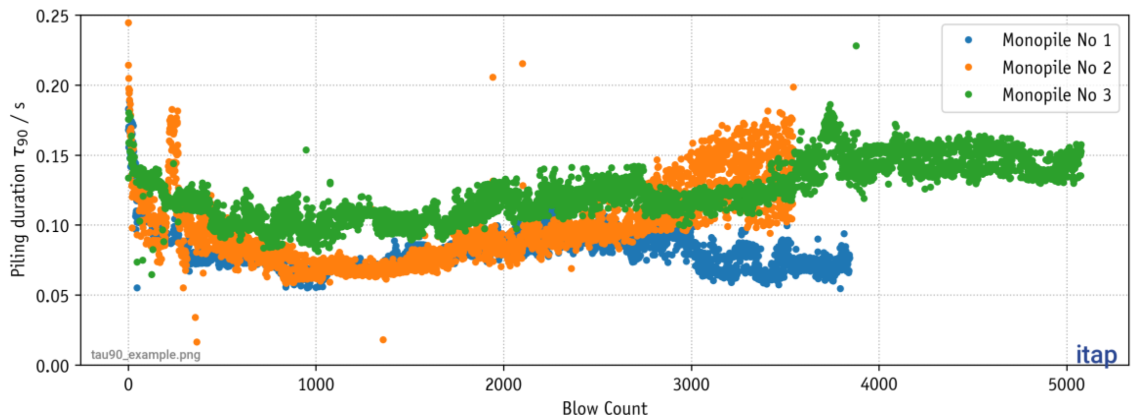


Figure 9: Pile-driving duration τ_{90} of single strikes for three different monopile installations in accordance with de Jong et al. (2011).

5.4.2 Step 2: Frequency-dependency of the source level and transmission loss

Estimations for the broadband Sound Exposure Level (SEL) and the zero-to-peak Sound Pressure Level ($L_{p,pk}$) value are based on empirical broadband data from different OWF construction phases (e. g. Bellmann *et al.*, 2020). Sound propagation in the ocean, however, is frequency-dependent.

The spectral approaches for the piling noise at 750 m will be determined from empirical data (see chapter 5.3.4) and an approach for the Transmission Loss (TL) shown in Annex 1 will be considered. The selection of the spectral shape based on empirical data, as well as the overall level will be adapted to the predicted broadband Sound Exposure Level (SEL).

5.5 Model uncertainties

Both, the modeling of "source strength" or "source level" of the pile-driving noise and the pile-driving analysis for the determination of the maximum blow energies include a certain degree of uncertainty and thereby the derived calculated/predicted level values as well as their impact range.

Measurements from completed construction projects Bellmann *et al.* (2020) with large monopiles show, that the measured SEL at the end of the pile-driving sequence stays constant or decreases by up to 25 % despite an increase of the blow energy, i. e., it does not increase. One possible explanatory approach for this is the high penetration depth of the monopiles and the resulting elevated stiffness of the pile to be driven.

Pile-driving activities of tripod / jacket pin piles (skirt piles) mostly starts with hammers above the water surface and usually ends just a few meters above the seabed. As a result, the sound-reflecting pile surface area continuously decreases with ongoing pile-driving activity (Nehls and Bellmann 2015). In contrast to this, the hammer energy increases continuously with increasing ground resistance (SRD value) during the entire pile-driving sequence. In general, the evaluation-relevant level values rise continuously with increasing blow energy within the first 50 to 65 % of the total driving time with 75 % to 80 % of the maximum blow energy usually being reached.

At the end of the pile-driving, the level values can diminish by several dB despite a further increase in the blow energy due to the reduced pile surface area. For a prognosis of the expected relevant level values, the hammer energy and the sound-reflecting pin-pile jacket surface must therefore be considered theoretically. However, measurements with a constant SEL are also available, in which the radiating pile surface area decreases and the blow energy increases during driving. This is often due to the use of so-called pile extension units (pile followers). Since the use of pile followers is usually not finally planned when creating the underwater noise prognosis, the maximum blow energy is always used in all calculations.

Figure 10 shows an example of a typical SEL vs. time plot of a typical monopile and pin pile installation.

Determining the source level using only the input parameter "pile diameter" results in an uncertainty of ± 5 dB (Figure 7). To reduce the uncertainty, assumptions are made for the second relevant effective parameter "pile-driving energy" (blow energy) and additions and deductions are taken into account on the basis of an initial value.

By considering the effective parameter "blow energy", the uncertainty is significantly reduced. The comparison of the model with real measurement data from 2012 to now shows an uncertainty of ± 2 dB (unpublished data from various projects) for the single strike SEL at a distance of 750 m to the pile-driving event with the tendency, that the model most of the time slightly overestimates the measured values.

The most important influencing parameter with regard to the forecast uncertainty is the transmission loss (TL), as this parameter significantly depends on the weather (wind and waves) and bathymetry. This means, that with predicted levels over long distances (< 10 km), uncertainties of more than 2 dB can occur. As a rule, all semi-empirical and theoretical approaches for sound propagation over large distances underestimate the transmission loss, which corresponds to an overestimation of the levels at large distances. But the effect of the predicted sound levels at a distance of 750 m from the pile through the use of various empirical and semi-empirical approaches for the transmission loss is very limited.

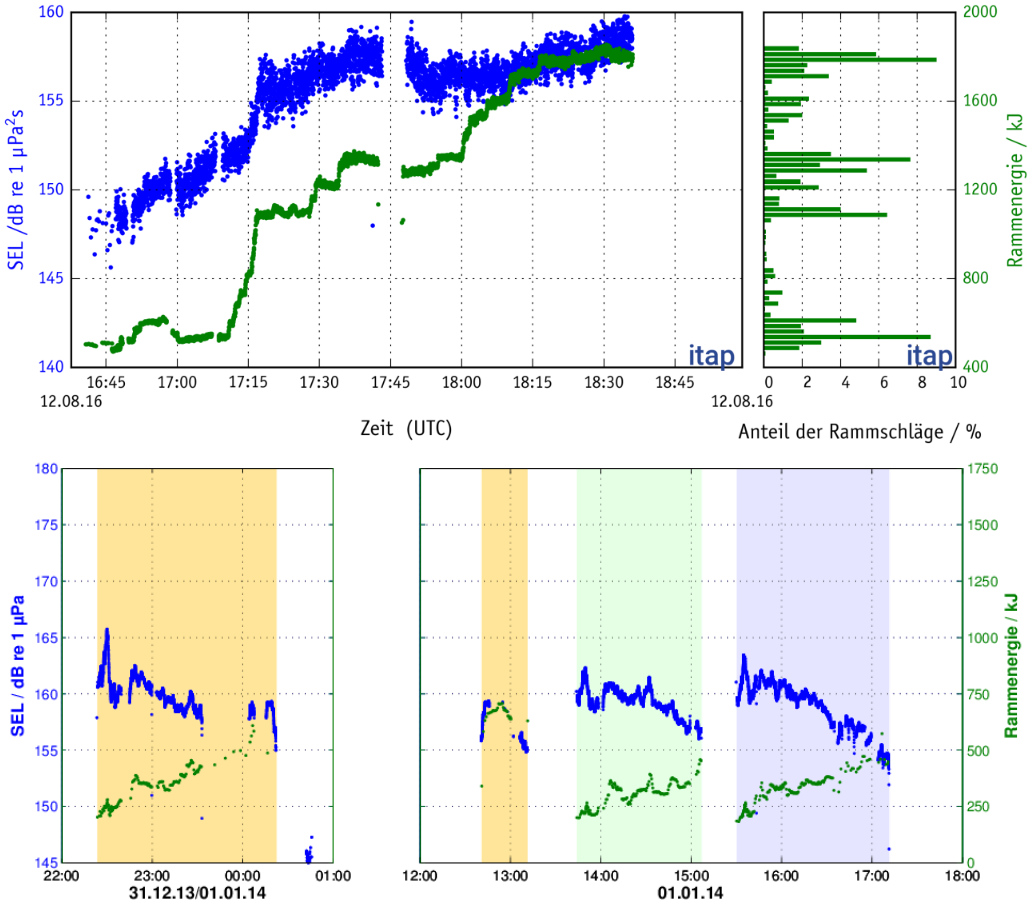


Figure 10: *Top: Simple single event level (SEL) as a function of time (blue line) and the blow energy used (green line) for a typical monopile installation in the North Sea.*

Below: A possible example of a jacket installation with three pin piles (the colored background marks the three different piles).

6. Modeling scenarios

6.1 Used model

The transmission loss in water depends on the composition of the water, the spatial extent (water depth) and the attenuation at the boundary layer to the sediment. These are accounted for in the model as follows:

Table 3: Input parameter for transmission loss model. For the model it is assumed, that the salinity, temperature and sound speed are constant over the water depth.

Parameter	Value
Water depth:	Accoding to Annex 2
Water temperature:	10°C
Salinity	20 ‰
Sound speed in water	1,469 m/s
Seabed density	1.6 g/cm^3
Seabed Attenuation	0.8 dB

The model does not consider any background level. It will be assumed that the signal-to-noise-ratio between the pile-driving noise and the background noise will always be ≥ 10 dB.

6.2 Acoustically relevant input data

For the underwater noise prognosis of the upcoming WTG installations, the following input data and model assumptions are applied in agreement with the client:

Input parameter:	Preferred project design and Alternative 1	Alternative 2
- Pile Diameter:	8.0 m	7.0 m
- max. Blow Energy:	4,000 kJ	3,500 kJ
- total Blows:	3,424	2,840

Model assumptions and global input parameter:	
- Input Parameter #1:	Pile Diameter
- Input Parameter #2:	2.5 addition or deduction per doubling resp. halving of the blow energy (based on a reference value)
- Soil Conditions:	no additions or deductions
- Pile Skin Surface:	constant, no additions or deductions
- Water Depth:	90 Hz cut-off frequency at the modelled locations
- Noise Abatement Systems:	None and including DBBC
- Soil Conditions:	layers of different sands with clay inclusions
- Water Depth:	~ 6 m - 27 m within the project area 9 m – 10 m at the modelled locations
- Piling frequency:	30 blows / minute
- Foundation Type:	monopile

The reference distance of the used model is 750 m. The following Figure 11 shows the different reference SEL at this distance for the considered locations in water depths between 9 m and 10 m.

