N05-A
Offshore Gas Platform

Modeling of underwater noise emissions during pile-driving construction work

Oldenburg, November 19th 2021

Version 2

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Revision table

Version	Date	Comment
1	13.10.2021	First draft
2	19.11.2021	Textual changes

This version replaces all previous versions.

Units:

µm/s - micrometer per second

µPa - micropascal

bar - 100 kPa

dB - decibel

Hz - hertz

kHz - kilohertz

kPa - kilopascal

m - meter

min - minute

mm - millimeters

Pa - pascal

s - second

Metrics:

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

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

SEL - single strike Sound Exposure Level

SEL_{05} - 5 % exceedance Sound Exposure Level

SEL_{cum} - cumulative Sound Exposure Level

SPL - (energy-) equivalent continuous 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

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

p_{pk} - maximum sound pressure

v - particle velocity

Abbreviations:

BfN	Bundesamt für Naturschutz (engl. Federal Agency for Nature Conservation)
BMU	Bundesministeruim für Umwelt, Naturschutz und nukleare Sicherheit, engl. Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
BSH	Bundesamt für Seeschifffahrt und Hydrographie (engl. Federal Maritime and Hydrographic Agency
DBBC	double Big Bubble Curtain
DP	Dynamic Positioning
EEZ	*Exclusive Economic Zone*
FEED	Front-End Engeneering Design
GABC	Grout Annulus Bubble Curtain
IIg	zone classification according to Thiele & Schellstede
MNRU	*Menck* Noise Reduction Unit
MSFD	marine strategy framework directive
MSL	Mean Sea Level
NAS	Noise Abatement System
NMS	Noise Mitigation System
PTS	Permanent Threshold Shift
rms	root mean square, root mean square
SRD	Soil Resistance Value
TTS	Temporary Threshold Shift

1. Executive summary

ONE-Dyas is planning the construction and installation of a Jacket foundation for the *N05-A* offshore gas platform in the EEZ of the Dutch *North Sea*. It is intended to install 6 pcs skirt-piles with a maximum diameter of 2.743 m to fix the Jacket foundation into the seabed. In addition, 12 pcs conductor-piles with a pile diameter of 0.8 m in the vicinity of the Jacket platform will to be installed.

The installation of foundation structures into the seabed by means of impact pile-driving causes noise levels, which might be harmful for marine mammals and fish (Lucke, et al. 2009). The *itap – Institute for Technical and Applied Physics GmbH* was commissioned to carry out the modeling of underwater pile-driving noise during the construction of the *N05-A* gas platform.

Modeling scenarios, including pile diameter, hammer type and platform location, were defined to reflect the actual project to the highest extent possible, with the objective to determine expected noise levels, allowing for accurate environmental impact assessment of the pile-driving activities. Three different blow energies from 604 kJ up to 1,090 kJ are used to model the pile-driving noise for the skirt piles of the gas platform within this report. For the conductor piles only one blow energy is considered. Modelling included single strike Sound Exposure Levels (SEL) as well as zero-to-peak Sound Pressure Level ($L_{p,\,pk}$) levels based on the Dutch and German requirements.

The following SEL and $L_{p,pk}$ levels at a distance of 750 m to the impact pile-driving are forecasted for the unmitigated pile-driving.

Pile type	Diameter [m]	Blow Energy [kJ]	SEL_1 in 750 m distance	$L_{p,pk}$ in 750 m distance
skirt-pile	2.743 m	604	171	194
skirt-pile	2.743 m	845	172	196
skirt-pile	2.743 m	1,090	173	197
conductor-piles	0.8	90	159	183

Seasonal noise mitigation values for impulsiveness noise are defined for single location installations like offshore-supply stations in 750 m to source in the Netherlands. In the first tertial from January to May inclusive (T1), the $SEL1$ (corresponding to the maximum SEL) must not exceed 162 dB, from June to August inclusive (T2), the $SEL1$ must not exceed 167 dB and from September to December inclusive (T3), the $SEL1$ must not exceed 169 dB.

Independent on the construction period and the maximum blow energy used, the application of noise mitigation measures is required to comply with the defined noise mitigation values determined by the responsible authority *Rijkswaterstaat*.

Two possible noise mitigation concepts for the *N05-A* Jacket installation are the application of a double Big Bubble Curtain (DBBC) or single Big Bubble Curtain (BBC) in combination with a Grout Annulus Bubble Curtain (GABC). With both noise mitigation concepts, it is possible to reduce the noise to such an extent that compliance with the Dutch noise mitigation values is ensured irrespective of the blow energy used and the time of year. However, the prerequisite for the compliance of the Dutch noise mitigation values is that the applied noise abatement systems Big Bubble Curtain and Grout Annulus Bubble Curtain are project-specifically optimized according to the state-of-the-art (Bellmann, et al. 2020).

For the conductor-piles no noise mitigation is required.

Nevertheless, the Jacket foundation as well as the conductor-piles will be installed very close to the German border and two German Natura 2000 Special Areas of Conservation (SAC) are located in distances of 4.5 km and 14.6 km to pile-driving. For such sensitive areas the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU 2013) defined additional noise mitigation specifications to prevent a significant habitat loss by impulsiveness noise:

Therefore, 10 % of the German EEZ shall not be polluted by impulsiveness noise events with the potential to significantly disturb harbor porpoises at any time (habitat loss). In the marine mammal sensitive period from May to August the habitat loss Natura 2000 Special Areas of Conservation should not exceed 1 % if Harbor porpoise reproduction is a special conservation target of the Special Areas of Conservation, otherwise 10 % applies. However, based on the noise mitigation concept (BMU, 2013) reactions and temporal habitat losses are expected in distances up to 8 km – corresponding with 140 dB Sound Exposure Level (SEL) - from pile-driving in case the general noise mitigation values of 160 dB for the Sound Exposure Level and 190 dB for the peak Sound Pressure Level are fulfilled in 750 m distance. Therefore, a temporal habitat loss is the area of the habitat exposed by SEL values of 140 dB and more.

Without noise mitigation measures the habitat loss defined in BMU (2013) guideline where the Sound Exposure Level (SEL) is greater or equal 140 dB is expected at 52.9 % for the Natura 2000 SAC "Borkum Riffgrund" and 5 % for the Natura 2000 SAC "Nationalpark Niedersächsisches Watttenmeer" for skirt-pile installation of the Jacket installation. The habitat loss for "Borkum Riffgrund" will be reduced to 0.55 % by application of an optimized double Big Bubble Curtain (DBBC). The "Nationalpark Niedersächsisches Wattenmeer" will not be exposed with impulsiveness noise of 140 dB_{SEL} or more by mitigated pile-driving during the skirt-pile installations. Alternatively, to an optimized DBBC a combination of a single BBC and a Grout Annulus Bubble Curtain (GABC) can be used as well.

During pilling of the conductor-piles the habitat loss without noise mitigation measures is 0.8 % for Natura 2000 SAC "Borkum Riffgrund" and 0 % for the Natura 2000 SAC "Nationalpark Niedersächsisches Watttenmeer".

Oldenburg, November 19th 2021

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2. Project description and scope of this document

ONE-Dyas is starting the Front-End Engeneering Design (FEED)-engineering of the *N05-A* gas platform. The platform is to be erected on a 6-legged jacket structure with 6 pcs skirt-piles. The connection between structure and the piles will be envisaged by means of a grouted connection. For the skirt piles a pile diameter of 2.743 m has been chosen. In addition, 12 pcs conductor-piles with a pile diameter of 0.8 m in the vicinity of the Jacket platform will to be installed.

The planned location is close to Dutch and German ecologically important areas, designated as Natura 2000 areas. For projects close to such protected areas, the Dutch/ EU law requires an assessment to determine whether there will be significant adverse effects on the conservation objectives. A permit can only be granted if it is demonstrated that there is no significant effect.

The soil in the plan area essentially consists of medium dense to very dense sand. The water depth in the project area is approximately 25.8 m (MSL).

The installation of foundation structures into the seabed by means of impact pile-driving caused noise levels, which might be harmful for marine mammals and fish (Lucke, et al. 2009).

The *itap – Institute for Technical and Applied Physics GmbH* was commissioned to carry out the modeling of (un-) mitigated underwater pile-driving noise during the construction phase of the N05-A platform and to evaluate if and how a compliance with the Dutch seasonal noise mitigation values is possible by application of noise mitigation.

Furthermore, the pile-driving noise from the Dutch offshore project must also comply with the German noise mitigation values of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU 2013) for the nearby German Natura 2000 Special Areas of Conservation “Borkum Riffgrund” and “Nationalpark Niedersächsisches Wattenmeer” to avoid a significant loss of habitat due to impulsiveness noise.

