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THOR OFFSHORE WIND FARM

UNDERWATER NOISE

INSTITUT FÜR TECHNISCHE UND ANGEWANDTE PHYSIK GMBH

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CONTENTS

Units:

μm/s - *micrometer per second*
μPa - *micropascal*
bar - *100 kPa*
cm - *centimeter*
dB - *decibel*
Hz - *hertz*
kHz - *kilohertz*
kJ - *kilojoule*
km - *kilometer*
kPa - *kilopascal*
m - *meter*
min - *minute*
mm - *millimeter*
MW - *megawatt*
Pa - *pascal*
s - *second*

Metrics:

TL - *transmission loss*
α - *absorption coefficient*
λ - *wave length*
ρ - *density of a medium*
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*
SEL_{cum} - *cumulative sound exposure level*
SPL - *continuous sound pressure level*
T - *averaging time*
Z - *acoustic charactaristic 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:

AdBm - *product name of a noise abatement system, word origin is not known.*
BFN - *Federal Agency for Nature Conservation*
BSH - *Bundesamt für Seeschifffahrt und Hydrographie* (engl. Federal Maritime and Hydrographic Agency
DBBC - *double big bubble curtain*
DP - *dynamic positioning*
EMODnet - *European Marine Observation and Data Network*
HP - *harbor porpoise*
HSD - *hydro sound damper*, *hydro sound damper*
IHC - *Industriële Handels Combinatie*
IIg - *zone classification according to Thiele & Schellstede*
NMS - *noise mitigation sreen*
OWF - *offshore wind farm*
PS - *phocid seal*
PTS - *permanent threshold shift*
SRD - *soil resistance value*
TTS - *temporary threshold shift*
WTG - *wind turbine generator*

1. SUMMARY

As part of the Energy Agreement of 2018 all political parties in the Danish Parliament decided to build three new offshore windfarms in Denmark before 2030. The first windfarm will be the Thor offshore windfarm (OWF) in the North Sea west of Nissum Fjord, min. 20 km from the shore of Jutland.

The construction of the offshore wind farm involves activities that produce underwater noise. Installation of monopiles into the seabed by means of impact pile driving is regarded the most significant noise source with the potential to harm marine mammals and fish in the area. The *itap – Institute for Technical and Applied Physics GmbH* was commissioned to carry out modelling of underwater noise produced during construction of the offshore wind farm.

Modelling scenarios, including pile diameter, hammer type and turbine locations, were defined to reflect the actual project to the highest extent possible, with the objective to determine expected noise levels, allowing for accurate impact assessment of the piling activities. Modelling included both cumulative and single strike sound exposure levels as well as zero-to-peak sound pressure levels. A comparison with various criteria from the literature leads to the following impact ranges.

Table 1: **Distances to criteria level without any noise mitigation measures.**

Receptor	Impact type (Reference)	metric	fleeing speed [m/s]	Criteria [dB]	Range [km]
HP	PTS (Tougaard & Michaelsen 2018)	SEL_{cum}	1,5	190	16.017
HP	TTS (Tougaard & Michaelsen 2018)	SEL_{cum}	1,5	175	49.947
HP	Disturbance (Dähne *et al*. 2013)	SEL		140	48.183
Seal	PTS (Skjellerup *et al*. 2015)	SEL_{cum}	1,5	200	2.953
Seal	TTS (Skjellerup *et al*. 2015)	SEL_{cum}	1,5	176	47.344
Seal	Disturbance (Russel *et al*. 2016)	SEL		142	43.303
fish	Mortal injury (Andersson *et al*. 2016)	SEL_{cum}	0	204	5.868
fish	Mortal injury (Andersson *et al*. 2016)	$L_{p,pk}$		207	0.371
fish	recoverable injury	SEL_{cum}	0	203	6.641
fish	TTS (Popper *et al*. 2014)	SEL_{cum}	0	185	34.378
larvae	Mortal injury (Andersson *et al*. 2016)	SEL_{cum}	0	207	3.975
larvae	Mortal injury (Andersson *et al*. 2016)	$L_{p,pk}$		217	0.079

2. INTRODUCTION

As part of the Energy Agreement of 2018 all political parties in the Danish Parliament decided to build three new offshore windfarms in Denmark before 2030. The first windfarm will be the Thor offshore windfarm (OWF) in the North Sea west of Nissum Fjord, min. 20 km from the shore of Jutland.

The construction of the offshore wind farm involves activities that produce underwater noise. Installation of monopiles into the seabed by means of impact pile driving is regarded the most significant noise source with the potential to harm marine mammals and fish in the area. The *itap – Institute for Technical and Applied Physics GmbH* was commissioned to carry out modelling of underwater noise produced during construction of the offshore wind farm.

3. OBJECTIVES

The objective of the report is to use available knowledge about underwater sound propagation to determine the expected sound exposure into the North Sea as a result of pile driving operations during the construction of the Thor offshore wind farm. Modelling will be based on the design for the actual project where available, while a worst case assumption will be applied for currently unspecified input. Modelling includes the determination of impact ranges where significant impact on fish and marine mammals can occur and will be used in the environmental impact assessment.

4. PROJECT DESCRIPTION

The Thor offshore wind farm is located in the Danish North Sea west of Nissum Fjord at least 20 km off the coast of Jutland (Denmark) (Figure 1). The water depth in the project area is between 24 m and 32 m (EMODnet). At the current planning stage, there are several possible configurations with regard to the total capacity of the wind farm, the number of turbines and the capacity of each individual turbine. The several configurations lead to total capacities of 800 MW or 1,000 MW. For the wind turbine generator (WTG) different designs are also possible with capacities between 8 MW and 15 MW. The 8 MW WTG will be installed on monopile foundations with a maximum outer diameter of 10 m and for the 15 MW WTG monopiles with max. 13 m in diameter. Both types of WTG are possible for both total capacity options. Table 2 shows potential configuration examples of the Thor offshore wind farm.

Table 2: **Possible OWF configurations.**

800 MW OWF		**1,000 MW OWF**	
8 MW WTG	15 MW WTG	8 MW WTG	15 MW WTG
100 turbines	54 turbines	125 turbines	67 turbines

For the acoustic modelling of the OWF configuration with 8 MW or 15 MW WTGs, 4 representative possible locations at the windfarm corners and 1 at the center (see Figure 1) were chosen. The monopile foundations consist of a single, very large diameter steel pile that is driven into the seabed by an impact hammer. The larger the monopile, the more force is required to drive it into the seabed, and thus the higher the source level from the hammer blows.

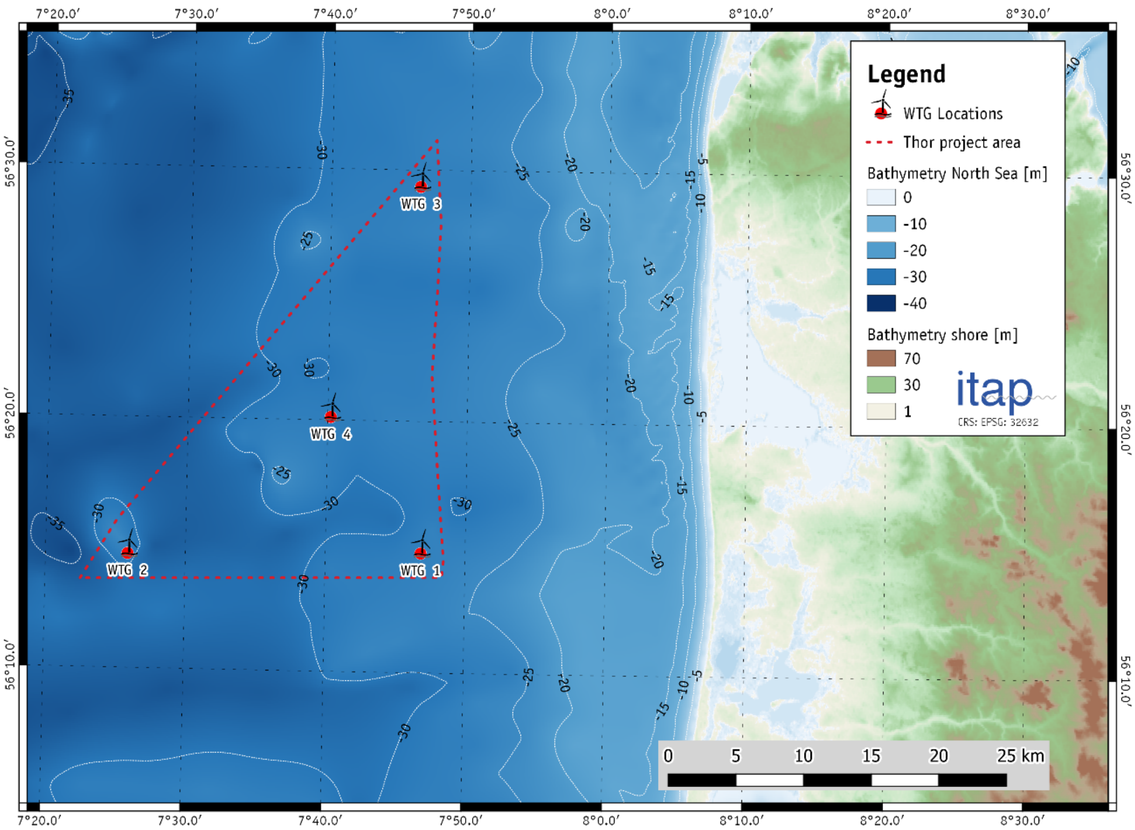

Figure 1: **Location of the Thor offshore wind farm and bathymetry (provided by EMODDnet).**

According to the current state of planning, no decision has yet been made as to which hydro hammer will be used in the construction work. For the modelling it is assumed to install the 13 m monopiles with an IHC S-4000 hydro hammer with a helmet weight of 3,000 kJ. For the underwater noise modelling, a piling sequence of 9,122 blows is assumed, considering a 81 minutes long ramp up interval to get to the maximum hammer energy (Figure 2 and Table 7 in Annex). The assumed piling sequence represent a realistic scenario as the detailed installation sequence is not known at this time. During actual installation the blow frequency will likely be considerably lower especially during the initial part of the installation (in comparison with real pile driving on similar ground (unpublished data by itap)).