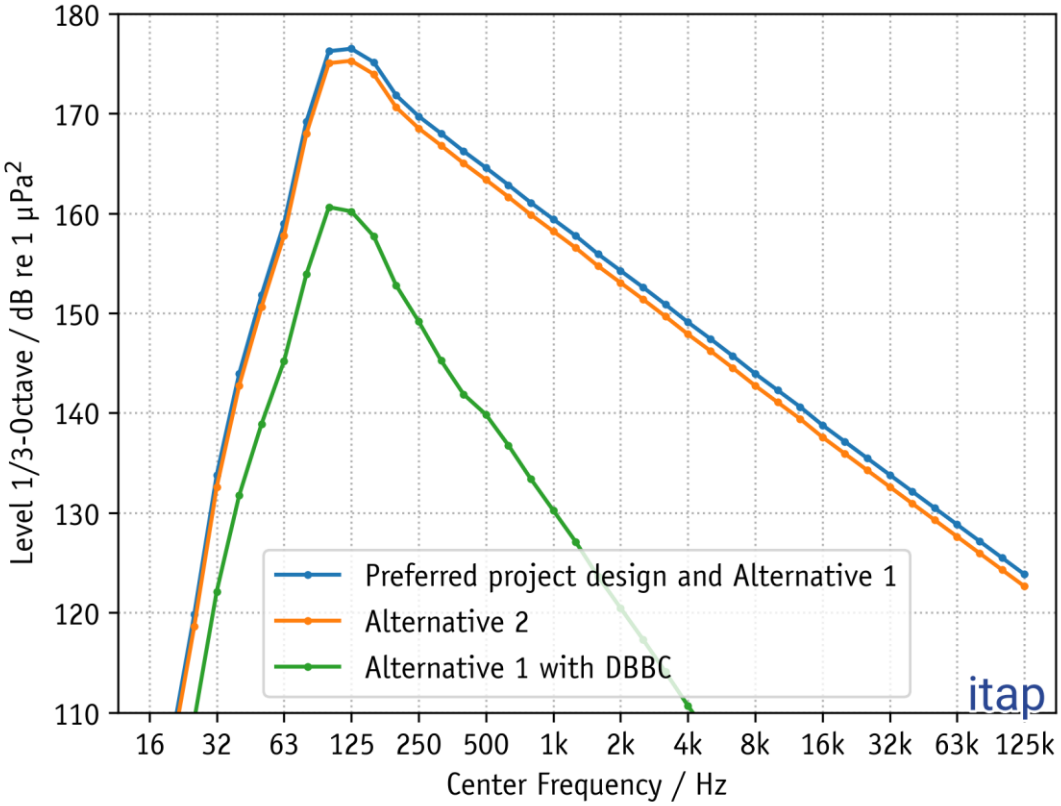


Figure 11: Reference Sound Exposure Level (SEL) in 1/3 octaves in 750 m distance for the considered locations in 9 m and 10 m water depth.

7. Model results

Considering the model approaches in chapter 5 and the piling sequences described in chapter 2, the following maximum levels are expected in 1 m, 750 m and 3 km distance (Table 5 to Table 12). Differences between the different locations are the water depth and the soil. As 750 m is the reference distance of this model, high transmission loss assumptions, which is the case for low frequencies in shallow water (Annex 1), lead to an unrealistically high amplification of the level values at distances of less than 750 m. For this reason, only the frequency range from 500 Hz was considered for the presentation of the results at a distance of 1 m (Table 5). For the SEL_{cum} estimation and estimation of impact distances no high pass filter was considered, that leads to an overestimation of all blows received below 750 m distance. The resulting cutoff frequencies for low frequencies caused by water depth differ by 108 Hz for the complete project area. So differences up to 3.8 dB are possible by the impact of water depth in 750 m. Figure 12 shows the calculated Sound Exposure Level (SEL) using 4,000 kJ blow energy as a function over the distance for the possible location WTG06 (preferred project design) in 165° direction.

Cumulative impacts also depend on the number of blows, which in turn depends on the soil properties. Based on the available pile driving analyses, it can be assumed that site-specific differences lead to a reduction in total number of blows.

Due to the escape behaviour of the respective species, the received SEL decreases with increasing distance to the monopile installation. For the SEL_{cum} this has the consequence that it is saturated and hardly increases with increasing number of blows. This is approximately the case when the SEL is at least 20 dB lower than the loudest SEL. This means that the sound energy ratio is below 1 % compared to the sound energy of the loudest blow. If, as assumed in this prognosis, the source level remains constant over the pile driving, this is the case from ten times the starting distance. For the example of a harbour porpoise swimming at 1.5 m/s and a start distance of 750 m, this is the case at 7,500 m or after 75 minutes. At a piling frequency of 30 blows/minute this corresponds to 2,250 blows.

Table 4: *Calculated level of the Sound Exposure Level (SEL), 125 ms Sound Pressure Level (SPL_{125ms}) and the zero-to-peak Sound Pressure Level ($L_{p,pk}$) in 1 m distance for different weightings (frequency range: 500 Hz – 125 kHz).*

MNFS weighting	SEL in 1 m distance	SPL_{125ms} in 1 m distance	$L_{p,pk}$ in 1 m distance
Preferred project design: 8.0 m Diameter, 4,000 kJ Blow Energy			
No	215	206	238
High frequency cetaceans	192	183	238
Phocid seals	210	201	238
Alternative 1: 8.0 m Diameter, 4,000 kJ Blow Energy			
No	213	204	236
High frequency cetaceans	189	180	236
Phocid seals	205	196	236
Alternative 2: 7.0 m Diameter, 3,500 kJ Blow Energy			
No	212	203	235
High frequency cetaceans	188	179	235
Phocid seals	204	195	235

Table 5: *Calculated level of the Sound Exposure Level (SEL), 125 ms Sound Pressure Level (SPL_{125ms}) and the zero-to-peak Sound Pressure Level ($L_{p,pk}$) in 750 m distance for different weightings.*

MNFS weighting	SEL in 750 m distance	SPL_{125ms} in 750 m distance	$L_{p,pk}$ in 750 m distance
Preferred project design 8.0 m Diameter, 4,000 kJ Blow Energy			
No	182	173	205
High frequency cetaceans	146	137	205
Phocid seals	165	156	205
Alternative 1: 8.0 m Diameter, 4,000 kJ Blow Energy			
No	182	173	205
High frequency cetaceans	146	137	205
Phocid seals	165	156	205
Alternative 2: 7.0 m Diameter, 3,500 kJ Blow Energy			
No	181	172	204
High frequency cetaceans	145	136	204
Phocid seals	164	155	204

Table 6: *Calculated level of the Sound Exposure Level (SEL), 125 ms Sound Pressure Level (SPL_{125ms}) and the zero-to-peak Sound Pressure Level ($L_{p,pk}$) in 3 km distance for different weightings.*

MNFS weighting	SEL in 3 km distance	SPL_{125ms} in 3 km distance	$L_{p,pk}$ in 3 km distance
Preferred project design 8.0 m Diameter, 4,000 kJ Blow Energy			
No	163	154	185
High frequency cetaceans	135	126	185
Phocid seals	153	144	185
Alternative 1: 8.0 m Diameter, 4,000 kJ Blow Energy			
No	166	157	189
High frequency cetaceans	135	126	189
Phocid seals	155	146	189
Alternative 2: 7.0 m Diameter, 3,500 kJ Blow Energy			
No	165	156	188
High frequency cetaceans	134	125	188
Phocid seals	154	145	188

Table 7. *Cumulative Sound Exposure Level for 200 m deterrence distance, different receptors and the preferred project design with 8.0 m pile diameter, 4,000 kJ Blow Energy and 3,434 blows.*

Receptor	weighting	Deterrence distance [m]	Fleeing speed [m/s]	SEL_{cum}
High-frequency cetaceans	VHF	200	1.5	175
Phocid seals	PCW	200	1.5	226
Herring	No	200	1.04	227
Adult Cod	No	200	0.9	228
Juvenile Cod	No	200	0.38	232
Larves	No	200	0.0	249

Table 8. *The cumulative Sound Exposure Level for 750 m deterrence distance, different receptors and the preferred project design with 8.0 m pile diameter, 4,000 kJ Blow Energy and 3,434 blows.*

Receptor	weighting	Deterrence distance [m]	Fleeing speed [m/s]	SEL_{cum}
High-frequency cetaceans	VHF	750	1.5	170
Phocid seals	PCW	750	1.5	189
Herring	No	750	1.04	204
Adult Cod	No	750	0.9	204
Juvenile Cod	No	750	0.38	208
Larves	No	750	0.0	218

Table 9. *The cumulative Sound Exposure Level for 200 m deterrence distance, different receptors and Alternative 1 with 8.0 m pile diameter, 4,000 kJ Blow Energy and 3,434 blows.*

Receptor	weighting	Deterrence distance [m]	Fleeing speed [m/s]	SEL_{cum}
High-frequency cetaceans	VHF	200	1.5	175
Phocid seals	PCW	200	1.5	196
Herring	No	200	1.04	222
Adult Cod	No	200	0.9	222
Juvenile Cod	No	200	0.38	226
Larves	No	200	0.0	243

Table 10. *The cumulative Sound Exposure Level for 750 m deterrence distance, different receptors and Alternative 1 with 8.0 m pile diameter, 4,000 kJ Blow Energy and 3,434 blows.*

