Technical Report

Underwater noise during percussive pile driving: Influencing factors on pile-driving noise and technical possibilities to comply with noise mitigation values

ERa Report

Experience report on piling-driving noise with and without technical noise mitigation measures

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List of abbreviations

AIS	Automatic identification system
BBC	Big Bubble Curtain
BfN	Bundesamt für Naturschutz (engl. Federal Agency for Nature Conservation)
BImSchG	Bundes-Immisionsschutzgesetz (engl. Federal Control of Pollution Act)
BMU	Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (engl. Federal Ministry for the Environment, Nature Conservation and Nuclear Safety)
BNatschG	Bundes-Naturschutzgesetz (engl. Federal Nature Conservation Act)
BORA	Berechnung von Offshore-Rammschall (R&D-project)
BSH	Bundesamt für Seeschifffahrt und Hydrographie (engl. Federal Maritime and Hydrographic Agency)
CAU	Christian-Albrechts-Universität zu Kiel
CTD	Conductivity, Temperature and Depth
dB	Decibel
DBBC	Double Big Bubble Curtain
DIN SPEC	Deutsches Institut für Normung e. V. (DIN), DIN-Specification
DP	Dynamic Positioning
DWD	Deutscher Wetterdienst (engl. German National Meteorological Service)
ESPOO	Convention on Environmental Impact Assessment in a Transboundary Context
EEZ	Exclusive economic zone
EIA (UVP)	Environmental Impact Assessment (german Umweltverträglichkeitsprüfung)
EIAA (UVPG)	Environmental Impact Assessment Act (german Gesetz über die Umweltverträglichkeits-prüfung)
ESRa	Evaluation von Systemen zur Rammschallminderung an einem Offshore-Testpfahl
et al.	and others (lat. et alia)
FAD	Free Air Delivery
FEP	Side Development Plan (german Flächenentwicklungsplan)
FFH-RL	Fauna and Flora Habitat Directive
f_g	Limiting frequency
FKZ	Förderungskennzeichen (engl. support code)
GABC	Grout Annulus Bubble Curtain
HELCOM	Baltic Marine Environment Protection Commission – Helsinki Commission
Hz	Hertz
HSD	Hydro Sound Damper
i. a.	among other things (lat. inter alia)
IEC	International Electrotechnical Commission
IHC -NMS	Noise Mitigation Screen der Firma IHC-IQIP bv
ISD	Institut für Statik und Dynamik der Leibniz Universität Hannover
ISO	International Organization for Standardization
itap (GmbH)	Institut für technische und angewandte Physik GmbH
k	Ausbreitungskonstante (für die dt. AWZ der Nord- und Ostsee überschlägig k = 15)
kHz	Kilo-Hertz
kn	Knots
LAT	Lowest Astronomical Tide
L_E / SEL	Sound Exposure Level
$L_{p,pk}$	zero-to-peak Sound Pressure Level
LUH	Leibniz Universität Hannover

MarinEARS	Marine Explorer and Registry of Sound (specialist information system for underwater noise and national noise-register for the notification of impulsive noise events in the German EEZ of the North- and Baltic Sea to the EU according to the MSFD)
MSFD (MSRL)	Marine Strategy Framework Directive (in german Meeresstrategie Rahmenrichtlinie)
NAS	Noise Abatement System
NavES	Environmentally sustainable development at sea (german Naturverträgliche Entwicklung auf See, R&D-project)
OSPAR	Oslo Paris Convention
OWTG	Offshore Wind Turbines Generator
OWF	Offshore Windfarm
PDA	Pile-Driving Analysis
PtJ	Projektträger Jülich (Forschungszentrum Jülich)
R&D	Research & Development
SL	Sensation Level
SNR	Signal-to-Noise Ratio
SPL	Sound Pressure Level
TL	Transmission Loss
TTS	Temporal Threshold Shift
TUHH	Technische Universität Hamburg Harburg
WTD 71	Wehrtechnische Dienststelle 71 (engl. technical center of the German armed forces)
Z	characteristic acoustic impedance

1. Summary

1.1 Relevance of the study

The use of renewable energy sources at sea is growing rapidly in Europe, including Germany, accelerated by the Renewable-Energy-Process after 2011. However, the demand for renewable energies must go along with an awareness of sustainability aspects, especially for the protection of marine ecosystems. Among other ecological issues, the underwater noise emissions have moved into focus, since the most offshore foundations are anchored in the seabed with the impact pile-driving procedure. This noise-intensive installation method leads to impulsive noise emissions (so-called pile-driving noise), which could harm the marine life (e. g. 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.

There are currently 18 offshore wind farms (OWF) in operation in the German Exclusive Economic Zone (EEZ), five more OWFs are under construction, with the noise-intensive installation phase of the foundations for the Offshore Wind Energy Turbines (OWET) already completed, and some OWFs are in the planning stage to achieve the expansion targets. Furthermore, re 35 substations, converter platforms and measurement platforms, like *FINO 1* to *FINO* 3 have been installed by now.

Based on the Marine Strategy Framework Directive (MSFD, 2008), the „Good Environmental Status" (GES) must be defined and guaranteed for European waters on a national, as well as on a regional basis for the respective indicator species. Other, non-European countries are also striving for a environmentally sustainable expansion of renewable energy sources, so that the handling and the reduction of impulsive noise input has long since become an international issue.

The harbour porpoise (*phocoena phocoena*) is the only whale species regularly occuring in German waters of the North- and Baltic Sea. For orientation under water, search for food resources and communication, the harbour porpoise uses an echo sounding system and therefore reacts sensitively to the increase of ocean noise. For these reasons, this species is considered a key species in the German North- and Baltic Sea in the context of the evaluation of anthropogenic noise input into the water.

The Federal Maritime and Hydrographic Agency (BSH) is the regulatory and monitoring authority for offshore projects in the German EEZ. Following the precautionary principle BSH established in 2008 for the first time worldwide a dual noise mitigation value criterion of 160 dB_{SEL} (to be met by the Sound Exposure Level) and 190 $dB_{Lp,pk}$ (to be met by the zero-to-peak Sound Pressure Level). The noise mitigation values at activity level were based on scientific advice given by the Federal Environment Agency (UBA) and on results from research projects. These noise mitigation values must comply at a distance of 750 m from the point of emission during pile-driving works. In 2013, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) has issued the noise mitigation concept for the harbour porpoise in the German North Sea, in which compliance with the noise mitigation values and a habitat approach to avoid and minimize cumulative effects are pursued.

1.2 Data and main objectives of the study

Up to the end of 2019, 1,447 foundation structures with a total of more than 2,400 piles (monopiles but also skirt piles) were anchored to the seabed in the German Exclusive Economic Zone (EEZ) of the North- and Baltic Sea, using the percussive pile-driving procedure. Since 2011, technical Noise Abatement Systems are applied serially for all percussive pile-driving works in German waters to comply with the above-mentioned noise mitigation values. It turned out, that in the years 2011 up to and including 2013, the noise mitigation values could not be reliably complied. Therefore, further research- and development (R&D) work was necessary with regard to technical noise mitigation. The german federal government has funded several R&D joint projects with the participation of industry for the development of Noise Abatement Systems (NAS). Finally, offshore-suitable Noise Abatement Systems were available from 2014, which led to a compliance with the noise mitigation values. However, it is to the credit of the offshore wind energy industry, who supported and developed the technical Noise Abatement Systems. The initial difficulties were mainly due to a lack of offshore-suitability and reliability of the Noise Abatement Systems available on the market. Since 2014, it has been possible to further develop several technical Noise Abatement Systems to state-of-the-art systems, with which the noise mitigation values can reliably be maintained in the German EEZ of the North- and Baltic Sea.

In addition, a standard monitoring of the noise input into the water was performed in accordance with the measurement specifications of the BSH (BSH, 2011; BSH, 2013a) and the StUK4 (BSH, 2013b). From the monitoring, comprehensive measurement data as well as evaluation-relevant accompanying information of the respective construction projects were collected in standardized form. Based on this information, a technical-analytic specialist information system for underwater noise (MarinEARS)[1] was developed and tested in the course of the R&D project NavES[2] under the leadership of the BSH, which is in operation since 2016. Thus, a large data set of processed underwater noise measurement data including extensive accompanying information is available in a standardized form.

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

[2] NavES: Nature-compatible development at sea, supported by the BMU and conducted by the BSH.
Phase 1: 10/2014 until 09/2015; Phase 2: 10/2015 until 12/2018; Phase 3: 10/2016 until 12/2019.

This technical report documents the cross-project analysis of all 21 pcs OWF construction projects including Offshore Supply Stations (OSS) and converter platforms of the years 2012 to 2019 from the German Exclusive Economic Zone (EEZ) of the North- and Baltic Sea. This report focuses on the technical Noise Abatement Systems and Noise Mitigation Measures, which have already been used throughout (series application) the construction of at least one complete OWF and have proven to be offshore-suitable and robust.

The aim of the report is to give an overview of site-specific and technical-constructional characteristics of noise generation and transmission due to percussive pile-driving as well as the necessary technical solutions by means of Noise Mitigation Measures to comply with the noise mitigation values.

On the one hand, the cross-project state of knowledge shall be made accessible for the environmental assessments carried out by authorities. On the other hand, it provides a cross-project, comprehensive and up-to-date knowledge data basis to enhance planning reliability with regard to the development of noise mitigation concepts for future construction projects by the industry.

1.3 Cross-project findings regarding percussive pile-driving noise and the application of Noise Abatement Systems

Technical-constructive influencing factors: The main factor of noise input during foundation works by means of impact pile-driving procedure is the noise source itself, i. e., the impact hammer comprising the hammer type and the hydraulic control resp. the applied pile-driving procedure. Added to this is the foundation design. In particular, by limiting the energy used and selecting the blow repetition frequency as well as the number of single strikes per defined embedding depth, the pile-driving procedure to be applied can eminently reduce the total noise emission (noise-optimized pile-driving procedure). In addition, the foundation design can also be varied project-specifically within certain limits with regard to compliance with the noise mitigation values. Thus, the technical-constructive influencing factors also represent a fundamental possibility of noise mitigation measures, in order to have a lasting effect on the compliance with the required noise mitigation values.

Site-specific influencing factors: Furthermore, site-specific influencing factors for the noise input into the water and for its propagation in water are also important. Thus, i. a., the seabed and the water depth or bathymetry have a considerable influence on the amplitude of the measured pile-driving noise. Usually, such influencing factors cannot be changed or influenced.

With regard to the monitoring of the noise input, the deployment height of the hydrophones in the water column must always be considered in the analyses. Measurements in the lower half of the water column show significantly higher levels than near the water surface.

Noise Abatement Systems: By using technical Noise Abatement Systems, the impact pile-driving noise already present in the water can be reduced. It turned out that the design of the foundation of OWETs or OSS foundation structure as a whole and especially the pile design also has an impact on the appropriate choice and the performance of Noise Abatement Systems.

As monopile foundations are currently the most frequently used foundation type, all technical Noise Abatement Systems were initially developed and designed for monopiles. A distinction is made between near-to-pile and far-from-pile Noise Abatement Systems.

In contrast, there are only a few Noise Abatement Systems, that are also suitable for the installation of Jacket-foundations. A major limitation in the selection of Noise Abatement Systems is due to the fact, that in multi-legged constructions (Jacket, Tripod, Tripile), several skirt-piles per foundation must be anchored to the seabed at a defined distance from each other. Thus, the skirt-piles are either driven through the existing Jacket-or Tripod-construction or alternatively a pile installation frame is used. Both possibilities considerably limit the application for near-to-pile Noise Abatement Systems.

Robust and offshore-suitable Noise Abatement Systems: In the last eight years, three Noise Abatement Systems have been successfully deployed in German waters under real offshore conditions in series operation, as a single application or in combination of near-pile and far-pile systems:

- aBig Bubble Curtain of several providers in single and double design (single Big Bubble Curtain – BBC; double Big Bubble Curtain – DBBC) in a distance of at least 60 m around the piling position (far-from-pile Noise Abatement System); care must be taken to ensure an optimum deployment of the BBC-system configuration,
- a pipe-in-pipe Noise Abatement System of the company *IHC IQIP bv* (noise mitigation systems (IHC-NMS)) as near-to-pile Noise Abatement System and
- a Hydro Sound Damper (HSD) of the company *OffNoise Solutions GmbH* also as near-to-pile Noise Abatement System.

Other technical Noise Abatement Systems have been developed as prototypes and were sporadically tested under offshore conditions or are still under development. However, these systems are currently not yet ready for a series application during the foundation works of a complete OWF or were not applied so far in the German EEZ in series.

Noise mitigation during monopile installations: BBC- und IHC-NMS systems could successfully be applied in the North Sea as single Noise Abatement Systems in water depths up to 25 m, in sandy soils and with monopile diameters up to 6 m, depending on the blow energy used. However, the near-to-pile HSD-system was developed especially for the noise abatement in the low frequency range and was always applied in combination with a single or double BBC-system.

For projects at locations, where the water depth was greater than 25 m and the pile diameter was mostly ≥ 6 m, a combination of two Noise Abatement Systems was used. The combined systems used included so far a BBC-system in the far field (in single or double design) and an IHC-NMS or HSD-system near the pile.

Noise mitigation during the installation of Jacket- or Tripod-constructions: Until now, only an optimized, single or double BBC was applied for Jacket-constructions. In a few cases, the DBBC was combined with a bubble curtain system near the pile for large water depths (Grout Annulus Bubble Curtain, GABC; small bubble curtain). Due to the usually much smaller pile diameters, the German noise mitigation criteria for water depths of up to 40 m and a noise-optimized pile-driving procedure could thus be met.

In the following, the three offshore-suitable Noise Abatement Systems are briefly described. For each of these Noise Abatement Systems, characteristics and relevant information are also summarized in Appendix A.

Big Bubble Curtain DBBC / BBC: The Big Bubble Curtain is a far-from-pile Noise Abatement System, which was most frequently applied in OWF construction projects so far. Experience with an optimized Big Bubble Curtain (BBC) shows, that the technical design and the components of the BBC-system directly influence the functionality of the Noise Abatement System and thus decisively determine the effectiveness of the noise reduction. The nozzle- and supply air hoses as well as the volume of compressed air incl. the type of the compressors belong to the main components. The deployment method of the nozzle hoses on the seabed regarding the form and the deployment precision as well as the distance to the pile-driving location are also essential for the achieved noise reduction at sea. Moreover, when a Big Bubble Curtain is used, there are always drifting effects due to the prevailing current, which can be compensated by deploying the bubble curtain system with a larger distance to the foundation in current direction at currents of up to 0.75 m/s (corresponds to approx. 1.5 kn). Furthermore, the achieved noise reduction in current direction decreases considerably. It also showed, that due to the static counter-pressure, the noise reduction steadily decreased with increasing water depth. The differences between an optimized single and an optimized double BBC with similar system configurations were around 3 dB, independent of the water depth. Noise reductions of up to 16 dB were achieved by means of an optimized, double Big Bubble Curtain (DBBC) at 40 m water depth.

With the application of an optimized DBBC-system, the compliance of the German noise mitigation values for Jacket-constructions up to 30 m water depth could be achieved. During monopile installations in very flat water (≤ 25 m), the noise mitigation values could already be observed at small pile diameters by likewise applying only an optimized DBBC-system, so that a near-to-pile Noise Abatement System was not necessary.

Thus, based on the experiences with the application of Big Bubble Curtain systems the minimum requirements were specified. According to the present knowledge, these requirements must be fulfilled in order to ensure an optimum noise reduction during foundations works with the impact pile-driving procedure.

The applications of the BBC- and DBBC-system in the German EEZ of the Baltic Sea to date show a slightly higher noise reduction compared to the applications in the North Sea. The primary cause therefore is, that the current in the Baltic Sea is mostly significantly lower than in the North Sea and thus, no or only very low drifting effects do occur.

Noise Mitigation Screen (IHC-NMS): Up to date, the IHC-NMS as near-to-pile Noise Abatement System was successfully applied several hundred times. The experiences with the IHC-NMS yield noise reductions in the range of 13 to 17 dB up to a water depth of 40 m and the current of less than 0.75 m/s. During the applications of the IHC-NMS of the latest generation in the years 2018 to 2020 with pile diameters of up to 8 m, the noise reduction was 15 to 17 dB. For pile diameters < 6 m in sandy soils and water depths < 25 m, the IHC-NMS in combination with a noise-optimized pile-driving procedure could comply with the German noise mitigation values as single technical Noise Abatement System. For pile diameters ≥ 6 m, the IHC-NMS was applied in combination with an optimized (D)BBC-system.

The advantage of the IHC-NMS is, that it serves not only as a Noise Abatement System, but also as a pile-guiding-system. Furthermore, the system can be used to measure the inclination of the pile.

The IHC-NMS has not yet been used in the German EEZ of the Baltic Sea.

Frequency-dependent noise reduction: Both, the (D)BBC and the IHC-NMS show a frequency-dependent noise reduction. The noise reduction in the frequency range < 250 Hz is lower than at higher frequencies (> 1 kHz) where even noise reductions of > 20 dB can be achieved by the single system. The broadband, single-value noise reduction of this two Noise Abatement Systems is thus marginally limited by the low-frequency range. The achieved noise reduction is more limited with a (D)BBC to low frequencies than with an IHC-NMS.

Hydro Sound Damper (HSD): The experiences with the HSD-system in different constructive designs show a potential for noise reduction in the lower double-digit decibel range in water depths up to 40 m, independent of the water depth and the prevailing current (< 0,75 m/s) at sandy soils in the German EEZ of the North Sea.

The HSD-system essentially consists of three technical components: (i) a lowering- and lifting system with winches, (ii) a net with HSD-elements and (iii) a so-called ballast-box, so that the HSD-net can be installed between the water surface and the seabed around the respective monopile completely enclosing it. The design of the HSD-system, particularly the one of the necessary ballast-box and the lowering- and lifting system connected thereto, seems to be essential for the entire reduction potential.

The advantage of this technical Noise Abatement System is, that different HSD-elements can be used, which can be adjusted to different frequencies depending on the water depth (and thus the static counter-pressure) in the low-frequency range due to their material characteristics and sizes. The HSD-system has its highest reduction potential mostly at low frequencies (< 200 Hz) and was always applied in addition to a (D)BBC for large monopile diameters and water depths of > 25 m. In contrast to the IHC-NMS, the HSD-system has no noise reduction potential in higher frequencies. Compared to the IHC-NMS, this system shows a lower total mass. However, it is necessary to adapt the pile-sleeve and the dimensioning to the HSD-system for each specific project.

So far, the HSD-system has only been applied for a single OWF construction project in the German EEZ of the Baltic Sea. The achieved noise reduction was considerably lower than in the North Sea. The reason for the reduced noise reduction could probably be due, i. a., to the design of the ballast-box and the very hard soil layers of the Baltic Sea.

Achieved noise reduction with combined Noise Abatement Systems: Broadband noise reductions of 10 to 15 dB, depending on the Noise Abatement System applied, can be achieved with a single Noise Abatement System to 25 resp. 30 m water depth (see explanations above). With increasing water depth, a reduced noise reduction can usually be assumed, especially when using a single or double BBC. With a combination of two independent Noise Abatement Systems (near-to-pile and far-from-pile Noise Abatement System), a noise reduction of average 20 dB at up to 40 m water depth was achieved.

State-of-the-art: From the point of view of the industry and the German regulatory authorities, the above described technical Noise Abatement Systems are state-of-the-art, after years of development and application in the construction of Offshore Wind Farms, concerning monopiles up to 8 m in diameter and water depths up to 40 m.

However, when applying each of these three technical Noise Abatement Systems, a project-specific adaptation must follow to guarantee for optimum functionalities and the applicability at specific offshore construction sites.

In addition, a noise-optimized pile-driving procedure with the largest possible impact hammer of the newer generation, used at about 50 to 60 % of its total energy, and an increased blow repetition frequency proved to be a reliable, additional noise mitigation measure to the Noise Abatement Systems mentioned above.

1.4 Outlook

Applications with technical Noise Abatement Systems during impact pile-driving activities at (mono) pile diameters larger than 8 m and / or water depths of > 40 m are currently neither in series use in Germany nor worldwide. Thus it cannot be excluded, that future OWF-projects in larger water depths with possibly larger diameters of the foundation-structures may require further development and optimization of the technical Noise Abatement Systems.

The same applies to soil characteristics, which do not correspond to the German EEZ of the North Sea (mainly sand- and clay layers of varying thickness and density). So far, only little experience has been gained with near-to-pile Noise Abatement Systems in the Baltic Sea (mud areas, sand deposits, followed by till and chalk layers of varying thickness).

Furthermore, there are only sporadic experiences worldwide with the application of Noise Abatement Systems with currents > 0.75 m/s. The application of a Big Bubble Curtain (BBC) shows, that stronger currents have a negative influence on the resulting noise reduction. It remains to be seen, what influence strong currents have on the applicability and the noise reduction of both near-to-pile Noise Abatement Systems.

2. Tasks and objectives

The acoustic pollution of the oceans by noise-intensive, human activities has increased in the recent years. In Germany, the Environmental Impact Assessment Act (UVPG) and the Nature Conservation and Landscape Management Act (BNatSchG) provide the framework for assessing significant impacts and determining measures to protect species and habitats.

Given the fact of the implementation of the European Marine Strategy Framework Directive (MSFD, 2008), the investigation of possible impacts of the sound input on the marine environment is also internationally of great importance.

The currently most commonly used installation method for foundation structures in offshore wind farms (OWF) is the impact pile-driving procedure. Whereby the foundation structures are driven into the sediment (seabed) using an hydraulic (impact) hammer, a so-called impact hammer. The resulting underwater noise immissions are considered as impulsive noise according to the Marine Strategy Framework Directive (MSFD, desciptor 11.1). The pile-driving works result in noise immissions (percussive pile-driving noise) in the water body, which can be potentially harmful to marine mammals, especially to the noise-sensitive harbour porpoises (comp. Lucke et al., 2009).

In the incidental provisions of approvals given by BSH for German offshore projects, a dual noise mitigation value criterion at activity level is set for percussive pile driving noise:

that must be monitored in a distance of 750 m to the pile-driving location. With this, temporal threshold shifts (TTS) in marine mammals, in particular harbour porpoises, shall be avoided. Since

dual noise mitigation criterion	• frequency-unweighted, broadband Sound Exposure Level (SEL_{05} or L_E) $\leq$ 160 dB (re 1 µ Pa^2s) and • zero-to-peak Sound Pressure Level ($L_{p,pk}$) $\leq$ 190 dB (re 1 µ Pa),

2011, the application of noise abatement systems for compliance with the above-mentioned noise mitigation values in the German EEZ of the North- and Baltic Sea is mandatory.

Within the scope of the mandatory construction monitoring – the efficiency control of the applied Noise Abatement Systems –, the subsea exposure to underwater noise must be recorded by measurements and evaluated during each noise-intensive work. Hence, underwater noise measurements are currently carried out at all foundation set-ups with the impulse pile-driving method. The results must be evaluated in accordance with the above-mentioned noise mitigation values.

The performed underwater noise measurements during unmitigated impulse pile-drivings, so-called reference measurements according to the DIN SPEC 45653 (2017) without applying Noise Abatement Systems, have shown the following measured values in a distance of 750 m

experience from field applications	➢ 162 dB ≤ Sound Exposure Level (SEL resp. L_E) ≤ 183 dB and ➢ 185 dB ≤ zero-to-peak Sound Pressure Level ($L_{p,pk}$) ≤ 205 dB,

depending on the foundation structure, the applied impact hammer and blow energy, so that usually extensive noise mitigation concepts must be taken, in order to obligingly observe the above-mentioned noise mitigation values.

It should be noted that other European nations, such as The Netherlands, Belgium or Denmark, have also developed requirements for the handling with noise-intensive activities. Thus, the handling with noise-intensive, impulsive activities and the use of Noise Abatement Systems and noise mitigation measures has increasingly become an international task for future OWF operators.

Currently, 18 Offshore Wind Farms (OWF) in the German Exclusive Economic Zone (EEZ) of the North- and Baltic Sea and three OWFs within the 12-sea-mile-zone are in operation. Five OWFs are under construction, whereas the noise-intensive installation phase of the OWTG foundations is already completed. Further OWFs are in the development phase to achieve the expansion targets of the Federal Government.

The Federal Maritime and Hydrographic Agency (BSH) is responsible for the approval procedures in the German Exclusive Economic Zone (EEZ) and for the monitoring of the compliance with the above-mentioned noise mitigation values. For this purpose, extensive underwater noise measurements in and around the erected OWFs are mandated within the scope of the construction monitoring according to the national measurement specifications (BSH, 2011 and BSH, 2013a). The data collected, consisting of raw data (time recordings) and post-processed result data of the underwater noise measurements as well as accompanying information (meta data) to project-specific and technical-constructive characteristics of each single OWF construction project, are hold by the BSH in a standardized form. For the storage and use of these data, the BSH developed a specialist information system for underwater noise: the MarinEARS[1].

Since 2016, the MarinEARS[1] is in operation and contains all data from underwater noise measurements as well as extensive, site-specific and technical-constructive accompanying information (meta data), such as georeference, pile-driving protocols and the application of technical noise mitigation measures for all projects since 2012 in the German EEZ. In the meantime, data from > 1,000 foundation structures and a total of almost 2,000 single piles with and without Noise Abatement Systems are available in the MarinEARS[1] and checked for quality assurance. Based on this database, cross-project evaluations were carried out in the context of this research project, which are summarized in this report, regarding

- the main influencing factors for the generation and the transmission of percussive pile-driving noise in water and
- the effectiveness of applied, technical noise mitigation measures.

With this report, extensive experiences and data from the application of noise mitigation measures during the installation by means of the impact pile-driving procedure from Germany are summarized and made publicly available.

The cross-project analysis of underwater noise data including site-specific and technical-constructive accompanying information, gives an overview on possible factors influencing noise generation but also the effectiveness of Noise Abatement Systems. The results are needed for assessing possible impacts in the framework of environmental impact assessments. A further example is the evaluation of submitted noise mitigation concepts and implementation plans before the start of construction for the purpose of construction releases.

Not only authorities, but also the industry and the public can also gain insight the results of the cros-project analysis. Especially wind farm developers and operators may gain additional information for planning reliability with regard to the development of noise mitigation concepts for future construction projects.

The aim of the report is to provide an insight into crucial site-specific and technical-constructive factors influencing impulsive pile-driving noise and to summarize the experiences with the application of Noise Abatement Systems.

Chapter 3 summarizes the legal requirements by the German Approval Agency BSH and the German Agencies for Nature Conservation (BfN) and Environment Protection (UBA) regarding impulsive noise inputs from pile driving activities into water. This chapter was made available by the Federal Maritime and Hydrographic Agency (BSH).

Chapter 4 summarizes the essential acoustic principles for the evaluation and assessment of underwater noise.

Chapter 5 addresses the impulsive underwater noise inputs (pile-driving noise) and the main influencing factors, which are divided into site-specific and technical-constructive characteristics.

Chapter 6 gives an overview of already existing and under offshore conditions applied, technical, secondary Noise Abatement Systems. In the following, however, only those secondary Noise Abatement Systems are presented and discussed, that have been established as offshore-suitable for series application in German waters. Furthermore, the achieved noise reductions of the secondary Noise Abatement Systems are presented both as broadband and spectral insertion loss.

Chapter 7 discusses the effectiveness of the offshore-suitable Noise Abatement Systems already available on the market in terms of preventing damage and avoidance or disruption to the marine environment. Moreover, the challenges for future Noise Abatement Systems or noise mitigation measures when applied in future offshore construction projects with probably larger foundation structures and in larger water depths are discussed. Finally, further noise mitigation measures as well as alternative, low-noise foundation structures and -methods, which have been used in the

German EEZ of the North- and Baltic Sea on a test basis, are briefly summarized with regard to their expected noise inputs into the water and the achieved noise reduction.

3. Legal requirements for the protection of the lively marine environment against impulsive noise entry by percussive pile-driving works

In Germany, mandatory mitigation values for noise induced by percussive pile-driving have been applied since 2008. For the protection of the marine environment from impact due to impulsive noise from impact pile driving and for compliance with the noise mitigation values, comprehensive noise mitigation measures, especially also technical Noise Abatement Systems, are applied.

The Federal Maritime and Hydrographic Agency (Bundesamt für Seeschifffahrt und Hydrographie – BSH) is responsible for approval and monitoring of offshore-projects in the German EEZ of the North- and Baltic Sea. Setting threshold values at activity level for impact pile driving in incidental provisions of approvals for offshore projects is based on many years of research work and also on scientific support by the German authorities for Nature Conservation and Protection of the Environment – the Federal Environment Agency (Umweltbundesamt – UBA) and the Federal Agency for Nature Conservation (Bundesamt für Naturschutz – BfN). The research was focused on the one hand on purely physical aspects of underwater noise, transmission and on the development of standards for measurement and evaluation of impulsive noise entry and on the other hand on possible effects of pile-driving noise on the marine environment.

3.1 Setting thresholds at activity level to prevent impact of percussive pile driving on the marine environment

The introduction of mandatory noise mitigation values is based on results, that have shown the evocation of temporary hearing threshold shifts (TTS) using a physical method, the so-called acoustically evoked potentials (AEP) in a harbour porpoise under experimental conditions by sonication with an impulsive sound source (Lucke et al., 2008, 2009).

As a result of research projects, the reference value of 160 dB re 1µPa s^2 for the Sound Exposure Level (SEL resp. L_E), which was to be met at in 750 m to the pile-driving site, was introduced in approvals given by BSH already since 2004. In parallel, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) funded further research projects. The main focus of the research has been on the development of technical Noise Abatement Systems and on the determination of thresholds for physical injury and interference by the noise entry of pile-driving works.

Following the experimental determination of a physical injury in the form of a temporary hearing threshold shift (TTS) for harbour porpoises, the BSH introduced threshold values for the noise entry by pile-driving works in all approvals given from 2008 on.

From 2008 to 2011, the BSH, in agreement with the German authorities BMU, UBA and BfN, tolerated pile-driving works without technical noise abatement due to the lack of technical systems according to the state-of-the-art in science and technology, under the condition, that the industry actively participated in the research and development of Noise Abatement Systems. Two Offshore Wind Farms, the test field „alpha ventus“ and „BARD Offshore I“, carried out construction works in this phase. Both windfarms have contributed significantly to the development of technical noise abatement through research and development. In particular, the research- and development projects StUKplus[3] and the first phase of BORA[4] should be mentioned here.

Since 2011, pile-driving works at all construction projects in German waters are carried out under the mandatory application of technical Noise Abatement Systems. However, until 2013, the state-of-the-art in science and technology was not available for the technical noise mitigation. For this reason, the BSH, in agreement with the BMU, UBA and BfN, has tolerated the exceeding of the noise mitigation values of up to 3 dB re 1µ Pa²s (SEL_{05}) under strict conditions. The focus of the conditions was on the further development and optimization of technical Noise Abatement Systems and on improvement of

Since 2014, the extensive funding within the framework of joint research- and development projects (R&D) involving industry and research institutes has led to improvement of technical Noise Abatement Systems, that, single or in combination, reliably ensure compliance with the noise mitigation values.

The incidental provisions in approvals given by BSH containing measures to reduce noise and protect the environment apply to all offshore-projects (wind farms and network connection platforms) in the German EEZ of the North- and Baltic Sea. The incidental provisions apply across projects, provide the framework for the development of concepts for noise mitigation measures and contain instructions for the implementation of noise mitigation concept and monitoring in the construction phase. The noise reduction at the source and the restrictions to prevent noise related pressure on habitats are the main measures to ensure protection ofthe key species harbour porpoise and other marine species, while providing the industry with the framework necessary for the safe planning of offshore-projects and the development of noise-reducing technologies.

[3] R&D project StUKplus: Ökologische Begleitforschung am Offshore-Testfeldvorhaben *alpha ventus* zur Evaluierung des Standarduntersuchungskonzeptes des BSH, funded by BMU and RAVE, FKZ 0327689A, project duration 05/2008 till 04/2014 http://www.trianel-borkum.de/media/TWB/Downloads/Studien/2014_StUKplus-Endbericht_BSH-Koordination.pdf

[4] BORA: Development of a calculation model for the prediction of the underwater noise during pile-driving works for the foundation of OWET, supported by PTJ and BMWI, FKZ 0325421A/B/C, project duration 11/2011 until 10/2015. https://bora.isd.uni-hannover.de/. The underwater noise measurements were each anchored to the ground once at a monopile, a Tripod and a Tripile as foundations for the OWTG by means of the impact pile-driving procedure; Figure 10 in chapter 5.2.1.

Further information conserning nature conservation issues can be found in the UBA recommendation (UBA, 2011) and in the noise mitigation concept of the BMU (BMU, 2013).

For the protection of the marine environment, the BSH follows the precautionary principle, considers the state of knowledge andrequirements set by BMU, UBA and BfN. The framework set by BSH includes following issues:

- The strategy for the protection of the marine environment from percussive pile driving noise, is based on two aspects:
  - reduction of underwater noise entry at the source,
  - reduction of habitat loss for marine species through avoidance behavior induced by noise emissions.
- The key species in German waters of the North- and Baltic Sea is the harbour porpoise (as a strictly protected species according to BNatSchG (Federal Nature Conservation Act) and FFH-directive).
- Temporary threshold shift (TTS) of the harbour porpoise is classified as an injury.
- For the protection of the harbour porpoise and the marine environment against effects of pile-driving noise, thresholds at activity level have been set.
- Compliance with the specified thresholds at activity level requires the application of technical noise mitigation measures.
- The thresholds at activity level are based on a dual criterion, consisting of the Sound Exposure Level (SEL) and the zero-to-peak Sound Pressure Level, both measured in 750 m distance to the pile-driving site.
- The noise mitigation values are intentionally set as broadband levels, that can provide the framework necessary for the development of technical noise mitigation for offshore construction sites and thus contribute to the achievement of the targets for the reduction of the noise entry at the source and the associated reduction of habitat loss.
- The multiple acoustic stress due to several single strokes per pile is taken into account by two additional measures:
  - definition of the noise mitigation value at 160 dB re 1µPa^2 s, to be observed by the 5% exceedance level of the Sound Exposure Level (SEL_{05}) with 4 dB under the level of 164 dB, in which a temporary threshold shift (TTS) was experimentally found for a harbour porpoise,
  - definition of the 5% exceedance level (SEL_{05}) as reference parameter for proving the compliance with the noise mitigation values; the SEL_{05} is with at least 3 dB above the median value.
- Cumulative effects on the key species harbour porpoise are avoided or reduced according to the noise mitigation concept of the BMU (2013) by restricting the acousticpressure on habitats to a maximum allowed area of the EEZ and the nature conservation areas.

3.2 Incidental provisions for noise mitigation measures in approvals for OWFs and platforms in the German EEZ

Approvals for OWF and grid connections given by BSH consider the preceding Environmental Impact Assessment and the project-specific EIA-report. They also consider the results from the participation according to the EIAA and the ESPOO convention. The parts of the EIA-reports in BSH approval procedures relevant for the noise mitigation include the following aspects:

- description and assessment of the occurrence of sound-sensitive animal species, in particular harbour porpoises, seals and fish on the basis of the results of the standard investigation of the impacts of offshore wind farms on the marine environment (StUK, 2013) within the framework of the baseline surveys or the monitoring of already implemented projects,
- description and assessment of noise-related effects on the marine environment caused by the construction and operation of the installations,
- prognosis of the expected noise emissions due to pile-driving works using empirical or numerical models,
- description of the noise-related impacts relevant to species protection in accordance with the legal requirements of the BNatSchG,
- description of the noise-related impacts relevant to habitats of protected species in accordance with the legal requirements of the BNatSchG,
- description of measures to avoid and reduce significant impacts due to noise entry for the protection of the marine environment in accordance with legal requirements according to national law (UVPG, BNatSchG) and the implementation of European law (FFH-RL, MSRL), as well as requirements set by European and international agreements and conventions (especially OSPAR, HELCOM, ASCOBANS),
- description of measures for the monitoring of noise-related impacts on the marine environment according to national and international standards.