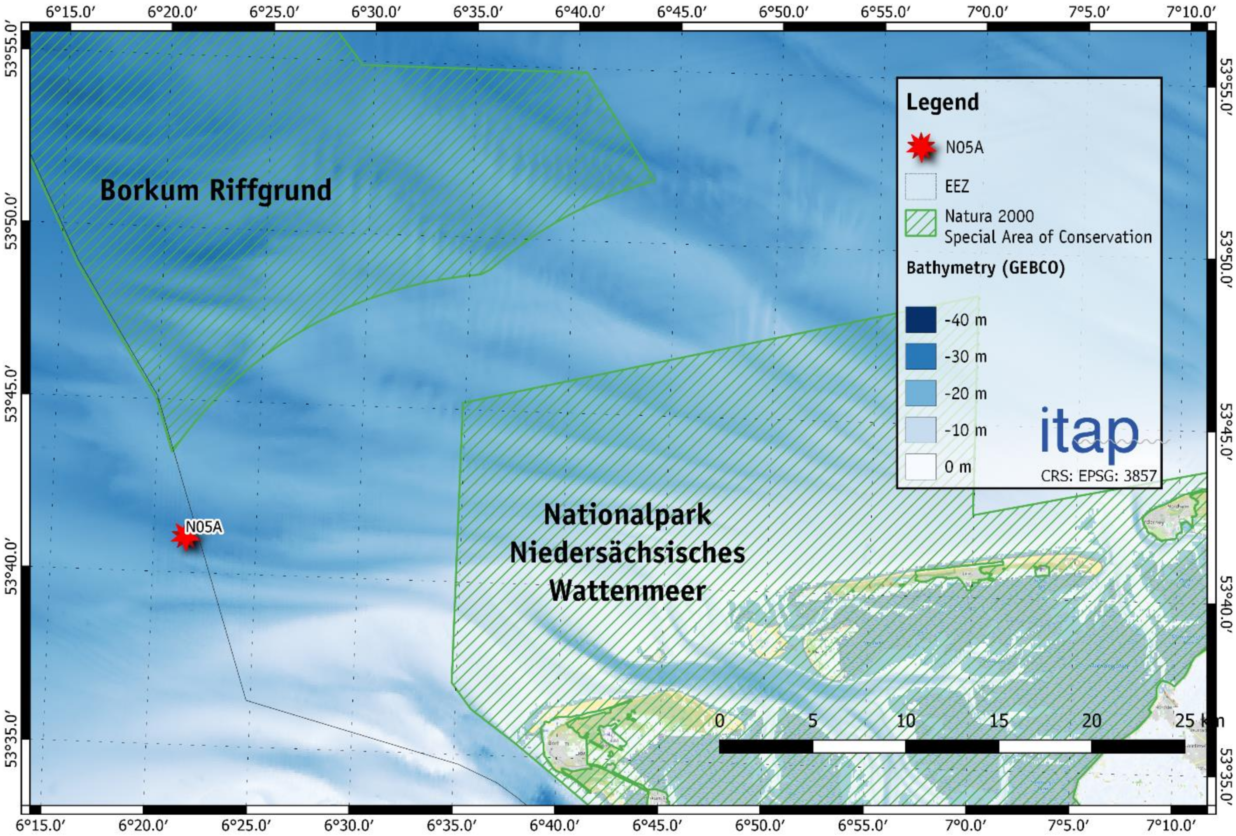

Figure 1: Location of the N05-A platform within in the Dutch AWZ in the North Sea.

The skirt-piles and conductor-piles are large steel piles that are driven into the seabed by the application of a hydraulic hammer. According to current planning it is expected to use blow energies of 604 kJ, 845 kJ and 1,090 kJ for the skirt-piles and 90 kJ for the conductor-piles.

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, 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 $L_{p,pk}$.

[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 the literature.

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 sound 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 DIN ISO 18406 (2017) is used and the index rms is omitted and the SPL in this report is equal to SPL_{rms}, 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 sound (for instance > 10 dB), it can be calculated with a simplification of Equation 6 and a sufficient degree of accuracy as follows:

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

Equation 7

Note: In some guidelines for measuring underwater noise, i. e. Germany (BSH, 2011), an averaged Sound Exposure Level of 30 s is defined (SEL_{30s}) according to Equation 7.

Note: The $SEL1$ (also known as SEL_{max}) as noise mitigation value from Rijkswaterstaat denotes that all measured SEL values from each pile-driving activity most comply with the threshold.

Cumulative Sound Exposure Level (SEL_{cum})

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

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

Equation 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.

Technical note: In some guidelines for underwater noise measurements, the cumulative SEL_{cum} shall be determined to evaluate the impact on defined species (e. g. NOAA, 2018; Danish Energy Agency, 2016). The information on SEL_{cum} is included in this report for informational purposes only.

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

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:

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

Equation 10

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

Figure 2 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 and SEL during pile-driving works is 20 dB to 25 dB. Some authors prefer the peak-to-peak value ($L_{pk,pk}$) instead of the $L_{p,pk}$. A visual definition of this parameter is given in Figure 2, but this metric is not defined in the ISO 18405 (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 maximal 6 dB higher than the zero-to-peak Sound Pressure Level ($L_{p,pk}$).

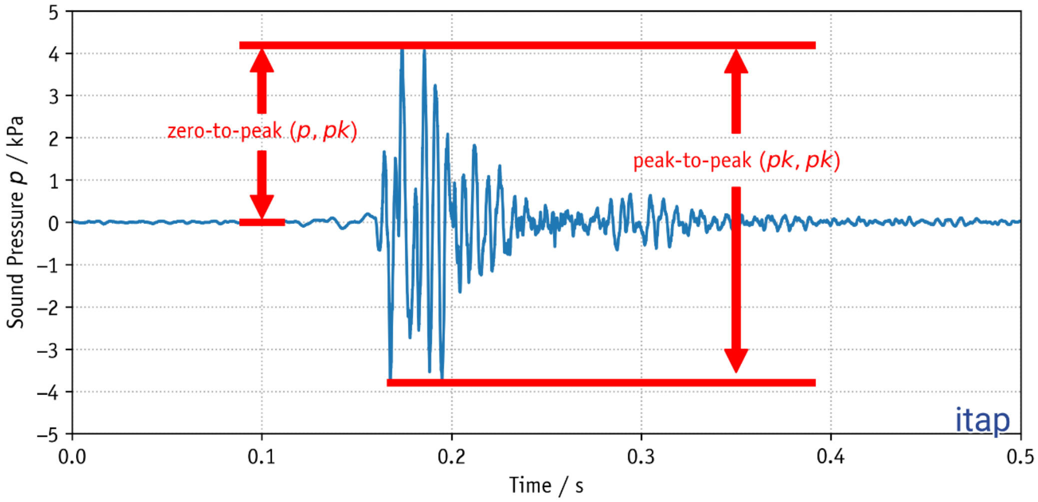

Figure 2: Typical measured time signal of underwater sound due to pile-driving in a distance of several 100 m.

4. Model approaches

4.1 Sound propagation in the North Sea

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 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

For regions in the *North Sea* with water depths below 50 m, the following Equation 13 leads to realistic results compared to pile-driving 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, typically a "smooth" sea is required.

So, the following equation for shallow water and smooth sea (IIg) will be compared with measurement results from different OWF construction phases by means of impact pile-driving in the *North Sea* in Figure 3:

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

Equation 14

with

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

r – distance [m].