Within the Thor project area, the uppermost surface layer of the sediment consists of a mix of sand, gravel and clay. The sediment of can have effects on the expected noise level (see chapter 6.4.3).

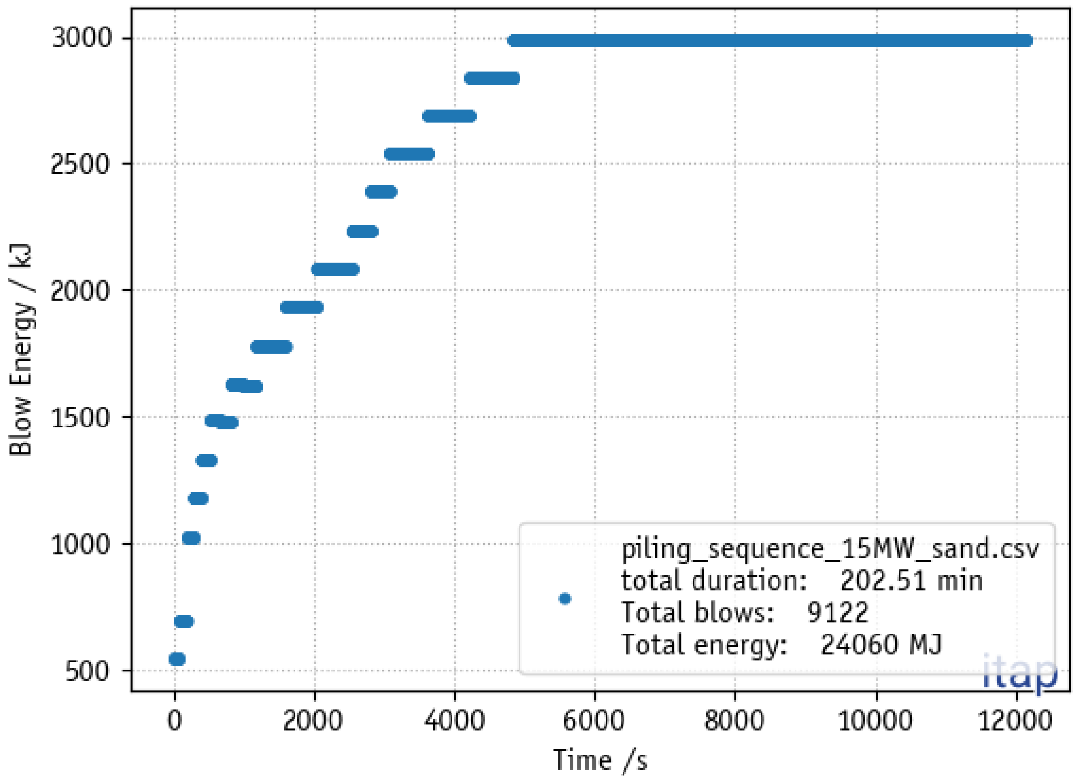

Figure 2: **Pilling sequence used for modeling.**

5. 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 level of 120 dB re 1 µPa; see chapter 3.1), a particle velocity in water of appr. 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, however:

- (energy-) equivalent continuous sound pressure level – SPL ,
- single strike sound exposure level – SEL,
- cumulative sound exposure level - SEL_{cum}
- zero-to-peak sound pressure level $L_{p,pk}$.

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.

[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 sound, values of ≥ 5λ can be found in literature.

(Energy-) equivalent continuous sound pressure level (SPL)
The SPL is the most common measurement in acoustics and is defined as:

$$SPL = 10\ \log_{10}\left(\frac{1}{T}\int_{0}^{T}\frac{p(t)^2}{p_0^2}\,dt\right)\ [\text{dB}]$$

Equation 3

with

$p(t)$ - time-variant sound pressure,
p_0 - reference sound pressure (in underwater sound 1 µPa),
T - averaging time.

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 the sound exposure level – SEL is more appropriate. Both values are defined as follows:

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

Equation 4

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

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:

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

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 sound (for instance > 10 dB), it can be calculated with a simplification of Equation 6 and a sufficient degree of accuracy as follows:

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

Equation 7

Cumulative sound exposure level (SEL_{cum})

A value for the noise dose is the cumulative sound exposure level (SEL_{cum}) and is defined as follows:

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

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,

This parameter is a measure for sound pressure peaks. Compared to sound pressure level (SPL) and sound exposure level (SEL), there is no average determination:

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

Equation 10

with

$|p_{pk}|$ - maximum determined sound pressure level.

An example is depicted in Figure 3. 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 definition of this parameter is given in Figure 3. This factor does not describe the maximum achieved (absolute) sound pressure level, but the difference between the negative and the positive amplitude of an impulse (Figure 3). This value is maximal 6 dB higher than the zero-to-peak sound pressure level $L_{p,pk}$,.

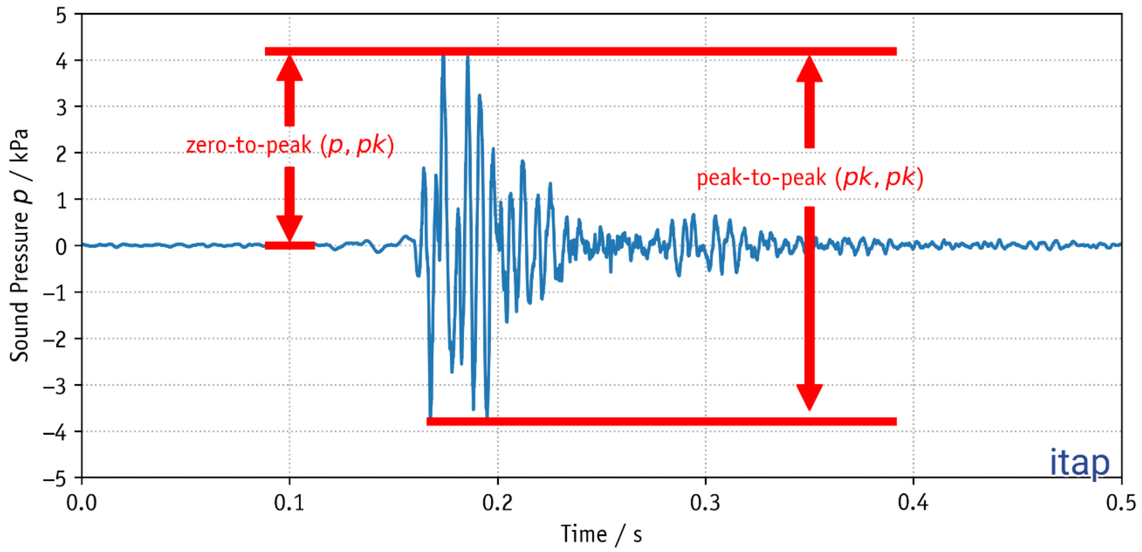

Figure 3: **Typical measured time signal of underwater sound due to pile-driving in a distance of several 100 m.**

6. MODEL APPROACHES

6.1 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 a pile-driver in a distance of 1 m. Often, this is called source level. Equation 11 is then reduced to $TL = -k \log_{10}(r)$. Additionally, it has to be considered, that the equation mentioned 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 sound pressure. This is considered with a constant α proportional to the distance. Equation 11 expands to:

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

Equation 12

For regions in the North Sea with water depths below 50 m the following Equation 13 leads to realistic results compared with noise measurements in different regions in the North Sea. The example in the „Guideline for underwater noise – Installation of impact-driven piles" (Danish Energy Agency, 2016) considered the same transmission loss.

$$TL = -14.72\ \log_{10}(r) + 0.00027\ r\ \text{[dB]}$$

Equation 13

Thiele and Schellstede (1980) specified frequency dependent approximation equations for the calculation of sound propagation in different regions of the North Sea as well as for "rough" and "smooth" sea. For the installation of the foundations, a "smooth" sea is required. So, the following equation for shallow water and smooth sea (IIg) will be compared with measurement results from different offshore wind farms in the North Sea in Figure 4:

$$TL = -(23 + 0.7\ F) \log_{10} r + (0.3 + 0.05\ F + 0.005\ F^2)\ r\ 10^{-3}\ \text{[dB]}$$

Equation 14

with

F = $10\ \log_{10}(f\ \text{[kHz]})$, with the frequency f [Hz]

r – distance [m].