Receptor	weighting	Deterrence distance [m]	Fleeing speed [m/s]	SEL_{cum}
High-frequency cetaceans	VHF	750	1.5	171
Phocid seals	PCW	750	1.5	190
Herring	No	750	1.04	206
Adult Cod	No	750	0.9	206
Juvenile Cod	No	750	0.38	210
Larves	No	750	0.0	218

Table 11. *The cumulative Sound Exposure Level for 200 m deterrence distance, different receptors and Alternative 2 with 7.0 m pile diameter, 3,500 kJ Blow Energy and 2,840 blows.*

Receptor	weighting	Deterrence distance [m]	Fleeing speed [m/s]	SEL_{cum}
High-frequency cetaceans	VHF	200	1.5	174
Phocid seals	PCW	200	1.5	195
Herring	No	200	1.04	221
Adult Cod	No	200	0.9	221
Juvenile Cod	No	200	0.38	225
Larves	No	200	0.0	241

Table 12. *The cumulative Sound Exposure Level for 750 m deterrence distance, different receptors and Alternative 2 with 7.0 m pile diameter, 3,500 kJ Blow Energy and 2,840 blows.*

Receptor	weighting	Deterrence distance [m]	Fleeing speed [m/s]	SEL_{cum}
High-frequency cetaceans	VHF	750	1.5	169
Phocid seals	PCW	750	1.5	189
Herring	No	750	1.04	204
Adult Cod	No	750	0.9	205
Juvenile Cod	No	750	0.38	208
Larves	No	750	0.0	216

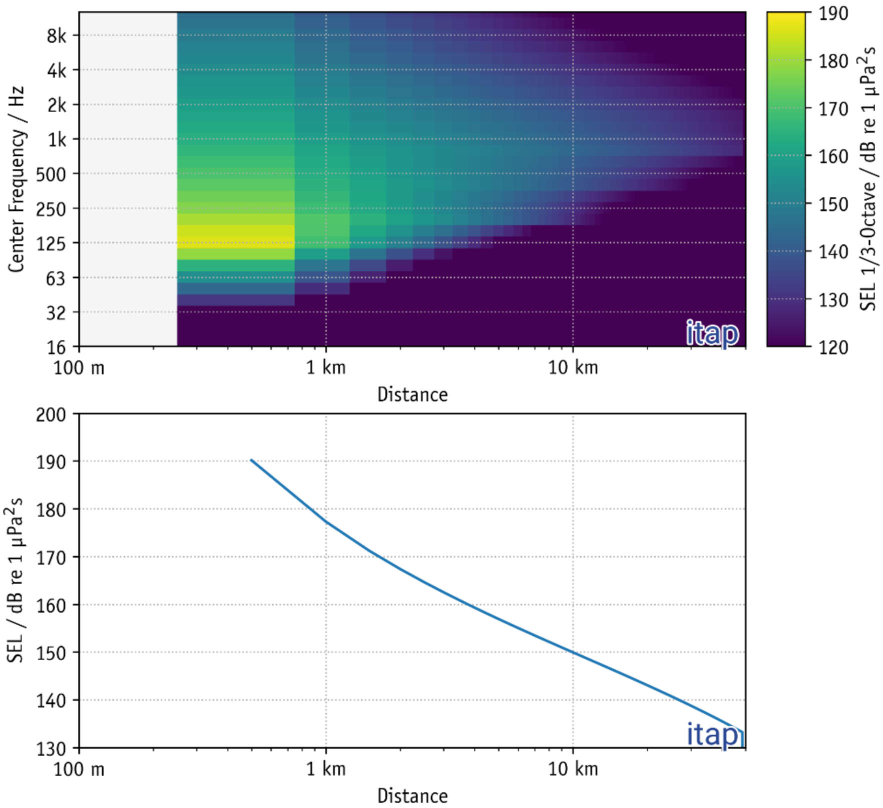


Figure 12: Predicted SEL (unweighted) of sounds due to driving monopiles with a diameter of 8.00 m at maximum blow energy of 4,000 kJ as function of distance for the location WTG06 (preferred project design) in 165° direction. The spectrogram on top shows the SEL divided in 1/3-octave components. On the y-axis the frequency is listed and on the x-axis the distance is shown. The value of the unweighted SEL 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 SEL.

For the threshold levels in chapter 4, the following impact ranges are expected in which these values are reached without noise mitigation (Table 13 to Table 18). In the noise map below (Figure 13) these threshold levels are given as contour lines for location WTG06 (preferred project design) as an example.

Marine Mammals:

Table 13: *Distances to thresholds for marine mammals for the preferred project design WTG06.*

Receptor	Impact type	metric	Criteria [dB]	Fleeing speed [m/s]	Range [km] No NMS
High-frequency cetaceans	PTS	$SEL_{\mathrm{cum,\ VHF}}$	155	1.5	7.96
High-frequency cetaceans	TTS	$SEL_{\mathrm{cum,\ VHF}}$	140	1.5	33.49
High-frequency cetaceans	Avoidance	$SPL_{\mathrm{VHF,\ 125ms}}$	103	1.5	> 50 km
Phocid seals	PTS	$SEL_{\mathrm{cum,\ PCW}}$	185	1.5	1.66
Phocid seals	TTS	$SEL_{\mathrm{cum,\ PCW}}$	170	1.5	20.26

Table 14: *Distances to thresholds for marine mammals for alternative 1 WTG18.*

Receptor	Impact type	metric	Criteria [dB]	Fleeing speed [m/s]	Range [km] No NMS
High-frequency cetaceans	PTS	$SEL_{\mathrm{cum,\ VHF}}$	155	1.5	11.96
High-frequency cetaceans	TTS	$SEL_{\mathrm{cum,\ VHF}}$	140	1.5	48.86
High-frequency cetaceans	Avoidance	$SPL_{\mathrm{VHF,\ 125ms}}$	103	1.5	> 50 km
Phocid seals	PTS	$SEL_{\mathrm{cum,\ PCW}}$	185	1.5	2.55
Phocid seals	TTS	$SEL_{\mathrm{cum,\ PCW}}$	170	1.5	29.55

Table 15: *Distances to thresholds for marine mammals for alternative 2 WTG20.*

Receptor	Impact type	metric	Criteria [dB]	Fleeing speed [m/s]	Range [km] No NMS
High-frequency cetaceans	PTS	$SEL_{\mathrm{cum,\ VHF}}$	155	1.5	9.64
High-frequency cetaceans	TTS	$SEL_{\mathrm{cum,\ VHF}}$	140	1.5	45.89
High-frequency cetaceans	Avoidance	$SPL_{\mathrm{VHF,\ 125ms}}$	103	1.5	> 50 km
Phocid seals	PTS	$SEL_{\mathrm{cum,\ PCW}}$	185	1.5	1.85
Phocid seals	TTS	$SEL_{\mathrm{cum,\ PCW}}$	170	1.5	25.02

Fish:

Table 16: *Distances to thresholds for fish for the preferred project design WTG06.*

Receptor	Impact type	metric	Criteria [dB]	Fleeing speed [m/s]	Range [km] No NMS
adult Cod	Mortal injury	SEL_{cum}	204	0.9	0.77
adult Cod	recoverabel injury	SEL_{cum}	203	0.9	0.84
adult Cod	TTS	SEL_{cum}	185	0.9	7.71
juvenile Cod	Mortal injury	SEL_{cum}	204	0.38	1.06
juvenile Cod	recoverabel injury	SEL_{cum}	203	0.38	1.17
juvenile Cod	TTS	SEL_{cum}	185	0.38	9.09
Herring	Mortal injury	SEL_{cum}	204	1.04	0.73
Herring	recoverabel injury	SEL_{cum}	203	1.04	0.80
Herring	TTS	SEL_{cum}	185	1.04	7.39
larves	Mortal injury	SEL_{cum}	207	0	1.45

Table 17: *Distances to thresholds for fish for alternative 1 WTG18.*

Receptor	Impact type	metric	Criteria [dB]	Fleeing speed [m/s]	Range [km] No NMS
adult Cod	Mortal injury	SEL_{cum}	204	0.9	1.01
adult Cod	recoverabel injury	SEL_{cum}	203	0.9	1.15
adult Cod	TTS	SEL_{cum}	185	0.9	12.30
juvenile Cod	Mortal injury	SEL_{cum}	204	0.38	1.52
juvenile Cod	recoverabel injury	SEL_{cum}	203	0.38	1.72
juvenile Cod	TTS	SEL_{cum}	185	0.38	13.81
Herring	Mortal injury	SEL_{cum}	204	1.04	0.93
Herring	recoverabel injury	SEL_{cum}	203	1.04	1.06
Herring	TTS	SEL_{cum}	185	1.04	11.94
larves	Mortal injury	SEL_{cum}	207	0	1.87

Table 18: *Distances to thresholds for fish for WTG20 Alternative 2.*

Receptor	**Impact type**	**metric**	**Criteria [dB]**	**Fleeing speed [m/s]**	**Range [km]** No NMS
adult Cod	Mortal injury	SEL_{cum}	204	0.9	0.85
adult Cod	recoverabel injury	SEL_{cum}	203	0.9	0.97
adult Cod	TTS	SEL_{cum}	185	0.9	10.09
juvenile Cod	Mortal injury	SEL_{cum}	204	0.38	1.28
juvenile Cod	recoverabel injury	SEL_{cum}	203	0.38	1.44
juvenile Cod	TTS	SEL_{cum}	185	0.38	11.33
Herring	Mortal injury	SEL_{cum}	204	1.04	0.79
Herring	recoverabel injury	SEL_{cum}	203	1.04	0.90
Herring	TTS	SEL_{cum}	185	1.04	9.79
larves	Mortal injury	SEL_{cum}	207	0	1.57