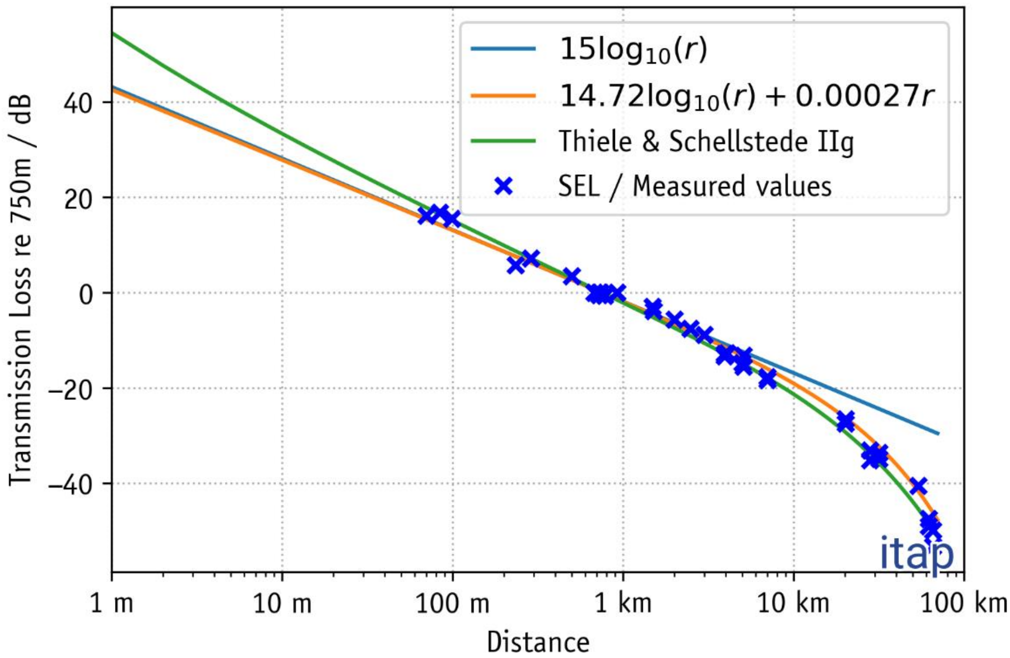

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Figure 3: *Different predicted Transmission Loss (TL) curves according to* Equation 11 *(15 log$_{10}$ R),* Equation 13 *(14.72 log$_{10}$ R + 0.00027 R) and the semi-empirical approach of Thiele und Schellstede IIg (1980) (*Equation 14*), compared with existing offshore measurement data. The measurement data originate from pile-driving measurements from different offshore wind farms in the North Sea in Germany and the Netherlands. The water depth in all OWF was less than 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 3) in different regions of the *North Sea* with comparable water depths. Only for distances less than 100 m, the equations differ from each other. The more common Equation 14 is considered for the *N05-A* prognosis.

The Transmission Loss will be considered for each direction. Site-specific changes in the bathymetry will be considered by the frequency-dependent impact of the water depth as described below.

Impact of the water depth

The water depth also influences the sound propagation in the ocean. 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 the water depth is depicted in Figure 4. 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 than it is calculated with Equation 14.

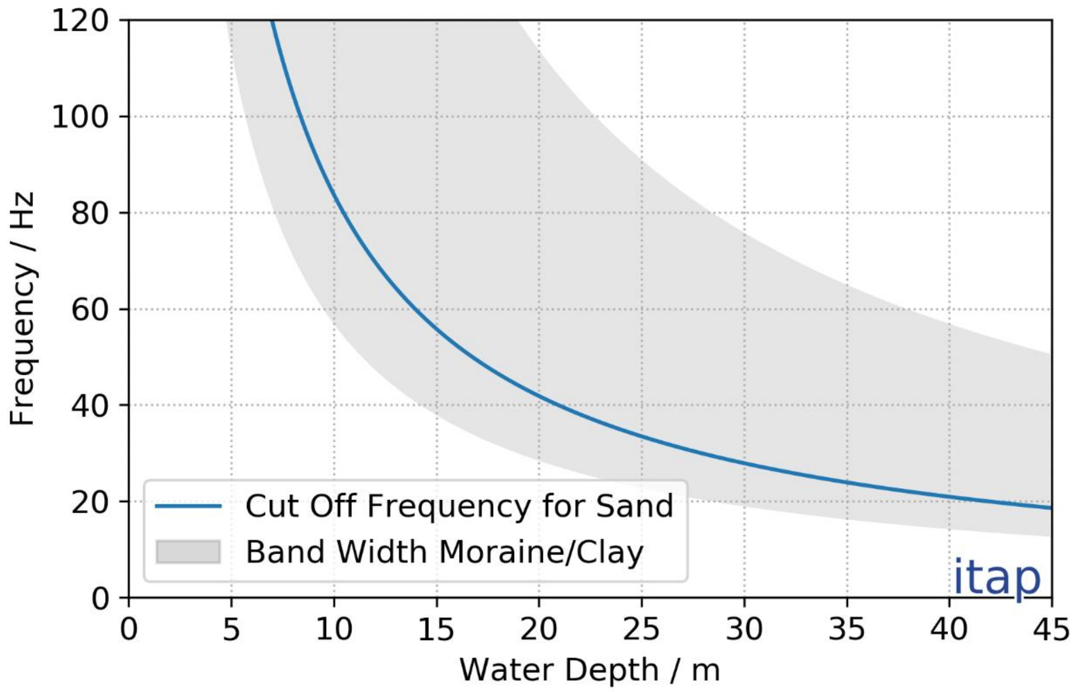

Figure 4: *Theoretical lower (limit) frequency (f_g) for an undisturbed sound propagation in water as a function of the water depth for different soil stratifications (example adapted from Urick (1983); Jensen et al., (2011); the example shows the possible range caused by different layers, the layer does not necessarily correspond to the layers in the construction field).*

4.2 Underwater noise mitigation regulations

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 Levels might have the potential to harm marine mammals or fish, potentially leading to behavioral disturbance, temporary hearing loss (TTS, Temporary Threshold Shift) or permanent hearing loss (PTS, Permanent Threshold Shift). (Lucke, et al. 2009)

The marine strategy framework directive (MSFD) contains an obligation for the member states to determine a marine strategy (action plan) within a certain period. In execution thereof, the Netherlands and Germany have already defined environmental targets incl. noise mitigation values for impulsiveness noise such as pile-driving noise.

4.2.1 Compliance in the Netherlands

Rijkswaterstaat as the Ministry of Infrastructure and Water Management is the regulatory and monitoring authority for offshore projects in the Dutch EEZ and has defined the following noise mitigation values to prevent injury caused by impulsiveness noise.

Any impulsiveness noise events – like the installation of the *N05-A* platform by impact pile-driving shall comply with the following underwater noise levels (Table 1). These noise mitigation values are defined for the maximum Sound Exposure Level $SEL1 = SEL_{max}$ in a distance of 750 m to the source:

Table 1: Seasonal noise mitigation values for impulsiveness noise based on the Sound Exposure Level ($SEL1 = SEL_{max}$) at 750 m of the noise source (here: pile-driving activity).

Tertial	Duration	Noise mitigation value [dB re µPa²s]
T1	January to May	162
T2	June to August	167
T3	September to December	169

4.2.2 Compliance in Germany

Two German Natura 2000 SAC: “Borkum Riffgrund” and “Nationalpark Niedersächsisches Wattenmeer” are located in close distances to the *N05-A* platform. Therefore, the potential impact on marine fauna shall be taking into account on the German side of the North Sea for these SAC either.

A Sound Exposure Level (SEL) of 160 dB and a zero-to-peak Sound Pressure Level ($L_{p,pk}$) of 190 dB in a distance of 750 m to the source are defined as noise mitigation values for impulsiveness noise entry to prevent injury. The 5 % percentile value of the Sound Exposure Level (SEL_5) per pile installation must comply with the 160 dB criterium. However, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (in German: Bundesministeruim für Umwelt, Naturschutz und nukleare Sicherheit, BMU) defined in 2013 also noise mitigation specifications to prevent a significant loss of habitat for marine mammals (reaction or disturbance of marine mammals based on impulsiveness noise entry). Based on that guideline it is not allowed that more than 10 % of the German EEZ or Natura 2000 SAC is polluted by impulsiveness noise events with the potential to significantly disturb harbor porpoises at any time. Based on the noise mitigation concept (BMU 2013) reactions and temporal habitat losses are expected in distances up to 8 km from pile-driving in case the general noise mitigation values of 160 dB for the Sound Exposure Level and 190 dB for the peak Sound Pressure Level are fulfilled in 750 m distance – corresponding with 140 dB Sound Exposure Level (SEL), So a habitat loss is the area of the habitat exposed by (SEL) values of 140 dB and more. Furthermore, during the marine mammal sensitive period from May to August not more than 10 % of the Natura 2000 Special Area of Conservation (SAC) shall be polluted by more than 140 dB_{SEL5} (BMU 2013) if Harbor porpoise reproduction is not a special conservation target of the Special Areas of Conservation. This is the case for the Special Area of Conservation (SAC) listed in Table 2. The areas of the Natura 2000 Special Areas of Conservation (SAC) and the distances to *N05-A* location are summarized in Table 2.

Table 2: Areas and distances to project location of German Natura 2000 Special Areas of Conservation.

Natura 2000 Special Area of Conservation	Area [km²]	Distance to *N05-A* [km]
Borkum Riffgund	625.189	4.551
Nationalpark Niedersächsisches Wattenmeer	2,766.301	14.633

4.3 Model description

The (standard-) model of the *itap GmbH* is an empirical model, 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 e. g. wall thickness, blow energy, diameter and soil composition (soil resistance) and water depth. However, 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 5 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 5, which 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. Therefore, the model is likely to be conservative.