Approvals given by BSH include two **incidental provisions with measures for the protection of the marine environment from noise impact due to pile-driving works**:

a) **Reduction of the noise at the source**: Mandatory application of low-noise working methods according to the state-of-the-art for the installation piles and <u>mandatory restriction of the noise emissions</u> during pile-driving works. The condition primarily aims at protecting marine animal species from impulsive noise entries by avoiding killing and injury.
b) **Avoidance of significant cumulative impacts**: The spatial extension of pressure from noise emissions must not exceed certain percentages of the area of the German EEZ and

the nature conservation areas at any time. This ensures, that the animals will always find sufficient high-quality habitats unaffected from significantly disturbing noise emissions. The primary purpose of the condition is to protect marine habitats by avoiding and minimizing disturbances by impulsive noise.

The incidental provisions define the framework of measures, allow the safe planning of offshore-projects for the industry and ensure same rules among all offshore-projects.

Under **the incidental provision a)**, i. a., following measures are defined:

- A **working method, which according to the state-of-the-art** and the circumstances found appears to be as quiet as possible, shall be used for the foundation and installation of the constructions/structures. Detonations are not permitted.
- In a distance of 750 m to the pile driving location, **the noise emission** (Sound Exposure Level SEL_{05}) must not exceed 160 decibels (dB re 1 µ Pa²s) and the zero-to-peak Sound Pressure Level must not exceed 190 decibels (dB re 1 µ Pa). Detonations must be avoided.
- The **duration of the pile-driving works** per monopile shall usually not exceed 180 min., for Jacket-piles 140 min. This includes (1) the application of acoustic deterrence devices by pinger, seal scarer system or FaunaGuard-system, (2) the soft-start procedure incl. the determination of the verticality of the pile to be driven and (3) the pile-driving itselfs up to embedding depth.
- A **noise mitigation concept** must be developed on the basis of the specifically defined foundation structures and the planned installation process and must be submitted to the BSH for approval with the documents of the 2nd release, preferably two years before the start of construction.
- The **implementation plan** of the noise-minimizing and noise-preventing measures, which were determined by the authorities in the course of the set-up of the noise mitigation concept, must be submitted to the BSH for approval at least six months prior to the start of construction.
- The **prognosis** of the expected noise entries by pile-driving works shall be updated using empirical or numerical models within the framework of the noise mitigation concept and shall be used as a basis for the selection of technical Noise Abatement Systems.
- **Technical Noise Abatement Systems** according to the state-of-the-art in science and technology must be planned single or in combination to comply with the noise mitigation values and must be agreed with the authorities.
- **Offshore–tests** must be performed under comparable offshore-conditions prior to the start of construction, unless the selected Noise Abatement Sysetm is already considered state-of-the-art. The documentation on the testing shall be submitted to the BSH at least three months prior to the start of construction.

- Impact-preventing measures, like **soft-start** and **deterrence** for the protection of animals beingin the vicinity of the pile-driving location, must be planned within the scope of the noise mitigation concept and must be agreed with the authorities.
- The **effectiveness of the noise-protecting and noise-reducing measures** must be monitored and documented by means of measurements.
- A **measuring concept** to monitor the effectiveness of the measures must already be submitted together with the noise mitigation concept for harmonization and must be further concretized within the context of the implementation plan.
- When setting up the measuring concept for the monitoring of the underwater noise entry, the **„measuring instruction for underwater noise monitoring" of the BSH (2011) and the ISO standard 18406 (2017)** must be taking into account. The construction-related noise entry by construction vessels and pile-driving works must be measured. During the execution of the noise-intensive works, underwater noise measurements must be performed at distances of 750 m and 1,500 m to the pile-driving location and in the nearest nature conservation area and shall be documented in a suitable manner.
- The effectiveness of the Noise Abatement Systems applied must be proved according to the instruction of the **BSH (2013) "measuring specification for the quantitative determination of the effectiveness of noise control systems"** and the **DIN SPEC 45653 (2017)**.
- Impact-preventing and noise-minimizing measures must additionally be examined for their efficiency during the works by **applying temporarily deployed harbour porpoise detectors – PODs** or comparable systems. The acoustic recording of the activity of the harbour porpoise and the recording of the noise entry must be carried out preferably at the same measuring points.
- The results from the measurements must be submitted to the BSH for examination in the form of **reports** at short notice (24 hours after the foundation of a pile). The intervals and formats, in which measurement reports and data (raw- and post-processed data) are subsequently submitted, must be agreed with the BSH in the course of implementation.
- BSH always makes a reservation to demand **technical improvements**, if noise thresholds and duration limit are not met or other measures are not implemented as required..

Under **incidental provision b)**, i. a. measures are definedfor the avoidance and reduction of significant cumulative effects resp. disturbances of the stock of the harbour porpoise, that can be caused by impulsive noise entries. The rules and measures are directly derived from the concept of the BMU for the protection of the harbour porpoise in the German EEZ of the North Sea (BMU, 2013).

- It must be ensured, that at any time, not more than **10% of the area of the German EEZ of the North Sea** and not more than **10% of an adjacent nature conservation area** are affected by significant disturbance-causing noise due to pile-driving works for the foundations.
- During the sensitive period of the harbour porpoise from 1st May to 31st August, it must be ensured, that **not more than 1% of the subregion I of the nature conservation area „Sylter Außenriff – Östliche Deutsche Bucht“ with the special function of a breeding area** is affected by significant disturbance-causing noise due to pile-driving works for the foundations.

According to the noise mitigation concept of the BMU (2013), in order to ensure the protection of marine habitats, additional measures during the foundation works may become necessary, depending on the location of a project in the German EEZ resp. its proximity to nature conservation areas. Additional measures will be issued by the BSH within the context of the third construction permit, taking into account the site- and project-specific characteristics.

3.3 Implementation of noise mitigation measures in construction projects in the German EEZ of the North- and Baltic Sea

Within the scope of the 3rd release, the BSH specifies measures for the protection from pile-driving noise on the basis of the submitted and with the authorities agreed implementation plan. The specification of measures takes into account the respective site- and project-specific characteristics of the OWF or grid connection. The 3rd release is always issued by the BSH in appropriate tranches. In this way, the BSH reserves the right to evaluate the results of the monitoring with the participation of the BfN and, if necessary, to adjust the requirements resp. to order the improvement of the noise mitigation measures. The extension of the 3rd release depends i. a. on the success of the noise mitigation measures and the compliance with the noise mitigation values.

The installation of the piles may only be started, once the functional capability and operational readiness of the Noise Abatement Systems have been demonstrated by means of tests.

The noise mitigation measures cover all aspects, that have an influence on the effective protection of the animals from pile-driving noise as well as installation components, which influence the intensity and duration of the entry of pile-driving noise.

In the following, essential aspects of the noise mitigation requirements of the 3rd release from projects of the years 2017 to 2019 are summarized.

Protection of the animals in the vicinity of the pile-driving site:

- Prior to the start of the pile-driving works and prior to the startup procedure of the Bubble Curtain systems, the harbour porpoises are deterred from the endangered area by the FaunaGuard system.
- The pile-driving must always be initiated with a soft-start.
- The effectiveness of the deterrence must be monitored by acoustic recording of the harbour porpoise activity via CPODs or similar.

Pile-driving procedure:

- **Impact hammer:** The year of construction and the type of the hammer are registered. Based on the current pile design (diameter, length and embedding depth), new generation hammers with a capacity $\geq$ 3000 kJ are used. At the same time,
  - the service history of the impact hammer to be used and
  - the pile-driving protocol

  must be submitted in original after each single pile installation.
- A **noise-optimized pile-driving procedure** must be applied. For this purpose, it is expected, that the hammer will be technically capable of rapid acceleration, if necessary even at high energy with a high blow frequency, and will allow control of the pile-driving process in accordance with the soil conditions and the results from the online monitoring of the noise level.
- The maximum **blow energy** to be applied is limited to 50% to 60% of the hammer capacity. At the same time it must be ensured, that the embedding depth is reached. Substantiated deviations have to be documented. An increase of the blow energy is possible after checking the pile-driving protocols and the results from noise measurements.
- The maximum **pile-driving duration** per monopile including deterrence must not exceed 180 min. For Jacket-piles, the pile-driving duration is limited to 140 min.
- **Measurement of the verticality of the pile to be driven:** Suitable measuring systems must be used to ensure, that the verticality test can be performed without prolonged interruptions of the pile driving process.

Technical Noise Abatement Systems

Construction projects in water depths > 25 m and with pile diameters ≥ 6 m must apply **a combination of near-to-pile and far-from-pile Noise Abatement Systems**.

Three Noise Abatement Systems have reached the state-of-the-art so far: The Big Bubble Curtain (BBC) system, the HSD-system and the IHC-NMS. The noise reduction potential of new technical systems according to the state of science and technology must be demonstrated under offshore conditions. New Noise Abatement Systems can thus only be approved for use after successful offshore tests with a professional evaluation of the noise reduction potential.

IHC-NMS:

Of the three Noise Abatement Systems, that have reached the state-of-the-art, only for the IHC-NMS, no system-relevant offshore test is ordered prior to the installation of a project. This is related to the integration of the system in the installation process and its multiple functionalities.

System-relevant offshore tests are regularly ordered for Bubble Curtain systems as well as for the near-to-pile HSD-system before the start of the installation due to the project-specific and technical-constructive designs as follows:

Big Bubble Curtain system:

- Offshore-tests before the start of the installation:
    - The deployment of the hoses on the seabed must be checked via side scan sonar.
    - A test run of the compressors must be carried out and documented.
    - If necessary, operating results must be documented by means of recordings with drones.
- Technical realization:
    - New nozzle hoses must be applied, and the application history of the nozzle hoses must always be documented.
    - The length of a single (single) Big Bubble Curtain (BBC) is limited to 750 m. For a double Big Bubble Curtain (DBBC), a maximal length of 1,000 m for the outer nozzle hose is allowed.
    - The air volume shall at least be 0.5 $m^3/(min\ m)$.
    - The deployment accuracy of the nozzle hoses deployed on the seabed must repeatedly be measured and documented at the beginning of the pile-driving works.

- Compressors of the same type and of the latest generation must be used, which produce oil-free, compressed air. The total number of all compressors is limited to 20 (plus 2 spare compressors) for reasons of CO_2-emissions.
- The operation of the compressors used must be documented.

HSD-system:

The system is provided within the scope of the respective construction project in a technical design suitable for the project-specific installation procedure. The functional capability, in particular the lowering of the ballast box to the ground and the recovery, must be proven by **harbor- and offshore tests**, before the installation is started.

Monitoring of the effectiveness of the noise reduction:

Underwater noise measurements must be performed in 750 m and in 1,500 m distance to the pile-driving location as well as in the nearest nature conservation area:

- Compliance with the noise mitigation values must be proven by underwater noise measurements.
- The recording and the evaluation of the underwater noise measurements must be carried out during the pile-driving works for all foundations according to the instruction given by BSH (2011) and the ISO 18406 (2017).
- The installation of the monopiles or Jacket-piles is only allowed to start, once an accreditation of the institution responsible for the recording and the evaluation of the underwater noise have been proved. The proof of suitability must be provided by means of an accreditation according to the DIN EN ISO/IEC 17025 with regard to the ISO 18406 (2017) and the DIN SPEC 45653 (2017).
- A technical quality control by external experts of data from the measurements can be ordered by BSH randomly or, in justified cases.
- The protocols from the pile-driving works and from the noise reduction must be submitted to the BSH without delay after the installation of a monopile or a Jacket has been completed.
- The processed data of the underwater noise measurements must be uploaded without delay via the internet delivered portal to MarinEARS[1].
- The raw data must be submitted to the BSH for storing purposes. The transfer of raw data to third parties is not permitted.

Determination of the effectiveness of the noise reduction:

- Reference- and test measurements for the determination of the output level and the evaluation of the evectiveness of the Noise Abatement Systems must be performed considering the DIN SPEC 45653 (2017).
- The reference- and test measurements must be planned in the early phase of the installation phase in order to improve the noise reduction of the Noise Abatement Systems used.
- Reference measurements without the application of the Noise Abatement Systems are allowed in the German EEZ of the North Sea only beyond the time of 01st May – 31st August resp. in the German EEZ of the Baltic Sea only beyond the time of 01st November – 31st March.
- The evaluation of the noise reduction potential of the Noise Abatement Systems must be in accordance with the BSH measurement regulation for determining the effectiveness of noise abatement measures of 2013 and the DIN SPEC 45653 (2017) and presented in a separate experience report.

Coordination of pile-driving works:

The coordination of the pile-driving works with neighbouring projects must primarily be ensured and documented and any measures must be agreed with the BSH. This coordination must ensure the compliance with the requirements of the order for the protection of the harbour porpoise habitats.

4. Acoustic background

Sound is a rapid, often a 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 characteristic acoustic impedance Z, which characterizes the wave impedance of a medium, as follows:

$$Z = \frac{p}{v} \qquad \text{Equation No. 1}$$

In the far field, that means in a distance[5] of some wavelengths (frequency-dependent) from the sound source, the characteristic acoustic impedance is:

$$Z = \rho \cdot c \qquad \text{Equation No. 2}$$

with ρ – density of the medium

and c – propagation 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 approx. 0.7 µm/s is obtained.

4.1 Values at activity level

In acoustics, the intensity of sounds is generally not directly described by the measurand sound pressure (or particle velocity), but by the level in decibel (dB) known from the telecommunication engineering.

Nevertheless, there are different sound levels:

- (energy-) equivalent continuous Sound Pressure Level – SPL,

[5] The boundary between near and far field for underwater noise (hydro sound) is not exactly defined, but depends on the wavelength λ. In airborne sound, a value of $\geq 2\lambda$ is assumed. For underwater noise, values of up to $\geq 5\lambda$ can be found.

- Sound Exposure Level[6] SEL resp. L_E ,
- Peak Sound Pressure Level $L_{p,pk}$.(zero-to-peak).

SPL and SEL resp. L_E can be specified independent of frequency, which means as broadband single-digit values, as well as frequency-resolved, for example in 1/3-octave bands (third spectrum).

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

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

The continuous Sound Pressure Level (SPL) is the most common measurand in acoustics and is defined as:

$$\mathrm{SPL} = 10\log\left(\frac{1}{T}\int_0^T \frac{p(t)^2}{p_0^2}\,dt\right) \text{ [dB re 1 µPa}^2\text{]} \qquad \textit{Equation No. 3}$$

with

$p(t)$ – time-variant sound pressure,

p_0 – reference sound pressure (in underwater sound 1 µPa),

T – averaging time.

4.1.2 Sound Exposure Level (SEL resp. L_E)

For the characterization of pile-driving sounds, the continuous Sound Pressure Level (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 Level (SEL resp. L_E) is more appropriate and is defined as:

$$\mathrm{SEL} = 10\log\left(\frac{1}{T_0}\int_{T_1}^{T_2} \frac{p(t)^2}{p_0^2}\,dt\right) \text{ [dB re 1 µPa}^2\text{s]} \qquad \textit{Equation No. 4}$$

with

T_1 and T_2 – starting- resp. ending time of the averagings (to be chosen so that the noise event lies between T_1 and T_2 (Figure 1)),

T_0 – 1 second.

[6] In the ISO 18406 (2017), the Sound Exposure Level is abbreviated with SEL. The German measurement specification for underwater noise (BSH, 2011) has added the abbreviation L_E. Based on the definitions, the SEL corresponds to the L_E and can be used synonymously.

The Sound Exposure Level of a sound impulse (pile-driving blow) thus corresponds to the continuous Sound Pressure Level (SPL) of a continuous sound with a time duration of 1 s and the same acoustic energy as the impulse.

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

$$\text{SEL} = 10\log\left(10^{SPL/10} - 10^{L_{hg}/10}\right) - 10\log\frac{nT_0}{T} \text{ [dB re 1 µPa}^2\text{s]} \qquad \textit{Equation No. 5}$$

with

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

T_0 – 1 second,

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

Thus, Equation No. 5 provides the average Sound Exposure Level (SEL) of *n* sound events (pile-driving blows) from just one Sound Pressure Level (SPL) measurement over a defined measuring period.

In case, that the background level between the pile-driving blows is significantly lower than the pile-driving noise (signal-to-noise-ratio (SNR) ≥ 10 dB), an average Sound Exposure Level over a defined period of time, e. g. 30 s, can be determined with sufficient accuracy according to the ISO 18406 (2017) and the German measurement specification (BSH, 2011) as:

$$\text{SEL} \approx \text{SPL} - 10\log\frac{nT_0}{T} \text{ [dB re 1 µPa}^2\text{s]} \qquad \textit{Equation No. 6}$$

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

The zero-to-peak Sound Pressure Level $L_{p,pk}$ is a measure for short-time sound pressure maxima. In contrast to the continuous Sound Pressure Level (SPL) and the Sound Exposure Level (SEL), there is no averaging:

$$L_{p,pk} = 20\log\left(\frac{|p_{peak}|}{p_0}\right) \text{ [dB re 1 µPa]} \qquad \textit{Equation No. 7}$$

with

p_{peak} – maximum, positive or negative sound pressure.

Figure 1 shows an example. The zero-to-peak Sound Pressure Level $L_{p,pk}$ is always higher than the Sound Exposure Level (SEL). Usually, the difference between the zero-to-peak Sound Pressure Level ($L_{p,pk}$) and the Sound Exposure Level (SEL) during pile-driving works is 20 dB to 25 dB.

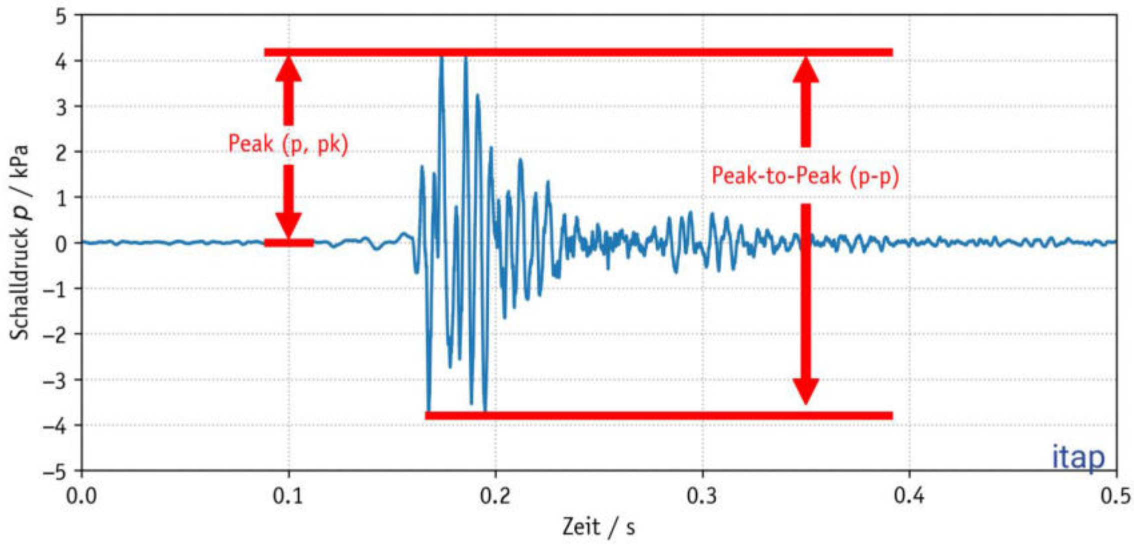

Figure 1: *Typical measured time signal of the underwater noise during pile-driving in a distance of several 100 m.*

4.2 Requirements to underwater noise measurements

In 2011, the BSH published a measurement specification for underwater noise measurements during the construction of offshore wind farms (BSH, 2011). Particularly the construction of foundation structures by means of the impulse pile-driving procedure (underwater noise) and their metrological recording, evaluation and documentation of the underwater noise input is standardized therein for German waters for the first time. Previously, there were neither national nor international guidelines nor standards. In conjunction with the StUK 4 (2013) (BSH, 2013b), the measurement regulation stipulates that an underwater noise measurement must be carried out and documented for each impulse pile-driving in distances of 750 m, 1,500 m and in the nearest protected area according to the fauna-flora-habitat-(FFH) directive „Special Area of Conservation (SAC)“ or nature reserves (Council Directive 92/43/EEC on the Conservation of natural habitats and of wild fauna and flora).

The measurements in 750 m distance are for the comparison with the defined noise mitigation value criterion; see chapter 3. The measurements in 1,500 m distance can serve as a validation measure or in case the measurements in 750 m distance have failed, as replacement measurements. The minimum measurement distance of 750 m is based on the mostly necessary safety radii of large construction vessels and the fact, that the measurement position is thus located in the acoustic far field.

The measurement specification (BSH, 2011) contains a technical description for the evaluation of impulsive underwater noise measurements; see chapter 4.1. In particular, a statistic presentation of the Sound Exposure Level over the entire impulse pile-driving per pile must be done; see chapter 4.3.

For measurements at a distance of 750 m and 1,500 m from the impulse pile-driving, it is generally assumed that the signal-to-noise-ratio between the impulsive pile-driving noise and the permanent background noise (continuous noise) is at least 10 dB. In shallow waters such as the German North- and Baltic Sea, this two measurement results can roughly be compared by means of the geometric propagation function $-15 * \log_{10}$ *(distance ratio)*-; see chapter 5.1.5.

The measurements at the nearest FFH protection area (usually at a distance of several kilometres) are used to record the acoustic pollution within these sensitive natural habitats of wild fauna and flora. Depending on the distance of this measurement position to the source and on the effectiveness of the noise abatement concept used, the signal-to-noise-ratio is usually < 10 dB, so that the impulsive pile-driving noise cannot be separated significantly from the background noise. As a result, it may not be possible to calculate the Sound Exposure Level, but only the Sound Pressure Level.

Based on the experience gained in the application of technical Noise Abatement Systems, also a measurement regulation for the recording and evaluation of Noise Abatement Systems was developed in 2013 (BSH, 2013a), based on the outcomes from one R&D project (Diederichs et al., 2014). Impulse pile-drivings each with and without Noise Abatement Systems are necessary for the evaluation of the applied Noise Abatement System. Measurements in different spatial directions serve to evaluate the directional dependence of the applied Noise Abatement System. In 2017, this measurement specification (BSH, 2013a) was transposed into a specification of the German standardization body DIN (DIN SPEC 45653, 2017).

With the ISO 18405 (2017), the terminology for underwater noise was standardized for the first time. Based on this, the ISO 18406 (2017) defines a first international standard for the recording, evaluation and documentation of impulsive underwater noise events during the impulse pile-driving procedure in shallow waters. Based on the already existing measurement experiences from Germany, a measurement at a distance of 750 m was specified as minimum requirement. Furthermore, the framework conditions for the evaluation of the ISO 18406 (2017) are identical to those of the German measurement standard (BSH, 2011).

4.3 Data management and evaluation of underwater sound data in the specialist information system MarinEARS[1]

The Sound Exposure Level (SEL) is usually determined in a single blow analysis according to the measurement specification for underwater noise (BSH, 2011) resp. the ISO 18406 (2017), where each impulse is analysed singlely as soon as the signal-to-noise-ratio is ≥ 10 dB. For the presentation of the results, the third spectra (IEC 61260) are limited to the frequency range of 12,5 Hz to 16 or 20 kHz.

Technical note: A simplified evaluation is also possible by determining the energy-equivalent continuous Sound Pressure Level $L_{eq,\ 30s}$ over 30 s and dividing it by the number of the single strikes recorded during this period (BSH, 2011 and Equation No. 6). However, this evaluation method provides an averaged Sound Exposure Level over 30 s. In the case of strongly varying blow energies and no continuous pile-driving, i. e., blow repetition frequency < 25 blows per minute, standard deviations in the single-digit decibel range can occur; for a continuous pile-driving with a comparable blow energy, the standard deviation is usually << 1 dB.

For the documentation and evaluation of pile-driving noise, the following parameters according to the measurement specification of the BSH (2011) are listed:

- SPL_{5s}: energetic average value of the continuous Sound Pressure Level over 5 seconds,
- SEL_{90} resp. L_{90}: exceedance level of the single blow analysis of the Sound Exposure Level, which was exceeded in 90 % of all single strikes over the considered time interval,
- SEL_{50} resp. L_{50}: exceedance level of the single blow analysis of the Sound Exposure Level, which was exceeded in 50 % of all single strikes over the considered time interval,
- SEL_{05} resp. L_{05}: exceedance level of the single blow analysis of the Sound Exposure Level, which was exceeded in 5 % of all single strikes over the considered time interval,
- $L_{p,pk}$: maximum zero-to-peak Sound Pressure Level of all single strikes.

Technical note: The Dutch regulatory authority Rijkswaterstaat has introduced the evaluation level SEL_1, which characterizes the maximum Sound Exposure Level (SEL_{max}) and is not to be put on a level with the SEL_{01}, i. e. the 1%-exceedance level.

By specifying exceedance levels for the Sound Exposure Level (SEL bzw. L_E), a statistical characterization of an entire pile installation is possible. At least for monopiles, significantly lower blow energies are applied at the beginning of the pile-driving than for achieving the final embedded depth, so that the Sound Exposure Level can change considerably in its amplitude during the pile-driving procedure; see chapter 5.2.2.

Furthermore, the comparison of the exceedance level of the Sound Exposure Level SEL_{05} takes into account the multiple stroke necessary to drive pile to embedded depth as well as the measurement uncertainty.

A mandatory standard for the storage of all processed pile-driving noise data sets was developed by the BSH in 2016 as part of the R&D project NavES[2]. The BSH also developed a specialist information system for underwater noise (MarinEARS)[1], which is in operation since 2016. The technical / analytical specialist information system is used on the one hand to record, check, validate and assure the quality of all information from underwater noise measurements, including all relevant meta data, such as bathymetry data, pile design and specifications of the applied Noise Abatement Systems, and on the other hand to analyze all data sets across projects. Thus, the specialist information system MarinEARS[1] represents a central knowledge base. By this, it can be guaranteed, that all processed result data as well as measurement raw data and project-specific additional information (meta data) can be made available in a standardized form with regard to the underwater noise measurements by means of a web application, independent of the OWF-operator.

On the basis of this specialist information system, tools can be developed for the authorities in the context of the approval procedure and (construction) monitoring for future OWF construction projects to assess nature conservation issues. Moreover, the BSH will make cross-project findings available to the public, so that e. g. wind farm developers and participating construction companies have access to the current findings regarding noise abatement.

As part of the R&D project NavES[2], all available underwater noise measurement data of all OWF construction projects from the German EEZ of the North- and Baltic Sea between 2012 and 2016 were re-evaluated in standardized form by the *itap GmbH* and integrated into the technical specialist information system MarinEARS[1].

Since the operationalization of the MarinEARS[1] technical specialist information system in 2016, as part of the construction performance, OWF construction projects are required to feed all underwater noise measurement data and associated accompanying information directly into the MarinEARS1. Processed underwater noise data and meta data are entered via a web application.

Table 1 summarizes the data sets from the technical specialist information system MarinEARS[1], which are available for the subsequent, cross-project analyses.

Table 1: *Overview of the current status (May 2020) of the MarinEARS[1] technical specialist information system. All existing data sets were available for the following analyses.*

Parameters	**Value range**	**Comments**
Offshore Wind Farms	21*[1]	3 pcs. in the Baltic Sea, 18 pcs. in the North Sea (construction times since 2012)
Grid connection and other platforms	28*[2]	incl. substations, converter platforms, met masts and research platforms
Water/ Soil conditions	EEZ of the German North- and Baltic Sea	North Sea: sands with different densities and thicknesses Baltic Sea: sand-, till- and chalk layers
Current	< 0.75 m/s	
Water depths	22 to 41 m LAT	both in the North-, and in the Baltic Sea
Number of foundations	1,458	~ 80 % of the foundations and skirt-piles were available for the following evaluation*[3]
Number of piles	2,464	
Pile diameters	1.829 to 8.0 m	
Type of installation vessel	floating vessel or jack-up platform	For floating installation vessels, vessels with a dynamic positioning system (DP-vessel) and vessels that hold themselves in position by means of anchors were used.

*[1] Due to their test character, the OWFs *Alpha Ventus* (construction phase 2009), *Trianel Borkum West II* construction phase 1 (2011/2) and *BARD Offshore I* (2010 to 2012) in the German EEZ have not yet been implemented in the MarinEARS[1] specialist information system. Due to the different responsibilities within the 12-sea-mile-zone, the three OWFs *Riffgrund* (2012, North Sea), *Nordergründe* (2016, North Sea) and *EnBW Baltic I* (2012, Baltic Sea) have not yet been integrated into the MarinEARS[1] specialist information system either.

*[2] Only foundation structures, that were embedded into the seabed by the impact pile-driving procedure; other installation methods see alternative foundation procedures and -structures in chapter 7.4.3.

*[3] Due to time constraints, it has not yet been possible to integrate all OWFs of the German EEZ of the North- and Baltic Sea from the construction years 2010 until 2014 into the specialist information system in a quality assured manner. Moreover, there have been partial failures of measurement devices, especially in the early years 2012 and 2013, so that for a small number of foundations/skirt-piles, no underwater noise measurement data are available.

4.4 Quality assurance

Until the publication of the ISO 18405 in 2017, there was no international terminology for underwater noise, but only national measurement specifications (e. g. BSH (2011) in Germany and de Jong et al. (2011) in the Netherlands), which sometimes used slightly different terms and definitions. With the ISO 18406, moreover, a minimum standard for the presentation of results from the impulse pile-driving procedure was standardized in 2017.

Based on the international standardization, the BSH decided to supplement the internal standard for the transmission of processed underwater noise data sets into the specialist information system MarinEARS[1] in 2017. All underwater noise measurement raw data available to the BSH until 2016 were re-evaluated in a standardized way for all OWF construction projects of the German EEZ and then subject them to a quality control.

It turned out that in some cases, there were deviations between single short reports, which were project-specifically compiled within 24 h after the end of a pile-driving, the technical final report and the quality-assured, processed data sets in the MarinEARS[1] of up to ±1 dB.

Differences between the short reports and the technical final reports per OWF construction project are mostly based on the fact, that in the case of disturbing noises and/or low signal-to-noise-ratios between the background noise and the pile-driving noise, no quality-assured and detailed evaluation could be made within 24 after the end of the pile-driving.

Differences between the processed data sets in the MarinEARS[1] and the respective final reports, compiled before 2017, vary on average up to 1 dB. The cause for the deviation is due to

(i) the definition of a single blow analysis (and thus, no 30 s average values are formed),
(ii) the better and faster single blow detectors incl. corresponding filter functions and
(iii) a smaller, allowable signal-to-noise-ratio of 6 instead of before 10 dB as well as
(iv) an introduction of commercial rounding to whole decibel values[7].

Technical note: Using the example OWF *Butendiek* with several hundred measurements at a distance of 750 m from the pile foundation, consisting of 80 monopile foundations with sometimes up to four measuring positions in different spatial directions and different hydrophone heights above ground, there were six deviations of 1 dB between the final report and the processed result data sets in the MarinEARS[1].

[7] In an evaluation from e. g. the year 2014 with 158.4 dB (rounded 158 dB), a subsequent and quality-assured analysis from the year 2018 showed a value of 158.6 dB (rounded 159 dB).

5. Generation and transmission of impulsive underwater noise during pile-driving works

During the construction of OWF foundations, different noise mitigation measures can be used to protect the environment. Principally, the following subdivisions can be made:

- application of primary noise mitigation measure (Noise Mitigation Systems) for the purpose of reducing impulsive noise inputs into the water and / or secondary noise mitigation measure (technical Noise Abatement Systems) for the purpose of mitigate the impulsive noise pollution in the water (chapters 6, 7.4.1 and 7.4.2),
- application of alternative foundation structures or –procedures to avoid impulsive noise inputs into the water (chapter 7.4.3).

For the application of technical Noise Abatement Systems during the installation of offshore foundation structures, it is necessary to know the influencing factors for the generation of pile-driving noise, the input into the water and the transmission in shallow water, in order to specifically reduce the resulting noise emissions of the OWF foundation works, if need be.

The cross-project evaluation of the existing MarinEARS[1]-database revealed the following influencing parameters:

- site-specific characteristics such as water depth, soil condition, topography, resp. bathymetry, current and the resulting noise propagation,
- technical-constructive characteristics such as foundation- and pile design, impact hammer type and blow energy, pile-driving procedure and embedding depth as well as the offshore logistics, consisting of e. g. the vessels involved in construction.

In the following subchapters, these influencing parameters are summarized and discussed on the basis of empirical data.

5.1 Site-specific influencing factors

5.1.1 Influence of the soil resistance

Different soil resistances, especially in the German EEZ of the North Sea with sand layers of varying density and partial inclusions of clay deposits, were reflected in the use of different blow energies during the foundation works. During the foundation installation, it is necessary to overcome the predominant soil resistance, depending on the respective embedding depth in the seabed. Generally, the following applies to the German EEZ of the North Sea: the larger the soil resistance, the higher is usually the blow energy required to overcome the soil resistance. Moreover, the measured noise level values in a distance of 750 m to the pile-driving source mostly correlate with the applied blow energies; see Figure 15 in chapter 5.2.2.

It also showed during the three OWF construction projects in the German EEZ of the Baltic Sea, that there was also a clear correlation between hammer type, piling procedure, applied blow energy and noise levels in 750 m.

The larger the blow energy used, the higher the noise level values measured; see chapter 5.2.2. Furthermore, the statistical analysis of all German construction projects in the EEZ of the North- and Baltic Sea showed, that the noise level in the Baltic Sea with comparable pile design and used blow energy was up to 2 dB higher than in the North Sea. It is assumed, that this could be related to the different, complex soil stratifications (sand, till and chalk layers).

For the German EEZ of the Baltic Sea, where the top layer mostly consists of sand or silt, followed by till and subsequent chalk layers, the soil resistances are in some cases much more varied and higher than in the sandy North Sea. In a German construction project from the Baltic Sea with very complex soil layers of varying thickness, an internal statistical analysis of the prevailing soil resistances, the blow energy used and the underwater noise measurement data recorded at a distance of 750 m was carried out with the help of geologists and acousticians. Apart from the correlation between applied blow energy and measured noise level values, however, no significant correlation between acoustic measurement data and different soil layers, nor between acoustic measurement data and soil resistances could be identified.

Technical note: It became apparent in the OWF construction projects in the German Baltic Sea, that the blow energy used in the hard soil layers, such as chalk, depended not only on the prevailing soil resistance, but also on the applied pile-driving procedure, especially the blow rate (blow repetition frequency). The connection between soil resistance, blow energy to be applied for overcoming the soil resistance and noise emission is therefore very complex and these three parameters are basically not linearly independent of each other.

5.1.2 Soil couplings

The soil coupling describes, that the blow energy or power introduced by the impact hammer into the pile to be founded is partly transmitted into the soil and then reflected in the lower soil layers back towards the water column and emitted into the water.

In the R&D project BORA[4] (Chmelnizkij et al., 2016), extensive underwater noise- and soil vibration measurements were carried out within three German OWF construction projects in the North Sea in different spatial directions and distances from the respective foundation. In each case, impact pile-drivings per OWF construction project were carried out with and without a technical Noise

Abatement System. Moreover, a so-called „Hydrophone Line-Array“ with a total of 16 hydrophones was used near the pile (max. distance 80 m) at different heights above the seabed (first hydrophone 2 m above ground, subsequent hydrophones each in a distance of 1.5 m height). By means of a steel cable and a fixation on board of the installation vessel, a precise vertical alignment of all hydrophones could be ensured. With this arrangement of several hydrophones in the water column, the influence of the hydrophone height on the measured noise input into the water in the immediate vicinity of the pile was investigated; see chapter 5.1.6.