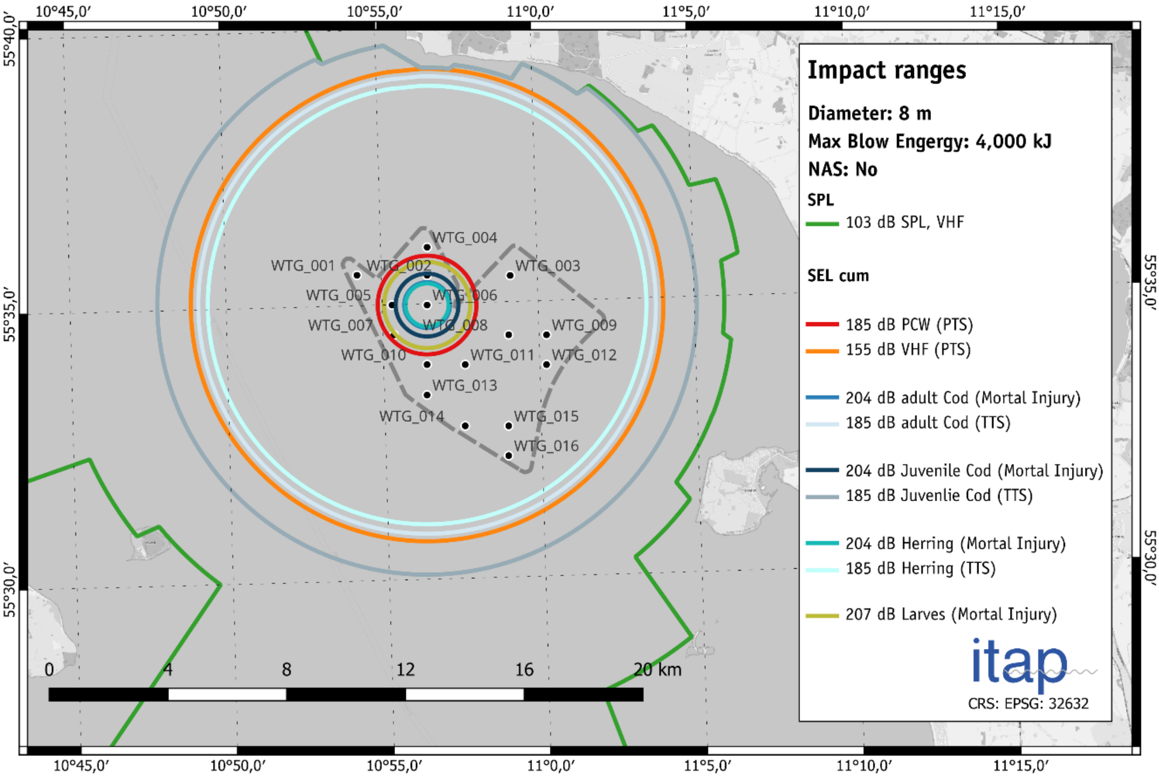


Figure 13: Impact ranges during the installation of the 8.00 m monopile foundation at WTG06 (preferred project design) with a maximum blow energy of 4,000 kJ and a piling sequence of 3,424 blows without noise abatement system (unmitigated – no NAS). The transmission loss estimated for 165° direction (Annex 1) used for all directions and water depths > 5 m.

8. Noise Mitigation

8.1 In general

In general, noise mitigation can be achieved by applying

- Noise Mitigation Systems, means to reduce the sound source level, like new hammer technologies,
- Noise Abatement Systems (NAS), means to reduce/damp the pile-driving noise in the water.

A general overview of Noise Mitigation Systems, technical Noise Abatement Systems and possible alternative low-noise foundation structures and -procedures was published on behalf of the German Federal Agency for Nature Conservation (BfN) for the first time in 2011 (Koschinski and Lüdemann 2011). In the following years, this study was updated twice (Koschinski and Lüdemann 2013). In Verfuss, Sinclair and Sparling (2019), a general overview of technical NAS is also given on behalf of the Scottish Natural Heritage. In this study, the effectiveness of each single Noise Abatement System and the expected costs of application are assessed by questionnaires. In (Bellmann, et al. 2020), an overview of the achieved overall noise reductions with Noise Mitigation Systems and Noise Abatement Systems within German waters is summarized.

However, in the following subsections, the Noise Abatement System BBC will be described.

8.2 Noise Abatement System (NAS)

8.2.1 Big Bubble Curtain (BBC)

The only far-from-pile Noise Abatement System is the single or double Big Bubble Curtain (BBC resp. DBBC). This system is currently available on the market from several suppliers and was already applied as a single and/or double Big Bubble Curtain in serial use in already completed OWF construction projects in the North- and Baltic Sea.

With a bubble curtain, a wall of air shall be created, which envelopes the foundation structure incl. the pile to be driven into the seabed. The aim is to generate an acoustic impedance gap in the water in order to reduce the sound propagation. In general, sound will partly be reflected, absorbed and transmitted at an impedance gap.

The higher the impedance, the smaller the transmitted percentage of sound energy. The acoustic impedance can be calculated with Equation 2. Air has a higher density (approx. 1,300 kg/m^3 in air and 1,000 kg/m^3 in water) as well as a lower sound velocity (approx. 330 m/s in air and 1,500 m/s in water) and like this a higher impedance and is thus well suited to disturb the sound propagation in water. In the best case, the curtain entirely consists of air. This is only a theoretical assumption; in reality, the curtain consists of a water-air-mixture and the impedance is somewhere between the impedance of water and air.

Additionally, the amount of noise reduction achieved also slightly depends on the BBC-diameter. The larger the diameter of the BBC, the higher the resulting noise reduction.

However, the resultant over noise reduction of a Big Bubble Curtain significantly depends on the frequency as well as on the current in the water.

The experiences regarding the technical application of the Big Bubble Curtain (BBC) is summarized in Bellmann *et al.* (2020). The main issues will be summarized in this chapter: The Big Bubble Curtain consists of perforated nozzle hoses, including non-perforated supply air hoses, compressors for generating compressed air and a supply vessel with devices (winches and air distribution system) for the deployment and the recovery of the nozzle hoses and the supply air hoses as well as for the storing and operation of the necessary compressors. Moreover, the nozzle hoses are provided with a deployed ballasting, so that due to the downforce of the ballasting, the nozzle hoses remain firmly on the seabed also during operation. By means of the supply vessel, the nozzle hose(s) is/are deployed on the seabed and connected to the compressors for the air supply via supply air hoses. Due to the pressure differences inside and outside the nozzle hoses, the air exits through air outlets and the air rises to the water surface. The static water pressure is crucial for the size of single air bubbles. With increasing water depth, the static pressure in the water rises, so that the defined supplied air volume decreases. The size and shape of the air bubbles can only be influenced to a very limited extent by the air outlets (holes) in the nozzle hose. Usually, different sizes and shapes of air bubbles form within the water column. The average ascent speed of the air bubbles is approx. 0.3 m/s (average value over all bubble sizes), whereby bigger and smaller air bubbles can also have ascent speeds between 0.2 m/s and 0.8 m/s (Nehls and Bellmann 2015). Usually, the ascent speed steadily increases with the size of the air bubbles. During the ascent to the water surface, the air bubbles are exposed to the prevailing current and are drifted away in current direction. Up to a flow velocity of up to 0.75 m/s (corresponds to approx. 1.5 kn), this drift can mostly be compensated by an elliptical deployment form of the nozzle hoses in current direction.

The development under offshore conditions and the further optimization of the Big Bubble Curtain were supported by two funded research projects[3] in the German EEZ of the North Sea (Diederichs, et al. 2014) and (Nehls and Bellmann 2015).

This Noise Abatement System is the most frequently used with several hundred applications in water depths of a few meters in coastal areas up to 41 m water depth. The BBC-system was applied for all foundation constructions so far, i. e. for monopiles, Jacket constructions, Tripods and Tripiles. There is also experience in other countries with Bubble Curtain systems in coastal areas and rivers (nearshore).

Independent of this, Big Bubble Curtains were already successfully applied in Europe during detonations of ammunition dumpsites (UXO clearance) in up to 70 m water depth in the North- and Baltic Sea. However, in most cases, no underwater noise measurements were carried out to evaluate the applied Big Bubble Curtain.

The Big Bubble Curtain in a project-specifically adapted, technical design (optimized system configuration) is able to reduce high frequencies very effectively. On the other hand, the reduction potential at low frequencies decreases steadily.

When used under offshore conditions, the following advantages of the Big Bubble Curtain became apparent:

- independent deployment of the nozzle hoses from the installation vessel by a variable deployment procedure[4],
- supplied air volume can be varied by the number and type of compressors used (air-water-mixture),
- the Noise Abatement System is independent of the foundation type and the installation vessel,
- applicable in different water depths,
- due to reliable noise reduction in higher frequencies, a high biologic relevance for key mammal species like high-frequency (hf) cetaceans is shown.

[3] www.hydroschall.de. Research project Hydroschall-OFF BW (2011-2012). FKZ 325309 supported by PtJ and BMU; further development Big Bubble Curtain (2013 – 2015). FKZ 325645 supported by PtJ and BMWi.

[4] The required nozzle hoses can be deployed on the seabed prior to the arrival of the installation vessel (pre-laying procedure) or only after the installation vessel is in position for the next foundation set-up (post-laying procedure). In the case of floating installation vessels with several anchor for the positioning, a pre-laying procedure is suitable. According to the size and deployment form, the pre-laying procedure is also partly applied with lifting platforms.

However, experience from previous OWF construction projects shows the following limitations:

- additional vessel capacity is necessary for the deployment and the operation of the Bubble Curtain,
- the proof of functionality of the different components of the Bubble Curtain must always be provided by means of harbor- and offshore tests before starting the installation,
- the components (compressors, nozzle hoses) must always be project-specifically configured to ensure a good balance between noise reduction and environmental protection,
- the noise reduction can be directional, depending on the sea area and prevailing currents.