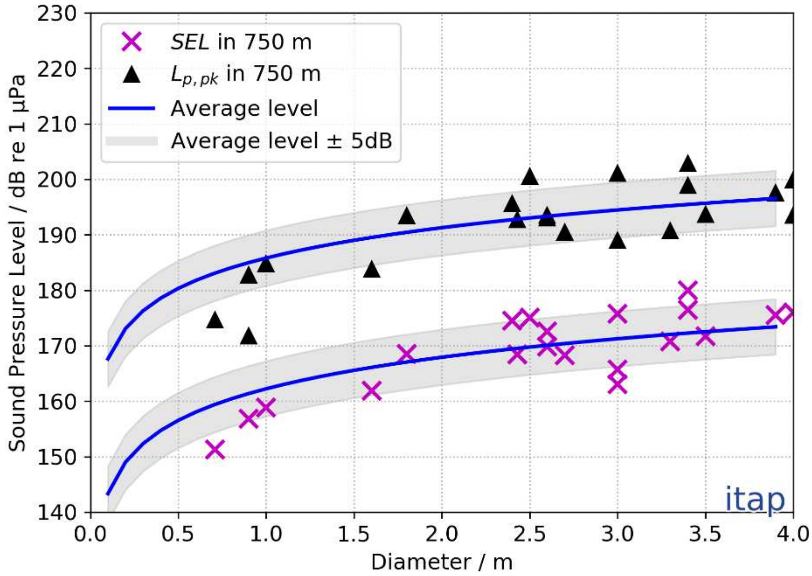

Figure 5: Measured zero-to-peak Sound Pressure Level ($L_{p,pk}$) and broadband 5 % exceedance Sound Exposure Levels (SEL_{05}) during unmitigated pile-driving construction works at a number of OWFs as function of the pile diameter.

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 found, 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 considerably influence the resulting sound pollution 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.

4.4 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 is based on the 5 % exceedance of the Sound Exposure Level (SEL_{05}) during one pile installation.

4.4.1 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.

The used blow energies were determined in cooperation with the client and are also based on the so far performed soil investigations. In order to achieve the final depth, maximum blow energy of the pile hammer (if necessary at all) will empirically only be applied for a short time to the end of a pile-driving.

An increase of the blow energy is required if a certain number of blows to achieve the penetration depth of e. g. 0.25 m is exceeded (risk of material fatigue due to too high blow rates).

The experiences from the practice show, that mostly lower blow energies are applied than predicted before in the "worst case".

4.4.2 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 and different hammers of the same type 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.

Based on experiences it is expected that a large hammer with reduced capacity will radiate slightly low noise into the water with a given same blow energy as a small hammer with full capacity (Bellmann, et al. 2020).

4.4.3 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 the construction field essentially consists of sand and a sand-clay mixture and the measurement data shown in chapter 4.3, Figure 5 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 5. For this reason, in the model, a frequency-independent safety margin for the soil conditions (ground coupling) is not necessary.

4.4.4 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 chapter 4.3 below are based on the broadband measuring data of different studies (Figure 5). However, sound propagation in the sea is highly frequency-dependent; see chapter 4.1. For this reason, estimations of the frequency composition of the respective source levels[2] have to be made for the calculations.

[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 6 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 60 Hz - 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 cut-off frequency for the steep fall-off at low frequencies depends on the water depth. The deeper the water, the lower the cut-off frequency. The water depth in the project area is 25.8 m, the cut-off frequency will be 32 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 6 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 ($L_{p,pk}$).

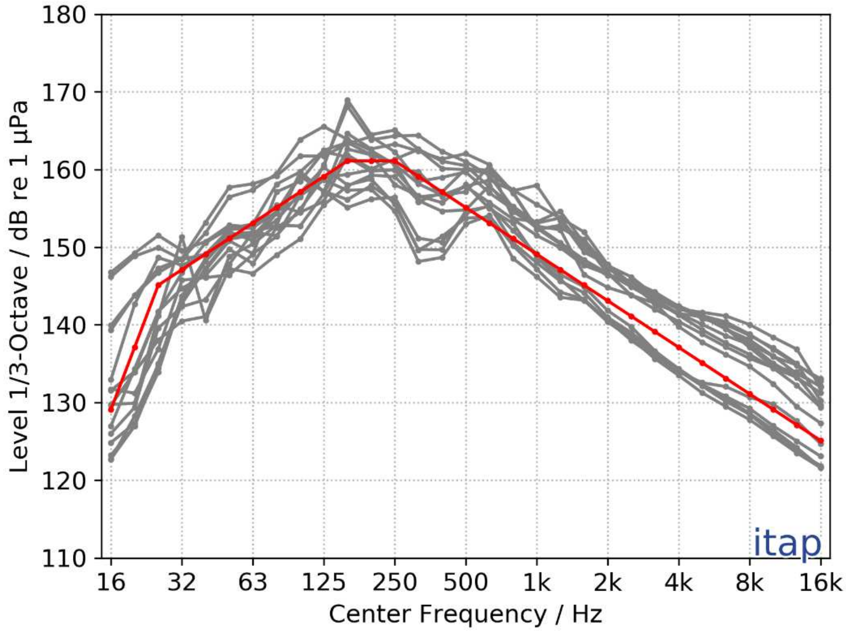

Figure 6: The model spectrum (red) estimated for piling noise, based on different measuring data (grey: measuring data) for skirt-piles.

4.4.5 Acoustic connections/couplings to the Jacket-structure

For the construction of Jacket-foundations, two different installation procedures are possible. The pre-piling and the post-piling procedure. With the pre-piling, first, the piles are inserted into the ground by a pile-driving template and afterwards, the Jacket-foundation is placed on the intended position. On the other hand, in the post-piling procedure, first, the Jacket-foundation is placed on the intendent position and afterwards, it is fixed to the ground with the driven piles.

From the acoustical point of view, both variants bear the risk that sound bridges can occur between pile and foundation structure or pile-driving template, whereby the vibrations of the pile are transferred to the foundation or the template. The consequence would be a higher sound input into the water due to rattling effects of the structure.

In order to consider possible acoustic connections/couplings, a safety margin of 2.5 dB needs to be added to the model for the piling noise emissions of the pin-piles. This addition is conservative and is considered to represent the worst-case conditions and based on experiences (Bellmann *et al.*, 2020).

4.4.6 Water depth

The water depth also influences the sound propagation in the sea. Below a certain cut-off frequency, however, a continuous sound propagation is not possible. The shallower the water, the higher this frequency is. Figure 4 in chapter 4.1 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, 2020). The water depth in the project area is approximately 25.8 m. This results in a cut-off frequency of 32 Hz for 25.8 m.

4.4.7 Pile length

For impact pile-driving two possibilities exist: For Monopiles the impact hammer is always above the sea surface and the pile length will always cover the full water column.

For Pin-Piles it might happen that the hammer is submerged towards the end of pile-driving (Lippert, et al. 2017). As a result, the sound radiating pile skin surface decreases continuously with the ongoing driving activity (Nehls und Bellmann 2015). In contrast, the hammer energy increases continuously throughout the piling sequence with increasing soil resistance (SRD-value). Generally, the evaluation-relevant level values increase continuously with increasing driving energy within the first 50 % to 65 % of the entire pile-driving, where usually 75 % to 80 % of the maximum driving energy is reached. At the end of pile-driving, the level values can be reduced by several dB despite a further increase of driving energy because of the reduced pile skin surface (Lippert, et al. 2017). Therefore, hammer energy and the sound radiating pile skin surface have to be regarded theoretically for a prognosis of evaluation-relevant level values to be expected. But there are also measurements with a constant SEL available where the radiating pile surface decreases and the blow energy increase during piling. In case a follower is used for the installation of Pin-Piles the stick-up length will increase significantly and thus reducing the impact of submerged hammering.

However, the embedded length of any pile in the seabed is highly correlated with the required blow energy to overcome the soil resistance. Therefore, the embedded length is not a linear independent parameter in the model.

An SEL example of a typical Monopile and Pin-Pile installation is shown in Figure 7.