Figure 2 shows the sound pressure time course of a single pile-driving blow near to the pile with and without the use of a near-to-pile Noise Abatement System at different heights above the seabed.

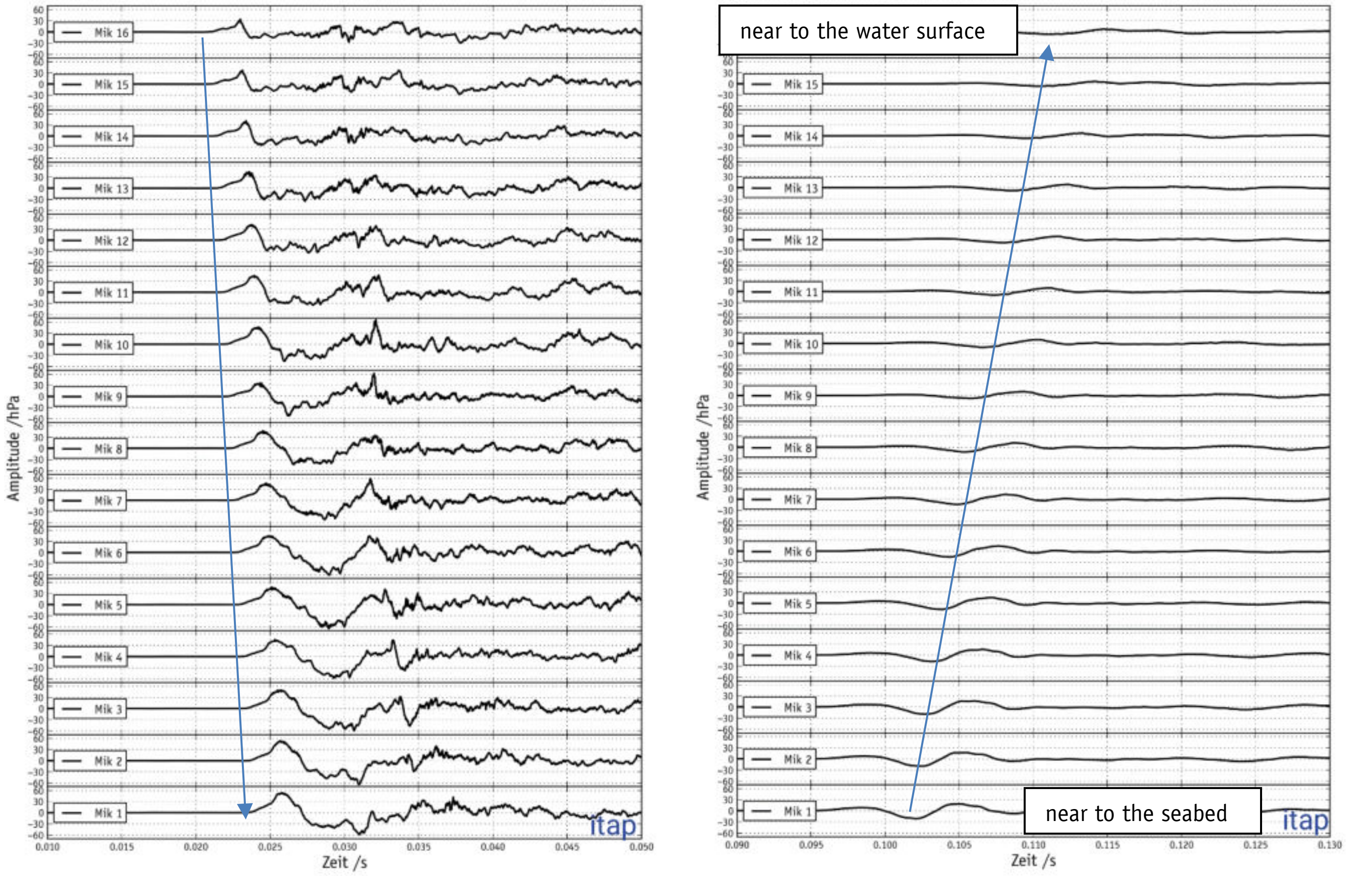

Figure 2: *Time course of a single strike at a monopile, measured in a distance of approx. 80 m with several hydrophones at different heights to the seabed without (left) and with (right) the use of a near-to-pile Noise Abatement System. Mik 1 marks the lowest hydrophone 2 m above the seabed, all further hydrophones were in a vertical distance of approx. 1.5 m to each other. The water depth in the construction project was approx. 30 m. (source: Gündert et al., 2015)*

Figure 2 shows two physical phenomena:

(i) (left): The impact pile-driving causes a structural oscillation in the monopile, which runs as a traveling wave with a certain speed from the pile top to the pile base. This causes a time delayed sound emission into the water according to the Huygens principle.

(ii) (right): During the impact pile-driving with a near-to-pile Noise Abatement System, a very large amount of the direct sound emission into the surrounding water is reduced. The measurements in the acoustic near field therefore show a significantly reduced pile-driving noise signal. However, this pile-driving noise signal still stands out clearly from the permanent background noise. Additionally, an impulsive signal with a significantly reduced amplitude is shown, which spreads with a time delay from the soil upwards in the water. This impulse signal is probably caused by the soil coupling. This energy input is then entered into the water as underwater noise, time- and locally displaced.

The *Technische Universität Hamburg Harburg* (TUHH), the *Leibniz Universität Hannover* (LUH) and the *Christian-Albrechts-Universität zu Kiel* (CAU) have scientifically investigated the soil couplings in the German EEZ of the North Sea with sandy soil within the scope of the R&D project BORA[4] (e. g. Chmelnizkij et al., 2016). It turned out, that the soil couplings are significantly dependent on the respective existing soil layers and soil resistances in sandy subsoils of the German EEZ of the North Sea.

Theoretical calculations of the soil couplings indicate, that the noise input into the water in sandy soils at an ideal, near-to-pile Noise Abatement System (assumption: 100 % of the direct noise input from the pile are reduced) is about 1/10 of the direct noise input from the pile (Stokes et al., 2010). This means, that the noise input into the water by soil couplings is approximately 20 dB less than the noise directly introduced into the water by the pile. For other soil layers and soil resistances, such as in the German EEZ of the Baltic Sea, it has not yet been clearly scientifically investigated, how big the soil couplings can be and on which parameters they depend.

Generally, it can be assumed, that the soil couplings do not significantly contribute to the total level in the far field due to the considerably lower amplitudes in case of unmitigated pile-driving noise. Nevertheless, the soil coupling can significantly influence the effectiveness, especially of near-to-pile Noise Abatement Systems; see chapter 6.3.

5.1.3 Influence of the water depth

The water depth can influence the pile-driving noise in shallow water in two ways:

(i) the noise entry or emission can be reduced due to the water depth,

(ii) the water depth influences the sound propagation into the water (see chapter 5.1.5).

The noise entry into the water is (theoretically) influenced by the water depth, especially in shallow water. Below a certain cut-off frequency, no continuous noise input and associated noise propagation is possible. The shallower the water, the higher this frequency is.

In water depths of approx. 25 m, this cut-off frequency f_g is below 50 Hz, depending on the sediment type (Urick, 1983). Figure 3 shows the lower cut-off frequency for predominantly sandy soils as a function of the water depth. Moreover, the bandwidths of the lower cut-off frequency for different soil layers, such as clay and till, are shown in shaded form (Jensen et al., 2010). Sound frequencies near and below the cut-off frequency can be coupled into the water considerable worse and is also damped stronger with increasing distance from the sound source (influence on the noise propagation; see chapter 5.1.5).

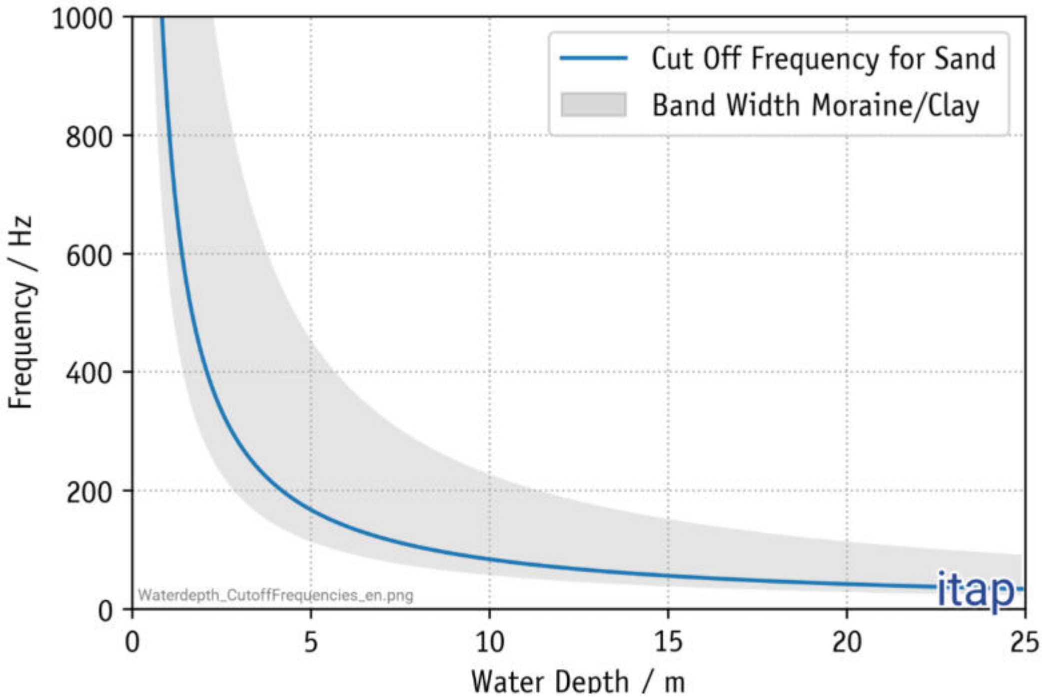

Figure 3: *Theoretical lower cut-off frequency f_g for an undisturbed sound propagation in the water for different soil layers: the blue line results assuming sandy soils and the grey shaded area sketches the influence of different soils, like clay and till (Urick, 1983; Jensen et al., 2010).*

The so far built OWFs in the German EEZ, which are also entered in MarinEARS[1], are in water depths between approx. 20 and 40 m (LAT). The cut-off frequency f_g for sandy soils, like in the German EEZ of the North Sea, is thus significantly lower than the maxima to be expected in the unmitigated pile-driving spectrum, which usually are between 63 and 250 Hz; see Figure 14 in chapter 5.2.1.

The measurement data confirm so far that the water depth between 20 and 40 m has no significant influence on the sound input into the water regarding the total level for impulsive pile-driving.

However, the *itap GmbH* has isolated pile-driving measurement data from very shallow waters (within the 12-sea-mile-zone of the German North Sea), which show the influence of the cut-off frequency; see Figure 4.

In the example shown (Figure 4), a technical Noise Abatement System was used during the pile-driving, so that there is only a very small noise input in the high-frequency range (> 500 Hz) in the water. At low frequencies, however, the influence of the different water depths becomes apparent. In a water depth of about 4.5 m, a noise emission of a pile is limited in the low frequency range. According to Jensen et al. (2010), a noise input into the water at 4.5 m water depth and sandy soil is only to be expected from a frequency of approx. 160 Hz.

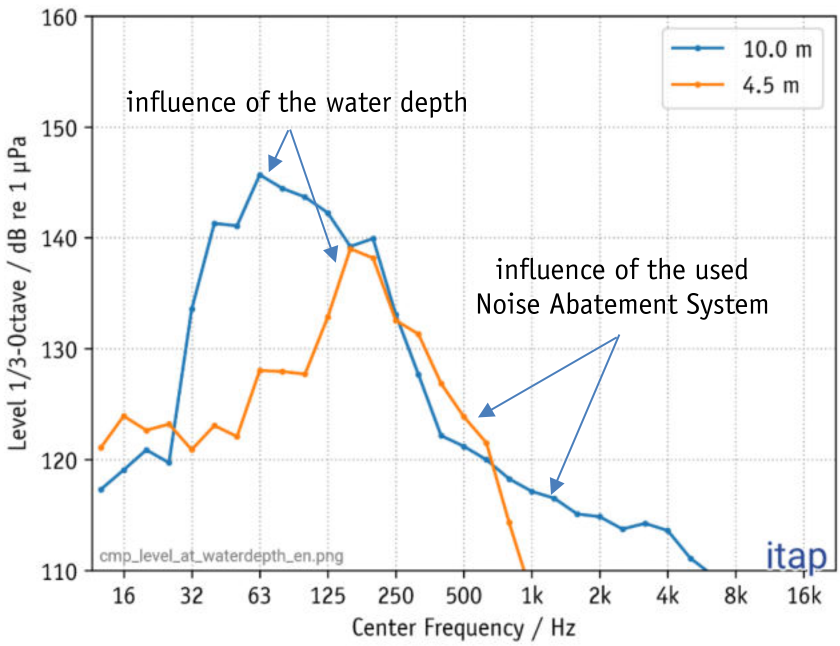

Figure 4: *Measured 1/3-octave-spectrum of a monopile installation in two different water depths (4.5 and 10 m water depth; sandy subsoil). Both installations were performed with comparable Noise Abatement Systems. (Source: Unpublished measurement data of the itap GmbH from a construction project not in the German EEZ.)*

5.1.4 Bathymetry, current and sound velocity

According to the national measurement specification (BSH, 2011), usually, underwater noise measurements are only ordered and carried out in one direction in measurement distances of 750 m, 1,500 m and in the nearest FFH protected area. For this reason, a statistic analysis of the parameters bathymetry, current and sound velocity is not completely feasible with the data sets available in the specialist information system MarinEARS[1]. However, at isolated foundation sites, underwater noise measurements for the detection of the directional dependency of the applied Noise Abatement Systems according to the measurement specification (BSH, 2013a) and the DIN SPEC 45653 (2017) are mostly ordered in 750 m distance, which can partially be used for the investigation of the mentioned parameters bathymetry, current and sound velocity.

In the R&D project BORA[4], underwater noise measurements in different spatial directions and distances of approx. 80 m to 20 km to the pile were carried out in three German OWF construction projects in the German EEZ of the North Sea. The water temperature, the current and the sound velocity were also recorded additionally to the underwater noise measurements. For pile-driving activities without Noise Abatement Systems, there was a tendency for differences of a few decibels between measurements at the same distance, but in different spatial directions. Strong differences in the bathymetry of these three OWFs did not show up either. However, an unsystematic measurement uncertainty, also in the range of a few decibels, is to be expected (ISO 18406; BSH, 2011), so that so far, no significant influence on the sound propagation could be measured in case of an approximately flat bathymetry and sandy soils with different densities and thickness. The measurements during impact pile-drivings without technical Noise Abatement System according to the DIN SPEC 45653 confirm this statement at least at a measuring distance of 750 m.

Due to the fact, that the North Sea is connected to the Atlantic Ocean from two sides, that there are tides and that the water depths in the German EEZ of the North Sea are between 20 m and approx. 50 m, there is mostly a very good mixing of the water. Occasionally, minor temperature stratifications could be measured during long periods of good weather. The temperature has an influence on the sound velocity, so that sound velocity profiles within the water column could metrologically be determined. In the shallow North Sea, these sound velocity profiles did not show a significant influence on the sound propagation of impulsive and low-frequency pile-driving noise (unpublished measurement data of the *itap GmbH*). Moreover, the measurements in the R&D project BORA[4] showed no significant influences of the current (usually in the German North Sea max. 0.75 m/s) on the sound velocity (usually ~ 1,500 m/s) (Bellmann et al., 2013 & 2015; Gündert et al., 2015).

In the German EEZ of the Baltic Sea, underwater noise measurements in two different heights (2 and 10 m above the seabed at a water depth exceeding 20 m) in accordance with the BSH measurement guideline (2011) and the ISO 18406 (2017) were carried out once. There were level differences of up to 5 dB between the lower and the upper hydrophone height during the entire pile-driving. Afterwards, a rock formation of several meters' height could be found in the construction field, which completely shielded the hydrophone at the lower position from the pile-driving site.

Basically, due to the water depth (chapter 5.1.3) and the frequency-dependent noise propagation in shallow water (chapter 5.1.5), an influence of the bathymetry cannot be excluded.

5.1.5 Sound propagation

For rough calculations, it can be assumed, that the sound pressure decreases with the distance according to a simple power law (geometric transmission loss). The sound level is then reduced by:

$$\text{TL} = k \cdot log_{10}\left(\frac{r_1}{r_2}\right) \text{ [dB]} \qquad \textit{Equation No. 8}$$

with

r_1 and r_2 – distance to the sound source increases from r_1 to r_2,

TL – transmission loss,

k – constant (for the German EEZ of the North- and Baltic Sea, roughly, k = 15 can be assumed).

Often, the transmission loss for the distance r_1 = 1 m (fictive distance to the imaginary point noise source) is specified. From this, the acoustic power of a pile to be driven at a distance of 1 m is calculated and often used in prognosis procedures. Equation No. 8 is then simplified to:

$$\text{TL} = -k \cdot log_{10}(r/Meter) \text{ [dB]} \qquad \textit{Equation No. 9}$$

In the "Guideline for Underwater Noise - Installation of driven piles" (Danish Energy Agency, 2016), the following transmission loss for noise events in the Baltic- and North Sea is indicated with water depths up to 50 m:

$$\text{TL} = -14.72 \cdot log_{10} r + 0.00027 \cdot r \text{ [dB]} \qquad \textit{Equation No. 10}$$

However, both of the above calculations do not take into account, that a decrease of the sound pressure is frequency dependent. Strictly speaking, these formulas only apply for the acoustic far field, i. e. valid from a distance of a few wave lengths to the source. Furthermore, the weather affects the noise level in the water at large distances. The Sound Pressure Level decreases much faster over the distance at strong winds and heavy seas. This is the result of a higher surface roughness of the sea and stronger air inclusions in the upper ocean layer due to the swell.

Thiele and Schellstede (1980) specify approximation equations for the calculation of the sound propagation in different regions of the North Sea as well as for „rough“ and „calm“ sea. The following equation for shallow waters and „calm“ sea (abbreviation IIg in Figure 5) can therefore be compared with the measurement results:

$$\text{TL} = -(23 + 0.7F)\, log(r) + (0.3 + 0.05F + 0.005F^2)\, r\, 10^{-3} \text{ [dB]} \qquad \textit{Equation No. 11}$$

with

$F = 10\ log(f/[\text{kHz}])$.

Actually, Equation No. 11 only applies for the German EEZ of the North Sea with good water mixing, "calm" sea and without a distinctive sound velocity profile.

Technical note: Up to now, for safety reasons, pile-driving works most likely take place at “smooth” seas and little wind, so that the approach of Thiele & Schellstede (1980) for “rough” seas should not be considered. However, due to the continually growing size of the installation vessels in relation to the wave height, the restrictions are likely to change, so that in the future, piles could be installed to the seabed by means of the impact pile-driving method also at “rough” seas. In “rough” seas, more air is brought into the upper water layer by wind and waves; this leads to a reduced sound propagation over long distances (> 8 km).

Figure 5 shows the three above mentioned propagation approaches (Equation No. 9 -$k = 15$-, Equation No. 10, Equation No 11) in comparison with real underwater noise measurements during impulsive pile-driving for monopiles.

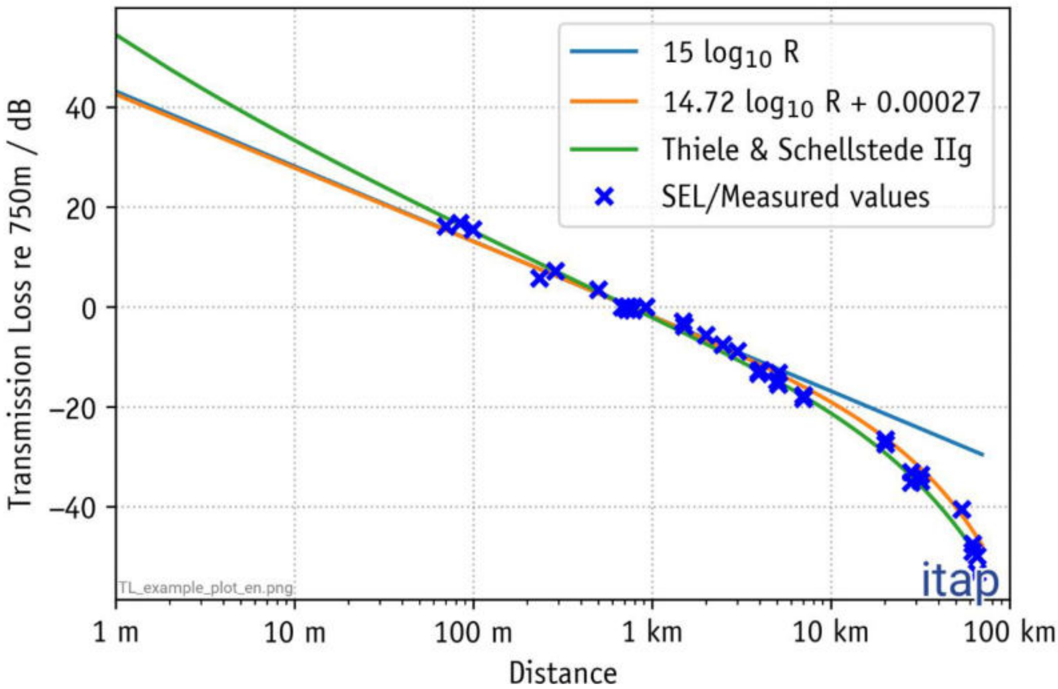

Figure 5: *Different, predicted transmission loss curves (continuous lines) for shallow waters: general, geometric transmission loss (conservative approach; 15 log R), semi-empiric approach defined in Danish Energy Agency (2016) (DK_log R) and semi-empiric approach of Thiele and Schellstede (1980) for shallow waters, „calm“ sea (IIg) in comparison with existing offshore measurement data (blue crosses).*

With reference to Figure 5, both semi-empiric approaches, the Danish Energy Agency (Equation No 10) and Thiele & Schellstede (1980) (Equation No. 11), are very similar to each other and also show a good match with actual underwater noise measurements during impulse pile-drivings in the North Sea. Only for distances less than 100 m and for distances larger than 10 km, the two equations differ considerably. These differences would also have a significant effect on a calculation of the source level.

Figure 6 shows the average, unmitigated pile-driving noise spectrum (SEL_{50} - 50% exceedance level = medium), measured at different distances to the foundation. It can be seen, that for large distances the amplitude of high frequencies is reduced stronger than of low frequencies.

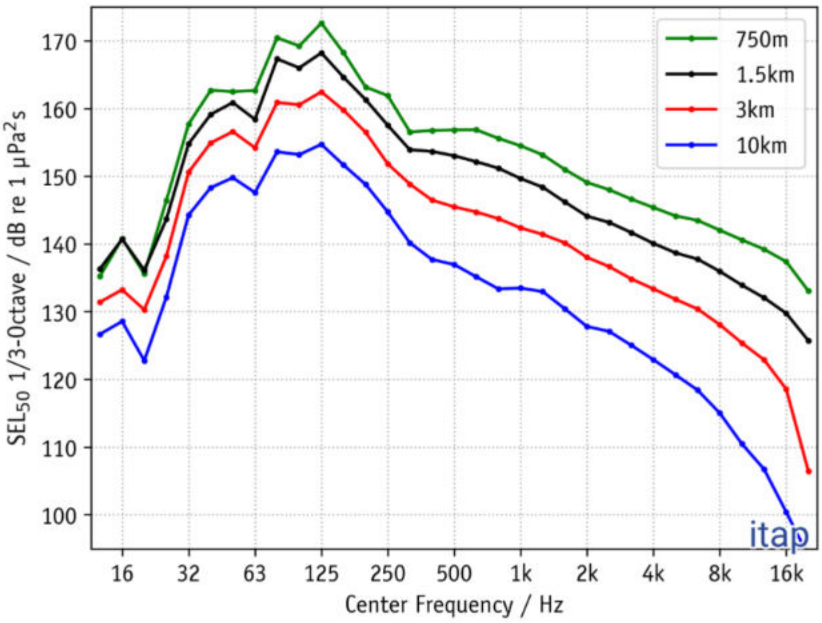

Figure 6: *Average 1/3-octave-spectra measured in different distances during the foundation construction of a monopile with the impact pile-driving method.*

Technical note: The transmission loss (TL) has a significant influence on the sound propagation over large distances. It may be significantly different from the above mentioned transmission loss, e.g., in the case of strongly varying bathymetry, soil conditions (chapters 5.1.1 and 5.1.2) other than those in the North Sea, e. g. Baltic Sea with till and chalk layers, or in calculations of spectrally weighted evaluation levels (e. g. National Marine Fisheries Service, 2018; Southall et al., 2019). When applying spectral weightings for propagation calculations over more than 10 km a direct metrological recording of the existing transmission loss is recommended.

The frequency-dependent sound propagation (transmission loss) is also related to the multiple reflections at the water surface and on the seabed. This effect is called dispersion and does not only cause a frequency-dependent transmission loss and an associated, frequency-dependent reduction of the amplitude, but also, that an impulsive signal expands temporally; see Figure 7. The noise of a single strike is thus temporally stretched with increasing distance. Moreover, the amplitude decreases steadily with the distance to the source, so that the signal-to-noise-ratio continuously decreases. This leads on the one hand to a mixing of a single pile-driving blow with the permanent background noise and on the other hand, it can lead to an overlay of consecutive single strikes at high blow rates. Thus, the pile-driving noise in the water in large distances to the source is no longer measured as impulsive pile-driving event (MSFD, descriptor 11.1), but is metrologically recorded as continuous noise event (MSFD, descriptor 11.2).

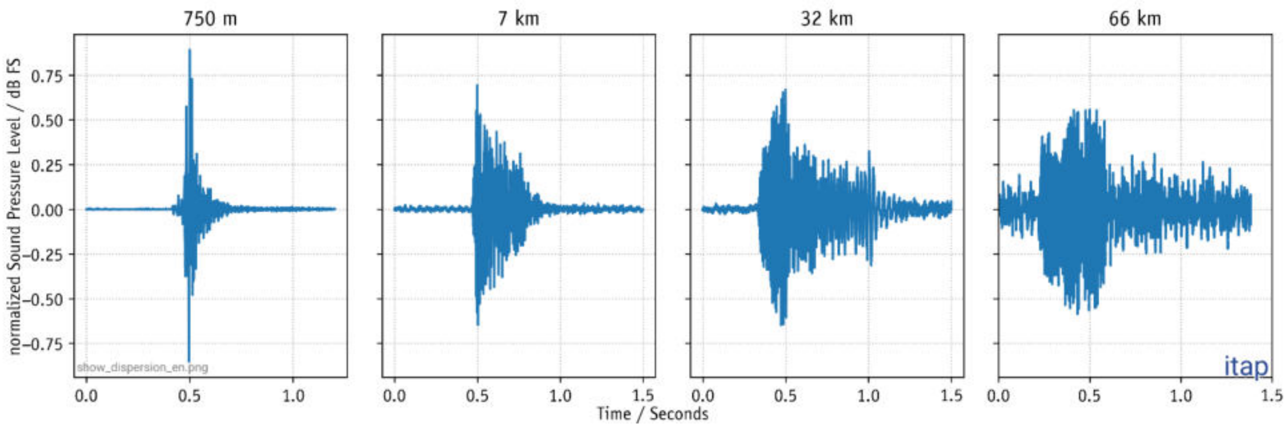

Figure 7: *Time signal of a single strike, measured in different distances to the pile-driving activity.*

Remark: sound propagation in the Baltic Sea

Due to the geographic location and topography of the Baltic Sea, there hardly is any exchange with water from the Atlantic Ocean. Compared to the North Sea, where the Atlantic water flows in from two directions and a constant mixing is ensured, the currents in the Baltic Sea are primarily the result of weather influences. Thus, a long-lasting wind from the northwest can push water into the Baltic Sea. As soon as the wind direction changes or there is no wind, the water flows out of the Baltic Sea. As a result, especially in the summer months, flow conditions can occur, in which a complete mixing of the water can no longer be guaranteed as expected for the assumed transmission loss according to Equation No. 11. Instead, stratifications of varying salinity and temperature may form in the water. This results in a strong sound velocity profile over the entire water column.

Because of the different stratifications, channels can form, in which the sound waves can propagate with a significantly lower transmission loss. These so-called „sound channels“ or “Baltic ducts” are formed in areas, where the propagation velocity of the sound is lower than in the layers above and below. Since the propagation velocity of the sound under water increases with rising temperature and salinity, the sound diffracts at transitions between two layers towards the layer with the lower propagation velocity. If this effect occurs at two opposite boundary layers (e. g. top: higher temperature, bottom: higher salinity), the sound can propagate with a significantly lower transmission loss due to a more directional distribution of the existing acoustic power and lower losses through reflections within this stratification. This creates a „sound channel“. However, this is only true, if the wavelengths are not too large in relation to the height of the sound channel. In order to transmit sound immissions of the pile-driving blows, which are usually in the frequency range << 500 Hz (Figure 14 in chapter 5.2.1), in such channels, a vertical sound channel extension of >> 30 m would be required (Johnson, 1982). This is highly unlikely for water depths in the German EEZ of the Baltic Sea of up to 45 m.

The German Navy (military service / „Wehrtechnischer Dienst – WTD71“) was able to metrologically prove the influence of such sound channels on acoustic signals several times in less frequented areas of the Baltic Sea[8]. The effect of the sound channels was 10 dB and more over a distance of several kilometers. This means, sound inside the sound channel was reduced in the amplitude by 10 dB less in the sound propagation over several kilometers than sound above and below this sound channel. However, the study clearly indicated, that the test signals were not low-frequent pile-driving noise, but (sinus- or pulse-) signals in frequency ranges of several kHz (sonar). Though, it was made clear, that the presence of such sound channels is dependent on defined hydrographic conditions, which can change rapidly and significantly at a time, e. g. by a vessel passage, due to the mixing caused by the propulsion. Moreover, the vertical expansion of these sound channels was only a few meters. Thus, the sound signals used there are higher in frequency by a factor of 10 and more than the pile-driving noise considered in this report.

> *Technical note:* A point sound source was also used in the tests of the German Navy; a pile to be driven represents a spatially extended line sound source. It is currently not clear, what influence the type of sound source has on the coupling of the radiated noise to such sound channels.

In a completed OWF construction project in the German EEZ of the Baltic Sea, corresponding measurements of the salt-, temperature- and sound velocity profiles were metrologically recorded over the water depth on several days and at several measuring positions by means of conductivity, temperature and depth (CTD)-probes[9]. These measurements were ordered by the BSH within the scope of the construction release. During a measurement in late summer, after a long period of "good weather", a sound channel could once metrologically be recorded. The expansion of this channel was approx. 10 m in height. At that time, the underwater noise was recorded simultaneously at three different heights above ground during the pile-driving activities of a monopile installation. There was one hydrophone below the sound channel, one hydrophone in the middle and one hydrophone at the upper edge of the sound channel; see Figure 8. However, the measurement

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[8] Presentation of the WTD71 on the 2nd DUH Noise Abatement Conference, Berlin, 2014.

[9] CTD-tubes are applied in the water to record the water depth, conductivity resp. salinity and temperature in the water. By recording the above mentioned parameters, the sound velocity as function of the water depth can be determined.

results of this piling in several hydrophone heights in a distance of 750 m to the source only had a variance of < 2 dB, which is within the range of the general measurement uncertainty.

Long-term studies in the Baltic Sea show, that such sound channels are to be regarded as temporally very unstable, since, for example, the water column is usually at least partially mixed by currents, wind or vessel movement (propulsion). An overview of the temporal variability resp. the rapid change of temperature and salinity within hours can be read using the data from the Marine Environmental Monitoring Network (Meeresumweltmessnetz) of the BSH, which i. a. contains data from the measuring platform FINO2

(https://www.bsh.de/DE/DATEN/Meeresumweltmessnetz/meeresumweltmessnetz_node.html).

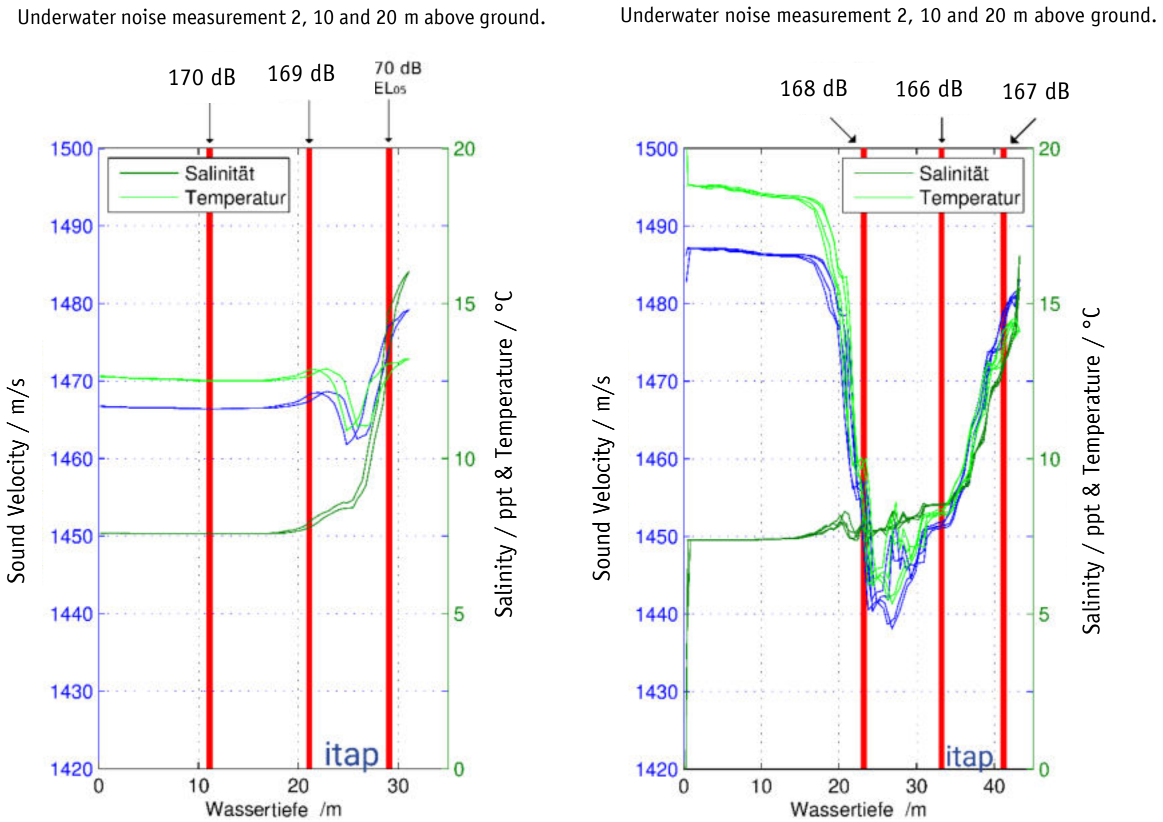

Figure 8: *Water depth-dependent sound velocity profiles measured in the Baltic Sea after a long-lasting good weather period (right) and after a complete mixing of the water column (left). Furthermore, during the pile-driving works, underwater noise measurements in three different hydrophone heights above ground (2 m, 10 m and 20 m above ground at a water depth of 31 m left and 43 m right LAT) were performed (red lines).*

5.1.6 Influence of the hydrophone height in the acoustic far field

According to the German measurement specification for underwater noise measurements (BSH, 2011) and the ISO 18406 (2017), hydrophones must be positioned in the bottom half of the water column at minimum 2 m above ground. In the R&D project BORA[4], per measuring position, two hydrophones (2 and 10 m above ground, water depths in all three OWF construction projects > 20 m, German EEZ of the North Sea) were deployed in different spatial directions and distances to the pile-driving construction site. Overall measurement data, there was no significant influence of the hydrophone height above ground on the noise measurement values. Unsystematic, maximum level differences of up to ± 2 dB could be detected in some cases. This was also confirmed by a construction project in the German EEZ of the North Sea from the year 2014, where partly underwater noise measurements in 2, 5 and 10 m above ground at a water depth of > 20 m were performed.