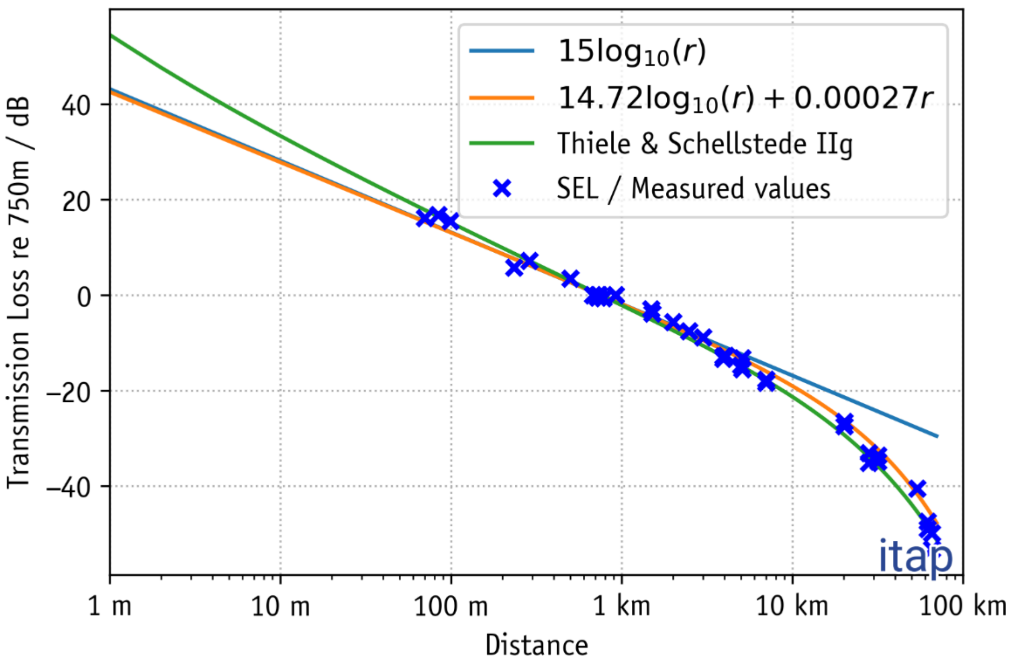

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Figure 4: **Different predicted transmission loss (TL) curves according to Equation 11 (15 $\log_{10}$ R), Equation 13 (14.72 $\log_{10}$ R + 0.00027 R)and the semi-empirical approach of Thiele und Schellstede IIg (1980) (Equation 14), compared with existing offshore measurement data. The measurement data comes from pile driving measurements from different offshore wind farms in the North Sea in Germany and the Netherlands. The water depth in all windfarms was below 50 m.**

Equation 13 and Equation 14 show a high similarity and a high correspondence with the measured values of the sound exposure level (SEL) during pile driving (see Figure 4) in different regions of the North Sea with comparable water depths. Only for distances less than 100 m, the equations differ from each other. So both equations, Equation 13 and Equation 14 are valid for the Thor project area. For modeling, Equation 13 is considered. The transmission loss will be considered omnidirectional (no differences for different directions were made). Site specific changes in bathymetry, especially towards the shore, will be considered by the frequency dependent impact of water depth as described below.

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

5. 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.,* 2010). Sound around the cut-off frequency (f_g) is reduced or damped to a larger extent with an increasing distance to the sound source than it is calculated with Equation 13.

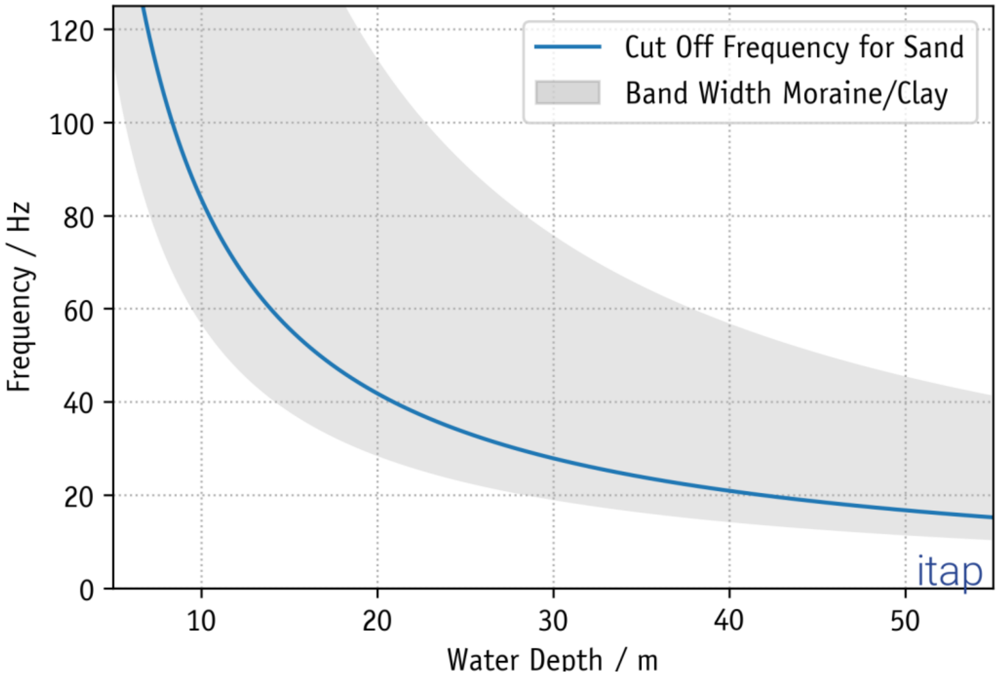


Figure 5: **Theoretical lower (limit) frequency (f_g) for an undisturbed sound propagation in water as a function of the water depth for different soil stratifications (example adapted from Urick, 1983; Jensen et al., 2010; the example shows the possible range caused by different layers, the layer does not correspond to the layers in the construction field).**

6.2 Threshold level

The emission of underwater noise during pile driving 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 or fish potentially leading to behavioral disturbance, temporary hearing damage (TTS, temporary threshold shift), permanent hearing damage (PTS, permanent threshold shift) or even physical injury (cf. Table 3).
To assess the impact from underwater noise on harbor porpoise (HP) phocid seal (PS) and fish, the threshold levels presented in Table 3 were modeled. For further details of the threshold levels, the reader is encouraged to consult the respective references provided in Table 3. Pertaining to threshold levels for auditory injury of marine mammals, only unweighted threshold levels are modeled.
For the harbor porpoises as well as the phocid seals a constant fleeing speed of 1.5 m/s is assumed (Tougaard & Michaelsen, 2018). Fish, however, cannot be assumed to flee from the piling location due to the noise. They are therefore considered to be stationary receivers.

Table 3: **Noise modelling threshold criteria. PTS: permanent threshold shift; TTS: temporary threshold shift.**

Receptor	Impact type	metric	Criteria [dB]	References
Harbor Porpoises (HP)	PTS	SEL_{cum}	190	Tougaard & Michaelsen 2018
	TTS	SEL_{cum}	175	Tougaard & Michaelsen 2018
	Disturbance	SEL	140	Dähne *et al*. 2013
Phocid Seal (PS)	PTS	SEL_{cum}	200	Skjellerup *et al*. 2015
	TTS	SEL_{cum}	176	Skjellerup *et al*. 2015
	Disturbance	SEL	142	Russel *et al*. 2016
fish	Mortal injury	SEL_{cum}	204	Andersson *et al*. 2016
		$L_{p,pk}$	207	Andersson *et al*. 2016
	TTS	SEL_{cum}	185	Popper *et al*. 2014
larvae	Mortal injury	SEL_{cum}	207	Andersson *et al*. 2016
		$L_{p,pk}$	217	Andersson *et al*. 2016

6.3 Model description

The (standard-) model of the *itap GmbH* is an empirical model, i. e., it is based on measured values for the sound exposure level (SEL) and for the zero-to-peak sound pressure level ($L_{p,pk}$) 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 e. g. 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 6 shows sound levels measured during pile-driving construction works at a number of windfarms 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 increase 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 6 that is probably due to further influencing factors, such as e. g. blow energy and reflecting pile skin 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 (not published data). Therefore, an application in the present case is possible from a practical point of view. So the model is likely to be conservative.

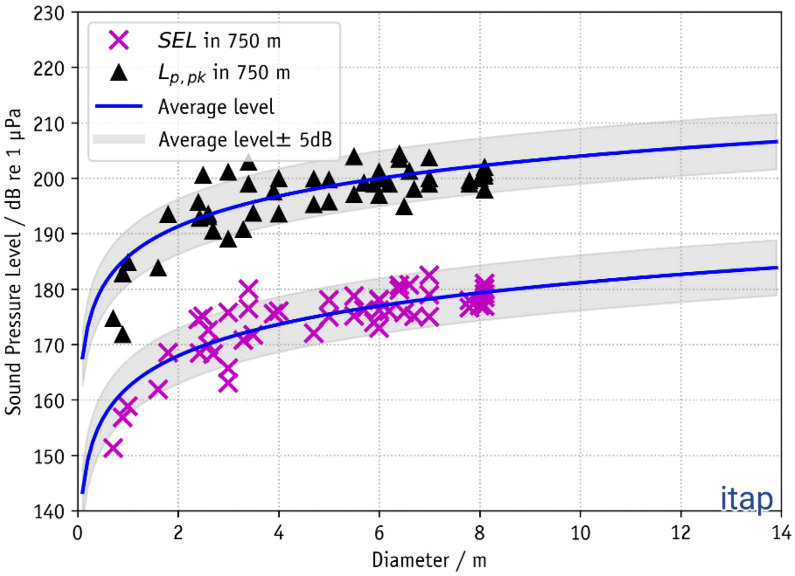


Figure 6: **Measured zero-to-peak sound pressure level ($L_{p,pk}$) and broad-band 5 % exceedance sound exposure levels (SEL_{05}) at pile-driving construction works at a number of OWFs as function of the pile diameter.**

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".