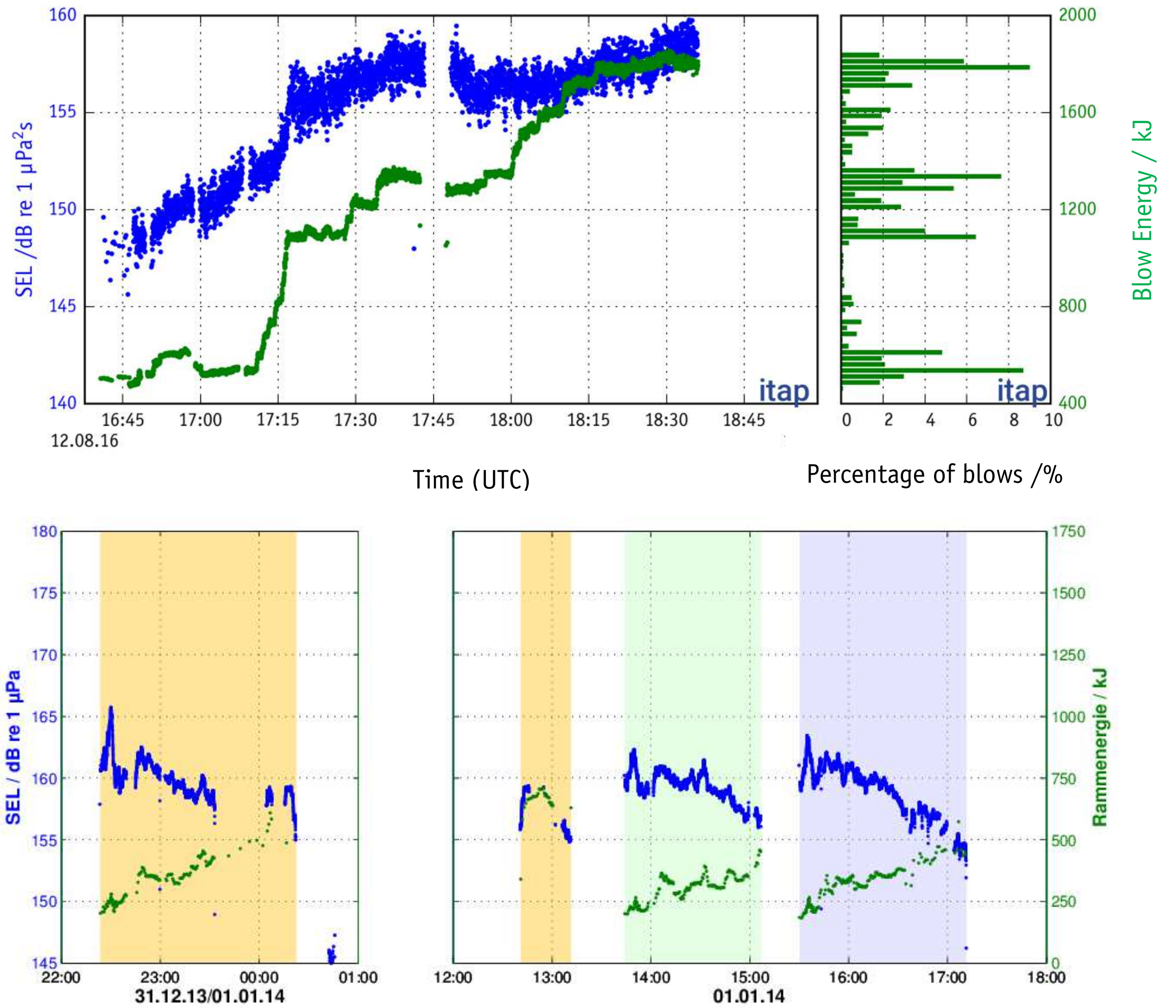

Figure 7 *Top: Sound Exposure Level (SEL) as a function of time (blue line) and the used blow energy (green line) for a typical monopile installation in the North Sea. Bottom: A possible example for a Jacket-installation with three skirt-piles (colored background marked the three different piles).*

4.4.8 Transmission loss

For modeling, Equation 14 is considered. 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 distances from the pile larger than the water depth, when the directly emitted sound from the pile is superimposed with the first reflections from the water surface and the sediment. Below 50 m from the pile, no plain wave field has formed within the water column, the noise level will be below the level calculated with Equation 14. In the model results, the noise level will be constant over the first 50 m from the pile.

4.4.9 Model requirements

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

Additionally, the *itap GmbH* is accredited for underwater noise predictions and measurements in accordance with the ISO 17025 (2018).

4.5 Calculation procedure

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

4.5.1 Step 1: Determination of SEL and $L_{p,pk}$ 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 with the requirements of the German measurement guidance (BSH 2011) and the international standard (ISO 18406 2017). 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. coupling effects, acoustic connections between pile and Jacket-structure.

4.5.2 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 (Bellmann, et al. 2020). Sound propagation in the ocean, however, is frequency-dependent, as discussed in chapter 4.1.

The spectral approaches for the piling noise at 750 m will be determined from empirical data (see chapter 4.4.4) and an approach for the Transmission Loss (TL) 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).

4.6 Model uncertainties

Both, the modeling of the “source strength“ or “source level“ of the pile-driving noise and the pile-driving analysis for the determination of the maximum blow energies as well as the modeling of the underwater noise propagation by applying Transmission Loss approaches (for instance the Transmission Loss according to Danish Energy Agency (2016) or Thiele & Schellstede; chapter 4.1) includes 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 Monopile 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 skirt-piles 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 5). 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. For pile diameter less than 1 m only a limited set of data sets is available in our empirical model. For such small pile diameter the uncertainty might be up to two decibels higher.

By considering the effective parameter “blow energy”, the uncertainty is clearly reduced. The comparison of the model predictions with real measuring data from 2012 until now shows an uncertainty of ± 2 dB (unpublished data from different projects) for the Sound Exposure Level in a distance of 750 m to the piling event with the tendency, that the *itap* model results with the input data “pile diameter” and “blow energy” leads to conservative metrics SEL and $L_{p,pk}$ in a distance of 750 m.

5. Modeling scenarios

5.1 Existing conditions

The water depth in the project area is approx. 25.8 m. For the forecast, skirt-piles with 2.743 m diameter and blow energies of 604 kJ, 845 kJ and 1,090 kJ and conductor-piles of 0.8 m in diameter and 90 kJ blow energy are considered. Differences in soil resistance (SRD-value) of the soil layer also result in different blow energies. 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. 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 on the cut-off-frequency caused by water depth (Jensen, et al. 2011).

The model does not consider any background level. Especially when considering a scenario including a mitigation system, some results can be below the background noise level.

5.2 Acoustically relevant input data

The following input data will be considered for the model:

Input data for the foundations	
- Foundation type:	skirt-pile, conductor-pile
- Pile diameter:	2.743 m, 0.8 m
- Water depth:	approx. 25.8 m (MSL) at *N05-A*
- Water condition:	Good intermixing of the water without a distinct sound velocity profile.
- Blow energy:	604 kJ, 845 kJ, 1,090 kJ for the Jacket skirt-piles, 90 kJ for the conductor-piles

Model assumption to calculate the source level:	
- Input parameter #1:	Pile diameter.
- Input parameter #2:	Blow energy: initial value (model internal parameter) 1,000 kJ for skirt-piles / 120 kJ for conductor-piles; 2.5 dB addition or deduction per duplication or halving of blow energy.
- Soil conditions:	No additions.
- Pile surface:	No deductions.
- Penetration depth:	No additions or deductions (see possible impact in chapter 4.4.3).
- Acoustic coupling	2.5 dB
- Transmission Loss:	According to Equation 14.
- Water depth:	Cut-off frequency 32 Hz (25.8 m)
- Model version:	1.03

6. Modeling results

Considering the model approaches in chapter 4, the following evaluation-relevant Sound Exposure Levels (SEL) and zero-to-peak Sound Pressure Levels ($L_{p,pk}$) are expected for different maximum blow energies at a distance of 750 m to the construction site:

For the model, the Sound Exposure Level (SEL) and zero-to-peak Sound Pressure Level ($L_{p,pk}$) are calculated separately by an empirical model (Model-Version: 1.03). The presented Sound Exposure Level (SEL) in Table 3 is related to the listed blow energy. This value represents the sound energy for every single blow by using this blow energy. However, pile driving usually requires several thousand blows with different pile driving energies. In addition, noise mitigation values do not refer to a single blow but to the level distribution during a complete pile driving. This means that the specified SEL values are identical to the maximum value (SEL_{max} = $SEL1$) to be maintained for a sequence, if the specified blow energy is identical to the maximum blow energy. For percentage exceedance levels, the specified SEL values are also equal to this if the percentage share of blows with maximum energy is greater than the exceedance share. If the noise mitigation value refers to a fixed average time, for example 30 s, the average Sound Exposure Level for 30 s (SEL_{30s}) is identical to the calculated values, provided the blow energy is constant over 30 s.

Table 3: Calculated unmitigated Sound Exposure Level (SEL_1) and unmitigated zero-to-peak sound pressure level ($L_{p,pk}$) in 750 m distance to the pile installations with different blow energies.