In the R&D project ESRa[10] as well as in the R&D project BORA[4], a so-called „hydrophone line-array“ was put up in the water column with up to 16 hydrophones each in 1.5 to 2.0 m vertical distance. This line-array was deployed in the acoustic near field in distances up to 80 m close to the pile installation and the used hydrophones almost covered the entire water column. These measurements showed, that in the lower half of the water depth, the sound level did not change significantly (unsystematic level differences of up to ± 2 dB), but in the upper half of the water depth, the total level steadily decreased towards the water surface (Wilke et al., 2012; Bellmann et al., 2013 & 2015; Gündert et al., 2013). Near to the water surface, differences from at least 5 dB to > 10 dB could be measured; see Figure 9. The reason for this is the large impedance difference on the water surface between air and water.

Figure 10 furthermore presents an averaged 1/3-octave-spectrum of a monopile installation by means of the impact pile-driving method, measured in 750 m distance in two different measurement heights inside the lower water column. It can be seen, that the measurement variance in single frequency bands is only in the range of a few decibels.

Figure 10 presents the averaged 1/3-octave-spectrum of the Sound Exposure Level (SEL_{50}) of a monopile foundation by means of the impulse pile-driving method, measured in 750 m in two different measurement heights (2 m and 10 m above ground at a water depth of larger 20 m). There is a high alignment between the two shown 1/3-octave-spectra. It appears that the measurement variance in single frequency bands is in the range of only a few decibels.

With the hydrophone height defined in the regulations (BSH, 2011; ISO 18406, 2017) of at least 2 m above the seabed and inside the lower half of the water, thus, the "loudest" case that can be measured is recorded during an impulse pile-driving in shallow water.

[10] ESRa – Evaluation of systems to reduce piling noise at an offshore test pile; technical final report, supported by BMU and PTJ, FKZ 0325307.

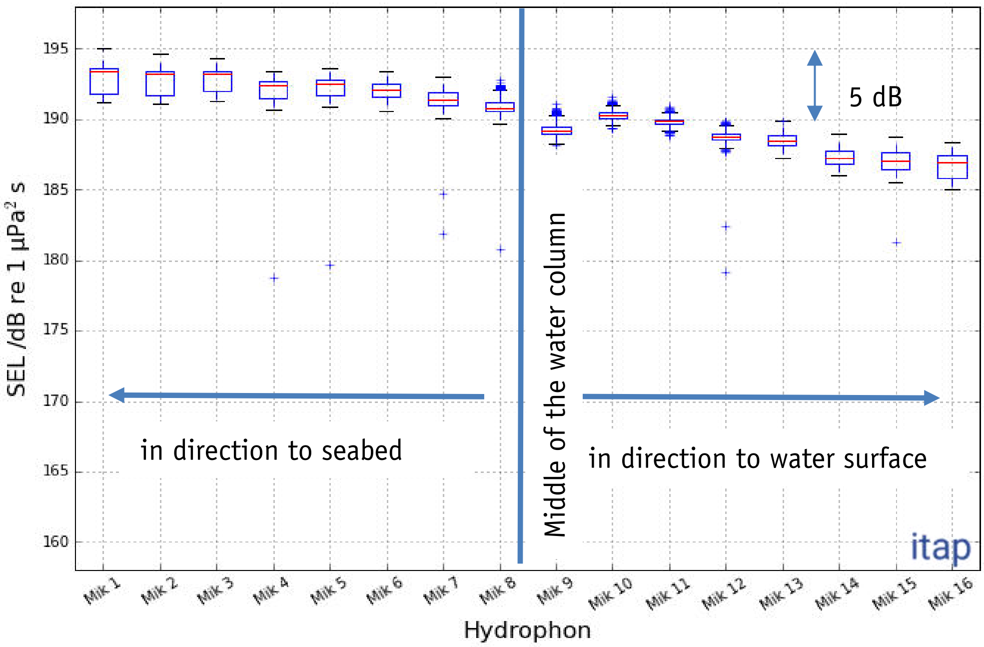

Figure 9: *Statistic presentation (boxplot) of the measured Sound Exposure Level (L_E resp. SEL) with 16 hydrophones of approx. 2 m above ground to the water surface during an impact pile-driving of a monopile without the application of a technical Noise Abatement System in a distance of approx. 80 m to the pile-driving inside the German EEZ of the North Sea. Mik1 marks the hydrophone 1 in 2 m above ground; all further hydrophones were located in a vertical distance of 1.5 m to each other; water depth ~ 30 m. (source: Gündert et al., 2015)*

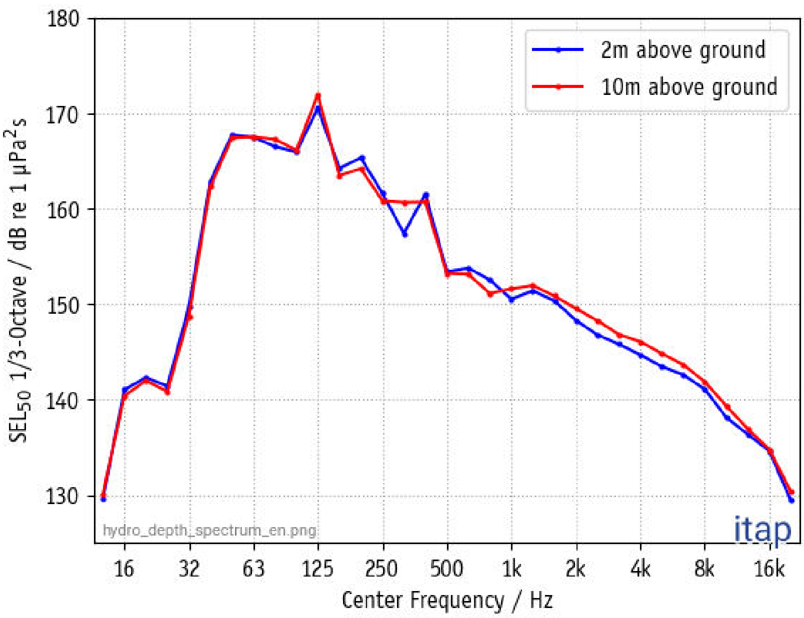

Figure 10: *Averaged 1/3-octave-spectrum of the Sound Exposure Level (SEL_{50}) of a monopile foundation by means of the impact pile-driving method, measured in 750 m in two different measurement heights (2 m and 10 m above ground at a water depth of larger 20 m).*

5.2 Technical-constructive influencing factors

5.2.1 Foundation- and pile design

Figure 11 schematically summarizes different foundation structures for OWTGs. The necessary piles for a Tripod, a Jacket-construction, a Tripile and a monopile are usually anchored to the seabed by the impulse pile-driving method. Depending on the construction and the technical design, no anchors or piles in the seabed using the impulse pile-driving method are required for a floating foundation structure or a gravity foundation. Floating foundation structures as well as gravity foundations (deutsch Schwerkraftfundament) belong to the alternative, low-noise foundation structures and are discussed in chapter 7.4.3.

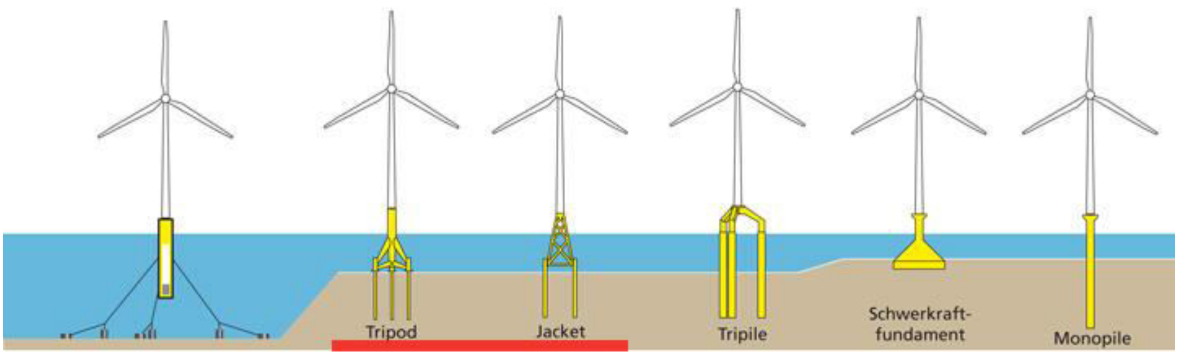

Figure 11: *Different foundation structures for OWTs (Source: Stiftung OFFSHORE-WINDENERGIE).*

Figure 12 represents the Sound Exposure Levels (L_E resp. SEL) and zero-to-peak Sound Pressure Levels ($L_{p,pk}$) as function of the used pile diameter during unmitgated impulse pile-drivings, measured in 750 m distance to the foundation site. Moreover, for this figure, the entries of the MarinEARS[1] were completed by further underwater noise measurements of the *itap GmbH* from the North- and the Baltic Sea within the 12-sea-mile-zone and in the European foreign countries, particularly for smaller pile diameters. No differences in the foundation design were made, i. e. both monopiles and skirt-piles for Tripods and Jacket-constructions as well as Tripiles were considered.

It can be seen, that with increasing pile diameter, the measured noise level values also increase. The 95-%-confidence interval of all recorded (impulse) pile-drivings is ± 5 dB, only depending on the parameter „pile diameter“. Moreover, it appears that with the same pile diameter, the measured noise level values can deviate from each other by up to 8 dB. It can therefore be assumed, that the pile diameter indeed is a dominant influencing parameter for pile-driving noise, but that other parameters co-determine the broadband noise level.

In Figure 13, monopile installations with diameters larger 5 m (right) and other piles (e. g. Tripiles, skirt-piles for Jacket-constructions) with diameters smaller 4 m (left) are considered. For the monopile installations, there is extensive information about the pile-driving process and the used impact hammers available. It can be seen that the measured noise level values tend to increase slightly with rising pile diameter. Small pile diameters with different pile designs (left figure) tend to have a much stronger influence of the pile diameter on the noise level values to be measured.

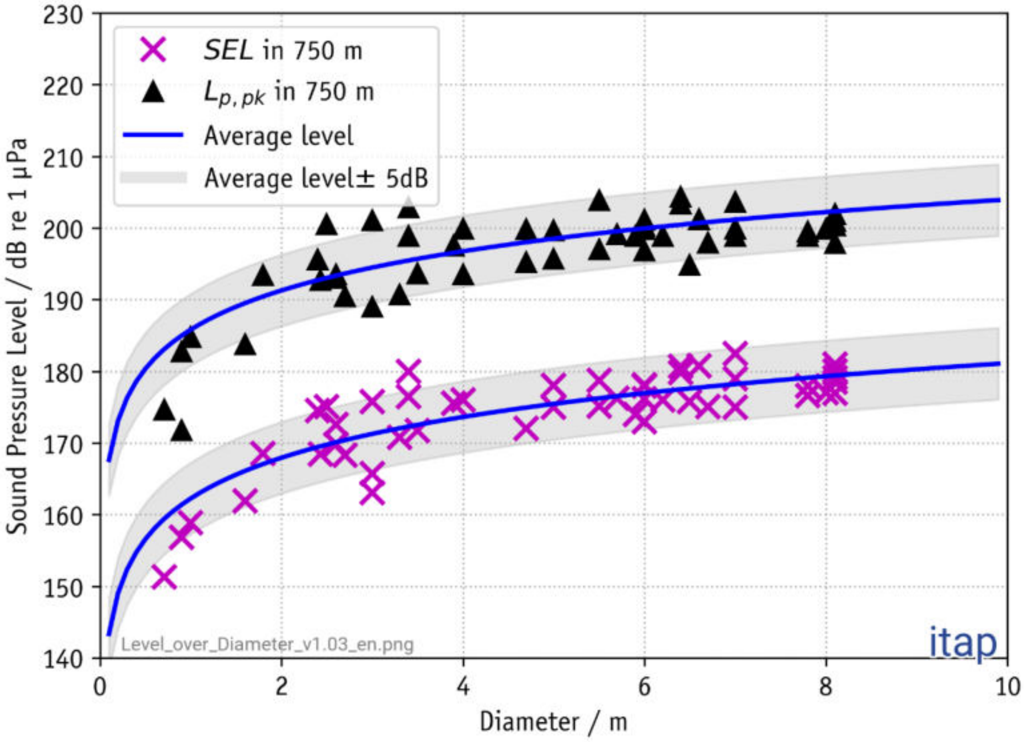

Figure 12: *Measured zero-to-peak Sound Pressure Levels ($L_{p,pk}$) and broadband Sound Exposure Levels (L_E resp. SEL_{05}) at foundation works at piles with a different foundation structure by the impulse pile-driving method of various OWFs as a function of the pile diameter. All pile-drivings were performed without the application of technical Noise Abatement Systems.*

Figure 14 shows, that with the pile diameter, not only the broadband noise level, but also the spectral composition of the pile-driving noise changes at a distance of 750 m. The tendency is for maximum pile diameters of 3.5 m (usually skirt-piles for Jacket-foundations) to result in a maximum in the 1/3-octave-spectrum in the frequency range of approx. 160 Hz. To higher and lower frequencies, the noise level steadily decreases approximately by 6 dB per octave. At frequencies < 50 Hz, the level decrease is again significantly larger and depends on the prevailing water depth.

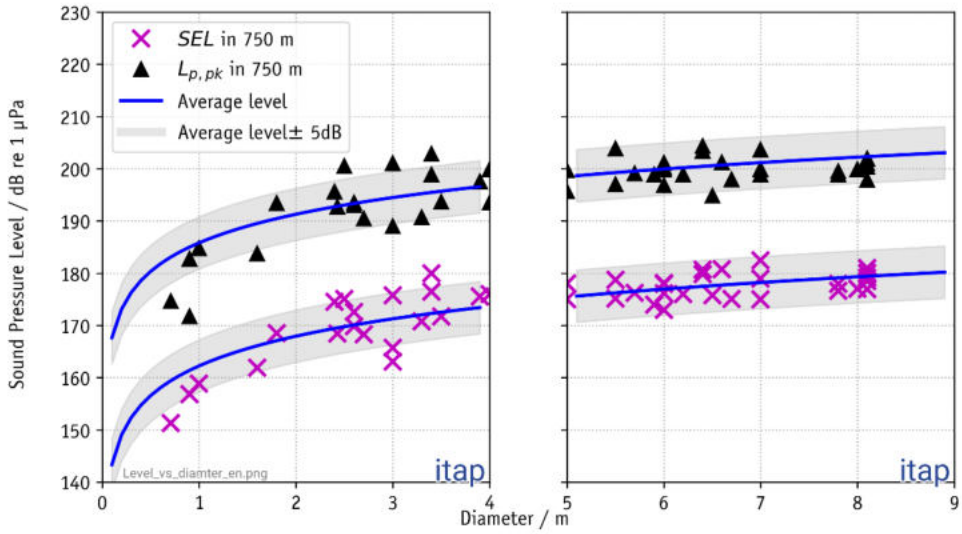

Figure 13: *Measured zsero-to-peak Sound Pressure Levels ($L_{p,pk}$) and broadband Sound Exposure Levels (L_E resp. SEL_{05}) at foundation works with the impulse pile-driving method of diverse OWFs as a function of the pile diameter. Left: different pile designs with pile diameters of up to 4 m. Right: only monopiles with pile diameters ≥ 5,0 m. All impulse pile-drivings in both figures were carried out in 750 m without the application of technical Noise Abatement Systems. However, for these measurement data, not all information on the technical-constructive influencing factors, such as the pile-driving process and the used impact hammers, is partly available. Therefore, it cannot be excluded, that the sometimes high levels at low pile diameters are permanently influenced by technical-constructive influencing factors, such as coupling effects of the skirt-piles to the Jacket-construction.*

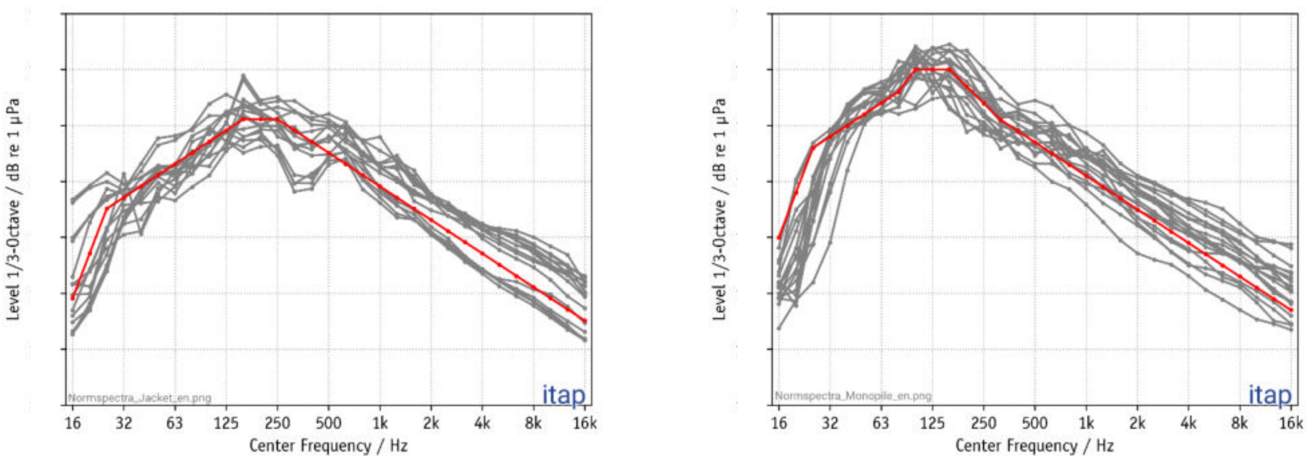

Figure 14: *1/3-octave-spectra of several impulse pile-drivings in different OWF construction projects, measured in 750 m distance. The pile-drivings were performed without the application of technical Noise Abatement Systems. Left: grey shaded lines mark the real measurement data of different pile diameters up to a maximum diameter of approx. 3.5 m (piles for Jackets); the red line characterizes an averaged, theoretical model spectrum (median). Right: grey shaded lines mark the real measurement data of different diameters (minimum 6 m, monopiles); the red line characterizes the averaged, theoretical model spectrum (median).*

With increasing pile diameter (monopile), the maximum in the spectrum shifts from approx. 160 Hz to lower frequencies. Pile-drivings with monopiles of diameters larger than 6 m partly show a maximum at below 100 Hz. The qualitative level response also changes slightly towards higher frequencies. The level decrease or -increase around the maximum is approximately 12 dB per octave instead of 6 dB per octave.

The data shown in Figure 13 are normalized in the broadband overall noise level with reference to the blow energy used and show approximately the same (normalized) broadband levels (see chapter 5.2.2). However, regardless of the shift of the maximum to deep frequencies, a high measurement variance of up to ± 10 dB in single frequency bands with comparable pile diameters is shown; this applies in particular to frequencies larger than 1 kHz.

Usually, with the diameter of the piles, also the necessary blow energy increases and thus the size of the impact hammer used. In particular, not only higher blow energies are necessary to overcome the soil resistance, but also significantly larger anvils are required for the impact hammer/pile transition. According to initial findings, it cannot be excluded, that the shift of the maximum in the pile-driving noise with increasing pile diameter is caused by the pile diameter itself, the anvil and/or the type and the size of the impact hammer. It can be assumed, that the three parameters mentioned are linearly dependent on each other; see chapter 5.2.2.

Technical note: Based on the experiences with different modelling methods (prognoses) prior to an OWF construction project and the comparison of the actual measurements during the construction of OWTG foundations, it turned out, that the broadband Sound Exposure Level and the zero-to-peak Sound Pressure Level are relatively highly predictable[1]. The detailed prediction of the 1/3-octave-spectrum however is only limitedly possible, since this is determined by many influencing factors, some of which are not completely independent of each other.

It should be noted, that when using pile diameters smaller than 4 m (mainly skirt-piles for Jacket-constructions), mostly pile installation frames or the piles were directly driven through the designated pile sleeves at the Jacket-construction, so that an influence of this pile-driving method on the pile-driving noise spectrum is also possible; see chapter 5.2.3.

Technical note: So far, no inclined piles, i. e. piles driven into the ground at an angle, have been installed in the German EEZ. Thus, no statement can be made about this pile design at present.

Technical note: Usually, the transition between the pile-head and the transition piece between the monopile and the tower of an OWTG is 6 to 6.5 m. The previous large monopiles with a diameter of up to 8 m thus had a slight taper towards the pile-head, which is usually located in the area of the water surface. The influence of a pile-tapering within the water column during an impulse pile-driving has therefore not yet been investigated in the German EEZ.

Furthermore, the site characteristics and environment variables can also have an influence on the respective pile-driving noise spectrum; see chapter 5.1.

5.2.2 Impact hammer, blow energy and pile-driving process

The interaction between impact hammer and pile during the impact pile-driving is a very complex process, which is not fully discussed in this technical report. In the following, the essential influencing parameters on the pile-driving noise, which have been shown in the cross-project analysis of all measurement data over the entire pile-driving process, will be documented. The following issues are essentially dealt with:

- blow energy, incl. soft-start and „noise-optimized" pile-driving procedure,
- third -octave spectrum of the Sound Exposure Levels over the course of pile-driving,
- impact hammer type resp. -size,
- embedding depth of the pile.

Blow energy ./. Sound Exposure Level

Figure 15 shows a complete (impulse) pile-driving of a monopile, depending on the used blow energy or depending on the embedding depth.

Figure 15 shows, as the blow energy increases, that the Sound Exposure Level at a distance of 750 m from the monopile installation increase steadily within the so-called ramp-up-procedure and later remains almost constant resp. this increase flattens out considerably. The ramp-up procedure includes the constant increase of the applied blow energy and the simultaneous raising of the blow repetition frequency at the beginning of a pile-driving. Furthermore, it is shown that there is a significant correlation between the mandatory blow energy to be applied and the embedding depth during pile-drivings in the North Sea. The blow energy mostly must be increased with growing embedding depth in order to steadily overcome the soil resistance (sands of varying thickness and density). Generally, all OWF construction projects from the German North Sea so far have shown, that the Sound Exposure Level either

(i) increased steadily,
(ii) remained almost constant after approx. 75 % of the pile-driving or
(iii) decreased slightly after approx. 75 %. (< 1 dB),

until the maximum embedding depth was reached and with increasing blow energy.

Overall, when the maximum embedded depth was achieved, taking into account the applied blow energy and the pile diameter, the Sound Exposure Levels were in the range of the measurement uncertainty. The reason for the increase, the constant course or the slight drop towards the end of pile-driving could not be clearly associated either with the soil resistance or the impact hammer used nor any other influencing parameter.

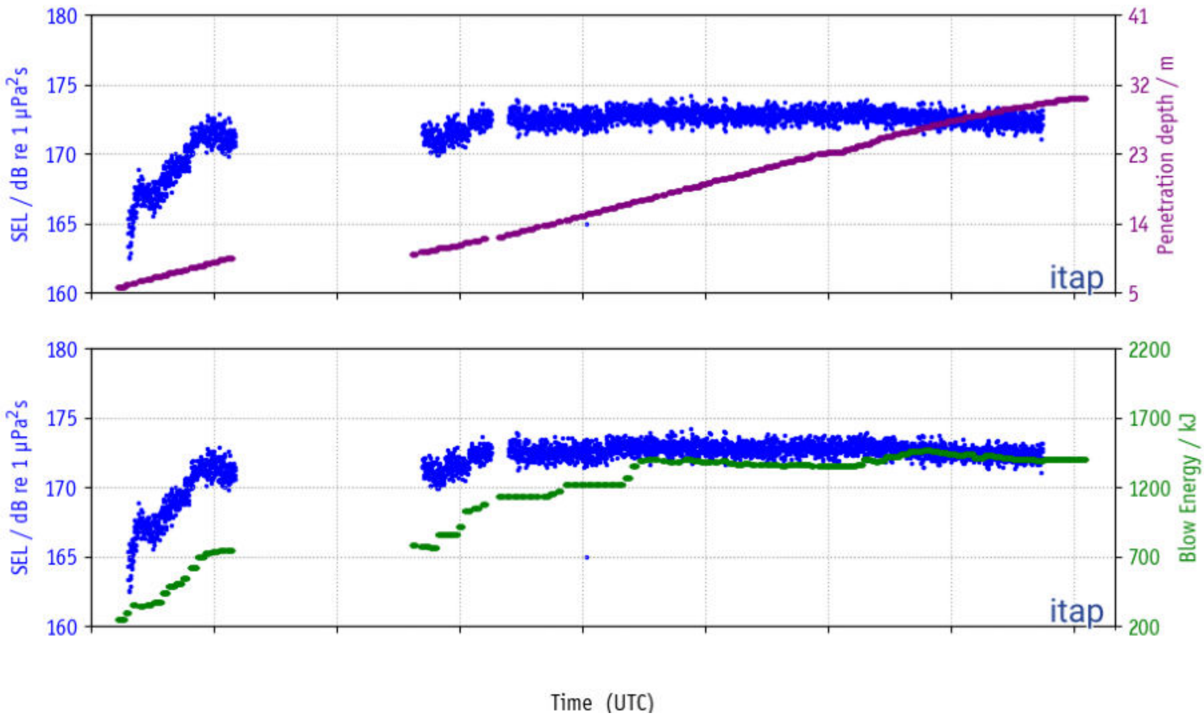

Figure 15: *Measured Sound Exposure Level (L_E resp. SEL) in 750 m during a monopile installation as a function of the time. The pile-driving was performed without the application of a technical Noise Abatement System. Additionally, the applied blow energy per blow (green) and the achieved embedding depth (purple) is shown.*

In several studies (Gündert et al., 2014; Brandt et al., 2011), a level increase of 2 to 3 dB per doubling of the blow energy during a continuous pile-driving was shown. A first statistical evaluation of underwater noise measurement data of all German OWF construction projects in the technical specialist information system MarinEARS[1] could confirm these values. However, it also showed, that this correlation is not always true for longer-term pile-driving interruptions. This is because the existing soil resistance must first be overcome, when restarting the pile-driving and therefore usually, slightly higher noise levels are to be expected.

Soft-start ./. Sound Exposure Level

At German OWF construction projects, the pile-driving usually starts with a soft-start, i. e. with about 10 % capacity of the impact hammer used (usually less than 400 kJ), where initially no or only a low pile-driving is achieved. This is intended to achieve an additional, stepwise, acoustic deterrence of marine mammals. In most cases, only single blows with larger pauses are executed during a soft-start. In the past majority of the construction projects, the soft-start lasted less than

15 minutes. The Sound Exposure Level at 750 m during soft start usually reached the lowest values within the entire pile-driving process.

Technical note: In Germany, the soft-start is an integral part of the noise mitigation concept, consisting of the use of acoustic deterrents (combined pinger / seal-scarer-system or from 2017 on the Fauna-Guard-system) and the soft-start. The soft-start is transformed into a continuous pile-driving process (ramp-up procedure), in which the blow energy of the impact hammer is gradually increased and the blow repetition frequency is successively increased starting from single blows (continuous pile-driving process).

Technical note: In an OWF construction project in the Baltic Sea with an optimal noise mitigation concept, consisting of a noise-optimized pile-driving method incl. impact hammer type, a near-to-pile and a far-from-pile Noise Abatement System, the signal-to-noise-ratio during the soft-start was mostly $\leq$ 6 dB, so that no error-free Sound Exposure Levels could be calculated for these first blows (requirements see chapter 4.2). Similar events have occurred in the North Sea in recent years, i. e. the noise mitigation concepts used are so efficient that, at low blow energies, the pile-driving noise is not significantly separated from the permanent background noise even at a distance of 750 m from the source.

It was shown in single construction projects, that in some cases, higher Sound Exposure Levels were measured during the soft-start than expected due to the low blow energy used; see Figure 16. A scientifically founded justification for this phenomenon does not exist at present. Up to now, it fails on further analyses to make statistically valid assignments to the impact hammer type or -size, to the soil resistance or to other parameters. An undesired interaction between pile, impact hammer or possibly pile-sleeve can currently not be excluded to be the reason for the unexpectedly high Sound Exposure Levels during the soft-start.

Noise-optimized pile-driving procedure

In Germany, for protection of the lively marine environment, a maximum pile-driving period of 180 minutes per monopile installation was defined in addition to the noise mitigation value criterion of 160 dB_{SEL} and 190 $dB_{Lp,pk}$ at a distance of 750 m (chapter 3). This 180-minute pile-driving duration includes an acoustic deterrence (varied up to 2019 between 20 and 50 minutes depending on the deterrence device used and the requirements of BSH), a soft-start (usually around 10 – 15 min.) and the subsequent continuous pile-driving incl. pile-driving interruptions for inclination measurements at the pile until the final embedding depth is reached. In addition, the BSH restricts the permissible maximum blow energy project-specifically as a further noise mitigation measure (depending on the hammer type and the local conditions; for monopiles previously $\leq$ 2.000 kJ), in order to be able to comply with the required noise mitigation values.

Due to the mandatory compliance with the German noise mitigation values, the time limitation of the total pile-driving duration as well as the limitation of the blow energy, a so-called "noise-optimized" pile-driving procedure (or smart pile-driving procedure) has been developed. This noise-optimized pile-driving procedure is thus accompanied by a high blow repetition frequency (blow rate) and an increased number of blows per defined embedding depth (blow count). Moreover, the blow energy applied is only increased (usually incrementally), if the present soil resistance can no longer be overcome without increasing the blow energy and thus no continuous pile-driving process can be guaranteed. Thus, with an optimized pile-driving procedure, the blow energy used per single blow is usually kept as low as necessary to keep the associated noise emission of the pile as low as possible; see Figure 15. The maximum blow energy specified by the authorities may only be exceeded to avoid a pile refusal.

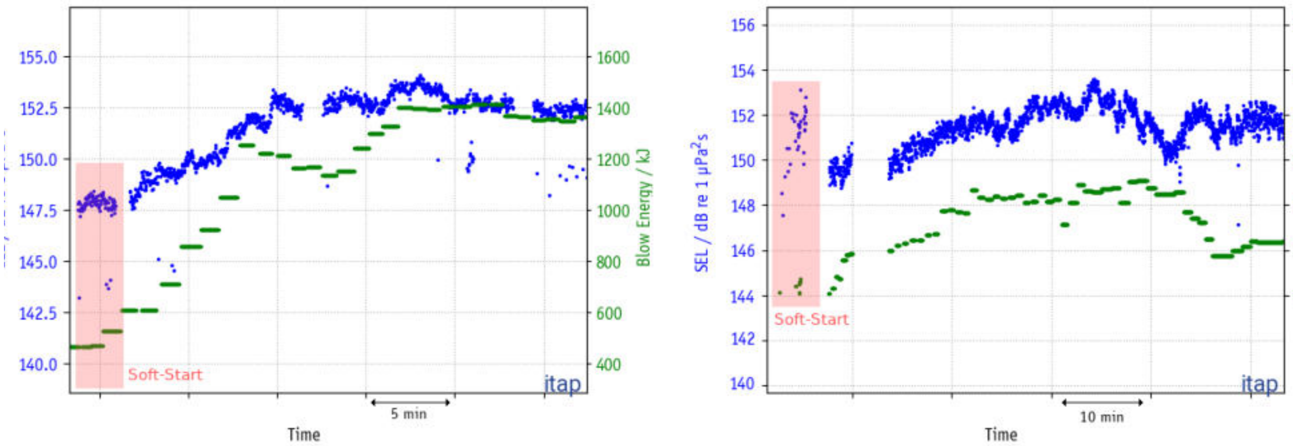

Figure 16: *The measured Sound Exposure Level (SEL resp. L_E) and the applied blow energy (green) during unmitigated monopile installations in a distance of 750 m as function of time. Left: The influence of the blow energy during the soft-start corresponds approximately to a level increase of 2 to 3 dB per doubling of the blow energy. Right: The influence of the applied blow energy during the soft-start is not proportional to the remaining pile-driving.*

For the installation of more than one pile per foundation, e. g. for a Jacket-construction, a maximum pile-driving period of 140 minutes per pile to be driven (including deterrence measure, if required) is stipulated. If the pile-driving break between two piles is less than 40 minutes, no additional deterrence measure is usually required for the second pile. If the pile-driving pause is longer than 40 minutes, the deterrence must be repeated before restarting the pile-driving.

Whether and in what form such a noise-optimized pile-driving procedure can be used, depends primarily on the technical design of the impact hammer (hammer type) and its control (power packs, hydraulic, etc.) as well as the coupling between hammer – pile head. Furthermore, the material fatigue effects at the pile to be driven and the impact hammer used are limiting factors for a noise-optimized pile-driving procedure. Moreover, the applicability and effectiveness of this pile-driving procedure additionally depends on several site-specific boundary conditions, e. g. the prevailing soil resistance, etc., and must be checked in advance for its applicability in single cases.

Technical note: In the event of non-compliance with the required pile-driving duration and/or the limited blow energy (e. g. to avoid a pile refusal, the blow energy must temporarily be increased), not only a technical deviation report must be written, but appropriate measures must also be taken in order to permanently comply with both requirements in the future.

Technical note: If it can clearly be proven by underwater noise measurements, that the noise mitigation values are mandatoryly undercut, an increase of the maximum permitted blow energy can be applied for. The risk of exceeding the mandatory noise mitigation values by increased blow energies is in responsibility of the OWF construction project.

Technical note: Prior to the start of construction, a so-called pile-driving analysis (PDA) of the foundation structures to be driven on the basis of soil profiles, the pile design, experience, etc. is performed and is usually part of the documentation for the certification of the installation procedure. The aim of a PDA is the calculation of the maximum blow energy necessary to bring each pile per construction project to the required final depth without the pile suffering significant fatigue or without damaging the used impact hammer. This also defines the minimum required capacity of the selected impact hammer for each project. Therefore, most assumptions for the PDA usually include appropriate safety margins. However, this type of PDA has not yet been standardized and is usually subject to a high degree of uncertainty due to the assumed safety margins and input data regarding the soil profiles, that cannot completely be recorded before the construction starts. Comparisons of the PDAs before the start of construction and the actual pile-driving profiles during the foundation works showed partly considerable deviations from each other, i. e. both higher and lower blow energies than predicted, as well as shorter or longer pile-driving durations than predicted (Gündert, 2014).

The noise-optimized pile-driving procedure therefore represents an effective method for reducing the sound source and can be counted among the Noise Abatement Systems. Experiences from the OWF construction projects in the German EEZ have shown, that the blow energy could in some cases be reduced to half of the predicted maximum blow energy and thus the noise mitigation potential can be estimated to a maximum of 3 dB. This measure is thus effectively applied to comply with the noise mitigation value criterion.

Technical note: Since approx. 2014, so-called underwater noise real-time measuring systems (online measurements) have been applied in all German OWF construction projects at a distance of 750 m from the pile-driving site as a supporting measure to the noise-optimized pile-driving procedure. Here, the respective hammer operator sees in real-time the Sound Exposure Level and the zero-to-peak Sound Pressure Level of the last blow as well as the evaluation-relevant exceedance level SEL_{05} for the previous pile-driving. Thus, when 160 dB are reached for the Sound Exposure Level, it can be checked, whether a reduction of the used blow energy, and thus a lowering of the Sound Exposure Level, is possible without endangering the pile-driving process (pile refusal). An example is shown in Figure 26.