Within the scope of a master's thesis at the *itap GmbH*, it was established, that the impact of the blow energy used is on average about 2.5 dB per duplication of 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 influence the resulting sound pollution significantly with a significant correlation of penetration depth and blow energy used. 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.

6.4 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.

6.4.1 Blow energy

The evaluation-relevant level values (SEL and $L_{p,pk}$) increase with growing 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.

6.4.2 Hydro hammer

Currently, the influence of different hydro 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.

6.4.3 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 and the measurement data shown in chapter 6.3 Figure 6 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 6. For this reason, in the model, a frequency-independent safety margin for the soil conditions (ground coupling) is not necessary.

6.4.4 Spectrum of piling noise

The estimations of the broad-band sound exposure level (SEL)- and zero-to-peak sound pressure level ($L_{p,pk}$)-value shown in chapter 8.1 below are based on the broad-band measuring data of different studies (Figure 6). However, sound propagation in the sea is highly frequency-dependent; see chapter 6.1. For this reason, estimations of the frequency composition of the respective source levels[2] have to be made for the calculations.
Figure 7 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

[2] “Source level” means the sound exposure level (SEL) or zero-to-peak sound pressure level ($L_{p,}$) at a fictive distance 750 m to an imagined point source of sound.

different distances as well as at different blow energies and pile diameters run similarly. The frequency spectrum shows a maximum within the range 60-250 Hz. At frequencies above approx. 250 Hz the level decrease gradually, while for frequencies lower than approx. 60 Hz, a steep decrease in levels is observed. The cutoff frequency for the steeply fall off at low frequencies depends on water depth. The deeper the water, the lower the cutoff frequency. For the water depths in the project area between 20 m and 26 m, the cutoff frequency will be within 32 Hz and 42 Hz.

From measurements collected over the last two years, it has become apparent, that the pile 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 modelling, an idealized model spectrum for the sound exposure level will be extracted from the measured data of comparable construction projects. The shape of this idealized 1/3-octave-spectrum is shown in Figure 7 in red color. The frequency-dependent amplitudes are measured 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 zero-to-peak sound pressure level ($L_{p,pk}$).

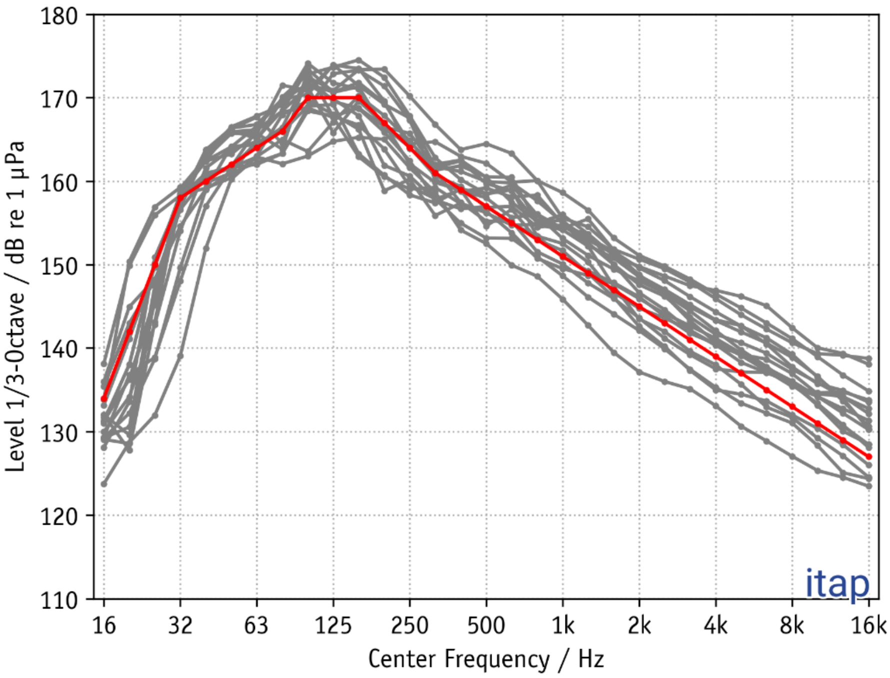


Figure 7: **The model spectrum (red) estimated for piling noise, based on different measuring data (grey: measuring data) for monopiles.**

6.4.5 Water depth

Sound propagation in the sea is also influenced by the water depth. Below a certain cut-off frequency, however, a continuous sound propagation is not possible. The shallower the water, the higher this frequency is. Figure 5 in chapter 6.1 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 used bathymetry data were provided from EMODnet. The water depth in the project area is between 24 m and 32 m. This results to cut-off frequencies of 35 Hz for 24 m and 26 Hz for 32 m.

6.4.6 Transmission loss

For modeling, Equation 13 is considered. Equation 13 shows a high level of agreement with the measurements in the North Sea and also takes account of the absorption in water. The impact of the absorption parameter α is increasing with the distance, so it becomes more relevant for larger distances. By modeling the transmission loss via such a propagation function, a plain wave in water is assumed. This is only the case for larger distance > water depth from the pile, when the directly emitted sound from the pile is superimposed with the first reflections from water surface and sediment. Below 50 m from the pile no plain wave field has formed within the water column, the noise level will be below the level calculated with Equation 13. In the model the noise level will be constant over the first 50 m from the pile.

6.4.7 Model requirements

The empirical pile-driving model fulfill the national guidelines from regulators in Germany (BSH, 2013) and Denmark (Danish Energy Agency, 2016) for pile-driving predictions including required outputs. International guidelines or standards do not exist today. Other nations do also not have 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, Netherlands, United Kingdom, Belgium, France, USA, Australia and Taiwan.

6.5 Calculation procedure

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

6.5.1 Step 1: zero-to-peak level and broad-band sound exposure level at 750 m

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 distance to the source after the requirements of the German measurement guidance (BSH, 2011) and the international standard (ISO 18406). The model results depend on the following parameter:

(i) the pile diameter,

(ii) the maximum blow energy (worst-case-scenario),

(iii) the water depth and

(iv) the safety margins for e. g. coupling effects, acoustic connections (coupling effects) between pile and Jacket-structure.

6.5.2 Step 2: frequency dependency of the source level and transmission loss

Estimations about the broad-band sound exposure level (SEL) and the zero-to-peak sound pressure level ($L_{p,}$) value are based on measured broad-band data from different studies. Sound propagation in the ocean, however, is frequency-dependent, as discussed in chapter 6.1.

The spectral approaches for the piling noise at 750 m will be determined from empirical data (see chapter 6.4.4) and an approach for the transmission loss (TL) will be considered. The selection of the spectral shape based on empirical data and the amplitude will be adapted to the predicted broad-band sound exposure level (SEL). The sound exposure level (SEL) is an energetic value, where the energy is distributed over different frequency windows. For a broad-band presentation, only one frequency window over the whole frequency domain is used. In contrast, the zero-to-peak sound pressure level ($L_{p,}$) represented the maximum sound pressure during one blow, which is independent of the frequency. So the $L_{p,}$ is only a single-number value.

6.5.3 Step 3: cumulative sound exposure level

The cumulative sound exposure level (SEL_{cum}) is a value for the noise dose, a marine mammal (e. g. a harbor porpoise) is exposed to. This value is the sum of the energy of all blows for one single foundation a marine mammal is exposed to within 24 hours (National Marine Fisheries Service, 2018), moving with a constant speed, increasing its distance with e. g. 1.5 m/s (Danish Energy Agency, 2016). In order to determine the impact ranges for fleeing receivers the cumulative sound exposure level (SEL_{cum}) will be calculated as a function over the start distance[3].
To predict the cumulative sound exposure level (SEL_{cum}), assumptions about the piling sequence have to be made. Therefore, the piling sequence in chapter 4 will be considered.

6.5.4 Step 4: impact ranges

For the threshold level listed in Table 3 chapter 6.2 impact ranges will be calculated where these level are reached. All calculations will be done in 1/3 octave frequency resolution.
The impact ranges refer to the distance from the pile at which the animals risk, e. g., PTS. For fleeing receivers, the calculated impact ranges refer to the start distance.

6.5.5 Step 5: noise maps

Based on the source level and defined transmission loss approaches, the noise metrics will be calculated as a function of distance, direction and water depth. The results will be plotted in colored noise maps.

[3] Start distance defines the distance where the fleeing receivers start fleeing with the first blow.

6.6 Possible sources of error

Both, the modelling of "source strength" or "source level" of the pile-driving sound and the pile-driving analysis for the determination of the maximum blow energies as well as the modeling of sound propagation under water (for instance the transmission loss according to Danish Energy Agency (2016) or Thiele & Schellstede; chapter 6.1) involve a certain degree of uncertainty and thereby the derived calculated/predicted level values as well as their impact range.
Measurements from completed construction projects (unpublished data from the construction monitoring in 2010 to 2018 by the *itap GmbH*) 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.
Occasionally, however, the sound exposure levels steadily increased until the maximum penetration depth was reached (at simultaneous increase of the blow energy). This is why always the maximum blow energy is applied for all calculations.
By determining the source level just with the input parameter "pile diameter", an uncertainty of +/- 5 dB arises (Figure 6). To reduce the uncertainty assumptions for the second relevant effective parameter "blow energy" are made and additions and deductions are considered based on an initial value.
By considering the effective parameter "blow energy" the uncertainty is clearly reduced. The comparison of the model with real measuring data from 2012 until now shows an uncertainty of ± 2 dB (not published data from different projects) for the sound exposure level in a distance of 750 m to the piling event with the tendency, that the model with the input data "pile diameter" and "blow energy" slightly overestimates the level values in most cases.