Pile type	Diameter [m]	Blow Energy [kJ]	SEL_1 in 750 m distance	$L_{p,pk}$ in 750 m distance
skirt-pile	2.743 m	604	171	194
skirt-pile	2.743 m	845	172	196
skirt-pile	2.743 m	1,090	173	197
conductor-pile	0.8	90	159	183

Figure 8 shows the Sound Exposure Level (SEL) during skirt-pile installation using 1,090 kJ blow energy as a function of distance. In the noise map below (Figure 9), the unmitigated Sound Exposure Level (SEL) is given with the pre-selected blow energy of 1,090 kJ. The areas for different Sound Exposure Level (SEL) values are shown in different colors.

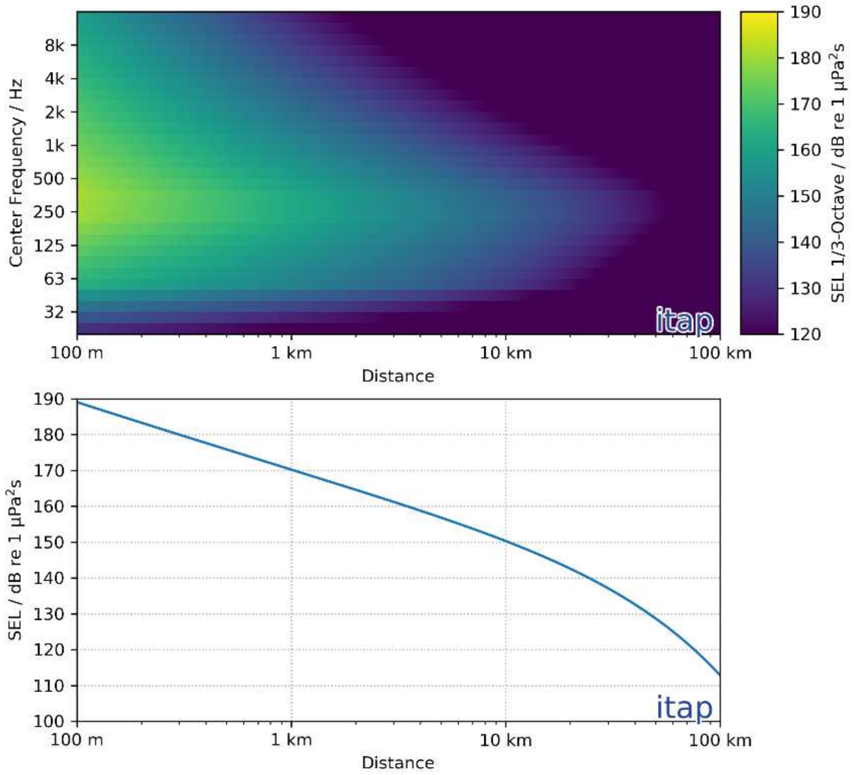

Figure 8: *Predicted SEL (unweighted) due to driving skirt-piles with a diameter of 2.743 m at a maximum blow energy of 1,090 kJ as a function of distance. The spectrogram on top shows the SEL divided in 1/3-octave components. On the y-axis, the frequency is listed and the x-axis shows the distance. The value of the unweighted spectrum 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 broadband values SEL.*

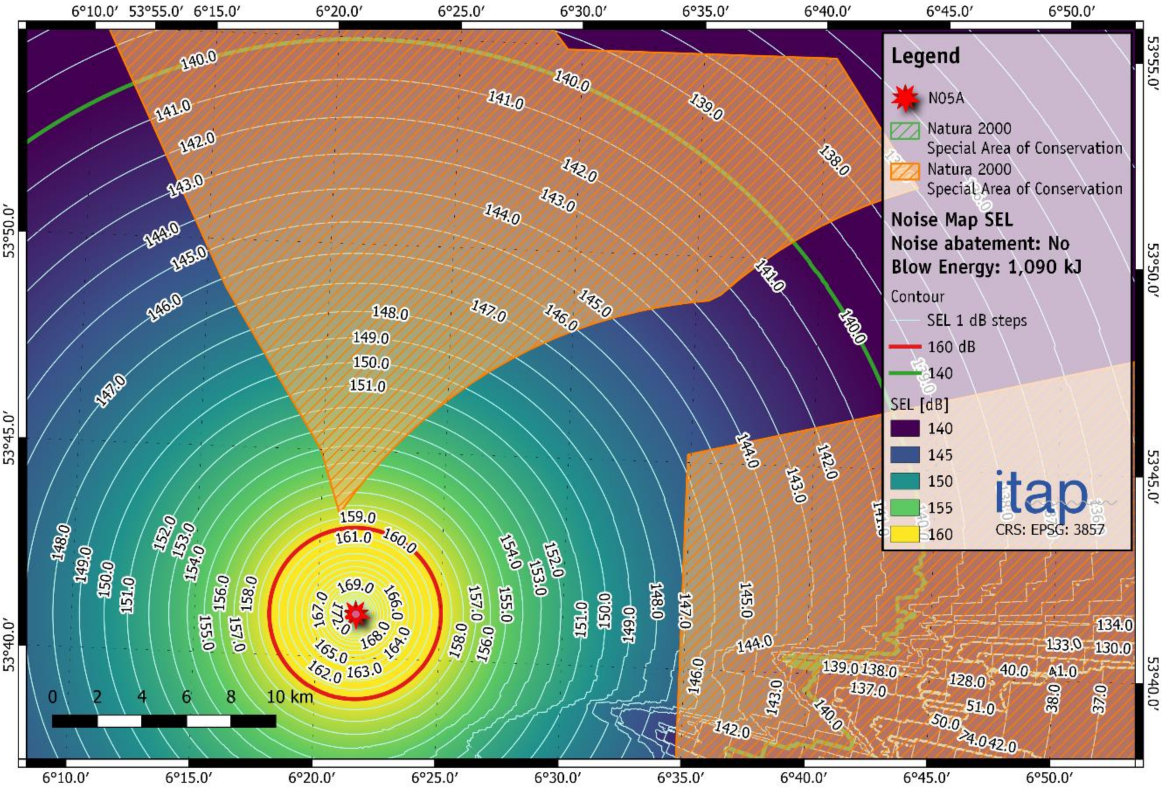

Figure 9: *Noise map for the unweighted SEL during the installation of a 2.743 m skirt-pile at the N05-A with a pre-selected blow energy of 1,090 kJ by without noise mitigation measures.*

7. Evaluation of unmitigated pile-driving to comply with German and Dutch noise mitigation values

A compliance with Dutch and German noise mitigation values (as described in chapter 4.2) for the *N05-A* platform installation is required. That means that on the Dutch side the maximum Sound Exposure Level ($SEL1$) shall not exceed the noise mitigation values listed in Table 4. Without application of any noise mitigation measures the expected Sound Exposure Level (SEL) will exceed these measures during skirt-pile depending on the season by 4 dB to 11 dB for the max. blow energy considered depending on season for the calculated scenarios (Table 4). Therefore, a noise mitigation concept is required.

Table 4: *Noise mitigation values ($SEL1 = SEL_{max}$) at 750 m of the impulsiveness noise source and expected exceedance by using a maximum blow energy of 1,090 kJ .*

Tertial	Duration	Noise mitigation value [dB re µPa²s]	Expected Exceedance for 1,090 kJ Blow Energy
T1	January to May	162	11
T2	June to August	167	6
T3	September to December	169	4

In 2022 the OWF *KASKASI II* will be installed by using vibro-piling in the period January till April. Impact pile-driving is only a back-up option. However, this OWF has to comply with the German guidelines and is more than 100 km distance to the relevant Natura 2000 Special Areas of Conservations (SAC). In summer 2022 the converter platform DolWin 6 will be installed by application of impact pile-driving. This project has also complied with the German regulations. This impact pile-driving will be in a distance of > 30 km to the SAC “Borkum Riffgrund” and > 50 km to the gas platform *N05*. Therefore, a habitat loss of more than 10 % of the German EEZ of the North Sea and the SAC “Borkum Riffgrund” can be excluded. Furthermore, these two offshore projects shall not be taken into account by the determination of habitat loss during the sensitive period from May to August.

Based on the underwater noise calculations the pile-driving activities at *N05* will comply with the general requirement of not polluting more than 10 % of the German EEZ of the North Sea and the Natura 2000 Special Areas of Conservation. But for the marine mammal sensitive season May to August the area which will be exposed by 140 dB during skirt-pile installation will exceed the 10% criteria for the Natura 2000 SAC “Borkum Riffgrund“ but for the Natura 2000 SAC “Nationalpark Niedersächsisches Wattenmeer“ in case a maximum blow energy of 1.090 kJ will be used. Therefore, also noise mitigation is required to comply with the German regulations for the sensitive period May to August.

Table 5: Exposed area and habitat loss of the Natura 2000 SAC "Borkum Riffgrund" based on BMU (2013) noise mitigation value.