Technical note: From 2016 onwards, a blow rate at a continuous pile-driving process of > 40 blows per minute (bl/min) has proven its worth. In addition, methods were developed to be able to carry out the necessary inclination measurements at the pile to be driven in the direction of the solder without pile-driving interruptions, so that both the gross and the net pile-driving duration[1] were considerably reduced, in order to be able to meet the above mentioned requirements regarding the pile-driving duration; see Figure 19.

Technical note: Based on the experience of the recent years, the combination of a very large impact hammer of the newest generation during an application of only approx. 50 to 60 % of its actual (total) capacity turned out to be a particularly effective design of a noise-optimized pile-driving procedure in practice (see chapter 3).

1/3 octave spectrum of the Sound Exposure Levels (SEL) in the course of a pile-driving

Figure 17 represents the 1/3-octave-spectrum (third spectrum) of an unmitigated monopile installation, measured in a distance of approx. 750 m. This figure shows the 5-, 50- and 90 %-exceedance level of the Sound Exposure Level ($SEL_{05,\ 50,\ 90}$), whereas the SEL_{90}-level mostly characterizes the pile-driving start (incl. soft-start), the SEL_{50}-level the pile-driving process during the ramp-up procedure, i. e. up to the half of the foundation works, and the SEL_{05}-level the pile-driving process towards the end of the pile-driving with the hightest blow energy.

A comparable spectral pattern is shown over the entire pile installation, this being a monopile installation in the German North Sea, where a sandy soil with different densities was present. Furthermore, no Noise Abatement System was applied. It can therefore be assumed, that in comparable soil layers with different (soil-) resistances, neither the embedding depth, nor the blow energy used have a noticeable influence on the spectral shape of the pile-driving noise. Pile-drivings from the German EEZ of the Baltic Sea with sand, till and chalk also show very comparable spectral shapes of the pile-driving noise over the course of the single pile-drivings, although the soil layers and the associated soil resistances differ significantly from each other.

Impact hammer ./. Sound Exposure Level

The essential characteristics of an (impulse) impact hammer are (i) the drop mass, (ii) the acceleration to be achieved - and thus the power to be applied - and (iii) the design of the anvil, i. e. the force application or force transmission from the impact hammer into the pile-head. For the lifting and acceleration of the drop mass, the hydraulic control by means of so-called power-packs is also decisive. The product of drop mass and acceleration corresponds to the acting force. For the introduction of the blow energy into the pile-head, the anvil has a decisive influence, since it must project-specifically be adapted to the pile diameter and the design of the pile-head.

The interaction of pile-head and impact hammer was also intensively investigated in the R&D project BORA[4] (Chmelnizkij et al., 2016). By means of modelling and measurements at the pile, it could be shown, that the design of falling mass and anvil has a decisive influence on a force-fit coupling between impact hammer and pile-head (Heitmann et al., 2015; Chmelnizkij et al., 2016). Thus, it cannot be excluded, that a non-force-fit connection between impact hammer and pile-head may result in considerable losses in the transmitting blow energy, which are at least partially radiated as sound.

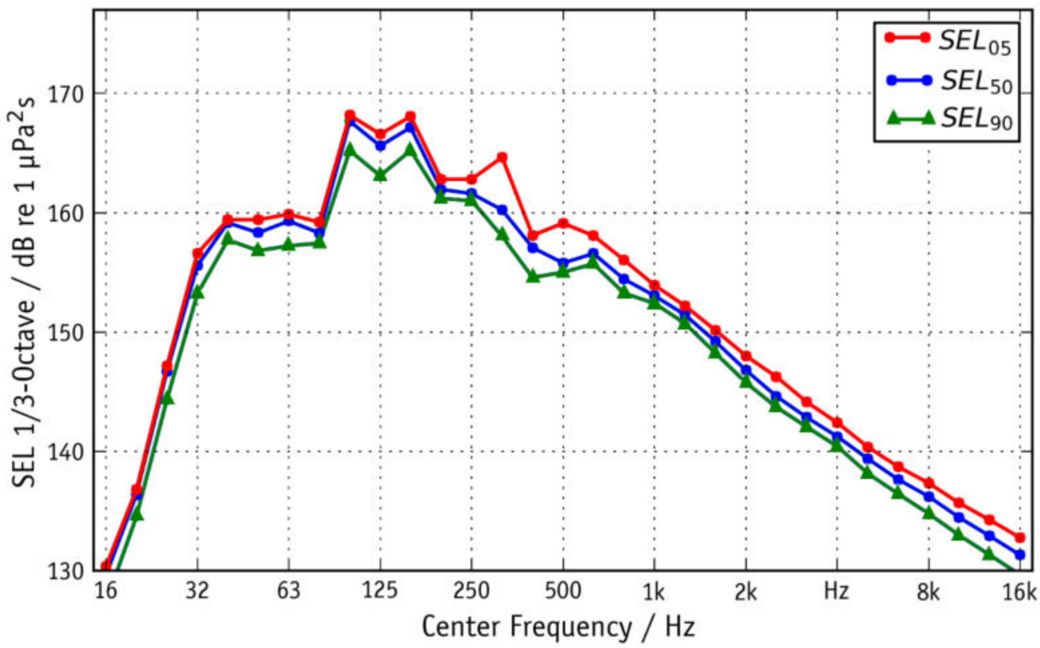

Figure 17: *1/3-octave-spectrum of the 5-, 50- and 90 % exceedance level of the Sound Exposure Level (L_E resp. SEL) in approx. 750 m distance during the foundation works of a monopile with an unmitigated impact pile-driving procedure. The SEL_{90}-level mostly characterizes the start of a pile-driving process with low blow energies incl. soft-start, the SEL_{50}-level the pile-driving process up to the half incl. ramp-up procedure of the blow energy and the SEL_{05}-level the end of a pile-driving process with maximum blow energy.*

Measurements of the introduced blow energy at the pile-head during the R&D project ESRa[10] showed that, usually, up to 95 % of the blow energy can be introduced from the impact hammer into the pile-head (Wilke et al., 2013).

Technical note: For acoustic reasons, it is recommended to use the largest possible impact hammer with a large or heavy falling mass and a reduced capacity (50 - 60 %) instead of a smaller impact hammer with a low falling mass with 100 % capacity to achieve the same blow energy. The physical-technical background is, that the contact duration between impact hammer and pile-head is extended by the larger falling mass at large impact hammers and thus theoretically, the maximum amplitude is reduced at the same force introduction into the pile-head.. However, in one construction project, two different construction companies were used, which installed the same monopile structures with different impact hammers, so that at least first reliable indications are available. Furthermore, by comparing the single construction projects with comparable pile-design and different impact hammers, a noise level difference of several decibels can also be derived.

Generation resp. type of impact hammer ./. Sound Exposure Level

In recent years, it became apparent, that a newer generation of impact hammers with blow energies of > 2.500 kJ became necessary due to the increasing monopile diameters. At present, impact hammers from two different manufacturers with blow energies between 3,000 and 4,000 kJ are available on the market. In Figure 18, the time courses of the Sound Exposure Levels measured in 750 m and the blow energy used from three different construction projects with three different impact hammer types from the North Sea are summarized. One small impact hammer (< 3,000 kJ) and two large impact hammers (> 3,000 kJ) were examined.

Figure 18 shows a principally comparable, temporal course of the measured Sound Exposure Level (SEL resp. L_E) with approximately comparable blow energies. In the pile-driving course, the necessary blow energy usually increases, which leads to a level increase. However, with two of the three impact hammers used, the applied blow energy could be adjusted almost continuously within the pile-driving, i. e. it could be increased or decreased. With the third impact hammer, the blow energy was only adjusted in discrete steps, i. e. no noise-optimized pile-driving procedure was applied.

In Figure 19, the gross pile-driving durations of the same impact hammers are compiled from Figure 18 each over one selected construction project in the German EEZ of the North Sea. Foundation installations with pile-driving interruptions of several hours were providently sorted out due to technical problems.

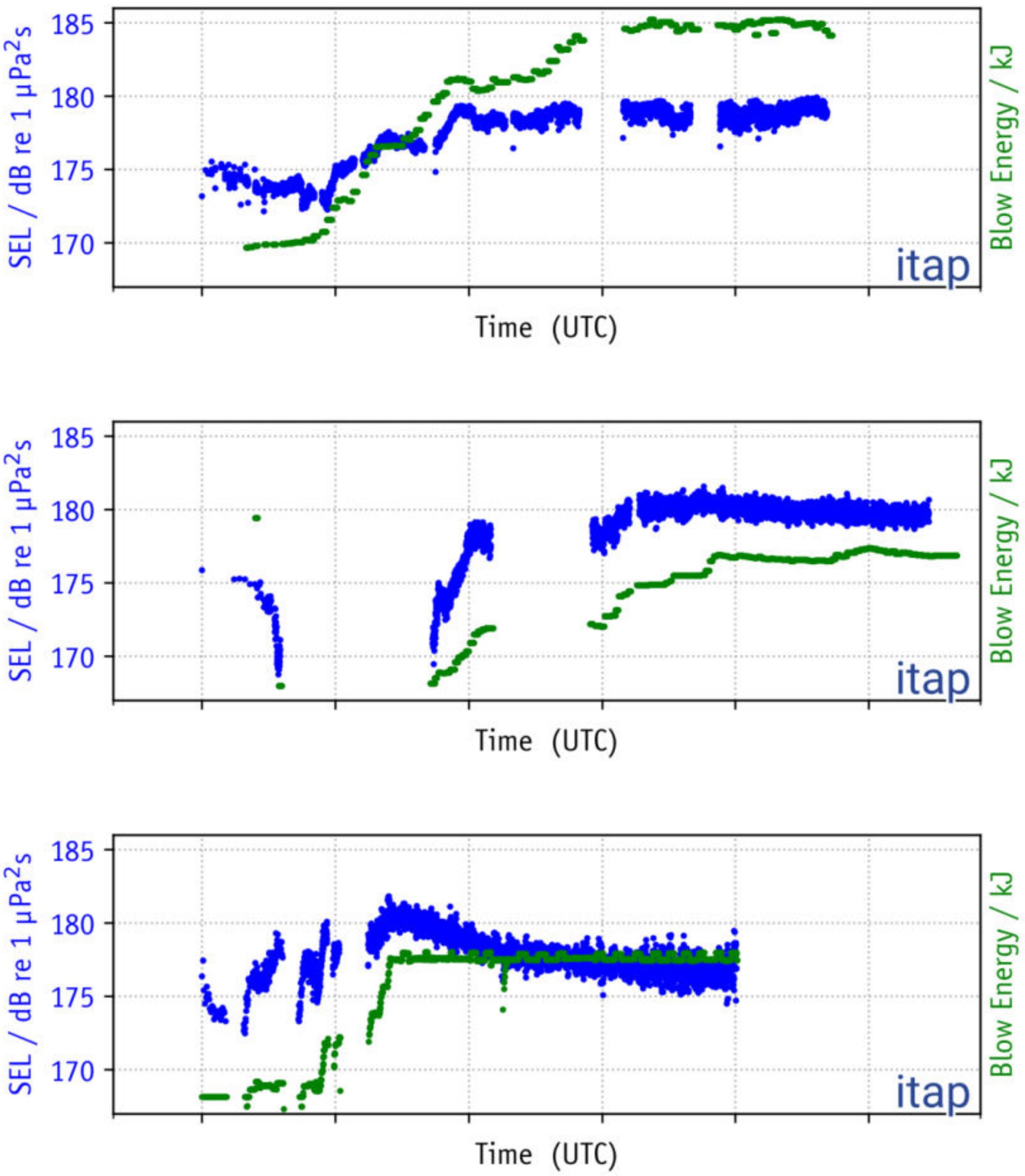

Figure 18: *Temporal course of the measured Sound Exposure Level (SEL resp. L_E, blue) and the applied blow energy (green) during monopile installations (diameter 5,5 to 7,5 m) in a distance of 750 m with three different impact hammer types in the German EEZ of the North Sea. All pile-drivings were performed without Noise Abatement Systems. Above: pile diameter 7.5 m with large impact hammer and application of a noise-optimized pile-driving procedure (> 3,000 kJ), middle: pile diameter 5.5 m with small impact hammer of the older generation (<3,000 kJ) and with a noise-optimized pile-driving procedure not yet fully developed, below: pile diameter 6.5 m with large impact hammer without noise-optimized pile-driving procedure (> 3,000 kJ).*

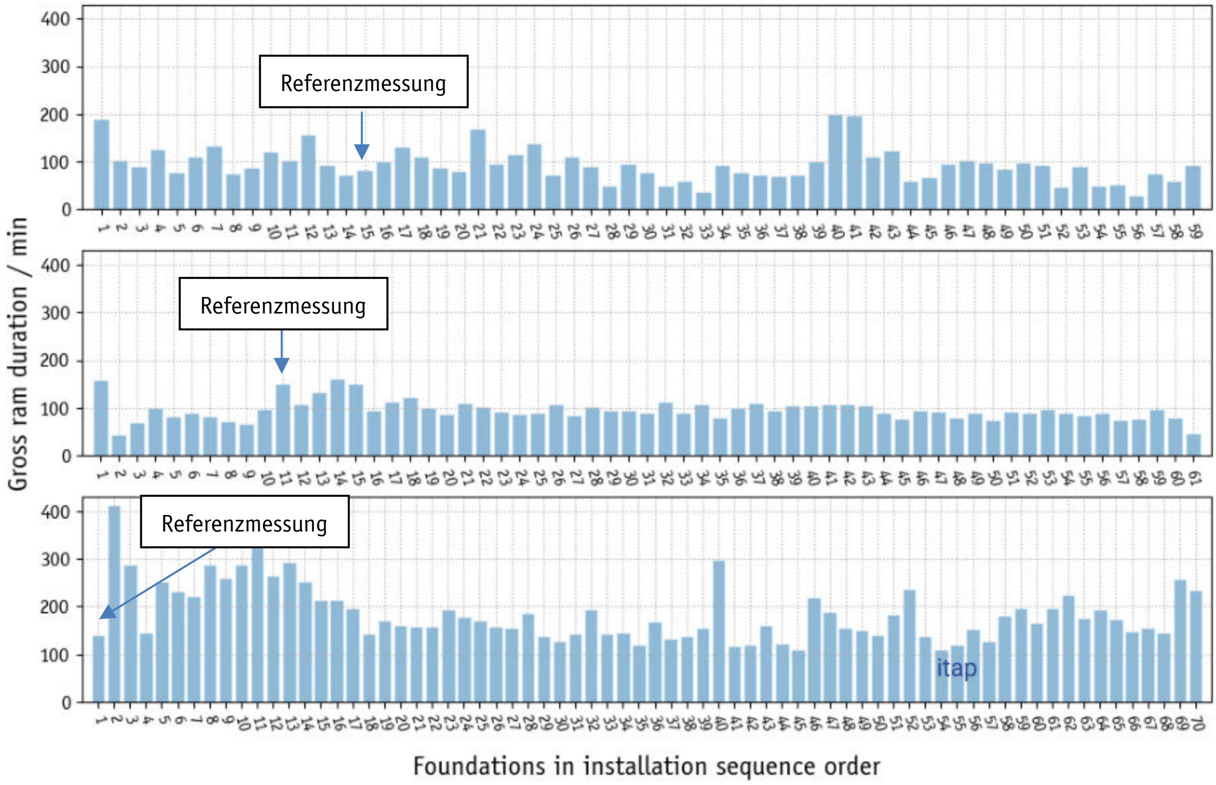

Figure 19: *Gross pile-driving duration per monopile installation with three different impact hammers, as described in Figure 18. For each construction project, only one monopile without noise abatement measure (reference measurement) was installed.*

The gross pile-driving duration[11] of the monopile installations at all three construction projects however differed significantly from each other. With a small impact hammer of the older generation (middle graph) and the early days of a noise-optimized pile-driving procedure, the gross pile-driving duration mostly was 100 min. per monopile and only occasionally, pile-driving durations of up to 180 min. were necessary. For one of the large impact hammers of the newer generation with a noise-optimized pile-driving procedure (upper graph), the gross pile-driving duration usually varied between less than 60 and 150 min. Based on the pile-drivability study, it was known, that five foundation sites showed a very complex soil stratification with sometimes very high soil resistances, so that a longer pile-driving duration was to be expected. In contrast to the other two construction projects, this construction project was also located in the EEZ of the German Baltic Sea. In the lower graph in Figure 18, a large impact hammer without a noise-optimized pile-driving procedure was used. The gross pile-driving duration mostly varied between 120 and 210 min.,

[11] Gross pile-driving duration: Time span from the first to the last blow incl. necessary pauses for e. g. inclination measurements.

although the pile diameter was lower than in the Baltic Sea. Occasionally, gross pile-driving durations of > 240 min. also occurred, mostly due to longer pile-driving interruptions for inclination measurements at the monopile and low blow repetition rates of the impact hammer used.

Figure 19 shows, that the gross pile-driving duration can vary considerably. Particularly the use of a noise-optimized pile-driving procedure shortens the gross pile-driving duration considerably and usually leads to a compliance with the required pile-driving duration of 180 min. per monopile installation.

Figure 20 again illustrates the use of a noise-optimized pile-driving procedure on the basis of the maximum blow energy applied. In the upper picture, a large impact hammer with a noise-optimized pile-driving procedure was used. Not a single pile-driving activity exceeded the noise mitigation values, although the largest pile diameter of all three construction projects was used and this construction project was located in the Baltic Sea with a very complex soil. Due to the significantly different soil conditions, different maximum blow energies were necessary to bring the monopiles to the final depth. Additionally, an underwater noise real-time measuring device was used to support the noise-optimized pile-driving procedure permanently in 750 m. In the middle figure, a small impact hammer of the older generation with the first beginnings of a noise-optimized pile-driving procedure was used. Here, too, it can be seen, that the applied blow energy varied considerably depending on the location. However, at that time, no underwater noise real-time measuring device was available on the market. In the lower figure, a large impact hammer without a noise-optimized pile-driving procedure was used. The maximum blow energy according to the BSH was automatically applied for almost all monopile installations, although an underwater noise real-time measuring device was available. At three monopiles, the ordered maximum blow energy was temporarily exceeded due to unforeseeable high soil resistances in order to bring the monopiles to the final depth.

Another important temporal factor is the inclination measurement in the soldering direction of the pile to be driven. In the course of the years, it could partially be refrained from pile-driving interruptions for inclination measurements, since suitable pile-sleeves, such as the Noise Mitigation Screen System (chapter 6.3.1) and/or optical measurement procedures, allowed such measurements to be performed during the continuous pile-driving.

Technical note: According to manufacturer specifications, a typical blow repetition frequency for impact hammers is usually around 30 blows per minute at 100% capacity of the impact hammer used (i. e. maximum blow energy). With newer generations of impact hammers and completely revised hydraulic controls, blow repetition frequencies of > 40 blows per minute at low blow energies resp. hammer capacities (50 to 60 %) are possible with the noise-optimized pile-driving procedure.

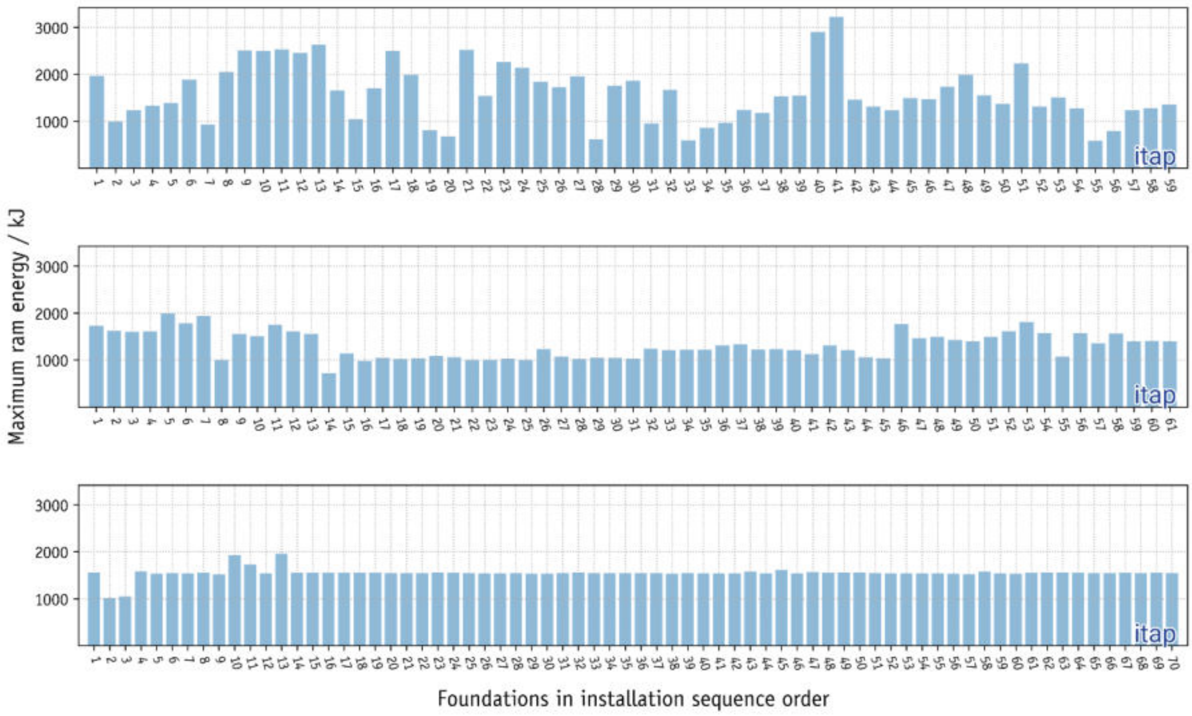

Figure 20: *Max. applied blow energy per monopile installation with three different impact hammers, as described in Figure 17. Above: large impact hammer of the newest generation with a noise-optimized pile-driving procedure, middle: small impact hammer with a not yet fully developed, noise-optimized pile-driving procedure, below: large impact hammer of the old generation without noise-optimized pile-driving procedure (max. blow energy allowed by the BSH was permanently applied).*

In Figure 21, the corresponding (narrow band) frequency spectra of the three OWF construction projects from Figure 18 and Figure 19 from the German EEZ of the North Sea are summarized. In each of the three construction projects, monopile installations without the application of noise abatement measures were used.

The three narrow band spectra from the monopile installations are very similar. Deviations mainly exist in the drop of the pile-driving noise level to higher frequencies (> 200 Hz) and in the low-frequency range between 40 and 80 Hz. The different drop of the noise level amplitude to higher frequencies usually has no relevant influence on the broadband total level. However, the differences below 100 Hz have a significant influence on both the unmitigated and the mitigated total level. Due to the fact, that these pile-drivings have been performed in three different OWF construction projects with three different impact hammers, different pile-designs and different site-specific conditions, the exact influence of each parameter cannot be statistically clearly stated.

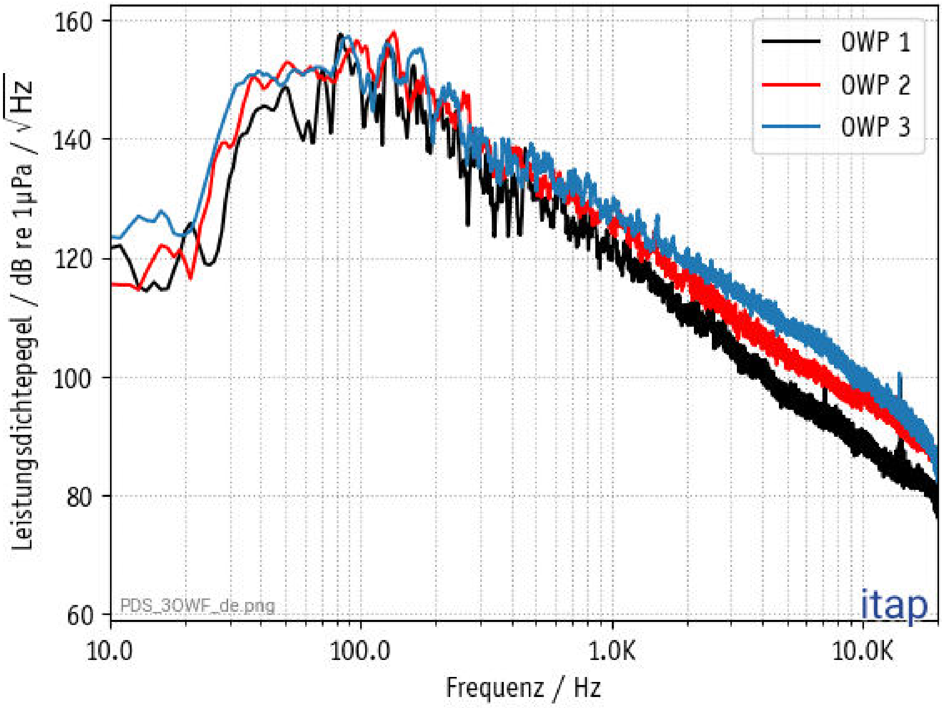

Figure 21: *Narrow band spectra of monopile installations with different impact hammers, as described in Figure 18. The measurement data were normalized regarding the applied blow energy and moreover, no Noise Abatement System was used.*

5.2.3 Pile-driving method and pile length

Pile-driving method ./. Sound Exposure Level

There are two different (impulse) pile-driving methods:

(i) pile-drivings above the water surface and

(ii) underwater pile-drivings.

With monopiles, the impact hammer normally always operates above the water surface, i. e. the noise-reflecting pile surface in the water column remains constant during the entire installation (entire water column).

With Jacket-constructions, there are also piles, which are installed through the pile-sleeve provided at the Jacket-construction above the water surface; these piles are usually called main-piles; see chapter 5.2.1. Alternatively, there are pile-sleeves with Jacket-constructions, which end only a few meters above the seabed. The pile is usually driven so far into the seabed, that it protrudes only a few meters from the pile-sleeve. The noise-emitting surface of such an installation decreases steadily in the course of the pile-driving, i. e. the impact hammer works under water at the end of the pile-driving (submerged hammering). Suchlike pile-designs are mostly called skirt- or pin-piles.

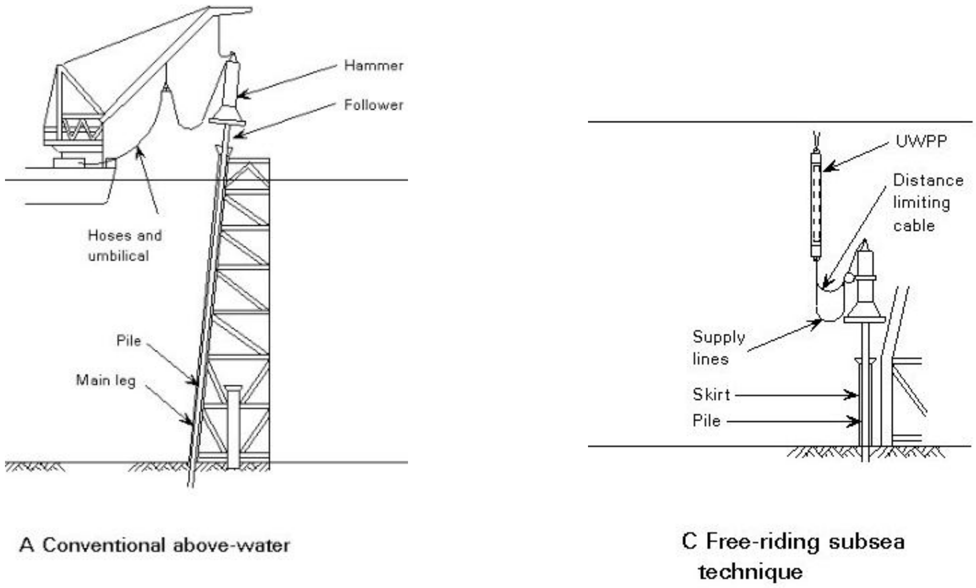

Figure 22: *Difference main- (left) and skirt-piles (right) as skirt-piles for Jacket-constructions. (Source: ESDEP Lecture note [WG15A] fgg-web.fgg.uni-lj.si).*

In Figure 23, the measured Sound Exposure Level and the applied blow energy as a function of the pile-driving duration for one main-pile (monopile) and one skirt-pile (skirt-pile of a Jacket-foundation structure with underwater pile-driving) are shown.

In case of the monopile resp. main-pile, the Sound Exposure Level increases with rising blow energy. In the case of a skirt-pile, the Sound Exposure Level at first increases with rising blow energy, but then falls off significantly towards the end of the pile-driving, although the applied blow energy continues to increase or remains constant. This decrease correlates with the reducing noise-reflecting surface of the pile to be installed. As the impact hammer is plunged into the water, the Sound Exposure Level declines.

With skirt-piles, it appears, that these piles are anchored in the seabed by both the pre-piling procedure, as well as by the post-piling procedure. This means, that the piles can be driven through the existing pile-sleeves of the Jacket-foundation structure (post-piling), but the use of so-called piling templates instead of the Jacket-foundation structures is also possible (pre-piling). Thus, on the one hand, coupling effects between the pile to be driven and the piling templates or Jackets cannot be excluded, and on the other hand, the architecture of each piling template or Jacket is single, so that possible coupling effects can spread differently in the respective structure.

A detailed analysis of the influence of coupling effects and vibration characteristics of the foundation structure in the pre- resp. post-piling process is currently not statistically valid due to the limited empirical data available in the MarinEARS[1]. A quantitative comparison between installations of monopiles and main-piles by the post-piling procedure showed, that in the post-piling procedure of the main-piles with comparable pile-design and applied blow energy, the measured noise level values can be louder by up to 2 dB. When using piling templates (pre-piling), a potential level increase depends on the architecture of this piling template.

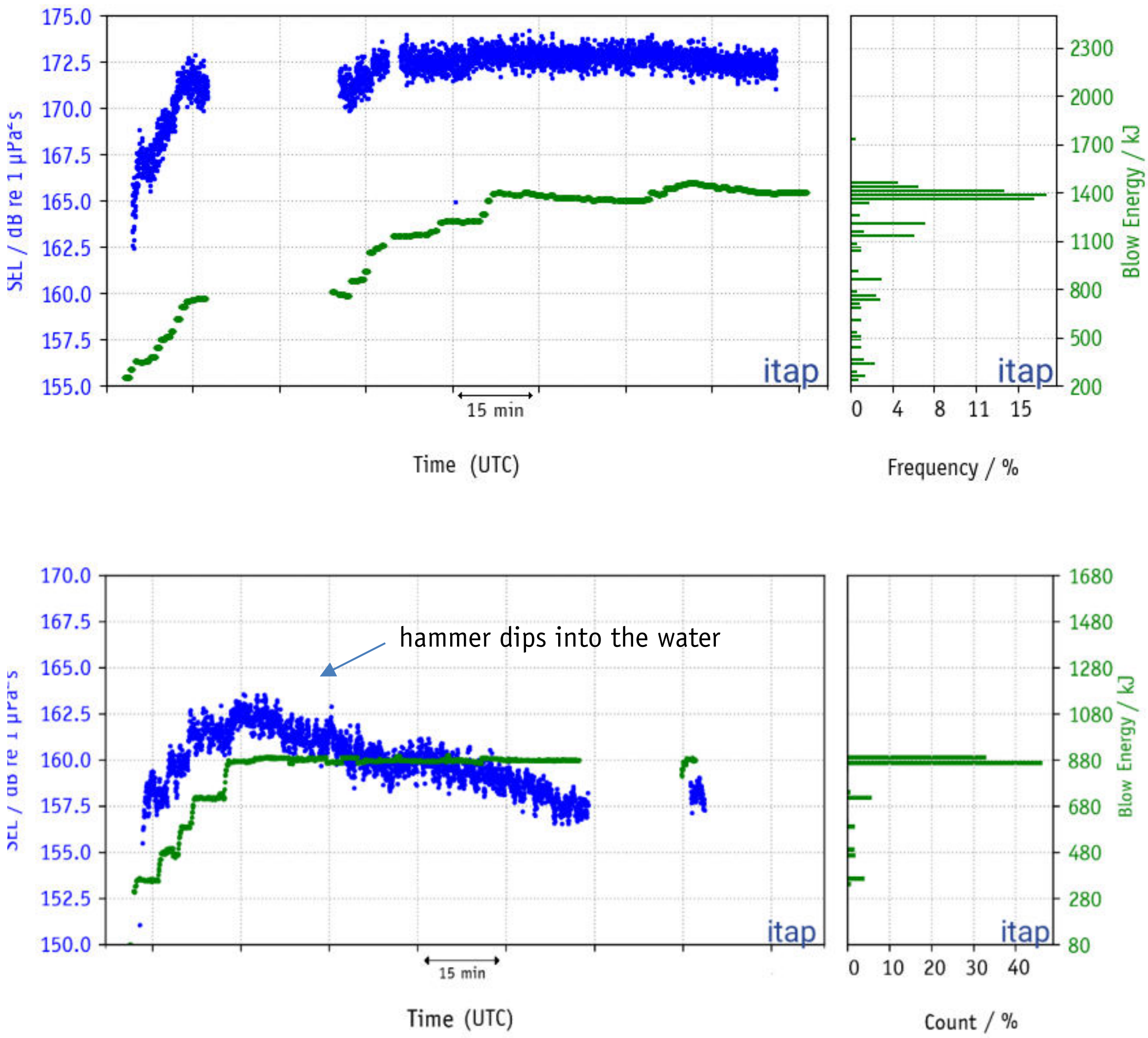

Figure 23: *Temporal course of the measured Sound Exposure Level (L_E resp. SEL) in 750 m distance and the blow energy applied. Both pile-drivings were performed without Noise Abatement System. Above: pile-driving of a monopile resp. main-pile (pile-drivings always above the water surface); below: pile-driving of a skirt- resp. pin-pile (pile-driving starts above the water surface and ends below the water surface; underwater pile-drivings).*

Moreover, during the pile-driving of so-called pin- or skirt-piles, followers are usually used between the pile-head and the anvil to prevent unwanted contact between impact hammer and pile-sleeve. On the basis of the previous empirical data available, the follower had the same effect as a pile-extension, i. e. a longer noise-emitting surface.

Pile length ./. Sound Exposure Level

Based on Figure 12, the blow energy required to achieve the final embedding depth usually increases with the pile diameter. Moreover, with the same pile diameter, the necessary blow energy increases with the embedding depth; see Figure 15. The soil resistance and the embedding depth are usually highly correlated. Thus, the pile length currently does not represent a linear independent influence parameter on the noise emission but is correlated with the used and necessary blow energy when using a noise-optimized pile-driving procedure.

For pin- resp. skirt-piles, the connection between the used blow energy, the embedding depth and the emitted noise also applies. However, the existing noise-emitting surface is added. An essential parameter is therefore the length of the pile under water. This depends on the parameters water depth, use of a follower and maximum length of the pile, sticking out of the seabed (stick-up length), when the maximum embedding depth is reached; Figure 23.

Installation vessel ./. Sound Exposure Level

Furthermore, jack-up vessels (lifting platforms) and floating installation vessels (with anchorages or a Dynamic Positioning System – DP) have been used in Germany so far. However, the analysis of all entries in the existing MarinEARS[1] database could not yet show a significant influence of the selected installation vessel type on the measured noise inputs into the water during unmitigated impulse pile-drivings.

Technical note: Nevertheless, a shielding effect of jack-up legs between pile-driving and measuring hydrophone in the range of several decibels could sporadically be observed. It is therefore recommended to position the measuring systems for underwater noise without obstacles to the pile to be driven.

Technical note: In the case of floating installation vessels, there may well be a reflection of the pile-driving noise on the vessel´s shell. However, it can be assumed in a first approximation, that these reflections are significantly lower in their amplitude than the direct sound, so that an influence on the total level in 750 m distance is unlikely.

5.3 Summary of influencing factors on pile-driving noise

The formation and transmission of impulsive underwater noise during the installation of foundation structures by the impulse pile-driving procedure depends, on the one hand, on the site-specific characteristics and, on the other hand, on the technical-constructive characteristics of an OWF construction project.