7. MODELLING SCENARIOS

7.1 Existing conditions

The water depths in the project area varies between 24 m and 32 m. The expected difference of the modelled metrics caused by water depth within the project area is approx. 0.05 dB and much lower than the model accuracy. Since the layout has not yet been determined the model will be performed for four fictive locations (see Table 4) at the corner and in the centre of the project area. With these locations the whole project area can be covered. For all locations the acoustically unfavourable design with 13 m diameter and a maximum blow energy of 3,000 kJ is considered. Differences in soil resistance (SRD-value) of the soil layer also result in different blow energies which are taken into account in the model by considering the piling sequence. Further significant impacts of the sediment are not to be expected for the existing sediment layer.

For the project area a good intermixing of the water without a distinct sound velocity profile can be assumed. This leads to a constant sound velocity over the whole water depth (see salinity forecast on www.fcoo.dk). For the model an average sound velocity of 1,480 m/s is assumed. The sound velocity in water depends on salinity and temperature and has a minor impact to the cutoff-frequency caused by water depth (Urick, 1983; Jensen *et al.*, 2010).

The model only considers the noise from the impulsive pile driving. The determination of the background level is not aim of this report. Especially when considering a scenario including a mitigation system some results can be below the background level.

Table 4: **Coordinates for considered turbine positions in the Thor offshore wind farm.**

Name	Location (WGS 84)
WTG 01	56° 14,748′ N 007° 46,821′ E
WTG 02	56° 14,542′ N 007° 25,873′ E
WTG 03	56° 29,330′ N 007° 46,398′ E
WTG 04	56° 20,117′ N 007° 40,219′ E

7.2 Acoustically relevant input data

The following input data will be considered for the model:

Input data for the foundations	
- Foundation type:	monopile
- Pile diameter:	13 m
- Water depth:	between 24 m and 32 m, for the noise maps the bathymetry provided from EMODnet is considered
- Water condition:	good intermixing of the water without a distinct sound velocity profile
- Maximum blow energy:	3,000 kJ

Model assumption to calculate the source level:	
- Input parameter #1:	pile diameter
- Input parameter #2:	blow energy: initial value (model internal parameter) 3,000 kJ; 2.5 dB addition or deduction per duplication or halving of blow energy,
- Soil conditions:	no additions
- Pile surface:	decreasing, no additions or deductions,
- Penetration depth:	no additions or deductions (see possible impact in chapter 6.4.3)
- Transmission loss:	according to Equation 13
- Water depth:	Cutoff frequency between 26 Hz and 35 Hz
- Modelversion:	1.03

8. MODELING RESULTS

8.1 Calculated level values

Considering the model approaches in chapter 6 and the piling sequence described in chapter 4, the following levels are expected in 750 m distance (

Table **5** and Figure 8 to Figure 11). For all locations the same piling sequence is considered the only difference between the four locations is the water depth. As described in chapter 7.1 the impact of water depth is negligible for all possible locations within the Thor OWF area. A distinction between the foundations can be omitted in the following. The expected sound exposure level (SEL) over the time is presented in Figure 8. Figure 9 shows the calculated sound exposure level (SEL) using 3,000 kJ blow energy as a function over the distance. In the noise maps below the unweighted sound exposure level (SEL) is given for all locations. The areas for different sound exposure level (SEL) values are shown in different colors.

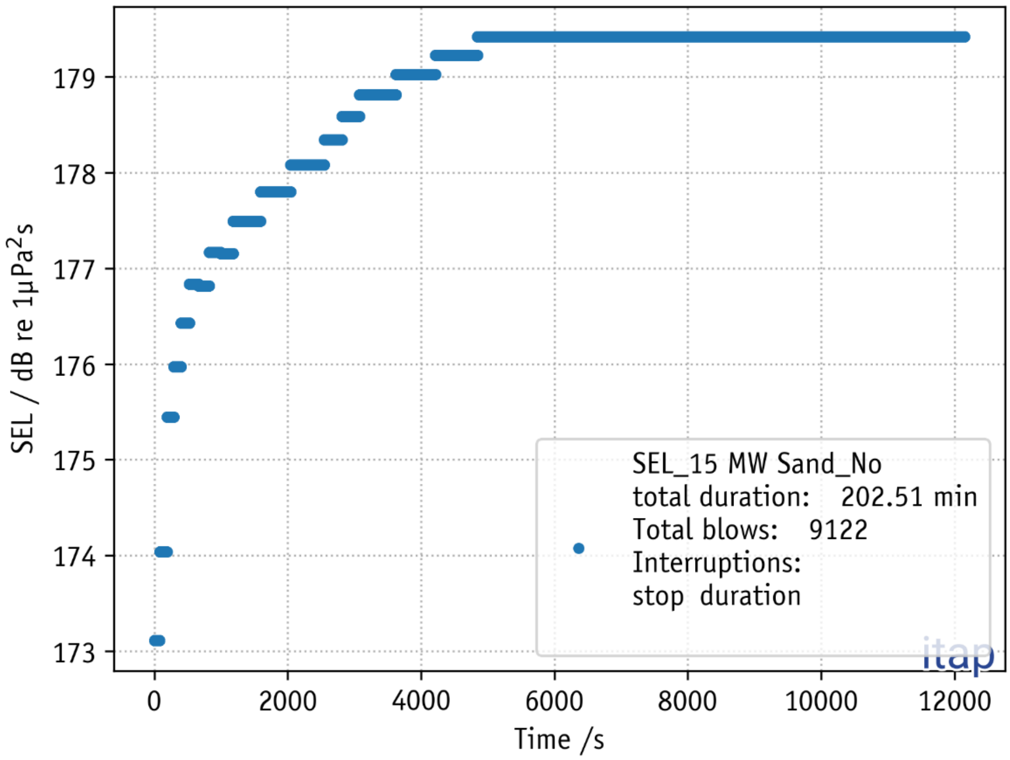


Figure 8: **Expected sound exposure level (SEL) in 750 m distance to the pile for all four locations WTG 01, WTG 02, WTG 03 and WTG 04.**

Table 5: **Calculated level of the unweighted sound exposure level (SEL) and the zero-to-peak sound pressure level (L_p) in 1 m and 750 m distance.**

SEL in 1 m distance	$L_{p,pk}$ in 1 m distance	SEL in 750 m distance	$L_{p,pk}$ in 750 m distance
226	245	183	206

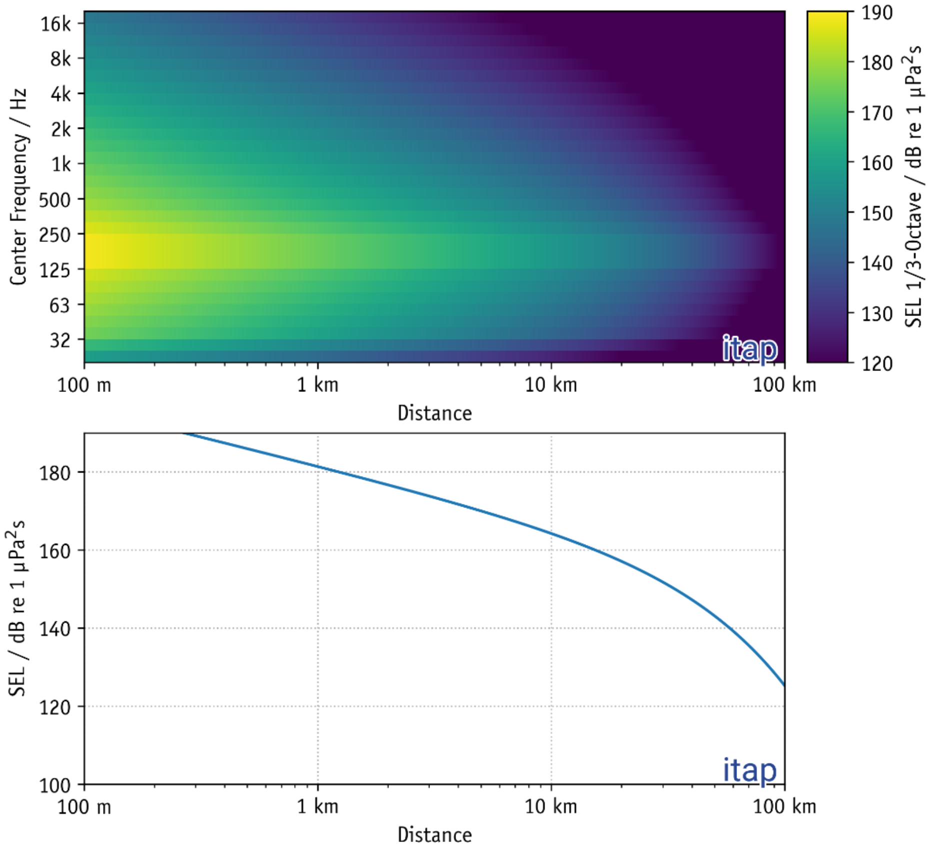


Figure 9: **Predicted SEL (unweighted) due to driving monopiles with a diameter of 13 m at maximum blow energy of 3,000 kJ as function of distance. The spectrogram on top shows the SEL divided in 1/3-octave components. On the y-axis the frequency is listed and on the x-axis the distance is shown. The value of the unweighted SEL in every 1/3 octave band is marked by different colours, yellow for high levels and blue for low levels. The diagram below shows the broad-band values SEL.**