Foundation type	Threshold level for SEL[dB]	criteria	Exposure area in Borkum Riffgund [km^2]	Habitat loss in Borkum Riffgund [%]
skirt-pile	140	significant disturbance	330.442	52.9
conductor-pile	140	significant disturbance	5.026	0.8

Table 6: Exposed area and habitat loss of the Natura 2000 SAC "Nationalpark Niedersächsisches Wattenmeer" based on BMU (2013) noise mitigation value.

Foundation type	Threshold level for SEL[dB]	criteria	Exposure area in Borkum Riffgund [km^2]	Habitat loss in Nationalpark Niedersächsisches Wattenmeer [%]
skirt-pile	140	significant disturbance	330.442	52.9
conductor-pile	140	significant disturbance	0	0

8. Noise mitigation

Impact pile-driving leads to impulsive noise emissions with high levels (so-called pile-driving noise), which could harm marine life (Lucke, et al. 2009). For the environmentally sustainable use of renewable energy sources at sea, it is therefore necessary to reduce this sound input into the water. Therefore, the seasonally different noise mitigation values for the Sound Exposure Level (SEL) are set by *Rijkswaterstaat (set in "Vergunning Wet Natuurbescherming" and "Ontheffing Wet Natuurbescherming")*, that have to be fulfilled at a distance of 750 m to the pile-driving construction site. The maximum Sound Exposure Level ($SEL1$) is relevant to observe the seasonal different noise mitigation values of 162 dB_{SEL} to 169 dB_{SEL} (see chapter 4.2.1Table 1), i. e. the $SEL1$ must be below these values depending on the month the construction work is performed and the maximum blow energy applied.

Hence, depending on the month the construction work is performed and the maximum used blow energy, noise mitigation measures must be planned for this project, that are able to reduce the pile-driving noise to comply with the noise mitigation value.

In general, noise mitigation can be achieved by the application of

- Noise Mitigation Systems (NMS), means to reduce the sound source level itself,
- 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 Federal Agency for Nature Conservation (BfN) for the first time in 2011 (Koschinski und Lüdemann 2011). In the following years, this study was updated twice (Koschinski und Lüdemann 2013) and (Koschinski und Lüdemann 2019). In Verfuss *et al.* (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.

8.1 Noise Mitigation System (NMS)

A robust and reliable possibility for reducing the source level during pile-driving 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, van der Par und Bellmann 2014) by applying “noise-optimized” pile-driving procedures with high blow rates and blow counts as well as low energy. Typically, for such a "noise-optimized" pile-driving, a large hammer of the latest generation is used by 50 % to 60 % of its capacity (Bellmann, et al. 2020).

The application of a "noise-optimized" pile-driving procedure significantly depends on the soil resistance, which is mostly highly depending on the penetration depth; the higher the penetration depth, the higher the blow energy usually must be. Furthermore, the application of the "noise-optimized" pile-driving procedure must be checked carefully before construction regarding pile fatigue, soil resistance and piling duration; means, this noise mitigation system is not applicable in all pile-driving projects.

The sound reduction potential of "noise-optimized" pile-driving procedures is currently estimated at several decibels and is mostly used in combination with a real-time (online) underwater noise monitoring at 750 m.

However, new impact hammer techniques are currently under development like the *Menck* Noise Reduction Unit (MNRU), *IHC* PULSE or the Blue-Piling hammer. These new hammer techniques try to reduce the peak amplitude of the force transmission between hammer and pile and to prolong the duration of each single strike. Currently, these new noise mitigation systems are under construction or development and no applications under offshore-conditions were performed, so that no reliable predictions regarding the overall noise reduction potential can be given now. However, manufacturer points out that the achievable overall noise reduction might be several decibels.

8.2 Noise Abatement Systems (NAS)

At present, noise reductions for the SEL of up to 15 dB are possible by using a single NAS (Bellmann *et al.*, 2020) and by applying a combination of two NAS, it was possible to achieve noise reductions of 20 dB in water depths of up to 40 m and moderate currents (≤ 0.75 m/s). The overall reduction of each NAS significantly depends on technical-constructive factors such as foundation type and site-specific factors as for example water depth. Therefore, all NAS shall project-specifically be adapted.

The achieved overall noise reduction of a single NAS or combinations of two NAS show variances of several decibels, especially by applying combinations of NAS, even when technical problems or malfunctions of the applied NAS can be excluded (Bellmann, et al. 2020). Nevertheless, experiences showed, that not project-specifically optimized NAS or technical problems significantly reduce the overall noise reduction (Bellmann, et al. 2020). Furthermore, the overall noise reduction is highly frequency-dependent. Thus, the resulting (single-number) sound reduction depends on the spectral composition of the unmitigated piling-driving noise (unmitigated pile-driving spectrum). An increase of the overall prediction uncertainty of several decibels for mitigated pile-driving is likely due to the uncertainties by predicting the unmitigated spectrum as well as the achievable noise reduction of the applied NAS.

8.2.1 Single or double Big Bubble Curtains (BBC and DBBC)

The single (BBC) and double Big Bubble Curtain (DBBC) is one of the most practicable and most frequently used NAS (> 600 applications). Additionally, the BBC-system is the only far-from-pile noise mitigation measure. Two funded R&D-projects were conducted to understand the main influencing factors of a Big Bubble Curtain on the overall noise reduction (Nehls und Bellmann 2015); (Bellmann, et al. 2020).

Experiences show, that by applying a BBC-system, the overall noise reductions for the Sound Exposure Level (SEL) significantly depend on the system configuration, current and water depth. With increasing water depth, the performance of a BBC slightly decreases. Experiences showed, that noise reductions of up to 18 dB (maximum measured noise reduction) in 40 m water depth are possible by using an optimized "Double Big Bubble Curtain" (DBBC) in the Baltic Sea with very low current (Bellmann *et al.*, 2020). The averaged noise reduction of an optimized DBBC with moderate current ($\leq$ 0.75 m/s) mostly ranged between 15 dB and 16 dB. For higher currents, the likelihood of drifting effects of the bubble curtain is extremely high, which means the overall reduction becomes direction-dependent. For shallower water, the overall noise reduction might increase slightly.

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 $\geq$0.5 m^3/(min*m) is currently state-of-the-art for water depths up to 40 m (Bellmann *et al.*, 2020). 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. Nevertheless, applying only a single BBC instead of a double BBC will reduce the overall noise reduction by 2 to 4 dB. Hereafter, the minimum BBC system requirements from already closed pile driving projects are listed (Bellmann, et al. 2020).

System configurations for an optimized single / double Big Bubble Curtain:	
hole size (diameter) and hole spacing:	1 - 2 mm all ca. 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
typical nozzle hose diameter:	currently 100 mm (limits the overall length of a single BBC to 1,000 m due to air flow dynamic boundaries)
total length of nozzle hoses:	≤ double: 1,800 m (single: < 1,000 m)
overall life-time of each nozzle hose is limited:	currently best practice < 80 - 100 applications
pressure of the compressed air inside the nozzle hoses:	2 – 3 bar higher than the static pressure of the water outside; -> in water depth of up to 30 m an operational pressure of the compressors shall be minimum 8.5 to 10 bar[3]
regular maintenance of the applied nozzle hoses	
no turbulence-producing obstacles in the nozzle hoses	

The achieved noise reduction is independent of the foundation design (Monopile of Jacket construction). The exact adaptation of a (D)BBC to local conditions is not part of an underwater noise forecast. Due to the high variances caused by different system configurations, it is not possible to make accurate predictions about the expected noise reduction. In order to achieve the maximum noise reduction a continuous underwater noise monitoring is recommended so that errors can be corrected immediately, and new adjustments can be made quickly.

8.2.2 Grout Annulus Bubble Curtain (GABC)

In the construction of Jacket-structures in the post-piling-procedure, the piles are driven through so-called pile-sleeves.

There are two possible types of pile-sleeves:

[3] 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 decreasing 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 always.

(i) The pile-sleeve is an inherent part of the Jacket-construction and extends from the lower edge, i. e. the seabed, to the upper edge above the water surface of the total Jacket-structure, i. e. the piles are always driven above the water surface and the pile-sleeve covers the entire water column.

(ii) The pile-sleeve is only several meters high and is rigidly connected to the Jacket-structure at the lower edge. Alternatively, instead of the Jacket-construction, a pile installation frame can be used. In the course of the pile-driving, the piles (Pin-Piles) are thus driven below the water surface and end only a few meters above the seabed resp. the pile-sleeve.

With the two methods described, compressed air can be introduced into the gap between pile and pile-sleeve. The compressed air is usually introduced via the permanently installed pipelines for the cementation of the piles (grouting lines), which are mostly located at the bottom of the pile-sleeve. The air bubbles ascend in the gap between pile and pile-sleeve to the top. The gap thus fills with an air-water-mixture.