For the site-specific characteristics, an influence of the following parameters on the sound-emission and the transmission could be shown on the basis of the cross-project analysis of the existing technical specialist information system MarinEARS[1]:

- Soil conditions with different soil resistances and stratifications; in particular, soil coupling occurs in the German EEZ of the North Sea with predominantly sandy soils, which are usually a factor of 10 (about 20 dB) lower than the underwater noise directly introduced from the pile into the water. These soil couplings can influence the noise reduction achieved by near-to-pile, technical Noise Abatement Systems; see chapter 6.4.2.3. The influence of soil coupling in other soil strata, such as in the German EEZ of the Baltic Sea with surface sands followed by till and chalk, can currently not quantitatively be estimated on the basis of the data available in the MarinEARS[1] specialist information system.
- The water depth has a significant influence on the spectral shape of the pile-driving noise in the water. The shallower the water, the higher the cut-off frequency, below which a noise input into the water is not or not automatically possible. The cut-off frequency also decisively depends on the soil profile and the associated soil resistance. The water depth therefore has a high-pass character in shallow water.
- In shallow water of the German EEZ of the North Sea, the bathymetry due to its "flat" character has not yet had any significant influence on the sound emission. The Baltic Sea is known for its pronounced topography, e. g. in area *Kriegers Flak* or *Adlergrund*. Here, however, the influence of the different water depths has not yet been metrologically investigated. Environmental parameters, such as current, temperature and conductivity of the water, have so far also shown no or only a minor influence on the sound emission and transmission of pile-driving noise in shallow water. So-called sound channels could metrologically be detected in the German EEZ of the Baltic Sea, but even these showed no influence on the sound emission and -transmission of impulsive pile-driving noise due to their spatial and temporal arrangement.
- Statistically, with comparable pile-designs and blow energies, the noise inputs in the German Baltic Sea can be up to 2 dB louder than in comparable North Sea projects. The reason for this is probably a significantly different soil structure in the North- and Baltic Sea.
- The hydrophone height has no influence on the sound propagation of impulsive pile-driving noise in the lower water half.

- The transmission loss is important role for the sound transmission over large distances (> 10 km) due to the frequency-dependent noise absorption in shallow water. For an initial, rough estimation of the transition loss, an assumption in shallow water of $15*\log_{10}$ (distance ratio) to approx. 10 km is acceptable. For propagation calculations over larger distances, frequency-dependent, empirical or semi-empirical approaches are mandatory.

However, it also appeared that the above-mentioned influencing factors are mostly not linear independent of each other, so that no clear, quantitative allocation of the influencing factors on the impulsive pile-driving noise could be made on the available empirical data basis.

The emitting noise level during an impact pile-driving (sound from percussive pile-driving) furthermore depends on many technical-constructive influencing factors, such as the pile-design, the blow energy, the impact hammer, the pile-driving method resp. -procedure. However, since all the parameters mentioned often interact with each other, it is not always possible to make quantitative statements about the influence of a single parameter on the basis of the available empirical data. One of the most important influencing parameters on the underwater noise is the spectral composition of the pile-driving noise and the noise propagation over larger distances. Usually, the unmitigated pile-driving noise has a low-frequency characteristic, which, depending on the pile diameter, has a maximum between 63 and 160 Hz. To higher and lower frequencies, the spectrum decreases steadily.

In general, the following qualitative assumptions can be made on the technical-constructive side for the impulsive pile-driving noise in shallow water:

- The pile diameter has a significant influence on the unmitigated pile-driving noise; the larger the pile, the louder the pile-driving noise.
- There usually is a dependency between the embedding depth resp. the soil resistance as well as the applied blow energy and the resulting pile-driving noise. The higher the soil resistance resp. the embedding depth, the more blow energy is needed and the louder the pile-driving noise is. In the statistical average, the pile-driving noise increases with 2 to 3 dB per doubling of the applied blow energy.
- With a similar pile-design, so-called main-piles are statistically on average 2 dB louder than comparable monopiles, when anchoring Jacket-constructions in the seabed. It can be assumed, that this level increase occurs due to coupling effects between the pile to be driven and the anvil or the Jacket, which cause this level increase.
- During installations of piles, which protrude only a few meters above the seabed at the end of the pile-driving (submerged pile-driving), when the sound-emitting surface is reduced, the pile-driving noise usually decreases significantly, while the blow energy remains constant.

- An analysis of the data from the reference measurements (without the application of Noise Abatement Systems) with different impact hammers has not yet been performed. Qualitatively, it is recommended, based on theoretical considerations and practical experience, to use a large impact hammer with a large falling mass at low blow energy (50 to 60 % of its maximum capacity), instead of a small impact hammer with a small falling mass at full capacity (comparable blow energies). The background is the influence of the higher falling mass on the contact time between impact hammer and pile-head. It also becomes apparent, that the use of a large impact hammer of the newer generation in combination with a noise-optimized pile-driving procedure also has an influence on the spectral shape and thus indirectly on the Sound Exposure Level.
- The selection of the impact hammer type and the use of a noise-optimized pile-driving procedure with low blow energy and high blow repetition frequency however also have a significant influence on the pile-driving duration. When using large impact hammers with a noise-optimized pile-driving procedure in combination with time-optimized inclination measurements at the pile in the direction of the solder, it can be seen, that the specification of 180 min. total pile-driving duration incl. deterrence measure is maintained even with monopile diameters up to 8 m.

6. Offshore-suitable and market-ready Noise Abatement Systems

6.1 Introduction and development steps

In 2008, Germany defined a dual noise protection criterion for the protection of marine mammals from a temporal threshold shift (TTS) by percussive pile-driving noise into the water. This criterion consisting of the broadband Sound Exposure Level (L_E resp. SEL) and the zero-to-peak Sound Pressure Level ($L_{p,pk}$, chapter 3), even though at that time, no offshore-suitable Noise Abatement System with a state-of-the-art technology was available on the market. After the first experiences with offshore research projects, the use of noise mitigation measures during impulsive, noise-intensive construction activities within OWF construction projects has been mandatory since 2011; see chapter 3.

In the R&D project EsRa[10], five different prototypes of technical Noise Abatement Systems were tested for the first time in 2011 on a pre-installed test-pile under almost realistic offshore conditions in the German Baltic Sea at a water depth of 8 m (Wilke et al., 2012). The achieved broadband noise reductions of all tested Noise Abatement Systems in the prototype stage were << 10 dB. Possible influencing factors for the low achieved noise reductions could be due to the very high embedding depth of > 60 m of the test pile and the growth tight effect (pile foundation > 10 years ago). Based on the fact, that, offshore wind energy was to be expanded, but there were no technically reliable measures for the compliance with the defined noise mitigation values in Germany, it became clear, that there was a need to develop offshore-suitable and effective, technical noise abatement measures, that could be used in series operation in the construction of foundation structures.

During the construction of the OWF *Trianel Borkum West II* (phase 1) in the German EEZ of the North Sea (construction time 2011 and 2012), a Big Bubble Curtain (BBC) was used for the first time as a serial Noise Abatement System on an experimental basis, i. e. the BBC should be applied for every impact pile-driving activity. The construction of the foundation constructions was accompanied by a R&D project regarding the development of a serially applicable and offshore-suitable Noise Abatement System (Diederichs et al., 2014)[12].

Until 2014, the Federal Republic of Germany supported a total of 18 pcs R&D projects in the field of noise abatement and noise abatement measures with a total funding of 27 M€ (Verfuß, 2014). Furthermore, the future OWF-operators and their participating construction companies spent additional money on the development and further enhancement of Noise Abatement Systems.

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[12] Development and testing of the Big Bubble Curtain for the reduction of the hydrosound emissions during offshore pile-driving works. Final report, supported by BMU and PTJ, FKZ 325309, www.hydroschall.de.

In general, all noise mitigation measures can be divided into two categories:

(i) primary noise mitigation measures (Noise Mitigation Systems) and
(ii) secondary noise mitigation measures (Noise Abatement Systems).

6.2 Primary noise mitigation measures

The purpose of primary noise mitigation measures is to reduce or prevent the creation of impulsive noise during the installation of foundation structures. This can be done in two ways: by actively reducing the source power, e. g. by reducing the used blow energy, (Noise Mitigation Systems) or by using alternative low-noise foundation structures resp. -methods, whereby the alternative foundation structures and -methods do not cause any impulsive noise input into the water according to the definition of the Marine Strategy Framework Directive (MSFD).

One primary noise mitigation measure, that has already proven itself in practice, is the noise-optimized pile-driving procedure, which was already described in chapter 5.2.2. Figure 26 shows the effectiveness of a noise-optimized pile-driving procedure in combination with a near-to-pile and a far-from-pile Noise Abatement System.

Further primary, technical noise abatement measures, which are currently under development and testing, are discussed in chapter 7.4.37.4.2.

6.3 Noise Abatement Systems

With secondary noise mitigation measures, the resulting impact pile-driving noise in the water is reduced to the greatest extent by technical measures, so-called Noise Abatement Systems.

The development of the secondary Noise Abatement Systems in the German EEZ of the North- and Baltic Sea can be divided into three phases:

(1) The first offshore-suitable Noise Abatement Systems, when building the first OWFs in Germany, were developed in the years 2011 to 2013 and, partly in the prototype stage, tested under real offshore conditions (phase 1). Figure 24 shows, that the noise mitigation value of 160 dB_{SEL} in 750 m distance was partly exceeded of up to 10 dB.
(2) Between 2013 and 2014, the first Noise Abatement Systems on the market, which turned out to be offshore-suitable in the prototype stage, were increasingly further developed and improved in terms of the achieved noise reduction. Despite an increase of the pile diameters, and the associated level rise of the source, the noise mitigation value for the

Sound Exposure Level was exceeded by max. 6 dB. The criterion for the zero-to-peak Sound Pressure Level was already partially met. This phase can generally be considered as phase 2 of the development of Noise Abatement Systems.

(3) Phase 3 of the development starts with the construction of the foundation structures (monopiles) of the OWF *Butendiek* (construction time OWT foundations 2014). In this project a combination of two independent technical Noise Abatement Systems was applied for the first time. Furthermore, the dual noise mitigation value criterion, consisting of Sound Exposure Level and zero-to-peak Sound Pressure Level could be complied with during the foundation works of monopiles with a pile diameter of up to 6.5 m for the first time. The background was, that der OWF *Butendiek* is located in the middle of the special area of conservation (FFH) „Sylter Außenriff" and thus, special attention was paid to nature-compatible construction. In the following years, the pile diameter increased to 8 m in 2018/19, but the dual noise mitigation value criterion was still further complied with; see Figure 24. Particularly in 2018 and 2019, it was shown, that by the combination of two independent Noise Abatement Systems in conjunction with a noise-optimized pile-driving procedure and the application of an underwater noise real-time monitoring, the balance between compliance of the noise mitigation values and the temporal specifications regarding the total pile-driving duration could be optimized, so that both requirements could be permanently be maintained.

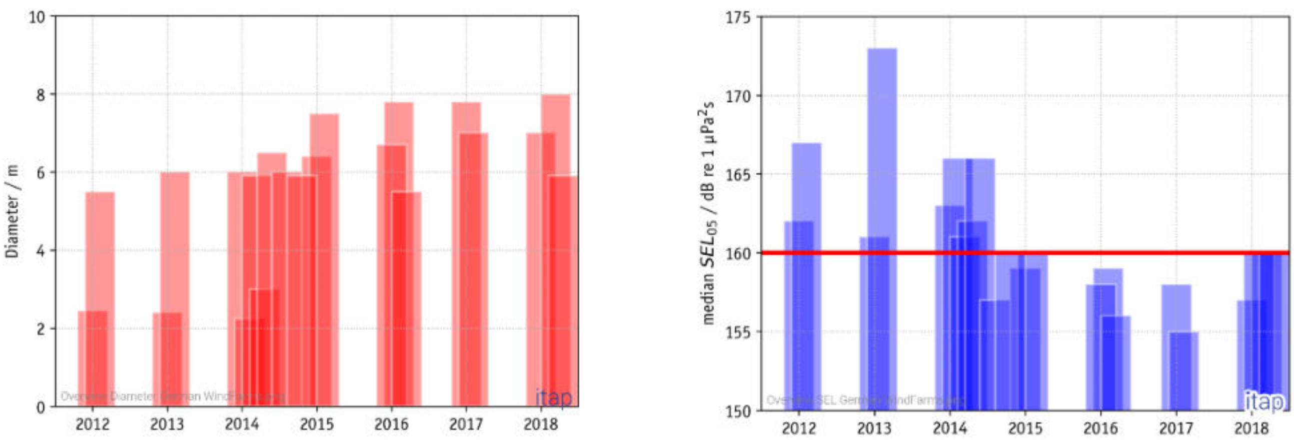

Figure 24: *Left: development of the pile diameters for foundation structures during the construction of OWFs in the German EEZ of the North- and Baltic Sea. Right: measured Sound Exposure Level (SEL_{05}) in a distance of 750 m when applying technical Noise Abatement Systems; the red line marks the mandatory noise mitigation value of 160 dB_{SEL}.*

This development was based on the steady further development (also without public funding) of the Noise Abatement Systems available on the market. Based on the dual noise mitigation value criterion in a distance of 750 m, the (further) development of Noise Abatement Systems and

- mitigation measures focused on the broadband reduction of pile-driving noise in the years to 2019. The spectral efficiency of Noise Abatement Systems is discussed in chapter 7.1.

Figure 25 shows the measured Sound Exposure Level (exceedance level SEL_{05}) in 750 m distance for all foundation installations of the OWF construction project *Butendiek* in the North Sea (year of construction 2014). The pile-driving activities were initially performed with only one Noise Abatement System. Due to the permanent exceeding of the noise mitigation values at the beginning of the construction project, a second Noise Abatement System was applied. By means of the combination of two independent Noise Abatement Systems without technical problems, the noise mitigation values were reliably complied with.

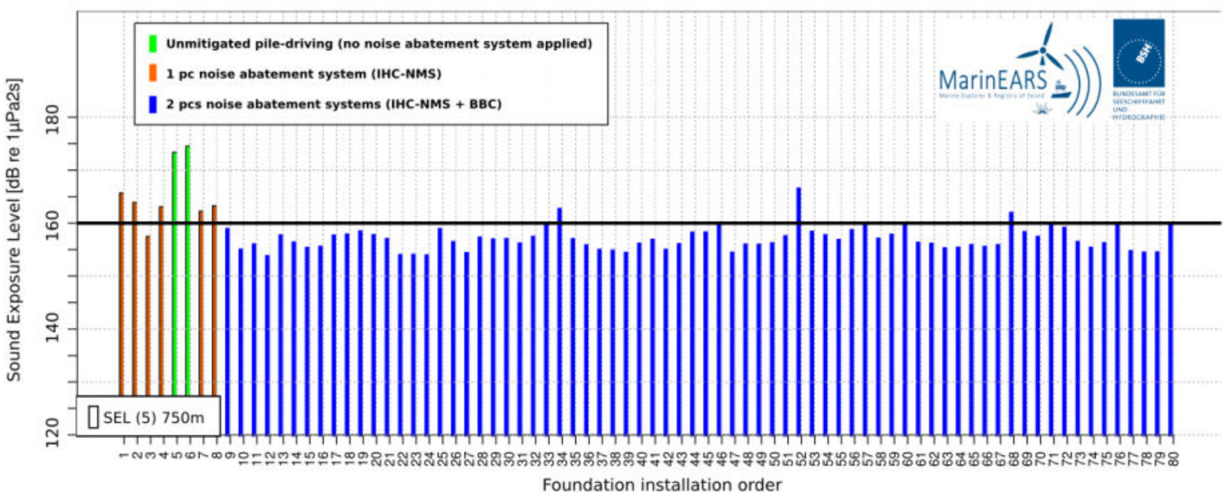

Figure 25: *Measured Sound Exposure Level resp. exceedance level (SEL_{05}) in 750 m distance to the respective monopile for all foundation installations of the OWF Butendiek in the North Sea with and without applications of Noise Abatement Systems. For this project, measurements in several spatial directions and hydrophone heights were performed. For this presentation, in each case, only the highest measured values in 750 m were shown. This construction project has applied two independent Noise Abatement Systems (near-to-pile and far-from-pile) in combination for the first time and reliably complied with the noise mitigation values after initial improvements (source: MarinEARS[1] data base of the BSH).*

Figure 26 shows an example of a later OWF construction project from the EEZ of the German North Sea. In this project a combination of a near-to-pile and a far-from-pile Noise Abatement System and the application of a noise-optimized pile-driving procedure, using a real-time underwater noise monitoring, was used as active feedback between the measured pile-driving noise at 750 m and the applied blow energy. Not shown are the first foundation sites, where extensive test- and reference measurements according to the DIN SPEC 45653 (2017) and the BSH guideline (2013), i. e. pile-drivings with Noise Abatement Systems not yet optimized and completely without noise mitigation measure, were performed.

<u>*Technical note:*</u> During the construction of the OWF *Butendiek*, extensive additional measurements to the requirements from the measurement specification (BSH, 2011) were demanded by the BSH. Thus, up to four measuring positions in different directions to the foundation (monopile) were ordered for monitoring purposes and at one measuring position up to three different hydrophones (2.5 and 10 m above ground). Thus, partly up to seven processed and quality-assured data sets per monopile are available. Based on the precautionary principle, Figure 25 only shows the highest measured values per monopile independent of the spatial direction and the hydrophone height.

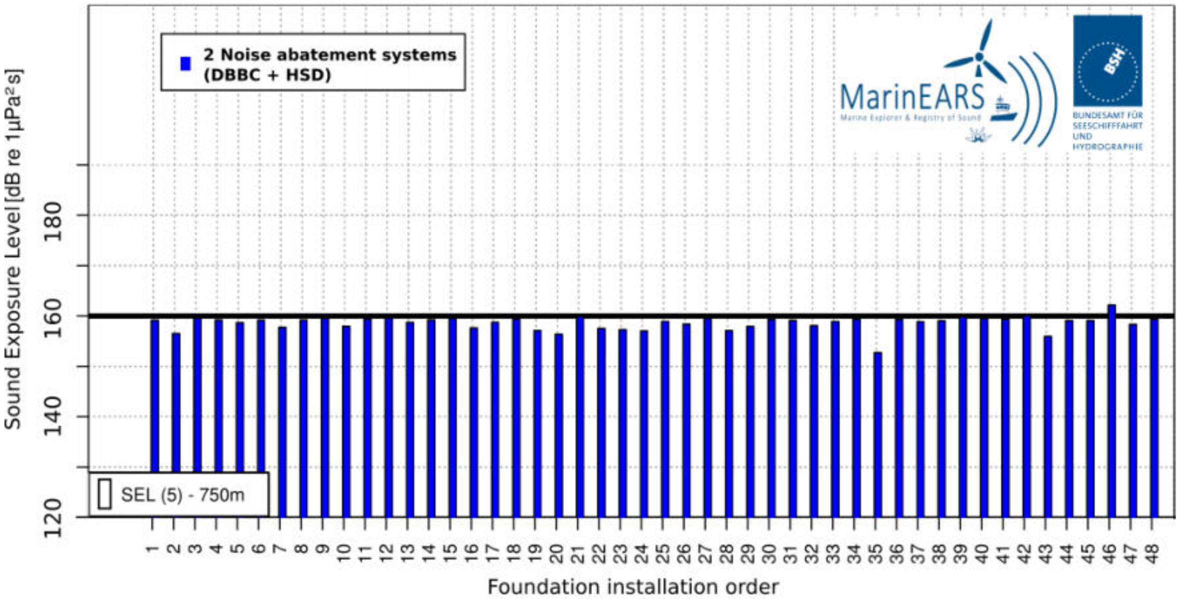

Figure 26: *Measured Sound Exposure Level resp. exceedance level (SEL_{05}) in 750 m distance to the respective monopile for all foundation installations of a later OWF construction project in the German EEZ of the North Sea with a near-to-pile and a far-from-pile Noise Abatement System and the application of an optimized pile-driving procedure by means of a real-time underwater noise monitoring as active feedback between measured pile-driving noise in 750 m and guidance of the hammer. Not shown are the first foundation sites, where extensive test- and reference measurements, i. e. pile-drivings with not yet optimized Noise Abatement Systems and totally without noise mitigation measures, were performed.*

It is shown that the active feedback from the measured noise level values in 750 m in real-time to the impact hammer operator can be an effective tool for a time-efficient and noise-optimized pile-driving procedure. Based on the continuous compliance with the noise mitigation values, a cancellation of the maximum blow energy restriktion to be applied was achieved at the BSH, so that the impact hammer could be used to its full extent within its technical possibilities. Thus, in the present case, the blow energy used was increased during the pile-driving process to the extent, that the noise mitigation values in 750 m were not exceeded, but the pile-driving process could be completed clearly below the required pile-driving duration of 180 min. due to the "high" blow energy used.

Technical note: Based on the experiences with the application of a Big Bubble Curtain in the years 2015 to 2019, the documentation with regard to the application of this Noise Abatement System has developed considerably (BBC protocol). Based on the BBC protocols, the use of all compressors and the total air volume to be derived from them can be calculated according to the current state of knowledge and, if necessary, conclusions can be drawn about possible technical difficulties in using the Big Bubble Curtain. This detailed recording was not yet available for the offshore construction project *Butendiek* in 2014, so that isolated exceedances of the 160 dB_{SEL}-value in Figure 25 and also possibly in Figure 26 could well be due to a direction-dependent noise reduction of the applied Big Bubble Curtain.

Technical note: It has been shown in all German construction projects in Germany, that if the 160 dB noise mitigation value is complied by the 5 % exceedance level of the Sound Exposure Level (SEL_{05}) at a distance of 750 m, the noise mitigation value of 190 dB was also complied by the zero-to-peak Sound Pressure Level ($L_{p,pk}$).

In the following, a general overview of the existing and in the German EEZ tested, Noise Abatement Systems is given. In the focus are the Noise Abatement Systems, which have proven themselves at least in one German OWF construction project in serial use. Further developments of Noise Abatement Systems, which have so far not been applied in serial use in German waters, are discussed in chapter 7.4.1.

The technical Noise Abatement Systems tested between 2011 and 2019 differ in their application in:

(i) theoretical modelling,
(ii) laboratory studies with small-scale experiments,
(iii) applications in the nearshore area, e. g. in port constructions with very low water depths and
(iv) large scale applications in the offshore area. In the offshore area can again be differentiated between test applications at single foundation sites in the context of R&D projects (application of prototypes) and applications in real OWF construction projects as a standard Noise Abatement System.

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. The following list contains an excerpt from the literature regarding developed secondary Noise Abatement Systems (prototypes and systems in serial operation), which were used in the German EEZ of the North- and Baltic Sea until 2019 (Koschinski & Lüdemann, 2011, 2013 & 2019).

Table 2: *Overview of secondary, technical Noise Abatement Systems, that were applied until 2019 in the German EEZ of the North- and Baltic Sea (excerpt from Koschinski & Lüdemann 2011, 2013 & 2019). The three reliable and offshore-suitable Noise Abatement Systems, which are applied as standard in Germany for the construction of OWFs, are marked in bold.*

Secondary, technical Noise Abatement System	Design	Comment
Big Bubble Curtain (BBC)	In single, double, triple and quadruple design, currently available on the European market from two suppliers.	Principle: air input into the water; far-from-pile Noise Abatement System. Application: Jacket-constructions, monopiles, Tripods, Tripiles, detonation of ammunition dumpsites.
Small Bubble Curtain	In guided and unguided design with regard to the drifting of air bubbles in the water. Different versions from different manufacturers were tested.	Principle: air input into the water; near-to-pile Noise Abatement System. Application: monopiles, Jacket, Tripod.
Noise Mitigation Screen (IHC-NMS)	Different designs regarding pile diameter and water depth.	Principle: pipe-in-pipe system; near-to-pile Noise Abatement System. Application: monopile.
Fire-Hose-System	Prototype in the R&D project ESRa[10].	Principle: combination of pipe-in-pipe system and small bubble curtain; near-to-pile Noise Abatement System. Application: monopile.
Cofferdam	Different designs regarding pile diameter and water depth.	Principle: pipe-in-pipe system; near-to-pile Noise Abatement System. Application: Jacket-construction.
BEKA-shell	Prototype in the R&D project ESRa[10].	Principle: pipe-in-pipe system; near-to-pile Noise Abatement System. Application: monopile.
Hydrosound Damper (HSD)	Different designs regarding pile diameter and water depth.	Principle: resonator; near-to-pile Noise Abatement System. Application: monopiles, pin-pile installations (pre-piling).
AdBm-System	Different designs regarding pile diameter and water depth.	Principle: resonator; near-to-pile Noise Abatement System. Application: small-scale test.
Grout Annulus Bubble Curtain (GABC)	Different designs with Jacket-constructions.	Principle: air input between pile-sleeve and pile to be driven; near-to-pile Noise Abatement System. Application: Jacket-constructions.

Technical note: Within the scope of the Noise Workshop 2012 in Berlin, some manufacturers of Noise Abatement Systems were able to present their prototypes and experiences from modelling with regard to a noise reduction to be achieved with their systems. Subsequently, most of these systems were applied and tested under offshore conditions. It turned out, that the noise reductions to be expected by modelling and small-scale experiments could not nearly be achieved under real offshore conditions. Based on these experiences, the BSH decided, that new or further developed Noise Abatement Systems as well as Noise Mitigation Systems must first prove their potential noise reduction on a large scale at an actual foundation installation under real offshore conditions, before they can serially be applied in Germany.

In Germany, so far, mostly monopiles were used as foundation structures of OWTGs. Only in the first years of development, Jacket-constructions in two OWFs and in one OWF a Tripod-structure, as well as in two OWFs, so-called Tripile-structures for OWETs were used. Due to their size and masses, substations and converter platforms incl. main- and/or skirt-piles were usually anchored in the seabed on Jacket-structures. Thus, the most Noise Abatement Systems were applied, tested and further developed during the construction of monopile structures.

For monopile installations, only

- the Noise Mitigation Screen (NMS),
- the Hydro Sound Damper (HSD) and
- the Big Bubble Curtain in single and double design (BBC and DBBC)

have proven themselves as secondary Noise Abatement Systems in series application until 2019.

For these three secondary, technical Noise Abatement Systems, which have so far proven their worth, Appendix A also contains technical short reports including the expected noise reduction.

During the installations of Jacket-foundations,

- the Big Bubble Curtain in single and double design and
- der Grout Annulus Bubble Curtain (GABC)

have proven themselves in serial use up to 2019.

In the following, all above-mentioned, Noise Abatement Systems are described and discussed in detail.

6.3.1 Noise Mitigation Screen (NMS)

The IHC-Noise Mitigation Screen (IHC-NMS), see Figure 27, 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; see Figure 27.

Figure 27: *Noise Mitigation Screen of the company IHC IQIP bv. Top left: technical construction drawings of the double-walled steel tube incl. inside pile-sleeve; top right: IHC-NMS in offshore use (close-up); below: IHC-NMS in offshore use. (Source: IHC IQIP bv)*

The IHC-NMS is a near-to-pile Noise Abatement System and was so far applied at water depths of up to 40 m and pile diameters of up to 8 m (monopiles). The IHC-NMS is the only one among the Noise Abatement Systems, that is a multifunctional system, which also serves as a pile guidance system (pile-sleeve) for the insertion of the monopiles up to the embedding depth. On the other hand, the IHC-NMS has sensors and technology for the centering of the piles and for performing inclination measurements in the direction of the solder.

As an additional noise-reducing measure, there is a small Bubble Curtain in the intermediate gap between the inner pipe and the pile to be driven, i. e. the intermediate space can be filled with an air-water mixture. The compressed air required for this is usually provided by the installation vessel or by an external compressor on deck of the installation vessel. This additional measure is mainly used to minimize possible disturbing interactions (vibration couplings) between the IHC-NMS, the pile to be driven and the seabed or scour protection.

The pile to be driven is then threaded into this double-walled tube and finally anchored to the seabed by the impulse pile-driving procedure. The IHC-NMS surrounds the pile to be driven along the entire water column. Usually, the monopile installation ends above the IHC-NMS-system, so that the impact hammer used does not come into contact with the Noise Abatement System.

Depending on the size of the pile to be driven and the expected water depth, the length and diameter of the double-walled tube must be adapted. In most cases, the Noise Mitigation Screen (NMS) is labeled with a four-digit number, which indicates the maximum diameter of the pile to be driven. Example: IHC-NMS8000 is designed for pile diameters up to 8,000 mm.

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 jack-up lifting platforms and floating installation vessels in the North Sea.

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 $\leq$ 0.75 m/s) and
- the spatial direction (omnidirectional noise reduction).

When used under offshore conditions, the following advantages of the IHC-NMS became apparent:

- compact system, which is fully integrated into the installation procedure; has multiple functionalities for the effective and efficient insertion of monopiles (pile-sleeve, measurements of the inclination of the pile to be driven toward the soldering direction),
- a proof of functionality by means of offshore tests before starting the installation is not required,
- through reliable noise reduction in low as well as in higher frequency ranges, a high biological relevance for the key species harbour porpoise is shown,
- during the installation of monopiles with diameters of up to 6 m, the achieved noise reduction was sufficient, in order to meet the noise mitigation values,
- highly applicable in water depths up to 40 m.

However, the experience from the nine OWF construction projects to date also shows the following limitations:

- Under offshore conditions, the handling due to the size and the mass (several 100 tons) is complex.
- During the installation of monopiles with diameters > 6 m and water depths > 25 m, the complementary application of a Bubble Curtain system is required to observe the noise mitigation values.
- Soil couplings can not be fully excluded, see chapter 5.1.2.
- The total length of the IHS-NMS is not automatically variable within a construction project, so that it has not yet been applied in construction projects with widely varying water depths.

6.3.2 Hydro-Sound Damper (HSD)

The Hydro-Sound Damper (HSD) was developed by the *OffNoise Solutions GmbH* and is another, near-to-pile Noise Abatement System. The HSD-system consists of a lowering- and lifting device (cable device with winches), a (fishing) net with HSD-elements and a ballast box; see Figure 28.

The HSD-elements on the net consist of different foam elements in different sizes and different materials. Each HSD-element acts in principle like a local resonator and can be tuned to different frequencies and water depths. It should be noted that the size of the HSD-elements in the water is reduced due to the static back pressure. The (further) development of the HSD-system was supported by two R&D projects[13].

The lifting device can usually be permanently installed on the installation vessel or fixed under the necessary pile-sleeve. Prior to the pile-driving, with the lifting device and the ballast box, the net with the HSD-elements can be stretched between the water surface and the seabed and cover the entire water column. The lifting device and the ballast box were previously manufactured singly for each project, so that the procedure for the pile-positioning and the HSD deployment was very variable. In one construction project, even an openable HSD-system including lifting device and ballast box was developed and could be successfully applied in serial use. Internal rollers hold the ballast box in position around the monopile.

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[13] Investigation and testing of Hydro-Sound Dampers (HSD) for the reduction of underwater noise during pile-driving works for foundations of OWTG, FKZ 325365, supported by the PtJ and BMU.

Evaluation of two jointly applied noise abatement measures (HSD and BBC) during the monopile foundations in the OWF Amrumbank West – Investigation of the noise couplings between pile, soil and water (short title: triad), supported by BMWi and PtJ, FKZ 0325681; running time 12/2013 to 7/2015; https://www.tu-braunschweig.de.

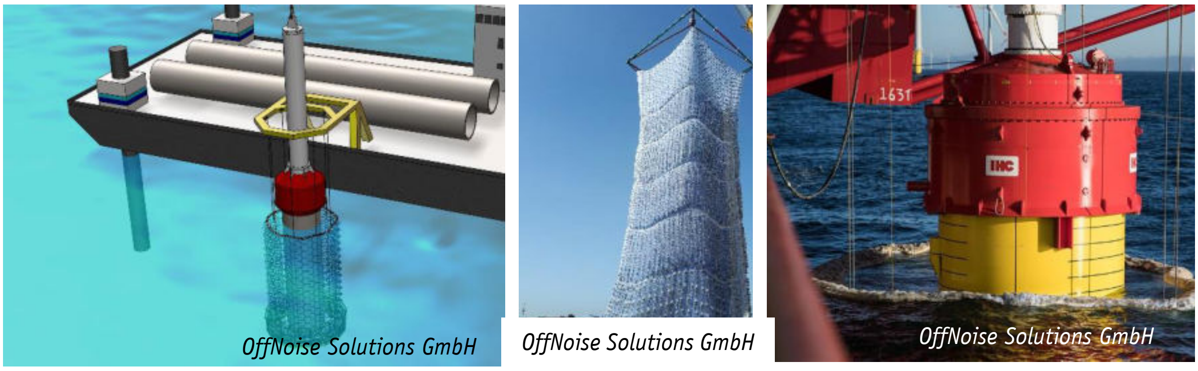

Figure 28: *Left: schematic drawing of a totally mobilized HSD-system, which hangs below a pile-sleeve system attached to the installation vessel. Middle: net with HSD-elements; HSD-system during a pile-driving. (Source: OffNoise Solutions GmbH)*

The HSD-system, particularly the HSD-net with its configuration with HSD-elements as well as the lifting device, is being developed and manufactured for specific projects. Prior to the start of installation, port tests and sometimes also offshore tests are always ordered by the BSH. These tests are used to check the functionality of the system, especially for the lifting device including ballast box and the HSD-net.

The whole system, consisting of ballast box, nets with HSD-elements and lifting device, can be telescoped into each other for the transport as well as for the mobilization and demobilization by means of winch systems.

The HSD-system is a near-to-pile Noise Abatement System and was until now applied at water depths of up to 41 m and pile diameters of up to 8 m (monopiles). Additionally, the HSD-system was once applied as prototype during the installation of a skirt-pile with a piling template (pre-piling procedure; see 5.2.1). The ballast box was placed on the piling template and the used impact hammer was guided within the HSD-net between the water surface and the piling template. This application however was performed in the Baltic Sea without strong current.

As an additional noise-reducing measure, HSD-elements can be fixed around and under the ballast box and a small Bubble Curtain can be pre-installed at or in the ballast box. The necessary compressed air can be provided by the installation vessel or by an external compressor on board the installation vessel. Both measures serve to minimize possible disturbing interactions (vibration couplings) between the ballast box, the pile to be driven and the seabed or scour protection.

In all previous applications, it has turned out, that the noise reduction of the system is constant and reliable, but mostly only at low frequencies. The system is therefore only suitable for combined use with a Bubble Curtain system.

When using this near-to-pile system with several hundred applications within five German OWF construction projects, technical problems with the lifting device could so far only be detected at the beginning of the development. Otherwise, all other applications showed, that this Noise Abatement System was offshore-suitable, faultless and robust.

The HSD-system was applied so far either from lifting platforms or from floating installation vessels.

The achieved noise reduction with the HSD-system proved to be independent of

- the water depth (up to 41 m), based on the different layouts of the HSD-elements at the net,
- the prevailing current (experiences up to a maximum of 0.75 m/s are available) and
- the spatial direction (omnidirectional noise reduction).

When applied under offshore conditions, the following advantages of the HSD-system were found:

- das HSD-System is also applicable for variable depths of 23 m to 41 m within a construction area without problems and without modifications,
- with a good constructive design, the HSD-system reliably produces a noise reduction of 10 dB in the low-frequency range (< 250 Hz),
- well applicable in water depths to 40 m.