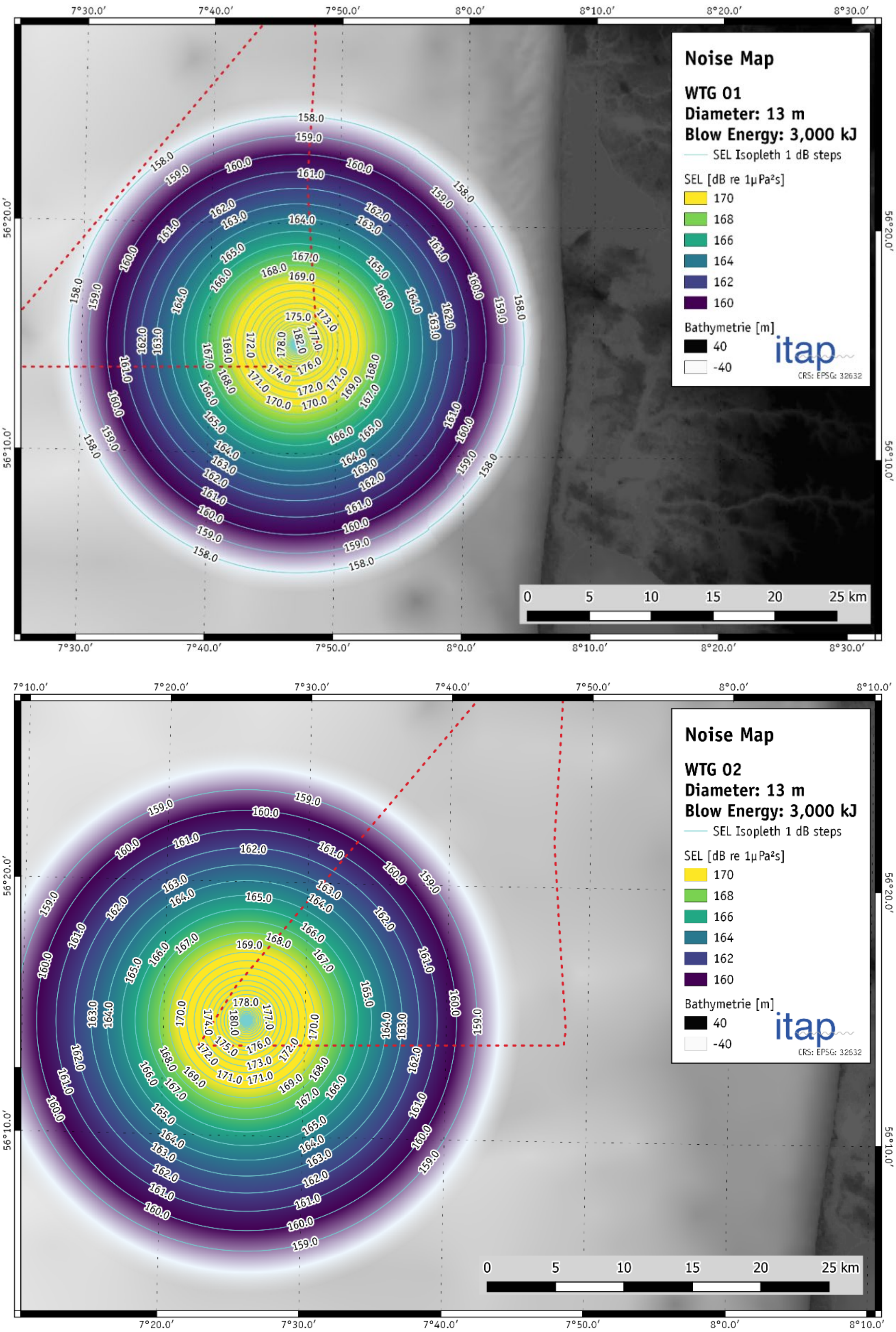
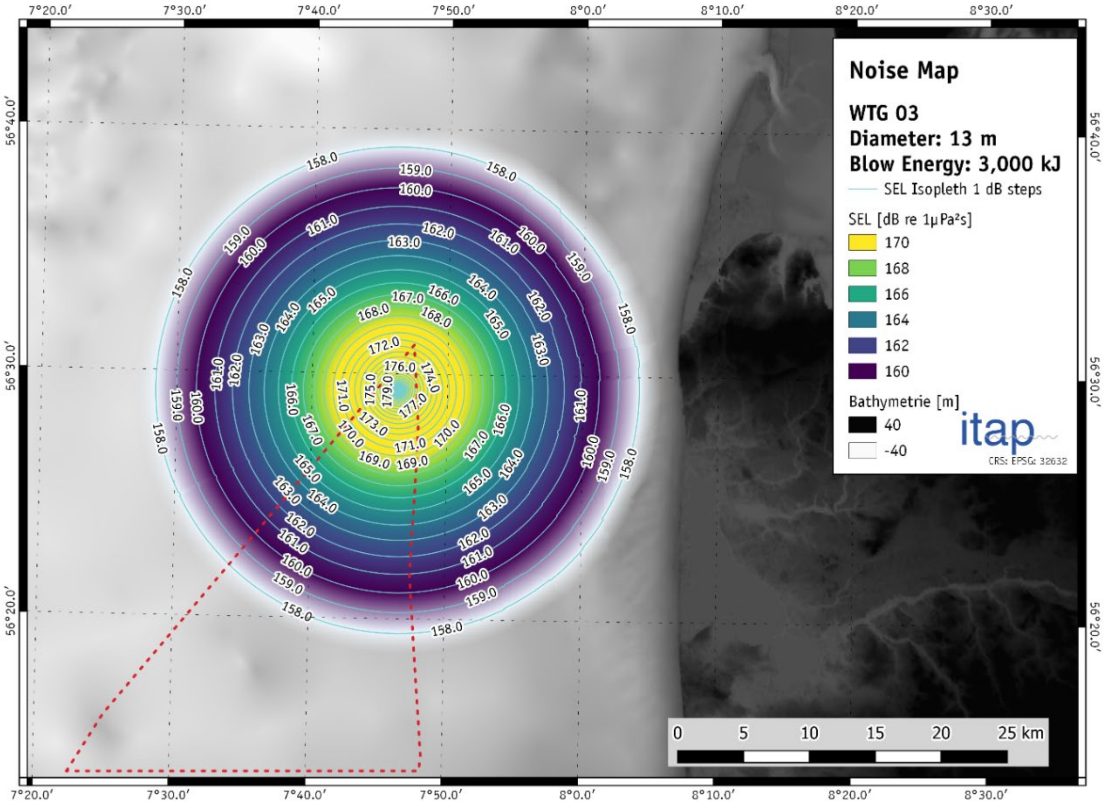


Figure 10: **Noise map for the unweighted *SEL* during the installation of the 13 m monopile foundations at WTG 01 and WTG 02 with a maximum blow energy of 3,000 kJ.**



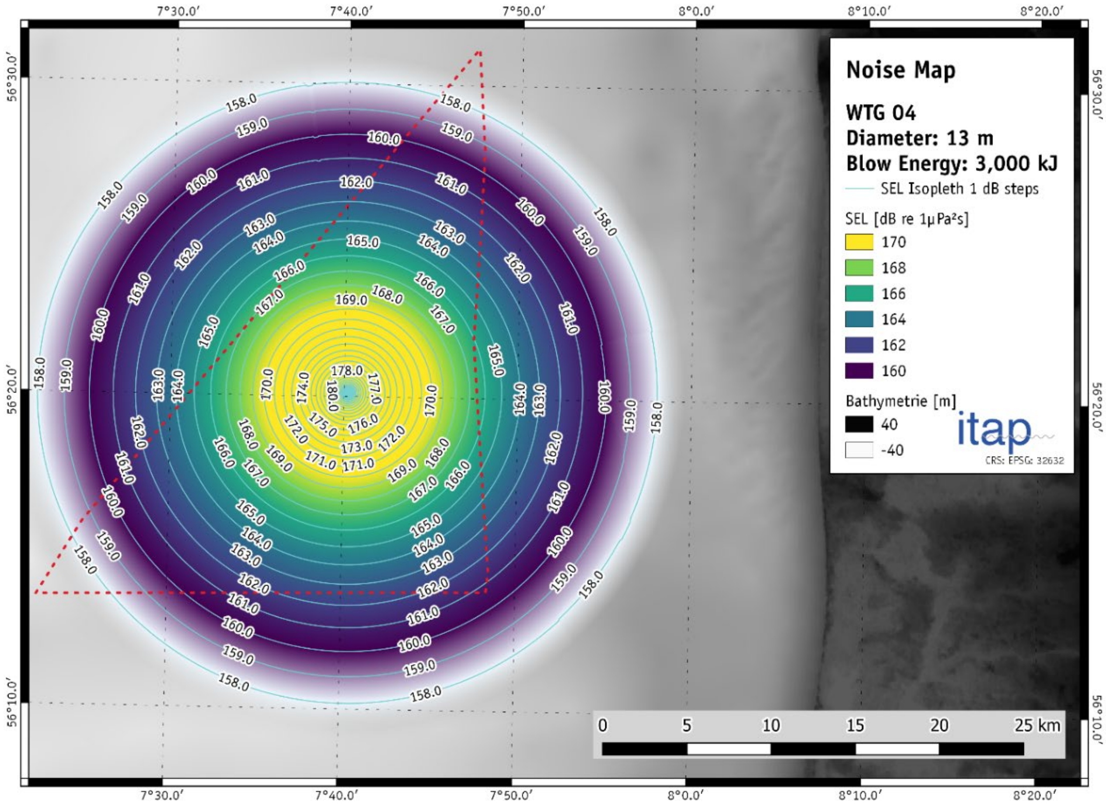


Figure 11: **Noise map for the unweighted *SEL* during the installation of the 13 m monopile foundations at WTG 03 and WTG 04 with a maximum blow energy of 3,000 kJ.**

8.2 Distances to threshold level

For the threshold levels in chapter 6.2, the following impact ranges are expected in which these values are reached.