Experiences have shown, that due to drifting effects, the noise-reducing effectiveness for Pin-Piles is in the range of a few decibels (Bellmann, et al. 2020). An exact evaluation of a GABC for Pin-Pile installation in accordance with DIN SPEK 45653 (2017) is not possible since this GABC was always applied in combination with a single or double BBC; only for several minutes of pile-driving the GABC was turned off and the measured levels at 750 m increased slightly. With pile-sleeves from the seabed to the water surface (so-called Main-Piles where no submerged hammering happened), a noise reduction of up to 7 dB can be achieved (Bellmann, et al. 2020). The main influencing factor of the achievable overall noise reduction are the sleeve height and the current. Because the raising bubbles will be drifted away by current above the pile sleeve. In case of pile sleeves with a stick-up length of several meters above seabed the overall noise reduction of a GABC is limited by drifting effects above the pile sleeve and only some decibel noise reduction is achievable.

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

At this point, it should be noted, that the noise reductions of each individual (separately) applied noise abatement system do not add up in the (single-digit) sum, but are spectrally summed up, i. e. two noise abatement systems of 13 dB noise reduction each for individual application do not result in a total of 26 dB noise reduction when applied simultaneously, but in a significantly lower total noise reduction.

For the actual project a combination of Grout-Annulus Bubble Curtain and single Big Bubble Curtain is one possible option. Experiences by application of a BBC and GABC for skirt-piles showed that the overall achievable noise reduction might increase by 2 to 3 dB compared to only apply a single BBC. Means the combination of BBC and GABC will achieve more or less the same overall noise reduction than a DBBC.

8.3 Level values using pre-selected noise mitigation concepts

Table 7 shows the predicted Sound Exposure Level (SEL) and zero-to-peak Sound Pressure Level ($L_{p,pk}$) values using noise mitigation measures to reduce the pile-driving during skirt-pile noise in the water. For the installation of the conductor-piles no noise mitigation is required. Either a double Big Bubble Curtain (DBBC) or a Grout Annulus Bubble Curtain in combination with a single Big Bubble Curtain as described in chapter 8.2.1 and 8.2.2 is assumed, resulting in an overall noise reduction of -16 dB for the DBBC and -15 dB for the combination of single Big Bubble Curtain and Grout Annulus Bubble Curtain (BBC+GABC) for the SEL. The reduction of the zero-to-peak level is approx. 5 dB to 6 dB higher.

Table 7: Calculated mitigated Sound Exposure Level (SEL) and zero-to-peak Sound Pressure Level ($L_{p,pk}$) in 750 m distance to the skirt-pile (diameter of 2.743 m) installation using a BBC+GABC or a DBBC with different blow energies.

Blow Energy [kJ]	NAS	SEL_1 in 750 m distance	$L_{p,pk}$ in 750 m distance
604	BBC+GABC	156	174
845	BBC+GABC	157	176
1,090	BBC+GABC	158	177
604	DBBC	156	174
845	DBBC	157	175
1,090	DBBC	158	176

In Table 8 and Table 9 the exposed area of the Natura 2000 Special Areas of Conservations close to pile-driving are determined. In Figure 10 the relevant Sound Exposure Level (SEL_5) as function of bathymetry is shown for a maximum blow energy of 1,090 kJ and the application of a double Big Bubble Curtain (DBBC) or combination of single BBC and GABC.

By application of a double Big Bubble Curtain (DBBC) or a combination of single Big Bubble Curtain and Grout Annulus Bubble Curtain (GABC) the mitigated pile-driving activity at the gas platform *N05* will comply with the Dutch regulation regarding avoidance of injury and with the German regulations regarding significant habitat loss in Natura 2000 Special Areas of Conservations in the marine mammal sensitive period May to August.

Table 8: Exposed area and habitat loss of the Natura 2000 Area of Conservation "Borkum Riffgrund" for disturbance criteria by using a double Big Bubble Curtain (DBBC) and a blow energy of 1,090 kJ.

Threshold level for SEL[dB]	criteria	Exposure area in Borkum Riffgund [km^2]	Habitat loss in Borkum Riffgund [%]
140	habitat loss between May and August	3.434	0.55

Table 9: Exposure Area and habiltat loss of the Natura 2000 Area of Conservation "Nationalpark Niedersächsisches Wattenmeer" for injury and disturbance criteria criteria by using a double Big Bubble Curtain (DBBC) and a blow energy of 1,090 kJ.

Threshold level for SEL[dB]	criteria	Exposure area in Nationalpark Niedersächsisches Wattenmeer [km^2]	Habitat loss in Nationalpark Niedersächsisches Wattenmeer [%]
140	habitat loss between May and August	0	0

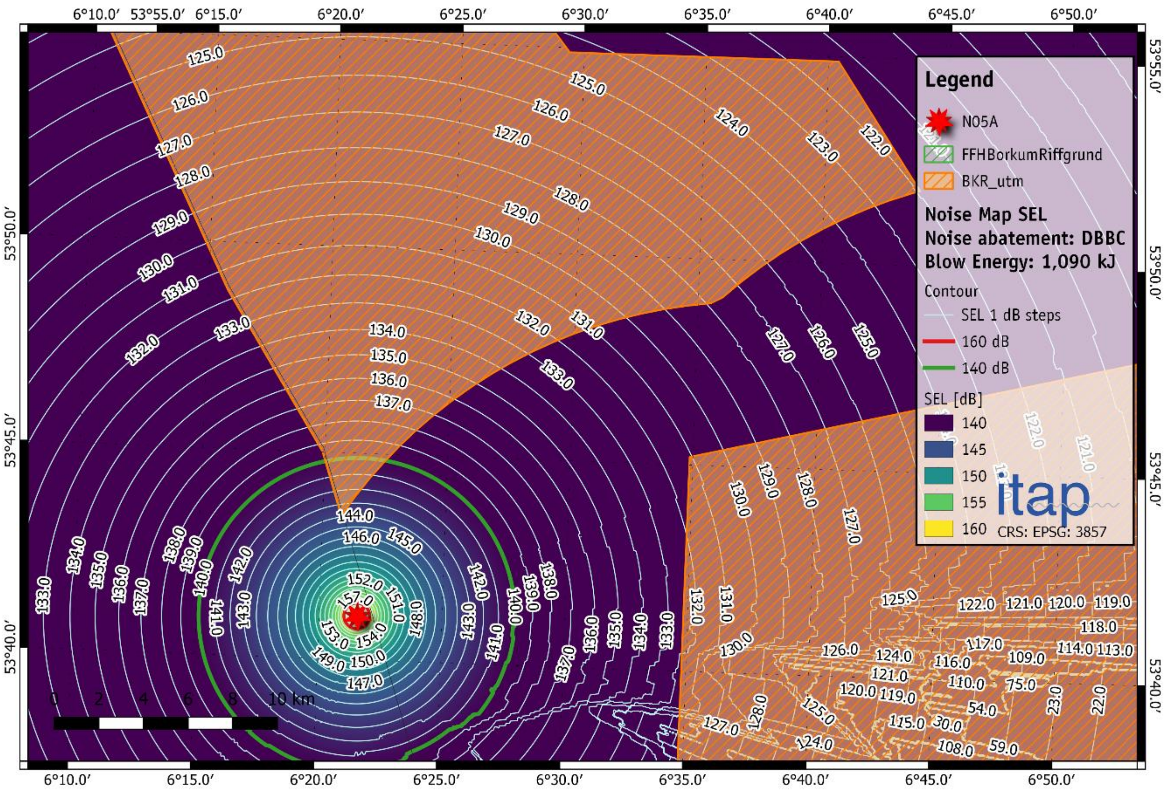

Figure 10: *Noise map for the unweighted SEL during the installation of a 2.743 m skirt-pile at the N05-A with a pre-selected blow energy of 1,090 kJ by using a double Big Bubble Curtain (DBBC).*

For the pile-driving, seasonal noise mitigation values are defined for offshore-supply stations in the Netherlands for the Sound Exposure Level in 750 m to the piling. In the first Tertial from January to May inclusive (T1), the $SEL1$ (corresponding to the maximum SEL) must not exceed 162 dB, from June to August inclusive (T2), the $SEL1$ must not exceed 167 dB and from September to December inclusive (T3), the $SEL1$ must not exceed 169 dB.

Depending on the construction period and the maximum blow energy used, the application of noise mitigation measures is required to comply with the defined noise mitigation values determined by the responsible authority *Rijkswaterstaat*.

A compliance of the Dutch noise mitigation values is expected for both considered noise mitigation measures.

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