Based on the available data of the research projects and the measurement data from different offshore construction projects, technical and physical minimum requirements for the application of an optimized single and double Big Bubble Curtain could be derived to achieve a maximum noise reduction in water depths up to 41 m during impulse pile-driving works (Bellmann, et al. 2020). These minimum requirements were again significantly extended in the course of the construction projects in the years 2016 to 2019 in Germany, based on practical experience (MarinEARS[5]).

In the following, all information regarding the system configuration used and the noise reduction achieved is presented anonymously from the OWF construction project and the BBC supplier(s). In case of non-compliance with these technical and physical minimum requirements, it could be shown for completed construction projects in the offshore range, that the noise reduction decreases considerably and in the worst case, no noise reduction happens (Bellmann, et al. 2020).

The noise reduction to be achieved essentially depends on the following factors:

(i) used air volume (air-water-mixture),

(ii) hole size and hole spacing,

(iii) and in the case of a double Big Bubble Curtain, the distance between the two nozzle hoses deployed on the seabed (depending on the current and the water depth),

[5] MarinEARS – Marine Explorer and Registry of Sound; specialist information system for underwater noise and national noise-register for the notification of impulsive noise events in the German EEZ of the North- and Baltic Sea of the EU according to the MSFD (https://marinears.bsh.de).

(iv) water depth resp. statistic counter-pressure (air-water-mixture),

(v) prevailing current[6].

There is a correlation between the introduced air volume and the achieved noise reduction. The impedance difference between water and air-water-mixture is decisive for the noise-reducing effect of a Bubble Curtain in the acoustic far-field. Moreover, in a research project[3], a half-empiric, hydrodynamic Bubble Curtain model was developed and tested. Thus, the system configuration of a Bubble Curtain can be optimized in advance for an appropriate construction project ((Nehls and Bellmann 2015); (Bellmann, et al. 2020)).

Based on calculations, measurement data and experiences with the handling from the practice of more than 1,200 pile installations, the following requirements to the technical realization of a Big Bubble Curtain must be fulfilled, so that an optimal and direction-independent noise reduction can be achieved:

- hole size (diameter) and hole spacing: 1 – 2 mm, every 20 – 30 cm,
- used air volume: $\geq 0.5\ m^3/(min \cdot m)$,
- regular maintenance of the used nozzle hoses
  (i. e. check of the available hole openings in the nozzle hose; if necessary, re-drilling or cleaning of holes),
- no turbulence-creating obstacles in the nozzle hoses, such as ballast chains, sand, etc.,
- distance of the nozzle hoses:
  - minimum distance between Bubble Curtain and pile-driving construction site of 30 m to 40 m; this information refers to the distance from the source to the BBC at the water surface; due to currents and signs of drift, the distance on the seabed must project-specifically be determined and is usually larger,
  - minimum distance between inside and outside nozzle hose for a double Big Bubble Curtain corresponds at least to the water depth at the application site; this information is strongly dependent on the current.

[6] According to the state-of-the-art, an optimized Big Bubble Curtain up to a current of approx. 1 kn (corresponds to approx. 0.75 m/s) can be used without any problems. Larger currents have a negative effect on the noise reduction in current direction.

- Nozzle hose length:
  - the minimum nozzle hose length of a single, closed nozzle hose (e. g. inner ring at a DBBC) usually is $\geq$ 600 m in case of a double-sided air supply,
  - the maximum nozzle hose length of a single, closed nozzle hose (e. g. outer ring at a DBBC) is $\leq$ 1.000 m in case of a double-sided air supply,
  - the total length of a DBBC is $\leq$ 1.750 m.
- The lifetime of the nozzle hoses to be applied is limited. Based on the experiences, however, a nozzle hose can be applied up to 100 times, if appropriate maintenance work and visual inspections are carried out regularly. If a nozzle hose is used too frequently, material fatigue can occur due to the high mechanical stress[7].
- In a research project, pressure sensors inside the nozzle hose were developed and installed (Nehls and Bellmann 2015). It was shown, that with increasing distance to the air injection points, the internal pressure in the nozzle hose decreases as expected. There must be at least an overpressure of 2 – 3 bar in contrast to the static water pressure at each air outlet of the nozzle hose to ensure a uniform and optimum air outlet, so that the resulting noise reduction is as equal as possible in all directions. In addition, pressure losses have already been observed between the compressors on board the BBC supply vessel and the air injection points located on the seabed. For a water depth of up to 40 m, an operating pressure of 9 bar to 10 bar of the compressed air per compressor on board the BBC supply vessel is usually sufficient.
- According to the current state-of-the-art, the nozzle hose diameter is 100 mm. The ballasting must be attached to the nozzle hose from the outside (not inside). At present, tests are also being carried out with larger diameters, in order to be able to increase the air volume considerably. This has led to considerable problems with the ballasting in test applications so far, which have not yet been completely solved.
- The operating conditions of each single compressor must regularly be documented (the total compressed air volume (Free Air Delivery – FAD) for the Big Bubble Curtain must be calculated from the rotational speed and the operating pressure of each single compressor). Usually, the compressed air volume decreases slightly with the set

[7] A nozzle hose consists of several materials and layerings. Peeling of the inner rubber coating causes turbulences in the nozzle hose, which negatively affects the air flow within the nozzle hose.

operating pressure at the compressor, so that with increasing operating pressure, more compressors are required to ensure 0.5 $m^3/(min \cdot m)$.

- Currents $\leq$ 1.5 kn resp. approx. 0.75 m/s. In case of larger currents, the noise reduction in current direction significantly decreases due to drifting effects. The result is a direction-dependent noise reduction of the applied Bubble Curtain.
- Oil-free compressors (corresponds to an air quality of the class 0 of the international standard (ISO 8573-1 2010) and an application of fuel according to the EN590 for the compressors) should always be used to avoid a contamination of the water and the air.

It has been shown in practice that a Big Bubble Curtain can be a very effective, robust and offshore-suitable Noise Abatement System, but each Bubble Curtain must significantly be adapted to each construction project with regard to site-specific and technical-constructional characteristics, such as current, water depth, installation process, etc. Furthermore, it has been shown, that a Big Bubble Curtain must be intensively maintained several times especially at the beginning of a construction project, i. e. re-drilling of the nozzle hoses, until an optimized and omnidirectional noise reduction has been achieved. If the above mentioned minimum requirements or specifications are not met, the noise reduction decreases considerably and in the worst case, only a total noise reduction of a few decibels is achieved.

Achievable noise reduction

In the following table, the achieved noise reductions by a single and double Big Bubble Curtain in different water depths and with different air volumes are summarized. The prevailing current was always $\leq$ 0.75 m/s.

Table 19: *Achieved broadband noise reduction by an optimized single or double Big Bubble Curtain with different system configurations regarding the supplied air volume and in different water depths. Note: A non-optimized system configuration resulted in significantly lower noise reductions (source: Bellmann et al. (2020)).*

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

Table 19 shows, that with the same water depth and the same system configuration of the applied Big Bubble Curtain, the difference between an optimized single and double Big Bubble Curtain is approx. 3 dB. This would be accompanied by a halving of the noise intensity. Tests with a 3rd and 4th BBC ring led to increased logistical challenges regarding the availability of compressed air (number of compressors), nozzle hose lengths (partly nozzle hose lengths of >> 1,000 m), handling under real offshore conditions with two BBC supply vessels with hardly any appreciable increase (~ 1 dB) of the overall noise reduction.

It can also be seen from Table 19 that the resulting noise reduction by a Bubble Curtain with the same system configuration decreases steadily to larger water depths. This effect can at least partially be compensated by increasing the amount of air supplied.

The noise reductions shown in Table 19 are all based on the installation of monopiles in water depths of 20 to 40 m and at currents ≤ 0.75 m/s, i. e. with compensable drifting effects.

Influence of the applied air volume on the spectral insertion loss of a Big Bubble Curtain

Figure 14 shows for comparison the spectral insertion loss for an optimized single Big Bubble Curtain when using different air volumes. It is shown, that the spectral form of the insertion loss does not change significantly due to the amount of air volume supplied, but the higher the air volume, the higher the amplitude of the resulting transition.

The different decrease of the achieved noise reduction by a Big Bubble Curtain in Figure 14 at frequencies larger than 2 kHz does not result from the different supplied air volume, but is due to the influence of different signal-to-noise-ratios between the pile-driving noise and the permanent background noise. I. e., the permanent background noise in the OWF construction project limits the noise reduction in the high-frequency range.

The partially distinctive fine structure of the presented spectral transition loss is due to the fact, that the different air volumes were performed in several different OWF construction projects with different technical-constructive and site-specific framework conditions.