Table 6: **Distance to thresholds.**

Receptor	Impact type	metric	fleeing speed [m/s]	Criteria [dB]	Range [km]
HP	PTS	SEL_{cum}	1,5	190	16.017
HP	TTS	SEL_{cum}	1,5	175	49.947
HP	Disturbance	SEL		140	48.183
Seal	PTS	SEL_{cum}	1,5	200	2.953
Seal	TTS	SEL_{cum}	1,5	176	47.344
Seal	Disturbance	SEL		142	43.303
fish	Mortal injury	SEL_{cum}	0	204	5.868
fish	Mortal injury	$L_{p,pk}$		207	0.371
fish	recoverable injury	SEL_{cum}	0	203	6.641
fish	TTS	SEL_{cum}	0	185	34.378
larvae	Mortal injury	SEL_{cum}	0	207	3.975
larvae	Mortal injury	$L_{p,pk}$		217	0.079

9. NOISE MITIGATION

The piling noise during installation has impacts on marine mammals. For the nature-compatible expansion of renewable energy sources at sea, the reduction of this noise input into the water is therefore absolutely necessary.
Therefore, noise mitigation measures must be planned to comply with the regulatory decree.
In general noise mitigation can be achieved by application of

- Noise Mitigation Systems, means technics to reduce the source level
- Noise Abatement Systems, means systems which are able to reduce the pile-driving noise in the water.

A general overview of technical noise abatement systems, noise mitigation systems and possible alternative low-noise foundation structures and -procedures was published on behalf of the Federal Agency for Nature Conservation (BfN) for the first time in 2011 (Koschinski & Lüdemann, 2011). In the following years, this study was updated twice (Koschinski & Lüdemann, 2013 & 2019). In Verfuss *et al*. (2019)), a general overview of technical noise abatement systems is also given on behalf of the Scottish Natural Heritage. In this study, questionnaires were used to assess the effectiveness of each single noise abatement system and the expected costs of application. 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. Based on that study only the noise optimized piling procedure as noise mitigation system and three noise abatement systems, the Big Bubble Curtain (BBC), Hydro Sound Damper (HSD) and IHC- Noise Mitigation Screen are well approved technics under real offshore-applications. A short exclusive summary of these technics is given in the following subsections:

9.1 Noise mitigation system

A possibility for underwater noise reductions is the reduction of the applied blow energy. Empirically, the acoustic parameters decrease about approx. 2.5 dB, when the blow energy is halved (Gündert, 2014), by applying "noise-optimized" pile-driving procedures with high blow rates and blow counts as well as low energy. The application of a noise-optimized pile-driving procedure depends significantly on the soil resistance value, which mostly is highly depending on the penetration depth; the higher the penetration depth, the higher the blow energy usually has to be. Furthermore, the application of the noise-optimized pile-driving procedure must be checked carefully before construction regarding pile fatigue and soil resistance. This noise mitigation system can't be applied in all OWF projects.

9.2 Noise abatement systems

At present, noise reductions for the SEL of up to 15 dB are possible by using a single noise abatement system (Bellmann *et al.*, 2020). By the combination of two noise abatement systems, it was possible to achieve noise reductions of more than 20 dB in the past. Therefore, all available noise abatement systems shall be adapted depending on the type of soil, water depth and the current of the local area. All previously developed and under offshore conditions tested noise abatement systems show high variances in noise reduction (Bellmann, 2014. & Bellmann *et al.*, 2018 ; unpublished measurement data from construction projects from 2011 to 2018 of the *itap GmbH*). The most variances could be traced back to technical problems or dysfunctions of the respective noise abatement system.
Each application of a noise abatement system without failures and technical problems shows, that the sound-reducing effectiveness results in variances on average of ± 2 dB (Bellmann *et al.*, 2020). This was found during a pile-driving at one location (usually several thousands of blows per location), as well as at the comparison of several locations with and without noise abatement systems.
Furthermore, the sound reduction of each noise abatement system is highly frequency-dependent and thus, the resulting (single-number) sound reduction depends on the spectral composition of the piling noise without the application of a noise abatement system.

9.2.1 Double Big Bubble Curtain (DBBC)

The double Big Bubble Curtain (DBBC) is one of the most practicable and most frequently used (> 600 applications) noise mitigation system. Additionally, two funded R&D projects were conducted to understand the main influencing factors of a Big Bubble Curtain on the overall noise reduction (Nehls & Bellmann, 2015; Bellmann *et al.*, 2018).
At the moment, noise reductions for the sound exposure level (SEL) of up to 18 dB (maximum measured noise reduction) are possible by using a "Double Big Bubble Curtain" (DBBC) in the North Sea at water depths till 40 m. The averaged noise reduction of an optimized DBBC mostly ranged between 15 dB and 16 dB. But the usage of single and double Big Bubble Curtains partly shows high variances in noise reduction (Bellmann, 2014; Bellmann *et al.*, 2018 and Bellmann *et al.*, 2015; Bellmann *et al.*, 2020). The most variances could be traced back to technical problems or dysfunctions of the respective noise abatement system or the application of not project-specifically optimized system configurations of the applied BBC system.
The noise reduction of Big Bubble Curtains depends on many factors like water depth, current, used hole configuration in the applied nozzle hoses on the sea bed and compressed air supply. It is important to enhance the Big Bubble Curtain system configuration to the local project-specific conditions (Bellmann *et al.*, 2018).

Decisive for a successful application are (i) a sufficient amount of compressed air and (ii) a complete wrapping of the pile by the Big Bubble Curtain. The required air volume depends on the water depth due to the static pressure of the surrounding water. In the North Sea (where the most BBC applications took place), an applied air volume of ≥ 0.5 m^3/(min*m) is currently state-of-the-art for water depths up to 40 m. In order to enable a complete wrapping of the pile, a sufficient distance of the Big Bubble Curtain nozzle hoses to the pile is required. This distance depends on the local current and the water depth (drifting effects). Means by setting up the BBC system configuration, the water depth and the current, but also the type of installation vessel (DP, anchor moored floating vessel of jack-up barge) shall be considered by designing the overall length of the applied nozzle hoses and the layout shape used. Typically, a current of up to 1 knot is no problem for applying an optimized BBC system with respect to the drifting effects.
Furthermore, the sound reduction of each noise mitigation system is highly frequency-dependent and thus, the resulting (single-number) sound reduction depends on the spectral composition of the piling noise, without the application of a noise abatement measure.
Applying only a single BBC instead of a double BBC will reduce the overall noise reduction by 2 to 4 dB.
Currently, no DBBC supplier is selected and the DBBC system configuration is not known. Therefore, the minimum DBBC system requirements from already finished pile-driving projects is listed (Bellmann et al., 2018):

- hole size (diameter) and hole spacing: 1 – 2 mm all 20 – 30 cm,
- applied air volume: ≥ 0.5 m^3/(min*m),
- distance of the nozzle hoses: ≥ a water depth between 1st and 2nd BBC,
- the BBC shall surround the foundation structure completely and shall have a minimum distance to the structure of 30 m to 40 m (distance between pile and nozzle hoses on the seabed significantly depending on the local current),
- typical nozzle hose diameter is currently 100 mm, which limits the overall length of a single BBC to 1,000 m due to air flow dynamic boundaries,
- regular maintenance of the applied nozzle hoses,
- no turbulence-producing obstacles in the nozzle hoses,
- the pressure of the compressed air inside the nozzle hoses must be 2 – 3 bar more than the static pressure of the water outside (over pressure); this means in water depth of up to 30 m an operational pressure of the compressors shall be minimum 8.5 to 10 bar[4],
- the overall lifetime of each nozzle hose is limited (currently best practice < 80 - 100 applications).

9.2.2 Noise Mitigation Screen (NMS)

The IHC-Noise Mitigation Screen (IHC-NMS) was developed and built by the company *IHC IQIP bv*. It consists of a double-walled steel tube, whereby the interspace is filled with air. The noise reduction is effected by the impedance differences on the double-walled steel tubes of the IHC-NMS. A detailed description is given in (Bellmann *et al.*, 2020).
During the application of this near-to-pile Noise Abatement System with several hundred applications within nine German OWF construction projects, so far, a technical problem was only detected once at the beginning of the development. Apart from this, all other applications showed, that this Noise Abatement System could be used offshore-suitable, error-free and robustly.
Until now, the IHC-NMS was applied from lifting platforms and floating installation vessels in the North Sea.