However, the experiences from the previous OWF construction projects show the following restrictions:

- The handling, particularly the deployment of the lowering and lifting device under offshore conditions, is complicated. Up to now, the lowering and lifting device and the ballast box were developed and designed singlely for each project and each installation vessel. This lowering and lifting device can also produce unwanted coupling noises between the pile and the ballast box, if the system design is unfavourable.
- Therefore, a proof of the functional capability of the HSD-system must always be provided by harbor- and offshore tests prior to the start of installation,
- The constructive design of the HSD-system must always be considered during the installation in connection with the collection of data i. a. on the inclination of the pile.
- The HSD-system can only be applied as complementary system to a Bubble Curtain system, also at low water depths and at piles with smaller diameters.
- A reliable noise reduction is only given in the low-frequency range, which means a lower biological relevance for the key species harbour porpoise.
- Soil couplings can generally not be excluded; see 5.1.2.
- The lifetime of the HSD-elements and the net are limited, so that a replacement may become necessary after approx. 30 applications.
- The net design regarding the length and the layout with HSD-elements must project-specifically be adjusted to the mass and the size of the ballast box. The more HSD-elements are used, the more downforce must be produced by the ballast box.

- The application of the HSD-system involves additional time since this system represents an additional component of the installation.

6.3.3 Big Bubble Curtain (BBC)

The only far-from-pile Noise Abatement System is the single or double Big Bubble Curtain (BBC resp. DBBC), Figure 29. This system is currently available on the market from several supplier and two suppliers have already applied a single and/or double Big Bubble Curtain in serial use for already completed OWF construction projects in the German EEZ of the North- and Baltic Sea.

Figure 29: *Double Big Bubble Curtain: left: circular deployment due to the very low current; right: elliptic deployment due to the current (larger diameter in current direction). (Source: Hydrotechnik Lübeck GmbH)*

The Big Bubble Curtain consists of perforated nozzle hoses, including non-perforated supply air hoses, compressors for generating compressed air and a supply vessel with devices (winches and air distribution system) for the deployment and the recovery of the nozzle hoses and the supply air hoses as well as for the storing and operation of the necessary compressors. Moreover, the nozzle hoses are provided with a deployed ballasting, so that due to the downforce of the ballasting, the nozzle hoses remain firmly on the seabed also during operation. By means of the supply vessel, the nozzle hose(s) is/are deployed on the seabed and connected to the compressors for the air supply via supply air hoses. Due to the pressure differences inside and outside the nozzle hoses, the air exits through air outlets and the air rises towards the water surface. The static water pressure is cruical for the size of single air bubbles. With increasing water depth, the static pressure in the water increases, so that the defined supplied air volume decreases. The size and shape of the air bubbles can only be influenced to a very limited extent by the air outlets (holes) in the nozzle hose. Usually, different sizes and shapes of air bubbles form within the water column. The average ascent speed of the air bubbles is approx. 0.3 m/s (average value over all bubble sizes), whereby bigger and smaller air bubbles can also have ascent speeds between 0.2 and 0.8 m/s

(Nehls & Bellmann, 2015). Usually, the ascent speed steadily increases with the size of the air bubbles. During the ascent to the water surface, the air bubbles are exposed to the prevailing current and are drifted away in current direction. Up to a flow velocity of up to 0.75 m/s (corresponds to approx. 1.5 kn), this drift can mostly be compensated by an elliptical deployment form of the nozzle hoses in current direction.

The development under offshore conditions and the further optimization of the Big Bubble Curtain were supported by two funded research projects[14] in the German EEZ of the North Sea (Diederichs et al., 2014; Nehls & Bellmann, 2015).

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

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

Big Bubble Curtain systems in a project-specifically adapted, technical design (optimized system configuration) are able to reduce high frequencies very effectively. On the other hand, the reduction potential at low frequencies decreases steadily; see 6.4.2.1.

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

- independent deployment of the nozzle hoses from the installation vessel by a variable deployment procedure[15],
- supplied air volume can be varied by the number and type of compressors used (air-water-mixture),
- the Noise Abatement System is independent of the foundation type and the installation vessel,
- applicable in different water depths,

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

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

- due to reliable noise reduction in higher frequencies, a high biological relevance for the key species harbour porpoise is shown.

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

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

Based on the available data of the research projects and the measurement data from different offshore construction projects, technical and physical minimum requirements for the application of an optimized single and double Big Bubble Curtain could be derived to achieve a maximum noise reduction in water depths of 41 m during impulse pile-driving works (Nehls & Bellmann, 2015). These minimum requirements were again significantly extended in the course of the construction projects in the years 2016 to 2019 in Germany, based on practical experience (MarinEARS[1]). The background to this is, that in recent years, the pile diameter has increased steadily and thus the noise input into the water resp. the requirements for noise abatement have also increased.
In the following, all information regarding the system configuration used and the noise reduction achieved is presented anonymously from the OWF construction project and the BBC supplier(s). In case of non-compliance with these technical and physical minimum requirements, it could be shown for completed construction projects in the offshore range, that the noise reduction decreases considerably and in the worst case, no noise reduction happens (Bellmann et al., 2018; Nehls & Bellmann, 2015).

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

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

(ii) hole size and hole spacing,

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

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

(v) prevailing current[16].

There is a correlation between the introduced air volume and the achieved noise reduction. The impedance difference between water and air-water-mixture is decisive for the noise-reducing effect of a Bubble Curtain in the acoustic far-field. Moreover, in a research project[14], a half-empiric, hydro-dynamic Bubble Curtain model was developed and tested. Thus, the system configuration of a Bubble Curtain can be optimized in advance for an appropriate construction project (Bellmann & Nehls, 2015).

Based on calculations, measurement data and experiences with the handling from the practice of more than 800 pile installations, the following requirements to the technical realization of a Big Bubble Curtain must be fulfilled, so that an optimal and direction-independent noise reduction can be achieved:

- hole size (diameter) and hole spacing: 1 – 2 mm, every 20 – 30 cm,
- used air volume: ≥ 0.5 m^3/(min·m),
- regular maintenance of the used nozzle hoses
  (i. e. check of the available hole openings in the nozzle hose; if necessary, re-drilling or cleaning of holes),
- no turbulence-creating obstacles in the nozzle hoses, such as ballast chains, sand, etc.,
- distance of the nozzle hoses:
  - minimum distance between Bubble Curtain and pile-driving construction site of 30 m to 40 m; this information refers to the distance from the source to the BBC at the water surface; due to currents and signs of drift, the distance on the seabed must project-specifically be determined and is usually larger,
  - minimum distance between inside and outside nozzle hose for a double Big Bubble Curtain corresponds at least to the water depth at the application site. This information is strongly dependent on the current.
- Nozzle hose length:
  - the minimum nozzle hose length of a single, closed nozzle hose (e. g. inner ring at a DBBC) usually is $\geq$ 600 m in case of double-sided air supply,

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

  - the maximum nozzle hose length of a single, closed nozzle hose (e. g. outer ring at a DBBC) ≤ 1.000 m in case of double-sided air supply,
  - the total length of a DBBC is ≤ 1.750 m.
- The maximum number of compressors with the double Big Bubble system is limited by the BSH to 20 pieces.[17]
- The lifetime of the nozzle hoses to be applied is limited. The BSH requires a maximum operating time of approx. 40 applications per nozzle hose. Based on the experiences, however, a nozzle hose can be applied up to 100 times, if appropriate maintenance work and visual inspections are carried out regularly. If a nozzle hose is used too frequently, material fatigue can occur due to the high mechanical stress[18]. For larger construction projects, the BSH usually requires the use of new nozzle hoses; chapter 3.
- In a research project, pressure sensors inside the nozzle hose were developed and installed (Nehls & Bellmann, 2015). It was shown, that with increasing distance to the air injection points, the internal pressure in the nozzle hose decreases as expected. There must be at least an overpressure of 2 – 3 bar in contrast to the static water pressure at each air outlet of the nozzle hose to ensure a uniform and optimum air outlet, so that the resulting noise reduction is as equal as possible in all directions. In addition, pressure losses have already been observed between the compressors on board the BBC supply vessel and the air injection points located on the seabed. For a water depth of up to 40 m, an operating pressure of 9 bar to 10 bar of the compressed air per compressor on board the BBC supply vessel is usually sufficient.
- According to the current state-of-the-art, the nozzle hose diameter is 100 mm. The ballasting must be attached to the nozzle hose from the outside (not inside). At present, tests are also being carried out with larger diameters, in order to be able to increase the air volume considerably. This has led to considerable problems with the ballasting in test applications so far, which have not yet been completely solved; chapter 7.3.3.
- The operating conditions of each single compressor must regularly be documented (the total compressed air volume (Free Air Delivery – FAD) for the Big Bubble Curtain must be calculated from the rotational speed and the operating pressure of each single compressor). Usually, the compressed air volume decreases slightly with the set operating pressure at

[17] The background for the limitation of the number of compressors is a nature-compatible use of this Noise Abatement System regarding the CO_2-output as well as a balanced cost-effectiveness. This number of compressors can be transported by a BBC supply vessel incl. winch systems, etc.

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

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

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

It has been shown in practice, that a Big Bubble Curtain can be a very effective, robust and offshore-suitable Noise Abatement System, but each Bubble Curtain must singlely be adapted to each construction project with regard to site-specific and technical-constructional characteristics, such as current, water depth, installation process, etc. Furthermore, it has been shown, that a Big Bubble Curtain must be intensively maintained several times at the beginning of a construction project, i. e. re-boring of the nozzle hoses, until an optimized and omni-directional noise reduction has been achieved. If the above-mentioned minimum requirements or specifications are not met, the noise reduction decreases considerably and in the worst case is only a total noise reduction of a few decibels; see Figure 30.

6.3.4 Grout Annulus Bubble Curtain (GABC)

During the set-up of Jacket-foundations in the post-piling procedure, the piles are driven by so-called pile-sleeves. There are two possible types of pile-sleeves:

(i) The pile-sleeve is a firm component of the Jacket-construction and extends from the lower edge, i. e. the seabed, to the upper edge above the water surface of the entire Jacket-structure, i. e. the piles are always driven above the water surface and the pile-sleeve covers the entire water column (main piles; chapter 5.2.1).

(ii) The pile-sleeve is only several meters high and is rigidly connected to the Jacket-structure at the lower edge. Alternatively, a piling template can be used instead of the Jacket-construction. The piles (called skirt-piles; chapter 5.2.1) 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 pipes for the cementing of the piles (grouting lines), which are usually located at the bottom of the pile-sleeve. The air bubbles rise upwards in the gap between pile and pile-sleeve. The gap thus fills with an air-water-mixture.

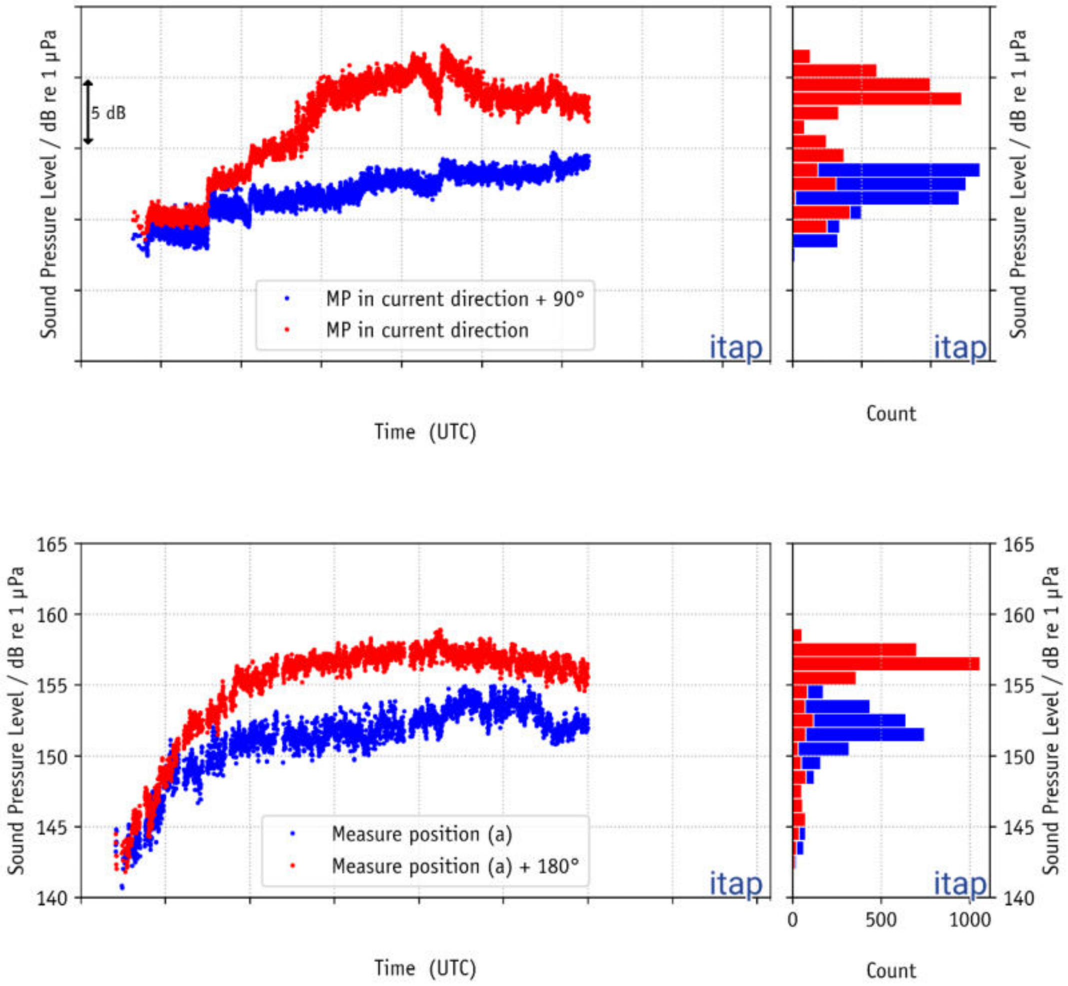

Figure 30: *The measured Sound Exposure Level at two measuring positions in 750 m in different spatial directions to the monopile installation with the application of a Big Bubble Curtain as secondary Noise Abatement System as function of time. Above: The difference between the two measuring positions resulted from drifting effects based on a current > 2 m/s. Below: The difference between the two measuring positions resulted from an unevenly distributed air introduction into the water. By means of re-drillings of the nozzle hose, these differences in different directions could be minimized.*

In the case of pile-sleeves, which do not reach the water surface, the rising air (air bubbles) can escape at the upper edge of the pile-sleeve and rise to the water suface. A „small" Bubble Curtain (Grout Annulus Bubble Curtain – GABC) is thus formed around the pile up to the water surface. Currents, like e. g. in the North Sea, lead to drifting effects of the air bubbles above the pile-sleeve. For this reason, it cannot be excluded, that current-dependent, large openings or holes in the Bubble Curtain may be created by drifting effects, which significantly lower the noise reduction. This principle is comparable to the „stepped small Bubble Curtain", which was tested once in the

OWF *Alpha Ventus*[19]. Here, however, there was no „duct“ in the lower area, so that due to the strong current, all air bubbles were on one side of the pile.

If the pile-sleeve reaches to the water surface, the GABC is led to the water surface. For this case, there is already experience from several Jacket-constructions in the German EEZ to water depths of 30 m.

It can be assumed, that the gap width and the quantity of air introduced have a significant influence on the air-water-mixture and thus on the noise reduction achieved. From the existing empirical data sets, however, no minimum requirement of the compressed air volume to be supplied can be derived. The gap between the pile and the pile-sleeve is usually only a few centimetres, so that only a relatively small amount of air can be introduced into this gap. Usually, only one compressor was used for the provision of the compressed air volume.

However, experience shows the following limitations:

- A GABC must singly be adapted for each Jacket-design.
- Soil couplings can basically not be excluded; see chapter 5.1.2.
- The supplied air volume is limited by the gap size.
- This Noise Abatement System is limited to the application at Jacket-constructions.
- In the case of skirt-piles, there may be drifting effects above the pile-sleeve, resulting in a direction-dependent noise reduction.
- The noise reduction potential can be classified as low compared to the three Noise Abatement Systems mentioned.
- This technical Noise Abatement System is only a supporting Noise Abatement System, which can be used in combination with a Big Bubble Curtain to observe the German noise mitigation values.

6.3.5 Combination of near-to-pile and far-from-pile Noise Abatement System

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 German OWF construction projects:

The following combinations have resulted in reliable compliance with the noise mitigation values, while at the same time meeting environmental protection aspects and practicable integration into the installation process:

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[19] Joint project: Investigation of the noise abatement measure „Little Bubble Curtain“ in the test field Alpha Ventus, FKZ325122, supported by PtJ and BMU.

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

Solutions, that have proven to be less practicable when integrated into the installation process or that could not reliably provide compliance with the noise mitigation values:

- double Big Bubble Curtain plus a half-open, single Big Bubble Curtain in direction of the FFH protected area,
- two double Big Bubble Curtains, thus, a quadruple Big Bubble Curtain.

For the installation of Jacket-foundation structures, so far, the following combination was successfully applied in serial use:

- single and double Big Bubble Curtain (BBC & DBBC),
- Grout Annulus Bubble Curtain (GABC) + double Big Bubble Curtain (DBBC),
- HSD + double Big Bubble Curtain (DBBC) - once, HSD-system in prototype-design.

Each of the above mentioned combination of Noise Abatement Systems was moreover applied in combination with a noise-optimized pile-driving procedure (see chapter 5.2.2).

With monopile diameters as of 6 m and/or water depths larger 25 m, an application of two independent Noise Abatement Systems – a near-to-pile and a far-from-pile Noise Abatement System – for the compliance with the German noise mitigation values have proved successful resp. is required by the German approval authority. In most cases, an additional noise-optimized pile-driving procedure is also used for monopiles with a large pile diameter.

In order to comply with the German noise mitigation values, the successful application of a combination of two Noise Abatement Systems at the Jacket-installation is very much dependent on the water depth, the pile-design and the prevailing current. Based on experiences, it may also be sufficient to simply use a double Big Bubble Curtain to comply with the noise mitigation values.

6.4 Evaluation of the effectiveness of Noise Abatement Systems

6.4.1 Definition and measurement concept of the insertion loss

For the quantitative characterization of the effect of a Noise Abatement System, usually the (noise) transmission loss resp. insertion loss is considered.

For this, the differences between the Sound Exposure Levels (L_E resp. SEL) of the reference measurement (unmitigated pile-driving) and a Noise Abatement System variant to be assessed (test measurement) is made. Based on the results of a R&D project, a technical measurement regulation for the quantitative determination of the effectiveness of noise-reducing measures (BSH, 2013) was developed[14]. This measurement regulation was transformed into a specification of the German standardization body DIN in 2017.

In principle, reference measurements without applying technical Noise Abatement Systems and test measurements with a defined noise mitigation configuration under large-scale offshore conditions are mandatory for the determination of the achieved noise reduction.

There are two different methods:

(i) the indirect and

(ii) the direct method.

In the case of the **(i) indirect method**, the test- and reference measurements are carried out at different foundation sites (monopiles) resp. in the case of different piles of a Jacket-construction at the same foundation site. The indirect method requires comparable, site-specific and technical-constructive characteristics, such as hammer type and pil-driving procedure,pile-design, water depth, embedded depth, soil resistance, used blow energy, etc. The advantage of the indirect method is, that measurement data can be obtained for the entire installation processs of piles, i. e. from the 1st stroke, „soft-start“ phase up to of the final embedding depth. Thus, when using the indirect method, besides the evaluation of the actual installation procedure, the effectiveness of a noise-optimized pile-driving procedure can also be quantified in terms of the pile-driving duration and the noise reduction achieved. The indirect method is particularly valuable, if the characteristics of the hammer are to be investigated and the source level is to be determined reliably in order to model the propagation and to optimize technical Noise Abatement Systems.

In the case of the **(ii) direct method**, test- and reference measurements are carried out at the same pile installation. The advantage of this method is, that some site-specific characteristics are almost identical. The disadvantage of this method is, that neither the pile-driving procedure, nor the effectivity of the used Noise Abatement System can be determined for the entire installation of the pile until the final embedding depth is reached. As the soil resistance, and thus the blow energy to be used, usually changes continuously with the embedding depth, the comparability of the data is limited. In addition, the mobilization and demobilization of Noise Abatement Systems require a pile-driving interruption, so that the total pile-driving duration can be considerably longer. It is not possible with the direct method to quantify the effectiveness of a noise-optimized pile-driving procedure with regard to the pile-driving duration and the noise reduction achieved.

Technical note: Applying an IHC-NMS has shown that only a direct method for test- and reference measurements is possible, because the IHC-NMS is additionally used as pile-guiding tool. This means, that the pile-driving of a monopile is first performed with the use of an IHC-NMS to an embedding depth, where the monopile can stand safely for a short time even without pile-guiding tool. After the demobilization of the IHC-NMS, the remaining pile-driving then takes place without applying this Noise Abatement System. However, it is absolutely necessary to ensure, that comparable blow energies are used immediately before and after the demobilization of the IHC-NMS.

Technical note: Usually, the BSH orders test- and reference measurements according to the specifications (DIN SPEC 45653, 2017 and BSH, 2013) using the indirect method.

The DIN SPEC 45653 (2017) further provides, that the measurements for the evaluation of the effectiveness of applied Noise Abatement Systems must be performed in multiple directions, in order to additionally obtain information about the directional dependency of the applied Noise Abatement System. Usually, the measurements must be carried out in 750 m and maximum 1,500 m distance to the pile-driving, in order to ensure a sufficient signal-to-noise-ratio ($\geq$ 10 dB according to the BSH,2011).

The quantitative determination of the effectiveness can be affected frequency-resolved or broadband.

Technical note: It has been shown that underwater noise measurements at distances of more than 1,500 m to the pile-driving cannot simply be used for the evaluation of the achieved noise reduction by the Noise Abatement System used. Especially if measuring positions are located outside the construction site, a sufficient signal-to-noise-ratio cannot always be guaranteed (e. g. influence of vessel noise).

Broadband insertion loss

In the case of the broadband presentation, the sum levels of the frequency-resolved Sound Exposure Levels (SEL) are deducted from each other. The higher the difference, the larger the transition loss and the better the Noise Abatement System resp. its applied configuration. The advantage of this parameter is, that the noise-reducing effect of a Noise Abatement System can be recorded and described with singular value. Moreover, it can be used to directly assess compliance with the German noise mitigation value. The disadvantage of this evaluation method is, that no information about the spectral dependence of the insertion loss is known. This is obstructive, for example, if specific measures for improvement of the applied Noise Abatement Systems become necessary, in order to comply with the German noise mitigation values. Irrespective of this, the frequency-dependent noise reduction is mandatory, if the hearing capacity of different species is in focus, as it is the case with the technical guidelines of the NOAA (National Marine Fisheries Service, 2018) and Southall et al. (2019), which are used in the environmental impact assessment (EIA) study, e. g. in the USA or UK; chapter 7.1.

Variances, caused by different maximum blow energies at the respective foundations, resp. test- and reference measurements were minimized in the following illustrations by a normalization. A level increase of 2.5 dB with doubling of the blow energy was assumed; see chapter 5.2.2.

Spectral insertion loss

For spectral insertion loss, the respective spectra of the reference- (without noise abatement measure) and the test measurement (with noise abatement measure) are subtracted from each other. In this report, the spectrum of the reference measurement was subtracted from the spectrum of the test measurement for better clarity. With this definition, the achieved transition loss of a Noise Abatement System increases with rising negative number. Positive values in the difference spectrum would thus indicate an amplification of the noise level by the application of a Noise Abatement System.

The spectral insertion loss is a decisive factor for the evaluation of the biological relevance of applied noise abatement measures, depending on the key species to be considered. This issue is discussed in chapter 7.1 and will also be the subject of another separate technical report.

Execution of test- and reference measurements according to the DIN SPEC 45653 (2017)

Per OWF construction project, usually a series of test- and reference measurements according to the DIN SPEC 45653 (2017) are ordered:

(i) reference measurement without Noise Abatement Systems,
(ii) optionally test measurements with the near-to-pile Noise Abatement System,
(iii) optionally test measurements with the far-from-pile Noise Abatement System,
(iv) optionally test measurements with the combination of near-to-pile and far-from-pile Noise Abatement System.

At the beginning of a construction project, reference- and test measurements for a project-specific optimization of single Noise Abatement Systems, such as the Big Bubble Curtain, are mostly ordered resp. performed. In this context, the main objective of further development of the Big Bubble Curtain is to improve or ensure the omni-directional effectiveness by re-drilling holes in the applied nozzle hoses. However, the results of these test measurements during the 1st installations do not include information on the noise reduction achieved after optimization measures has been applied.

For this purpose, the test measurements should be repeated after all optimizations on the Noise Abatement Systems have been applied.

The analysis of the reference- and test measurements is necessary to further develop and optimize single components of Noise Abatement Systems, including the impact hammer used. This analysis of the spectrally resolved, quantitative noise reduction of single Noise Abatement Systems is summarized for each construction project in a separate report, the so-called *Experience Report Noise Mitigation* according to the provisions of the BSH.

However, according to current knowledge, the success of the noise mitigation measures, as described above, depends on a number of technical-constructive and site-specific factors. In the following, the noise reduction achieved is therefore presented on the basis of all available data from the MarinEARS[1] specialist information system across all projects.

Technical note: From an acoustic point of view, especially for the Big Bubble Curtain, two different test measurements per OWF construction project are necessary. The first test measurement should be used to project-specifically optimize the applied Noise Abatement System and should take place at the beginning of a construction project. The second test measurement should preferably be carried out at the end of a construction project and be used for the evaluation of the applied Noise Abatement System according to the DIN SPEC 45653 (2017).

6.4.2 Achieved noise reduction

For the calculation of the total noise reduction achieved, not only the above mentioned test- and reference measurements per single OWF construction project, but all pile-drivings performed in the construction project were considered with the same Noise Abatement System configuration. This step provides an overview of the overall performance of the Noise Abatement Systems including the impact hammer used. Furthermore, the addition of all measurement data sets also shows the reproducibility of the Noise Abatement Systems applied.

6.4.2.1. Achieved noise reduction with a single and double Big Bubble Curtain

In chapter 6.3.3, it was already mentioned, that apart from the Big Bubble Curtain, the achieved noise reduction of all offshore-suitable Noise Abatement Systems attain a noise reduction due to their project-specific adaptation, which was independent of the water depth in the range of 20 to 40 m. In the case of the Big Bubble Curtain, the amount of air supplied and the available water depth are decisive parameters for the noise reduction to be achieved. This is based on the fact, that with increasing water depth, the static water pressure rises and this reduces the volume of the air bubbles of the Bubble Curtain. In the following table, the achieved noise reductions by a single and double Big Bubble Curtain in different water depths and with different air volumes are summarized. The prevailing current was always maximum 0.75 m/s.

Table 3: *Achieved broadband noise reduction by an optimized single or double Big Bubble Curtain with different system configurations regarding the supplied air volume and in different water depths. Note: A non-optimized system configuration resulted in significantly lower noise reductions.*

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

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

It can also be seen from Table 3, that the resulting noise reduction by a Bubble Curtain with the same system configuration decreases steadily to larger water depths. This effect can at least partially be compensated by increasing the amount of air supplied.

The noise reductions shown in Table 3 are all based on the installation of monopiles in water depths of 20 to 40 m and at currents < 0,75 m/s, i. e. with compensable drifting effects.

Technical note: Depending on the installation speed, a double Big Bubble Curtain including the necessary compressors can be deployed, operated and recovered from a BBC supply vessel. For a 3rd and further BBC-systems, at least one additional vessel in the construction field would have to operate in the smallest possible space. This was tested once in an OWF construction project. Based on these experiences, the BSH has prohibited the application of a 3rd and 4th BBC ring due to the disproportionate regarding costs, benefit and CO_2-consumption of the compressors.

Technical note: Applications of a Big Bubble Curtain abroad at currents up to 2 m/s have shown such powerful drifting effects, that the resulting noise reduction in current direction decreased considerably (> 5 dB); see Figure 30. It also showed, that different sizes of air bubbles have different ascent speeds, which leads to a different retention time of the air bubbles in the water during the ascent between the seabed and the water surface and thus to different characteristics of the drifting effects. At the water surface, the Big Bubble Curtain spread out spatially very strongly due to the drifting effects, which led to a significant reduction of the local air content in the water and thus to significantly lower noise reductions.

Technical note: In the years 2018 and 2019, the first signs of wear appeared on the applied nozzle hoses with drilled holes, which have already been used in several OWF construction projects. A quantitative and qualitative analysis with regard to the maximum duration of use of a nozzle hose on the basis of the MarinEARS[1] technical specialist information system is not yet completed.

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

Figure 31 shows for comparison the spectral insertion loss for an optimized single Big Bubble Curtain when using different air volumes. It is shown that the spectral form of the insertion loss does not change significantly due to the amount of air volume supplied, but with higher air volume, the resulting transition loss improves continuously, especially in the frequency range < 1 kHz.

The different decrease of the achieved noise reduction by a Big Bubble Curtain in Figure 31 at frequencies larger 2 kHz does not result from the different supplied air volume, but is due to the influence of different signal-to-noise-ratios between the pile-driving noise and the permanent background noise. I. e., the permanent background noise in the OWF construction project limits the noise reduction in the high-frequency range; see also Figure 33.

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

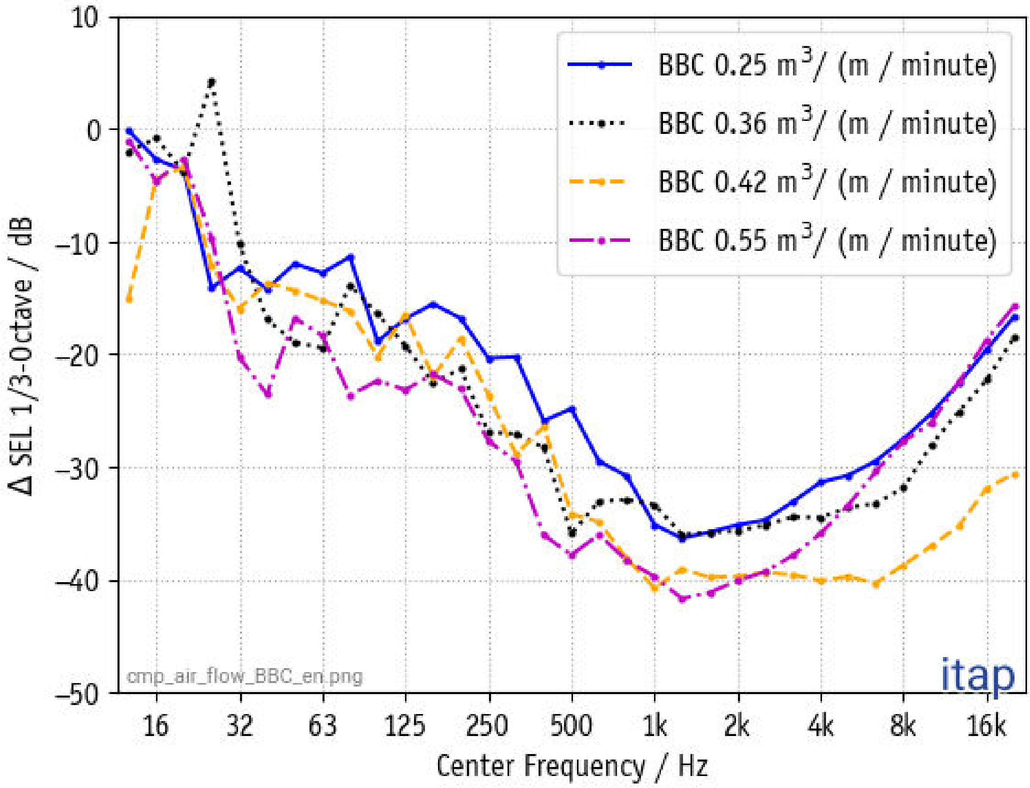

Figure 31: *Resulting averaged noise reduction (transition loss) from the test measurements according to the DIN SPEC 45653 (2017) with a double Big Bubble Curtain (DBBC) with different supplied air volumes.*

6.4.2.2. Achieved noise reduction of Noise Abatement Systems in the German North Sea

Table 4 gives an overview of the achieved broadband insertion loss of the offshore-suitable Noise Abatement Systems. Only the optimized system configuration of each applied Noise Abatement System is displayed and reflects an averaging across all applications in different construction projects. Due to the averaging over several construction projects with partly not completely comparable, site-specific and technical-constructive conditions and the general measurement uncertainty with underwater noise measurements, a statistical representation of the minimum, averaged and maximum achieved noise reduction is reasonable. The larger the differences between the maximum and minimum achieved noise reduction of a Noise Abatement System resp. a Noise Abatement System configuration, the more vulnerable the application of this Noise Abatement System, of this Noise Abatement System configuration resp. of this combination of Noise

Abatement Systems regarding the influence of site-specific and technical-constructive environmental conditions.

Furthermore, the analysis did not explicitly consider the type of the impact hammer. In this respect, the values shown here are for orientation purposes only.

Table 4: *Achieved noise reduction of single Noise Abatement Systems and combinations of secondary Noise Abatement Systems in their respective optimized system configuration depending on different, technical-constructive and site-specific framework conditions. All basic underwater noise measurement data were collected in the North Sea with currents of up to 0.75 m/s and a sandy soil.*

No.	**Noise Abatement System resp. combination of Noise Abatement Systems** (applied air volume for the (D)BBC; water depth)	**Insertion loss ΔSEL [dB]** (minimum / average / maximum)	**Number of foundations**
1	IHC-NMS (different designs) (water depth up to 40 m)	13 ≤ 15 ≤ 17 dB IHC-NMS8000 15 ≤ 16 ≤ 17 dB	> 450 > 65
2	HSD (water depth up to 40 m)	10 ≤ 11 ≤ 12 dB	> 340
3	optimized double BBC[*1] (> 0,5 m^3/(min m), water depth ~ 40 m)	15 – 16	1
4	combination IHC-NMS + optimized BBC (> 0,3 m^3/(min m), water depth < 25 m)	17 ≤ 19 ≤ 23	> 100
5	combination IHC-NMS + optimized BBC (> 0,4 m^3/(min m), water depth ~ 40 m)	17 – 18	> 10
6	combination IHC-NMS + optimized DBBC (> 0,5 m^3/(min m), water depth ~ 40 m)	19 ≤ 21 ≤ 22	> 65
7	combination HSD + optimized BBC (> 0,4 m^3/(min m), water depth ~ 30 m)	15 ≤ 16 ≤ 20	> 30
8	combination HSD + optimized DBBC (> 0,5 m^3/(min m), water depth ~ 40 m)	18 – 19	> 30
9	GABC skirt-piles[*2] (water depth bis ~ 40 m)	~ 2 – 3	< 20
10	GABC main-piles[*3] (water depth bis ~ 30 m)	< 7	< 10
11	„noise-optimized“ pile-driving procedure (additional additive, primary noise mitigation measure; chapter 5.2.2)	~ 2 - 3 dB per halving of the blow energy	

*[1] Currently, the optimal configuration of a double Big Bubble Curtain is 40 m water depth. A further increase of the supplied air volume is technically only possible to a limited extent due to the existing nozzle hose diameter.

*[2] Until now, a GABC-system has not been applied as a sole Noise Abatement System in the construction of Jacket-foundations with so-called pin-piles. Moreover, so far, no test- or reference measurements were allowed according to the DIN SPEC 45653 (2017) resp. BSH (2013). The GABC was always performed in combination with a single or double Big Bubble Curtain. During the pile-drivings, however, the GABC was partially deactivated for a short time. Thereby, a level increase in 750 m could be measured. This direct method of evaluation, however, carries the risk of underestimating the GABC, since in most cases, the time was not completely sufficient to allow the entire air to escape from the gap between the pile-sleeve and the pile to be driven.