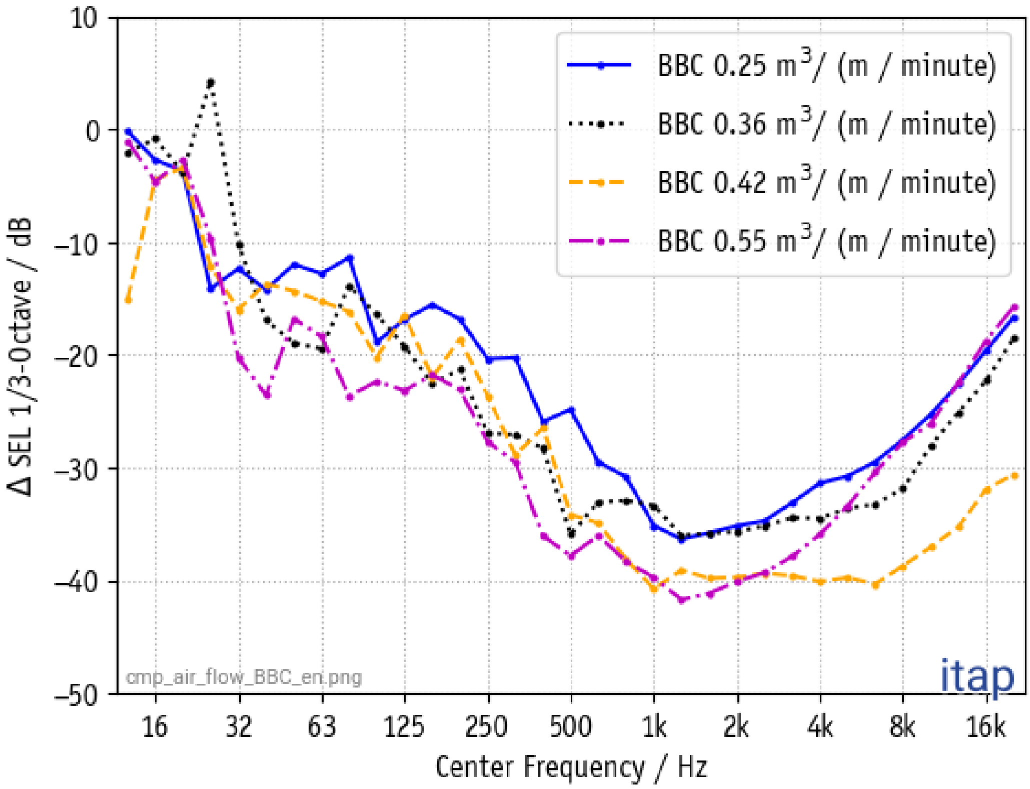


Figure 14: Resulting averaged noise reduction (transition loss) from the test measurements according to the (DIN 45653 2017) with a double Big Bubble Curtain (DBBC) with different supplied air volumes.

8.2.2 Modeled noise for the *Jammerland Bay Near Shore Wind Farm*

The piling noise during installation has impacts on marine mammals. In order to reduce the impact ranges the use of noise mitigation systems is recommended. One of the most practicable and most frequently used (> 600 applications) noise mitigation system is the double Big Bubble Curtain (DBBC). For illustrative purposes, a double Big Bubble Curtain (DBBC) with a total noise mitigation of 16 dB in 750 m distance for the Sound Exposure Level (SEL) and the 1/3 octave spectrum shown in Figure 11 has been considered. This leads to frequency weighted noise reduction of 59 dB_{VHF} for VHF and 22 dB for PCW in 750 m distance. Caused by the high transmission loss coefficients at low frequencies (Annex 1) an overestimation is expected for received single strike pulses in distances below 750 m within the considered piling sequences.

The comparison with the measured noise reductions in Table 19 shows that with the corresponding applied air volume (> 0.5 $m^3/(min \cdot m)$) higher attenuations are also possible in water depths up to 27 m.

Table 20 to Table 22 shows the cumulative Sound Exposure Level for 200 m deterrence distance. In Table 23 to Table 26, the resulting impact ranges for unmitigated and mitigated (DBBC) pile-driving noise are summarized. The noise maps below (Figure 15) show the expected impacted ranges for WTG06 (preferred project design) taking into account the influence of bathymetry.

Table 20. *Cumulative Sound Exposure Level for 200 m deterrence distance, different receptors and the preferred project design with 8.0 m pile diameter using a DBBC, 4,000 kJ Blow Energy and 3,434 blows.*

Receptor	weighting	Deterrence distance [m]	Fleeing speed [m/s]	SEL_{cum}
High-frequency cetaceans	VHF	200	1.5	138
Phocid seals	PCW	200	1.5	185
Herring	No	200	1.04	212
Adult Cod	No	200	0.9	213
Juvenile Cod	No	200	0.38	216
Larves	No	200	0.0	234

Table 21. *The cumulative Sound Exposure Level for 200 m deterrence distance, different receptors and Alternative 1 with 8.0 m pile diameter using a DBBC, 4,000 kJ Blow Energy and 3,434 blows.*

Receptor	weighting	Deterrence distance [m]	Fleeing speed [m/s]	SEL_{cum}
High-frequency cetaceans	VHF	200	1.5	135
Phocid seals	PCW	200	1.5	178
Herring	No	200	1.04	209
Adult Cod	No	200	0.9	209
Juvenile Cod	No	200	0.38	213
Larves	No	200	0.0	230

Table 22. *The cumulative Sound Exposure Level for 200 m deterrence distance, different receptors and Alternative 2 with 7.0 m pile diameter using a DBBC, 3,500 kJ Blow Energy and 2,840 blows.*

Receptor	weighting	Deterrence distance [m]	Fleeing speed [m/s]	SEL_{cum}
High-frequency cetaceans	VHF	200	1.5	134
Phocid seals	PCW	200	1.5	177
Herring	No	200	1.04	207
Adult Cod	No	200	0.9	208
Juvenile Cod	No	200	0.38	212
Larves	No	200	0.0	228

Marine Mammals:

Table 23: *Distances to thresholds for marine mammals for the preferred project design WTG06.*

Receptor	Impact type	metric	Criteria [dB]	Fleeing speed [m/s]	Range [km] No NMS	Range [km] DBBC
High-frequency cetaceans	PTS	$SEL_{\text{cum, VHF}}$	155	1.5	7.96	< 0.1
High-frequency cetaceans	TTS	$SEL_{\text{cum, VHF}}$	140	1.5	33.49	0.16
High-frequency cetaceans	Avoidance	$SPL_{\text{VHF, 125ms}}$	103	1.5	> 50 km	3.23
Phocid seals	PTS	$SEL_{\text{cum, PCW}}$	185	1.5	1.66	0.18
Phocid seals	TTS	$SEL_{\text{cum, PCW}}$	170	1.5	20.26	0.45

Table 24: *Distances to thresholds for marine mammals for alternative 1 WTG18.*

Receptor	Impact type	metric	Criteria [dB]	Fleeing speed [m/s]	Range [km] No NMS	Range [km] DBBC
High-frequency cetaceans	PTS	$SEL_{\text{cum, VHF}}$	155	1.5	11.96	< 0.1
High-frequency cetaceans	TTS	$SEL_{\text{cum, VHF}}$	140	1.5	48.86	< 0.1
High-frequency cetaceans	Avoidance	$SPL_{\text{VHF,125 ms}}$	103	1.5	> 50 km	3.96
Phocid seals	PTS	$SEL_{\text{cum, PCW}}$	185	1.5	2.55	< 0.1
Phocid seals	TTS	$SEL_{\text{cum, PCW}}$	170	1.5	29.55	0.40

Table 25: *Distances to thresholds for marine mammals for alternative 2 WTG20.*

Receptor	Impact type	metric	Criteria [dB]	Fleeing speed [m/s]	Range [km] No NMS	Range [km] DBBC
High-frequency cetaceans	PTS	$SEL_{\text{cum, VHF}}$	155	1.5	9.64	< 0.1
High-frequency cetaceans	TTS	$SEL_{\text{cum, VHF}}$	140	1.5	45.89	< 0.1
High-frequency cetaceans	Avoidance	$SPL_{\text{VHF, 125ms}}$	103	1.5	> 50 km	3.39
Phocid seals	PTS	$SEL_{\text{cum, PCW}}$	185	1.5	1.85	< 0.1
Phocid seals	TTS	$SEL_{\text{cum, PCW}}$	170	1.5	25.02	0.34

Fish:

Table 26: *Distances to thresholds for fish for the preferred project design and alternative 1 WTG06.*

Receptor	Impact type	metric	Criteria [dB]	Fleeing speed [m/s]	Range [km] No NMS	Range [km] DBBC
adult Cod	Mortal injury	SEL_{cum}	204	0.9	0.77	0.27
adult Cod	recoverabel injury	SEL_{cum}	203	0.9	0.84	0.28
adult Cod	TTS	SEL_{cum}	185	0.9	7.71	0.81
juvenile Cod	Mortal injury	SEL_{cum}	204	0.38	1.06	0.32
juvenile Cod	recoverabel injury	SEL_{cum}	203	0.38	1.17	0.34
juvenile Cod	TTS	SEL_{cum}	185	0.38	9.09	1.05
Herring	Mortal injury	SEL_{cum}	204	1.04	0.73	0.26
Herring	recoverabel injury	SEL_{cum}	203	1.04	0.80	0.27
Herring	TTS	SEL_{cum}	185	1.04	7.39	0.79
larves	Mortal injury	SEL_{cum}	207	0	1.45	0.56

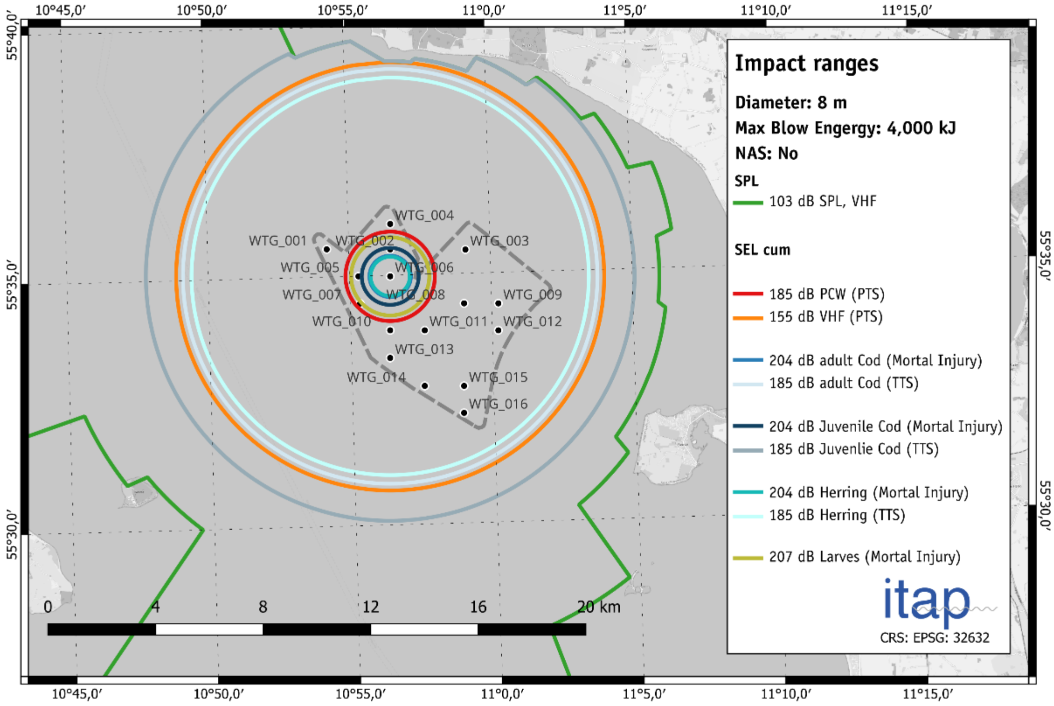
Fish:

Table 27: *Distances to thresholds for fish for alternative 1 WTG18.*

Receptor	Impact type	metric	Criteria [dB]	Fleeing speed [m/s]	Range [km] No NMS	Range [km] DBBC
adult Cod	Mortal injury	SEL_{cum}	204	0.9	1.01	0.13
adult Cod	recoverabel injury	SEL_{cum}	203	0.9	1.15	0.15
adult Cod	TTS	SEL_{cum}	185	0.9	12.30	1.09
juvenile Cod	Mortal injury	SEL_{cum}	204	0.38	1.52	0.20
juvenile Cod	recoverabel injury	SEL_{cum}	203	0.38	1.72	0.22
juvenile Cod	TTS	SEL_{cum}	185	0.38	13.81	1.55
Herring	Mortal injury	SEL_{cum}	204	1.04	0.93	0.12
Herring	recoverabel injury	SEL_{cum}	203	1.04	1.06	0.14
Herring	TTS	SEL_{cum}	185	1.04	11.94	1.02
larves	Mortal injury	SEL_{cum}	207	0	1.87	0.46

Table 28: *Distances to thresholds for fish for WTG20 Alternative 2.*

Receptor	**Impact type**	**metric**	**Criteria [dB]**	**Fleeing speed [m/s]**	**Range [km]** No NMS	**Range [km]** DBBC
adult Cod	Mortal injury	SEL_{cum}	204	0.9	0.85	0.12
adult Cod	recoverabel injury	SEL_{cum}	203	0.9	0.97	0.12
adult Cod	TTS	SEL_{cum}	185	0.9	10.09	0.95
juvenile Cod	Mortal injury	SEL_{cum}	204	0.38	1.28	0.17
juvenile Cod	recoverabel injury	SEL_{cum}	203	0.38	1.44	0.19
juvenile Cod	TTS	SEL_{cum}	185	0.38	11.33	1.36
Herring	Mortal injury	SEL_{cum}	204	1.04	0.79	0.11
Herring	recoverabel injury	SEL_{cum}	203	1.04	0.90	0.12
Herring	TTS	SEL_{cum}	185	1.04	9.79	0.89
larves	Mortal injury	SEL_{cum}	207	0	1.57	0.40



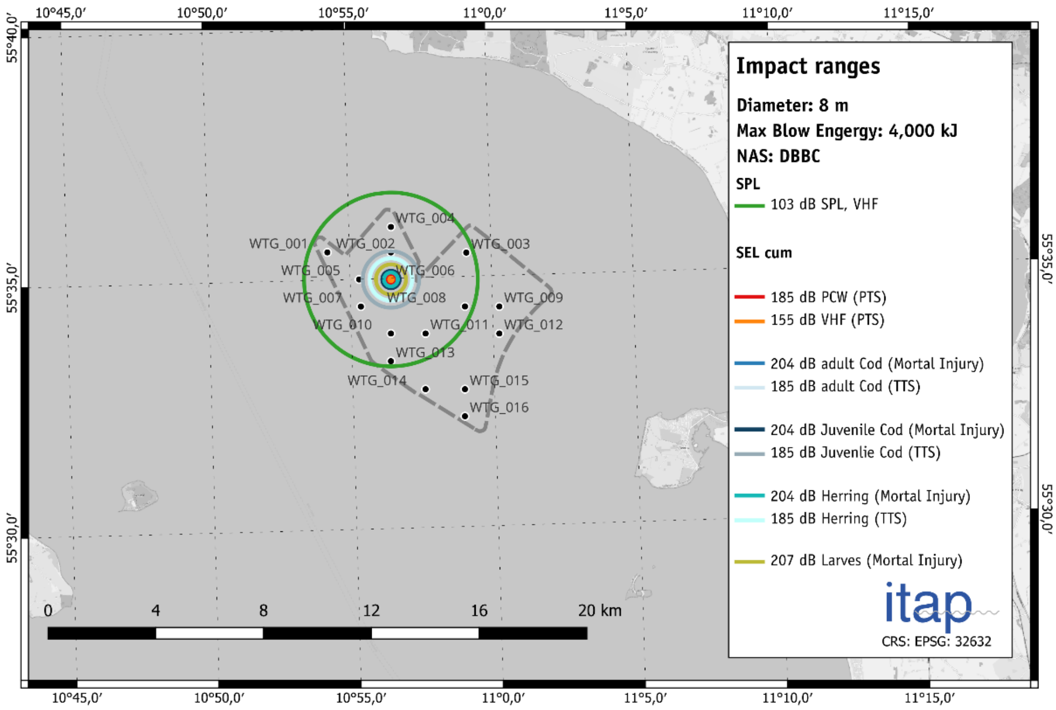


Figure 15: Impact ranges for during the installation of the 8.00 m monopile foundation at WTG6 (preferred project design) with a maximum blow energy of 4,000 kJ and a piling sequence of 3,424 blows. Top: without noise abatement system (unmitigated – no NAS). Bottom: mitigated with DBBC. The transmission loss estimated for 165° direction (Annex 1) used for all directions and water depths > 5 m.

9. References

Andersson, M. H., et al. "Underlag för reglering av undervattensljud vid pålning. Vindval rapport 6723." 8 2016.

Bellmann, Michael A., Jana Brinkmann, Adrian May, Torben Wendt, Stephan Gerlach, and Patrick Remmers. "Underwater noise during the impulse pile-driving procedure: Influencing factors on pile-driving noiseand technical possibilities to comply with noise mitigation values. Supported by the Federal Ministry for the Environment, Nature Conservation andNuclear Safety (Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (BMU)), FKZ UM16 881500. Commissioned and managed by the Federal Maritime and Hydrographic Agency (Bundesamt für Seeschifffahrt und Hydrographie (BSH)), Order No. 10036866. Edited by the itap GmbH." Tech. rep., itap GmbH, 2020.

BSH. "Measuring instruction for underwater sound monitoring – Current approach with annotations - Bundesamt für Seeschifffahrt und Hydrographie." 2011.

Collins, Michael D. "User's Guide for RAM Versions 1.0 and 1.0 p." *Naval Research Lab, Washington, DC* 20375 (1995): 14.

De Jong, C. A. F., M. A. Ainslie, and G. Blacquière. "Standard for measurement and monitoring of underwater noise, Part II: procedures for measuring underwater noise in connection with offshore wind farm licensing." *Report no TNO-DV C251*, 2011.

Diederichs, A., et al. "Entwicklung und Erprobung des „Großen Blasenschleiers zur Minderung der Hydroschallemissionen bei Offshore-Rammarbeiten (HYDROSCHALL OFF BW II), technischer Abschlussbericht." *Entwicklung und Erprobung des „Großen Blasenschleiers zur Minderung der Hydroschallemissionen bei Offshore-Rammarbeiten (HYDROSCHALL OFF BW II), technischer Abschlussbericht.* Förderkennzeichen 0325309 A/B/C, 2014.

DIN 17025. *DIN EN ISO/IEC 17025:2018-03, Allgemeine Anforderungen an die Kompetenz von Prüf- und Kalibrierlaboratorien (ISO/IEC 17025:2017); Deutsche und Englische Fassung EN/ISO/IEC 17025:2017.* Standard, Deutsches Institut für Normung, Beuth Verlag GmbH, 2018.

DIN 45653. *DIN SPEC 45653:2017-04, Hochseewindparks - In-situ-Ermittlung der Einfügungsdämpfung schallreduzierender Maßnahmen im Unterwasserbereich; Text Deutsch und Englisch.* Standard, Deutsches Institut für Normung, Beuth Verlag GmbH, 2017.

Energistyrelsen. "Guideline for underwater noise Installation of impact or vibratory driven piles." *Energistyrelsen, Center for Energiressourcer*, March 2022.

Gündert, S. "Empirische Prognosemodelle für Hydroschallimmissionen zum Schutz des Gehörs und der Gesundheit von Meeressäugern." *Masterarbeit an der Universität Oldenburg, Institut für Physik, AG Akustik*, 2014.

Gündert, S., S. van der Par, and M. Bellmann. "Empirische Modellierung zur Prädiktion von Hydroschallimmissionen bei Impulsrammung von Fundamenten für Offshore-Windenergieanlagen." 2014, 449-545.

ISO 18405. "ISO 18405:2017, Underwater acoustics — Terminology." Standard, International Organization for Standardization, Geneva, CH, 2017.

ISO 18406. "ISO 18406:2017, Underwater acoustics – Measurement of radiated underwater sound from percussive pile driving." Standard, International Organization for Standardization, Geneva, CH, 2017.

ISO 8573-1. "ISO 8573-1:2010, Druckluft – Teil 1: Verunreinigungen und Reinheitsklassen." Standard, International Organization for Standardization, Geneva, CH, 2010.

Jensen, Finn B., William A. Kuperman, Michael B. Porter, and Henrik Schmidt. *Computational ocean acoustics*. Springer Science & Business Media, 2011.

Koschinski, S., and K. Lüdemann. "Stand der Entwicklungen schallminimierender Maßnahmen beim Bau von Offshore-Windenergieanlagen, report on behalf of BfN." *Bonn, Germany*, 2011: 1–83.