[4] Typically, the pressure of the compressed air can be measured onboard of the BBC supply vessel on the manifold. Based on experiences the pressure will slightly decrease inside the nozzle hoses with distance to the manifold due to physical parameters like water temperature etc as well as due to the fact that air will leave the nozzle hose on the seabed. Based on measurements inside the nozzle hoses a pressure of 9.3 bar at the manifold is sufficient for water depth up to 40 m to ensure an overpressure inside the nozzle hose of 2 – 3 bars.

The achieved noise reduction with the IHC-NMS proved to be independent from

- the water depth (up to 40 m),
- the prevailing current (present application ≤ 0.75 m/s) and
- the spatial direction (omnidirectional noise reduction).

With the IHC-NMS noise reductions between 15 dB und 17 dB were measured during monopile installations in the North Sea by water depths up to 40 m.

9.2.3 Hydro Sound Damper (HSD)

The Hydro Sound Damper is a near-to-pile noise abatement system, which often is applied in combination with a single or a double Big Bubble Curtain.
The HSD-system consists of a net with HSD-elements and a lowering and lifting device. The HSD-elements consist of different foam elements in different sizes. Each HSD-element is adjusted to different frequencies and water depths, so that the HSD-system must be adjusted to each individual offshore project.
The whole system (lowering and lifting device, nets and HSD-elements) can be telescoped via winch systems for the transport as well as for the mobilization and demobilization.
Until now, this noise abatement system was used as standard in monopile installations with pile diameters up to 8 m and a water depth to approx. 40 m and showed a constant noise reduction of 10 dB in the North Sea at water depths of up to 40 m.
An application of the HSD-system in the Baltic Sea resulted in smaller noise reductions, whereby it could not be clarified at present, whether this decreased noise reduction was caused by the special soil conditions in the Baltic Sea (soil coupling) or a non-optimal design of the lowering device.

9.2.4 AdBm

The AdBm system is a close-to-pile noise abatement system which uses block-shapes filled with air instead of HSD-elements. The functioning of the AdBm system is very comparable to the HSD-system.
First offshore-applications of this new close-to-pile noise abatement systems indicates that the overall noise reduction is less than 10 dB and only limited in the frequency range around 100 to 200 Hz. But several hints for the enhancements of this system were identified during the first applications.
The AdBm system was not tested in German waters till 2020 under offshore conditions. Therefore, this noise abatement system is currently judged by the German regulator BSH as a not offshore-reliable mitigation measure and can’t be used for a serial application without further empirical evaluations of the overall noise reduction within the German EEZ at the moment.

9.2.5 Combination of near-to-pile and far-from-pile Noise Abatement Systems

So far, the following combinations of technical Noise Abatement Systems for the installation of monopiles in serial use have been used in the construction of the foundation structures using the impact pile-driving procedure in construction projects:

- IHC-NMS + single or double Big Bubble Curtain (BBC or DBBC),
- HSD + double Big Bubble Curtain (DBBC).

With the combinations listed here noise reductions of 20 dB and more could be achieved (Bellmann *et al*., 2020).

10. REFERENCES

Andersson *et al.* (2016). Andersson MH, Andersson S, Ahlsén J, Andersson BL, Hammar J, Persson LKG, Pihl J, Sigray P & Wikström A: Underlag för reglering av undervattensljud vid pålning. Vindval rapport 6723, August 2016.

Bellmann (2014). Overview of existing Noise Mitigation Systems for reducing Pile-Driving Noise. Proceeding on the Internoise 2014, Melbourne Australien.

Bellmann *et al.* (2015). Bellmann MA., Schuckenbrock J., Gündert S., Müller M., Holst H. & Remmers P.: Is there a State-of-the-Art to reduce Pile-Driving Noise, proceeding book: Wind Energy and Wildlife Interaction (Presentations from the CWW2015 Conference, Editor Johann Köppel, ISBN978-3-319-51270-9, Springer Verlag, 2015

Bellmann *et al.* (2018). Bellmann MA., Kühler R., Matuschek R., Müller M., Betke K., Schuckenbrock J., Gündert S. and Remmers P.: Noise Mitigation for large foundations (Monopiles L & XL) – Technical options for complying with noise limits, presentation on the BfN Noise Mitigation Conference, November 22nd/23rd 2018 in Berlin.

Bellmann *et al.* (2020). Bellmann MA, May A, Wendt T, Gerlach S, Remmers P, Brinkmann J: Unterwasserschall während des Impulsrammverfahrens: Einflussfaktoren auf Rammschall und technische Möglichkeiten zur Einhaltung von Lärmschutzwerten- ERa - Bericht

BSH (2011). Offshore-Windparks – Prognosen für Unterwasserschall (Mindestmaß an Dokumentation. Bericht Nr. M100004/29 der Müller-BBM GmbH

BSH (2013). Offshore-Windparks – Prognosen für Unterwasserschall (Mindestmaß an Dokumentation. Bericht Nr. M100004/29 der Müller-BBM GmbH)

Dähne *et al.* (2013). Dähne M, Gilles A, Lucke K: Effects of pile-driving on harbour porpoises (*Phocoena phocoena)* at the first offshore wind farm in Germany. Environmental Research Letters, 8: 025002

Danish Energy Agency (2016). Guideline for underwater noise – Installation of impact-driven piles. Energistyrelsen, Center for Energiressourcer, April 2016.

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

ISO 18406 (2017). Underwater acoustics – Measurement of radiated underwater sound from percussive pile driving

Jensen *et al.* (2010). Jensen FB, Kuperman WA, Porter MB und Schmidt H: Computational Ocean Acoustics. Springer Verlag, AIP Press

Koschinski, S. & Lüdemann, K. (2013). Development of Noise Mitigation Measures in Offshore Wind Farm Construction 2013, report on behalf of BfN, Bonn, Germany, pp. 1-97.

Koschinski, S. & Lüdemann, K. (2019). Noise mitigation for the construction of increasingly large offshore wind turbines -Technical options for complying with noise limits, report on behalf of BfN, Bonn, Germany, pp. 1-42.

Koschinski, S. & Lüdemann, K.(2011). Stand der Entwicklungen schallminimierender Maßnahmen beim Bau von Offshore-Windenergieanlagen, report on behalf of BfN, Bonn, Germany, pp. 1-83.

National Marine Fisheries Service (2018). Revisions to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0): Underwater Thresholds for Onset of Permanent and Temporary Threshold Shifts. U.S. Dept. of Commer., NOAA. NOAA Technical Memorandum NMFS-OPR-59, 167 p.

Nehls G & Bellmann MA (2015). Weiterentwicklung und Erprobung des Großen Blasenschleiers zur Minderung der Hydroschallemissionen bei Offshore-Rammarbeiten. Gefördert durch PTJ und BMWi, FKZ 0325645A/B/C/D (www.hydroschall.de)

Popper *et al.* (2014). Popper AN, Hawkins AD, Fay RR, Mann DA, Bartol S, Carlson TJ, Coombs S, Ellison WT, Gentry RL, Halvorsen MB, Løkkeborg S, Rogers PH, Southall BL, Zeddies DG & Tavolga WN: Sound Exposure Guidelines for Fishes and Sea Turtles. ASA S3/SC1.4 TR-2014, SpringerBriefs in Oceanography, Acoustical Society of America 2014.

Russel *et al.* (2016). Russel DJF, Hastie GD, Thompson D, Janik VM, Hammond PS, Scott-Hayward LAS, Matthiopoulos J, Jones EL & McConnell BJ: Avoidance of wind farms by harbour seals is limited to pile driving activities. Journal of Applied Ecology, 53, 1642-1652.

Skjellerrup *et al.* (2015). Skjellerup P, McKenzie Maxon C, Tarpgaard E, Thomsen F, Schack HB, Tougaard J, Teilmann J, Nehring Madsen K, Michaelsen MA, Heilskov NF: Marine mammals and underwater noise in relation to pile driving – Working Group 2014. Report to the Danish Energy Authority.

Thiele & Schellstede (1980). Standardwerte zur Ausbreitungsdämpfung in der Nordsee. FWG-Bericht 1980-7, Forschungsanstalt der Bundeswehr für Wasserschall und Geophysik

Tougaard & Michaelsen (2018). Effects of larger turbines for offshore wind farm at Krieger's Flak, Sweden - Assessment of impact on marine mammals

Urick (1983). *Principles of underwater sound, 3rd ed. Pensinsula Publishing, Los Altos*

Verfuss *et al*. (2019). **Verfuss, U.K., Sinclair, R.R. & Sparling, C.E.:** A review of Noise Abatement Systems for offshore wind farm construction noise, and the potential for their application in Scottish waters. Scottish Natural Heritage Research Report No. 1070.

APPENDIX

Table 7: **Assumed piling sequence including soft start/ramp up with different blow frequencies [blows/min].**

number of blows	blow_energy	Blow frequency
60	542.1	45
82	696.4	45
76	1021.1	45
83	1176.7	45
92	1331.9	45
102	1486.4	45
123	1479.5	45
126	1625.3	45
142	1620.9	45
145	1776.5	45
161	1777	45
163	1931.4	45
179	1931.4	45
181	2084.6	45
197	2084.6	45
197	2237.5	45
198	2389.1	45
198	2540.8	45
213	2540.7	45
213	2692	45
229	2691.9	45
228	2842.1	45
245	2841.9	45
244	2992.5	45
262	2992.4	45
281	2992.3	45
303	2992.2	45
328	2992.3	45
355	2992.9	45
386	2992.7	45
422	2992.6	45
464	2992.6	45
512	2992.4	45
569	2992.4	45
636	2992.3	45