Koschinski, Sven, and K. Lüdemann. "Development of noise mitigation measures in offshore wind farm construction." *Commissioned by the Federal Agency for Nature Conservation*, 2013: 1–102.

Nehls, G., and M. A. Bellmann. "Weiterentwicklung und Erprobung des „Großen Blasenschleiers“ zur Minderung der Hydroschallemissionen bei Offshore-Rammarbeiten. Gefördert durch PTJ und BMWi, FKZ 0325645A/B/C/D." Tech. rep., 2015.

Popper AN, Hawkins AD, Fay RR, Mann DA, Bartol S, Carlson TJ, Coombs S, Ellison WT,. *Sound Exposure Guidelines for Fishes and Sea Turtles.* ASA S3/SC1.4 TR-2014, SpringerBriefs in Oceanography, Acoustical Society of America, 2014.

Southall, Brandon L., et al. "Marine mammal noise exposure criteria: updated scientific recommendations for residual hearing effects." *Aquatic Mammals* 45 (2019).

Tougaard, Jakob, Andrew J. Wright, and Peter T. Madsen. "Cetacean noise criteria revisited in the light of proposed exposure limits for harbour porpoises." *Marine Pollution Bulletin* 90 (2015): 196-208.

Urick, R. J. *Principles of underwater sound.* 3. McGraw-Hill, Inc., 1983.

Verfuss, Ursula K., Rachael R. Sinclair, and Carol Sparling. "A review of noise abatement systems for offshore wind farm construction noise, and the potential for their application in Scottish waters (Report No. 1070)." Tech. rep., Scottish Natural Heritage, 2019.

10. Annex 1: Propergation and absorption coefficients

Table 29: Propergation and absorption coefficients for freqeuncy dependent Transmission loss based on water depth in 165° direction.

	WTG06		WTG18/20	
Frequency [Hz]	k	α	k	α
12,5	63,176	0,01364	63,176	0,01364
16	61,554	0,01308	61,554	0,01308
20	59,701	0,01245	59,701	0,01245
25	57,384	0,01166	57,384	0,01166
31,5	54,372	0,01064	54,372	0,01064
40	50,433	0,00929	50,433	0,00929
50	45,799	0,00771	45,799	0,00771
63	44,014	0,00878	39,774	0,00566
80	59,879	0,00348	31,897	0,00297
100	52,529	0,00295	29,367	0,00253
125	43,342	0,00229	26,205	0,00198
160	30,480	0,00136	21,778	0,00121
200	28,429	0,00112	20,762	0,00097
250	25,866	0,00081	19,492	0,00067
315	22,534	0,00041	17,841	0,00028
400	20,928	0,00032	16,971	0,00024
500	19,039	0,00023	15,946	0,00019
630	16,584	0,00011	14,615	0,00013
800	16,484	0,00010	14,655	0,00009
1000	16,367	0,00009	14,703	0,00005
1250	16,221	0,00008	14,763	0,00008
1600	16,356	0,00009	14,517	0,00009
2000	16,510	0,00010	14,237	0,00010
2500	16,703	0,00012	13,886	0,00012
3150	16,874	0,00015	13,873	0,00014
4000	17,098	0,00019	13,856	0,00018
5000	17,361	0,00023	13,836	0,00023
6300	16,828	0,00037	14,220	0,00020
8000	16,132	0,00055	14,722	0,00046
10000	15,314	0,00077	15,314	0,00077
12500	15,110	0,00098	15,110	0,00098
16000	14,826	0,00127	14,826	0,00127

20000	14,501	0,00160	14,501	0,00160
25000	14,389	0,00174	14,389	0,00174
32000	14,232	0,00194	14,232	0,00194
40000	14,052	0,00218	14,052	0,00218
50000	13,467	0,00343	13,467	0,00343
64000	12,647	0,00519	12,647	0,00519
80000	11,710	0,00720	11,710	0,00720
100000	11,514	0,00796	11,514	0,00796
125000	11,270	0,00891	11,270	0,00891

11. Annex 2: Water depth

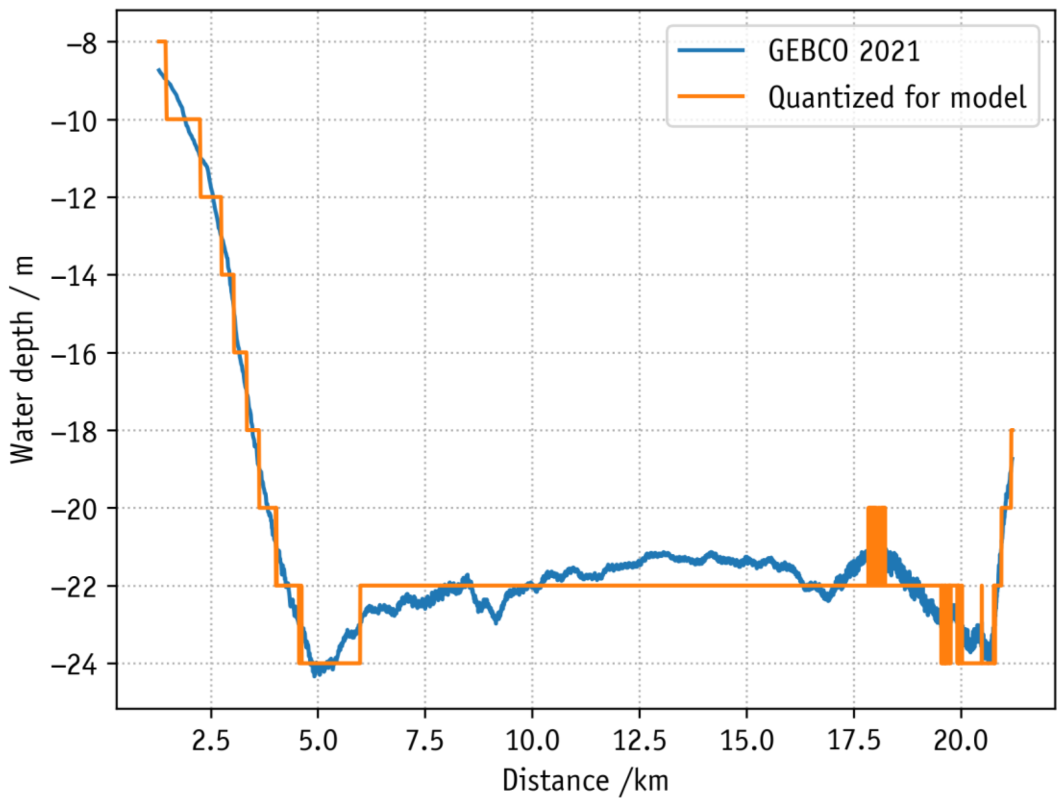


Figure 16: Waterdepth in 165° directions from WTG06 (preferred project design). Blue: Waterdepth according to GEBCO 2021 and orange: Quantized in 2 m steps used for modeling.

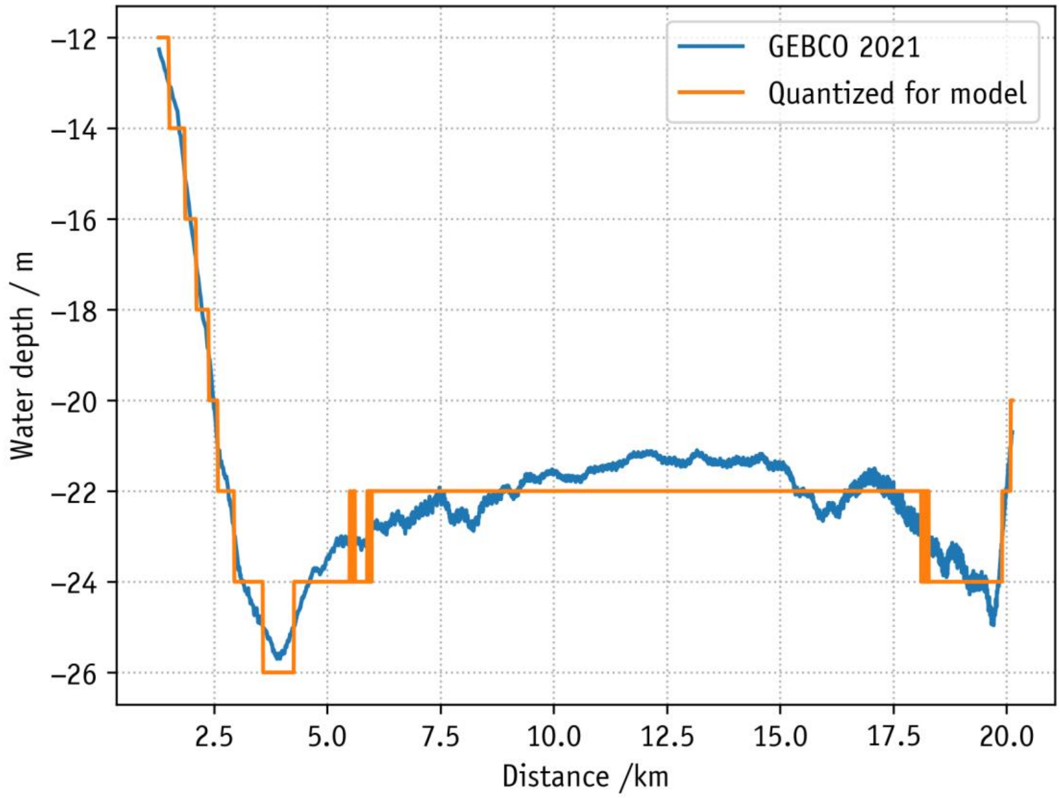


Figure 17: Waterdepth in 165° directions from WTG18/20 (Alternative 1 and 2). Blue: Waterdepth according to GEBCO 2021 and orange: Quantized in 2 m steps used for modeling.