*[3] At two converter platforms, main-piles were installed, i. e. the pile-sleeve of the main-piles covered the entire water column. Once the air was fed into the pile-sleeve from below and once from above. In both cases, an air-water-mixture could be realized. This Noise Abatement System was applied both times without using a further Big Bubble Curtain. However, even in this case, no complete reference measurements were carried out following the DIN SPEC 45653 (2017) resp. the BSH (2013), but the GABC was only temporarily switched off for a short time, so that a statistically valid evaluation of the expected noise reduction cannot be guaranteed.

Noise reductions of up to 17 dB in water depths up to 40 m can indeed be achieved with only one IHC-NMS or only one optimized DBBC. By the combination of a near-to-pile and a far-from-pile Noise Abatement System, the resulting noise reduction can be improved again by several decibels, so that noise reductions of $\geq$ 20 dB can be achieved.

Technical note: However, it is clearly shown, that the resulting noise reduction of two independent Noise Abatement Systems with a respective insertion loss of e. g. 15 dB does not lead to an overall noise reduction of 30 dB. The background to this is, that the input spectrum for the far-from-pile Noise Abatement System has already been considerably reduced by the use of the near-to-pile Noise Abatement System, and in some cases there is an insufficient signal-to-noise-ratio between the pile-driving noise and the background noise, especially for frequencies from 500 Hz; see Figure 33.

Moreover, the combination of a noise-optimized pile-driving procedure and the application of Noise Abatement Systems has the effect of an additive overall noise reduction. The background is, that the reduction of the blow energy in the noise-optimized pile-driving procedure can in principle be regarded as a primary Noise Abatement System, i. e. the noise-optimized pile-driving procedure reduces the sound source and does not affect the transition loss of a secondary Noise Abatement System.

For all Noise Abatement Systems resp. combinations, the noise reductions for the zero-to-peak Sound Pressure Level ($L_{p,pk}$) were generally slightly higher than for the Sound Exposure Level (SEL).

Technical note: A first statistical evaluation shows, that a significantly higher variance of the zero-to-peak Sound Pressure Level than of the 5 %-exceedance level of the Sound Exposure Level (SEL_{05}) can be expected.

6.4.2.3. Application of secondary Noise Abatement Systems in the German Baltic Sea

In an OWF construction project in the German Baltic Sea, a combination of a HSD-system and an optimized double Big Bubble Curtain (> 0,5 m^3/(min m)) in water depths between 20 and 40 m was applied as serial noise abatement concept. The resulting noise reduction varied between 15 and 28 dB. This large variance in the achieved noise reduction cannot be ascribed to technical failures of one of the two applied Noise Abatement Systems or to performed optimization measures at the used double Big Bubble Curtain (DBBC).

The performed reference- and test measurements indicate, that the achieved noise reduction by the near-to-pile Noise Abatement System Hydro Sound Damper (HSD) has remained far below the usual noise reduction of approx. 10 dB depending on the location (Baltic Sea: 5 dB for the Sound Exposure Level and 3 dB for the zero-to-peak Sound Pressure Level). Whereas the optimized double Big Bubble Curtain (DBBC) achieved a higher noise reduction than in the North Sea (Table 4) (Baltic Sea: 18 dB for the Sound Exposure Level at a water depth of 23 m). A statistical correlation between the achieved noise reduction and the water depth resp. the soil resistance could not be clearly established. For the double Big Bubble Curtain, however, one knows, that applications at very low current have a positive influence on the achieved noise reduction, since there are no drifting effects of the air bubbles.

For the near-to-pile HSD-Noise Abatement System, it is assumed, that a combination of non-optimised ballast box and predominant variable soil stratifications (soil couplings; see chapter 5.1.2) led to the significantly more variable, site-specific noise reductions than in applications in the North Sea. In the German Baltic Sea, mostly loose sands lying on top can be found, followed by till and chalk of varying thicknesses. Till and chalk have a much higher soil resistance and it is assumed, that due to the stratification of different materials, the soil couplings are much higher than in the North Sea, where mostly clay- and sand layers of different density and thickness are found; see chapter 5.1.2.

Technical note: It can therefore be assumed, that due to the soil couplings, each near-to-pile Noise Abatement System during the application in the Baltic Sea might have lower site-specific noise reductions than in the North Sea.

Spectral noise reduction

Figure 32 shows the frequency-resolved, averaged difference spectra of the 5 %-exceedance level of the Sound Exposure Level (SEL_{05}), summarized for each secondary Noise Abatement System resp. combination of Noise Abatement Systems in 1/3-octaves (third spectra).

Based on the fact, that measurement data from different construction projects and thus different, site-specific and technical-constructive characteristics are used for the averaged difference spectra, the partly existing fine structure of the difference spectra can be explained.

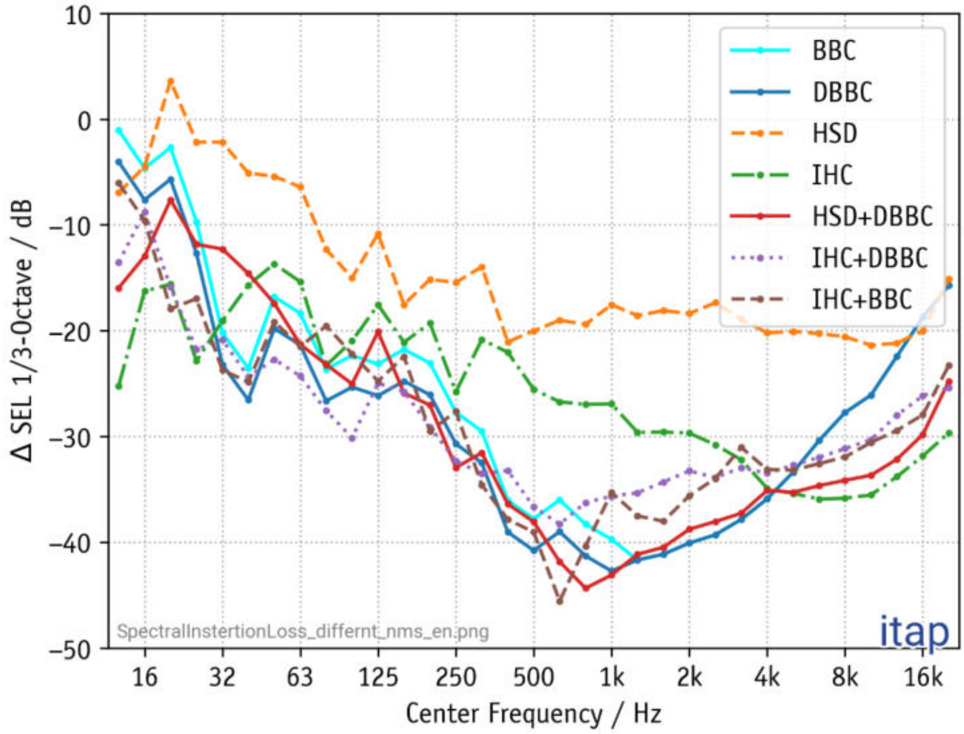

Figure 32: *Resulting noise reduction (transition loss) of the applied Noise Abatement Systems – IHC-Noise Mitigation Screen (NMS8000), Hydro Sound Damper (HSD) and optimized single/double Big Bubble Curtain (BBC/DBBC), averaged over all applications within the German EEZ of the North Sea. Note: The presentation of the insertion loss differs from the specification of the DIN SPEC 45653 to that extent, that not the difference from reference- and test measurement, but from test- and reference measurement is displayed. Negative values thus mark a high noise reduction.*

In principle, the insertion loss (resulting noise reduction) for all offshore-suitable Noise Abatement Systems or their combinations increases steadily with rising frequency up to about 1 kHz. To higher frequencies, the achieved noise reduction per frequency band either remains constant or decreases slightly. This effect at frequencies > 1 kHz is based on the facts, that on the one hand, the noise input into the water by impulse pile-drivings drops off considerably to higher frequencies (Figure 14 in chapter 5.2.1) and on the other hand, the pile-driving noise often does not stand out significantly (SNR < 10 dB) from the background noise with an optimized Noise Abatement System or with the combination of two secondary Noise Abatement Systems; see Figure 33.

The varying decrease of noise reduction at frequencies higher 2 kHz at all presented, secondary Noise Abatement Systems results from different signal-to-noise-ratios between the pile-driving noise and the permanent background noise except from the Hydro Sound Damper. The different, secondary Noise Abatement Systems have been applied in several different OWF construction projects with different, technical-constructive and site-specific framework conditions.

Based on the foundings, that the maximum noise input into the water by an impulse pile-driving is in the frequency range between 63 and 160 Hz, mostly depending on the pile diameter , it seems that, the broadband noise reduction is significantly influenced and affected by this frequency range.

However, in practical applications of Noise Abatement Systems, it turned out that due to technical problems, malfunctions or a non-project-specific, optimized system configuration of the applied Noise Abatement Systems, considerably worse noise reductions were achieved. This is especially true when using a Big Bubble Curtain.

Spectral effectiveness of the applied technical Noise Abatement Systems

Figure 33 summarizes the impulsive noise input into the water in a distance of 750 m to the foundation works at an OWTG-foundation with and without noise abatement measures at one big monopile. Moreover, during the pile-drivings, the permanent background noise at the same measuring position as well as the absolute threshold of hearing of a harbour porpoise (Kastelein et al., 2009) is shown.

The typical, spectral course of an unmitigated and mitigated pile-driving noise event in a distance of 750 m is shown. The applied combination of Noise Abatement Systems reduces the impulsive pile-driving noise in the low-frequency range about 15 to 20 dB. The noise reduction increases in the high-frequency range. However, the figure also shows, that the mitigated pile-driving noise is in the range of a few kHz in the range of the permanently present background noise. This explains, why, on the one hand, the spectral transition loss partly decreases towards higher frequencies and, on the other hand, why partly different noise reductions exist with different Noise Abatement Systems resp. configurations of Noise Abatement Systems in the high-frequency range. Due to the permanent background level within an OWF construction field is decisively dominated by the vessel noises of the vessels involved in the construction. Within the German OWF construction projects, there were isolated projects, where within a radius of few kilometers only three vessels were present: installation vessel, BBC supply vessel and guard vessel. In other construction projects, up to 20 vessels were in operation at the same time, as cable laying, turbine erection works and other activities took place in parallel.

Within the scope of a current study about cumulative effects of pile-driving works on the harbour porpoise population in the German Bight, the authors put forward the hypothesis, that avoidance effects in the environment of offshore construction sites may be related to the vessel traffic and other construction-site-related noise (Rose et al., 2019).

Actually, the public vessel traffic around the OWF construction projects in the German EEZ varies considerably based on Automatic identification system (AIS)-tracks, which can have a considerable influence on the background noise level. Thus, the vessel traffic noise might have significant influence on the measurement of the spectral insertion loss of the applied Noise Abatement System, especially during foundation works at the boundaries of the construction area.

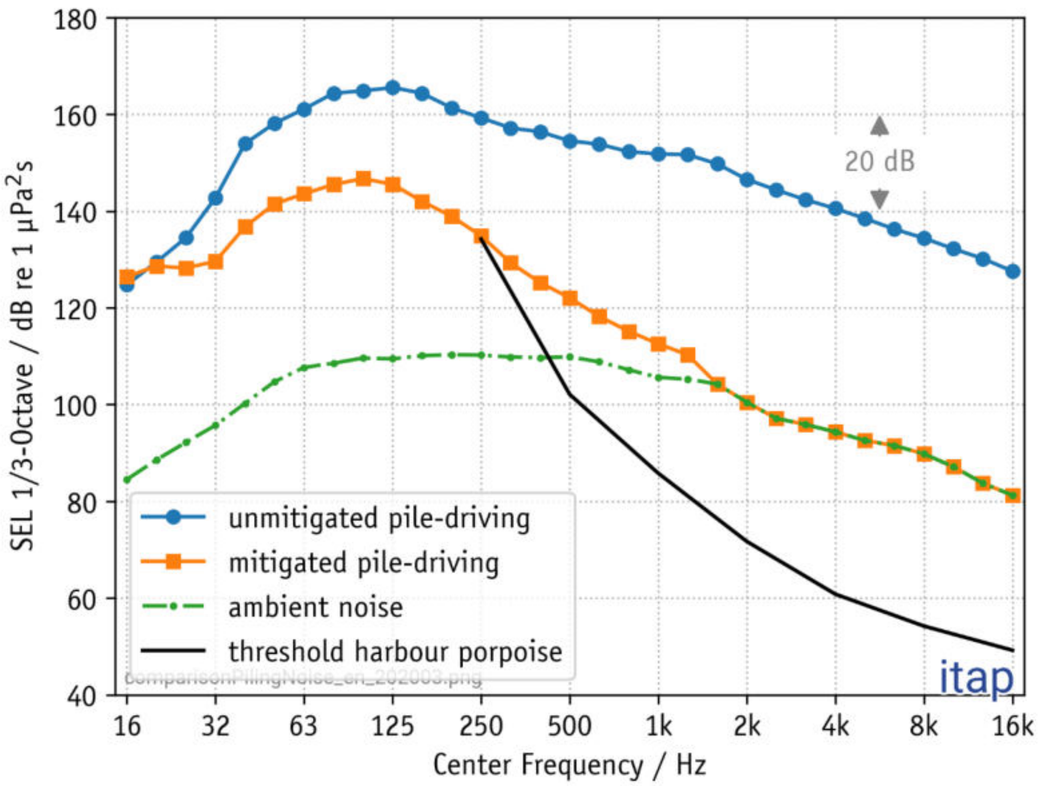

Figure 33: *Mitigated and unmitigated pile-driving noise, measured in a distance of 750 m to the foundation works at one large monopile. Moreover, the permanent background noise, measured between the pile-drivings with and without noise abatement measures, as well as the absolute threshold of hearing of the harbour porpoise (Kastelein et al., 2009) is shown.*

6.4.3 Summary of the experiences with the application of Noise Abatement Systems

Based on the experiences from 21 pcs OWF construction projects in the German EEZ of the North- and Baltic Sea in the MarinEARS[1] technical specialist information system, currently, only three Noise Abatement Systems have proven to be offshore-suitable, robust and ready for use in serial application. These are the two near-to-pile Noise Abatement Systems Noise Mitigation Screen (IHC-NMS) and the Hydro Sound Damper (HSD) and as far-from-pile Noise Abatement System the single and double Big Bubble Curtain (BBC and DBBC).

Based on the cross-project analysis, the following connections resulted:

- With the IHC-NMS or the Big Bubble Curtain, so far, noise reductions of approx. 15 to 17 dB to a water depth of 25 - 40 m could be achieved.
- With an HSD-system, independent of the water depth, noise reductions of 10 dB could be achieved with an optimum system design.
- The achieved broadband noise reduction with a single or double Big Bubble Curtain (BBC or DBBC) is very much dependent of the technical-constructive system configuration at the same water depth. Thus, especially the air volume and the configuration of the applied nozzle hose is of vital importance for the achieved noise reduction. Irrespective of this, it was shown, that for the same system configuration, the achieved noise reduction decreased by a Big Bubble Curtain with increasing water depth due to the rising static water pressure. When using a double instead of a single optimized Big Bubble Curtain (a DBBC instead of a BBC), the resulting noise reduction increases broadband by an average of 3 dB.
- Based on the previous applications with a Big Bubble Curtain (BBC and DBBC), technical-constructive minimum requirements for an optimized noise reduction with this Noise Abatement System could be derived; see chapter 6.3.3. If these minimum requirements are not met, the noise reduction achieved by a Big Bubble Curtain decreases significantly and may in the worst case be only 2 dB.
- With the large Bubble Curtain systems and partly with the HSD-system, the necessity of a site- and project-specific adaptation of the system configuration before and during the start of construction was often identified. For the project-specific adaptation, corresponding test- and reference measurements were carried out at the start of the project in accordance with the DIN SPEC 45653 (2017).
- Independent of the application of a Noise Abatement System, additionally, a noise reduction of a few decibels can be achieved with the primary Noise Mitigation System „reduction of the blow energy used" (noise-optimized pile-driving procedure; chapter 5.2.2 and 7.4.2).

- The spectral noise reduction of the applied Noise Abatement Systems is frequency dependent. Thus, it turned out, that
    - the HSD-system mainly achieved noise reductions in the low-frequent range and was therefore applied exclusively in combination with a Big Bubble Curtain (BBC or DBBC),
    - the Big Bubble Curtain (BBC and DBBC) achieves very high noise reductions in the high-frequency range (> 2 kHz), which is mostly limited by the permanent background noise level in this frequency range; to lower frequencies, the achieved noise reduction decreases steadily,
    - the IHC-NMS achieves a high noise reduction over a large frequency range.
- With the combination of a near-to-pile and a far-from-pile Noise Abatement System, a noise reduction of ≥ 20 dB at a water depth of up to 40 m is possible. To larger water depths, a resulting noise reduction of 20 dB currently presents a challenge. All the more, a suitable impulse impact hammer and a noise-optimized pile-driving procedure are required under such conditions.

Technical note: Based on experiences of all previous German offshore projects, the BSH has developed measures regarding the application of Noise Abatement Systems, which are usually ordered in performance; see chapter 3.3.

7. Discussion and outlook

7.1 Influence of the spectral insertion loss on the noticeable noise input into the water

In chapter 6.4, the averaged broadband and spectral insertion losses for all current serial- and offshore-suitable Noise Abatement Systems are summarized; Figure 32. The broadband, single-digit insertion losses are of decisive importance for the compliance of the German noise mitigation value criterion (Table 4), but also show, that the statistical representation of the achieved noise reductions means, that a certain uncertainty in the expected noise reduction due to site-specific and technical-constructive influencing factors must be taken into account.

The German noise mitigation values are mainly concerned with the reduction of the noise at the source and in the nearby area, as well as with the protection of marine life (irrespective of species) from injury by percussive pile-driving noise into the water (chapter 3). The noise mitigation values were, as shown in chapter 3, developed within the scope of R&D projects by means of findings regarding the key species (harbour porpoise) in German waters of the North- and Baltic Sea. The habitat approach is used for the assessment of disturbances, especially by cumulative effects (chapter 3).

In the USA and the UK, for example, the technical guidelines of NOAA (National Marine Fisheries Service, 2018) and Southall et al. (2019) with frequency-weighted parameters are applied singlely for different species. The background to this approach is, that a large number of marine mammals occur there and not all of these species can be scarred away by application of acoustic deterrence devices. The aim of this Environmental Impact Assessemnt with underwater noise modelling is the calculation of frequency-dependent impact radii for different species, based on various literature data regarding the avoidance of (i) damage and (ii) disturbance. In such an approach, the use of a broadband noise reduction per Noise Abatement System is neither target-aimed, nor appropriate. For this purpose, the spectral insertion losses are mandatory to frequency-dependently determine for different species the influence of Noise Abatement Systems on their hearing ability and thus also on the impact radii. However, it should be noted, that pile-driving noise is usually very low-frequent (< 1 kHz) and the noise input usually decreases sharply in the kHz-range, but in return, the hearing ability increases sharply, especially for marine mammals, in particular the harbour porpoise, in the high-frequency range; see for example Figure 33.

The so-called sensation level (SL) is therefore always of decisive importance when evaluating avoidance effects or disturbances caused by noise inputs[20]. This sensation level input, however, is

[20] For the evaluation of the interfering effect of airborne noise on the human being, mostly the specification dB(A) is used. The spectral A-weighting function indicates the inverted 40-phon isophones (curve of equal level intensity) of the ISO 226.

not only dependent on the frequency-dependent hearing ability of the single species, but also on the permanently present background noise (SNR). The spectral shape of the pile-driving noise is significantly influenced by the application of technical Noise Abatement Systems; see Figure 32. Moreover, both the bathymetry (chapter 5.1.4) and the frequency-dependent transition loss on a noise propagation have an influence over large distances (> 10 km; Figure 5 in chapter 5.1.5).

For the background noise level, according to recent underwater noise measurements, not only the number of vessels in and around the construction sites is important, but also the type of drives, such as vessels with dynamic positioning systems (DP-system), as well as the use of underwater communication means, such as echo sounders or sonars, etc.

An additional factor that makes evaluation even more complicated is the application of acoustic deterrence systems, which is applied in German construction projects before the actual impulsive pile-driving noise events. Several studies have shown that the disturbing effect of acoustic deterrers, e. g. the Seal Scarer, caused an avoidance effect of harbour porpoises up to several kilometres away from the actual pile-driving (Brandt et al., 2016; Rose et al., 2019).

It can therefore not be excluded at the present time, that the effectiveness of secondary Noise Abatement Systems depending on the considered species may be significantly underestimated by the indication of the broadband and spectral transition loss from chapter 6.4.2, if necessary with regard to the noise input.

7.2 Challenges for future construction projects

According to the current state of the art, monopiles with a pile diameter of up to 8 m (so-called XL-monopiles) can be installed in the zone 2 and 3 of the area development plan of the EEZ of the German North Sea (water depths to approx. 40 m) in the seabed on sandy soil in compliance with the German noise mitigation values by means of the impulse pile-driving procedure and the application of suitable Noise Abatement Systems. Future construction projects in German waters will also be in water depths of > 40 m and/or larger OWTG are installed, so that, if necessary, the diameters of the monopiles to be used could still increase.

Furthermore, construction projects in the Baltic Sea and in other European countries within the North Sea, e. g. Scotland, may involve more complex and harder construction grounds, so that higher blow energies may be required to overcome the soil resistances.

These aspects could lead to the fact, that the requirements to a noise reduction might increase in the next few years, in order to be able to comply with the German noise mitigation values. In the following sections, the influence of the above-mentioned factors on the requirements for a noise abatement concept are compiled and discussed quantitatively and qualitatively.

However, the application of alternative, low-noise foundation structures resp. –procedures could possibly be an alternative to the improvement of the noise abatement measures at the impulse pile-driving procedure (chapter 7.4.3). The application of low-noise foundation structures, however, is very much dependent on the location and must be examined for each single construction project.

7.2.1 Larger pile diameters for monopiles

Construction projects currently in planning are evaluating the possibilities of using monopiles with significantly larger pile diameters (so-called XXL-monopiles with pile diameters of $\geq$ 10 m) or alternatively Jacket-foundation structures. To estimate the resulting noise input by larger pile diameters, the measured, unmitigated pile-driving noise at a distance of 750 m is already shown in Figure 12 and Figure 13 as a function of the pile diameter used.

Therefore, it cannot be excluded, that with even enlarging pile diameters, the pile-driving noise will continue to rise at a distance of 750 m from the foundation sites. This will also increase the demands on a noise reduction, especially on the technical design of the pile-driving procedures to be applied, including the further development of impact hammers.

For future construction projects with larger monopile diameters and/or water depths, thus, improvements of the applied noise mitigation measures are absolutely necessary, in order to be able to continue to reliably comply with the noise mitigation values. According to present knowledge, the reduction of the source power (primary noise abatement measure) seems to be a more realistic option (chapter 7.4.2), than increasing the effectiveness of existing secondary, technical and offshore-suitable Noise Abatement Systems (chapter 7.4.1).

7.2.2 Application of Jacket-foundation structures

The use of Jacket-foundations in larger water depths does not seem to be an effective alternative for German waters from an acoustic point of view, since the smaller skirt-piles cannot be installed much quieter than monopiles with a larger pile diameter due to possible coupling effects (Figure 12 and Figure 13). Moreover, the application of near-to-pile Noise Abatement Systems is currently very limited; chapter 6.3. Only a Big Bubble Curtain in single and double design in combination with a Ground Annulus Bubble Curtain has been used in serial application so far; see chapter 6.3.5.

7.2.3 Soil condition and bathymetry

Independent of the foundation structure, the soil condition (soil stratification) and the bathymetry must also be considered for future construction projects. Thus, there is currently very few offshore experiences in the application of near-to-pile noise abatement measures from the German EEZ of the Baltic Sea. The influence of stony or rocky subsoil is currently still difficult to assess. However, it is to be expected, that the blow energy can increase to overcome the soil resistances. Moreover, it cannot be excluded at present, that strong soil couplings (chapter 5.1.2) could reduce the actual effectiveness on the broadband total level by near-to-pile Noise Abatement Systems.

7.3 Technical and physical limits of today´s Noise Abatement Systems and possible further developments

In the following, possible improvement measures on the existing offshore-suitable Noise Abatement Systems are presented and discussed. This chapter does not claim completeness.

7.3.1 Noise Mitigation Screen - IHC-NMS

The IHC-NMS has undergone an enormous technical development in the period from 2011 to 2019. In the IHC-NMS, the noise abatement was already integrated into the installation technique. This enabled the system to always follow the technical development in pile design and offshore logistics and to offer an effective solution for the installation and the necessary noise abatement.

The company *IHC-IQIP bv* is working on continuously improving the configuration of the IHC-NMS. Thus, it is currently i. a. being contemplated to use an external Bubble Curtain around the IHC-NMS in order to reduce the soil coupling. First ideas were presented, for example, at the noise mitigation conference of the BfN in 2018 by *IHC-IQIP bv* in the form of a lecture (van Vessem & Jung, 2018; Koschinski & Lüdemann, 2019). According to *IHC-IQIP bv*, however, these ideas are only in a very early design phase and cannot be named here in detail yet.

It remains to be seen, whether and which systematic modifications to the design of the IHC-NMS can be technically realized and which improvements can be achieved in the resulting noise reduction in test applications under real offshore conditions.

7.3.2 Hydro Sound Damper – HSD

Since, 2014, the HSD-system has achieved a constant reduction of 10 dB_{SEL}, depending on the design, whereby the reduction potential was always limited to the low frequency range. From an acoustic point of view, a further increase in the number of HSD-elements to raise the resulting noise reduction is desirable but is associated with considerable practical and technical difficulties. The background is, that the noise reduction is probably in a logarithmic relationship with the number of HSD-elements, so that an increase in the noise reduction by a few decibels would result in a doubling of the HSD-elements. Moreover, the increase in HSD-elements will also massively enhance the uplift/buoyancy, so that the ballasting must also be raised proportionally, which will have an impact on the offshore logistics. Furthermore, the requirement for storage space within the ballast box will grow as the number of HSD-elements increases.

In principle, however, there are several theoretical possibilities for gradually improving this secondary Noise Abatement System (Elmer, 2018):

- alternative HSD-elements with a higher noise reduction effect,
- noise-optimized design of the ballast box,
- completion or extension of the HSD-system to reduce soil coupling.

Here, too, some ideas have already been sketched by the company *OffNoise Solutions GmbH* in the course of lectures, but they are still in an early design phase and cannot be described in detail (Elmer, 2018; Koschinski & Lüdemann, 2019).

It remains to be seen, whether and which of the potential improvement measures can technically be realized and which improvements can be achieved in large-scale test arrangements under real offshore conditions.

7.3.3 Big Bubble Curtain – BBC and DBBC

The current design of the Big Bubble Curtain has not been technically exhausted by the two accompanying R&D projects alone (Nehls & Bellmann, 2015)[14]. It is not realistic to effectively increase the amount of air supplied with the current nozzle hoses and compressors, because the correlation between air volume and achieved noise reduction is logarithmic; see Figure 31 in chapter 6.4.2.

Possible technical further developments of the Big Bubble Curtain might for example be:

- Application of other nozzle hoses with larger diameters and simultaneous, significant increase of the air volume. However, this will also significantly increase the uplift/buoyancy.

- The application of more powerful compressors would also be required, in order to sufficiently supply nozzle hoses with larger diameters with air and to maintain the cost-benefit-ratio as well as the CO_2-balance.
- Use of other materials at the nozzle hoses/air outlets to ensure defined holes regarding hole size and -form. Initial tests indicate, that very small reproducible air bubbles can be produced with "small" defined nozzles instead of drilled holes, which could contribute to a possible increase of the resulting noise reduction. A complicating factor in this potential improvement, however, is, that smaller air bubbles will ascend slower to the sea surface and thus the drifting effect could probably develop much more.
- For applications of Big Bubble Curtains with water depths larger than 50 m, the operating pressure may also have to be increased from the current 9 bar to 10 bar.

Based on the experience gained so far, it is therefore necessary to further develop the Bubble Curtain system with regard to nozzle hoses and compressors. The further development of the Bubble Curtain system must be regarded as urgently necessary due to its special biological relevance for the protection of the high frequency communicating harbour porpoise.

7.4 Alternative Noise Mitigation Measures

7.4.1 Noise Abatement Systems under development

In Koschinski & Lüdemann (2011, 2013 & 2019), a chronological overview of different possibilities of primary and secondary noise mitigation measures and alternative foundation structures and -procedures are documented. Many new concepts for Noise Abatement Systems, such as the guided small Bubble Curtain or the HydroNas, are still in a very early design phase. For this reason, we will not list and discuss the possible noise reduction at this point.

The AdBm-system, another near-to-pile Noise Abatement System of the company *AdBm Corp.*, is currently under prototype development with first applications under real offshore conditions in other European countries. The mechanism of action is in principle comparable to the HSD-system. So-called stationary resonators are placed in the water column. Here, no HSD-elements made of different foams are placed, but air-filled so-called block-shapes are used (stationary Bubble Curtain with defined air volumes), which are open at the bottom (Wochner et al. 2017a & b).

The AdBm-system was not tested so far to scale under offshore conditions in Germany. In 2019/2020, the first application of a large-scale prototype in the installation of monopiles in other European countries took place. The first application at five locations in a Belgian OWF resulted in a noise reduction of < 10 dB (Degraer et al., 2019).

7.4.2 Optimizations of the impact pile-driving

At present, several concepts for optimizing the impulse pile-driving procedure by reducing the power peaks and for extending the power transmission are in the planning stage, which will briefly be summarized below.

Blue-Piling: The Blue-Piling hammer does not work with a metallic drop weight and a hydraulic unit to lift this mass, but with a large water tank. On the one hand, at the bottom, a small explosion creates an application of force on the pile, and on the other hand, some of the water in the tank is pushed upwards. As soon as the water returns to its original state, a second application of force is applied to the pile-head. Thus, the pile is not driven into the seabed by single single strikes but pressed into the seabed by a more or less steady pressure on the pile-head. This alternative impulse impact hammer is currently in the prototype stage. A first offshore prototype application by the company *Fistuca* took place in 2018 and showed, that this alternative pile-driving procedure can in principle be technically realized, but is not yet fit for an offshore service (Winkes, 2018, Koschinski & Lüdemann, 2019).

The principle of the Blue-Piling hammer was subsequently taken over by the manufacturer of impulse impact hammers *IHC IQIP bv* and is currently under further development. The manufacturer sees above all a possible application in future XL- and XXL-monopile installations (pile diameters > 10 m). According to the manufacturer, a practical suitability of this new type of hammer is planned for the coming years.

From an acoustic point of view, so far, no valid statement about the level of the expected primary noise reduction is possible. However, initial rough and theoretical modellings by the manufacturer assumes a noise reduction in the one- to two-digit decibel range.

MNRU and PULSE: There are currently two manufacturers of „large“ impact hammers, *Menck GmbH* and *IHC-IQIP bv*. Both manufacturers are currently developing additional units, which function as a kind of "spring-damper"-system between the standard impact hammer and the anvil to be used. In principle, this additional unit should also minimize power peaks and maximize the impulse duration, while maintaining the same force transmission. This would result in a comparable force transmission from the hammer to the pile-head, but less pile-driving noise would be produced by reducing the force peak.

Menck calls its additional unit **Menck Noise Reduction Unit** (MNRU), the unit of *IHC-IQ bv* is called **PULSE**. Both units are in the prototype development stage. According to the information from the manufacturers, the first test runs are planned for the years 2020 to 2021.

7.4.3 Alternative foundation procedures and -structures

Another primary noise abatement measure could be the application of alternative foundation structures and / or -procedures. However, from an acoustic point of view, it should be noted here, that for most of these alternative foundation structures and -procedures, no impulsive noise input into the water (MSRL, Deskriptor 11.1), but a continuous noise input (MSRL, Deskriptor 11.2) is to be expected. With regard to a continuous noise input into the water, there are currently neither nationally nor internationally mandatory standards or guidelines. The evaluation of continuous noise on marine life is currently still undergoing fundamental research. A good overview of possible alternative foundation structures and -procedures is summarized in Koschinski & Lüdemann (2013; update 2019).

In the following, the experiences of alternative foundation structures and –procedures, that were used in Germany, will be briefly documented.

Suction Bucket: With this installation method, in principle, a part of the foundation construction is sucked into the seabed by means of vacuum pumps. This installation procedure is considered to be very low-noise and usually, the installation noise is only caused by the vessels involved in the construction and any pumps used.

However, suction bucket foundations are not suitable for all soil types. In Germany, but also in other countries, suction bucket foundations were already used for both OWTG and substation foundations. A first so-called Jacket suction bucket for an OWTG was installed as a pilot plant in the German OWF *Borkum Riffgrund I* (2014) and the noise emissions were measured as part of a R&D project[21] (Remmers & Bellmann, 2015). Another 20 pcs OWT foundations (Jacket) were also installed in a construction project in the German EEZ of the North Sea (Ørsted, 2019). Moreover, a substation was installed on a suction bucket.

But this installation method requires special foundation structures and it must be checked in detail, whether this installation method is suitable for the existing subsoil/building ground of the respective project.

Floating foundation: Floating foundations also count as low-noise foundation structures. The principle is shown in Figure 11. The OWT is installed on a floating structure. This floating structure is also anchored in the seabed to be stationary. The way in which this anchoring is done is manifold.

[21] Joint project: Monitoring Suction Bucket Jacket, funded R&D project, FKZ 0325766A, supported by PTJ and BMWi; https://www.isd.uni-hannover.de/435.html.

In Germany, this low-noise foundation structure has not yet been applied under real offshore conditions and its noise input measured. However, there are isolated international experiences with prototypes (Walia, 2018). With regard to the noise emissions, however, there is very little measuring experience. In addition, with this foundation structure, it is important, how the anchorage in the seabed is made. If small foundation piles in the seabed must be introduced by means of impulse pile-driving noise, sufficient experience with Jacket piles is known. If the foundation is carried out with alternative methods, such as weight anchors, it remains to be seen, whether impulsive or continuous noise is introduced into the water.

Gravity foundation: The principle of a gravity foundation is shown in Figure 11. In this case, a „large" foundation structure is shipped onto position and then weighted down with filling material, e. g. sand. The foundation structure acts as a weight anchor.

So far, a gravity foundation structure for a converter platform has been installed in the German EEZ of the North Sea. Continuous noise can be expected from the vessels accompanying the construction work and from appropriate pumps for filling the gravity foundations with e. g. sand.

There is also some international experience, especially from the Baltic Sea at water depths of around 40 m with gravity foundations (Halldén, 2018; 4C-Offshore, 2019).

Vibro-Piling: Another possibly low-noise foundation procedure could be the vibration pile-driving procedure (vibro-piling). Here, the foundation structures are not driven into the ground with single strikes, but by continuous vibrations. Usually, the basic frequency of the vibration hammer is < 35 Hz. Noise inputs from the vibro-piling procedure are considered as continuous noise inputs in the sense of the MSFD and are usually very low-frequent (< 1.000 Hz).

For bridge construction, sheet pile wall installations (nearshore) or in port construction, this installation method must be considered state-of-the-art. For the installation of monopiles until final depth, however, this installation method was so far only applied sporadically for testing purposes at OWTGs abroad. The background is the so far missing proof of the dynamic pile load test.

In Germany, this method has so far only been used very sporadically and only for the installation of skirt-piles for the first few metres embedding depth (pre-installation). Measurement experience at a distance of a few hundred metres shows that, depending on the water depth, the basic frequency cannot usually propagate completely in shallow water. The most dominant noise inputs in a force-locked coupling between vibro-hammer and pile-head occur with the first harmonics[22].

[22] Harmonics mark the multiples of the resonance frequency.

However, isolated measurements have also shown, that a non-force-locked coupling significantly increases the noise level in the water and a large number of high-frequent components (> 1 kHz) are radiated into the water. This is usually accompanied by an increased airborne noise level and a low pile-drift, so that it is essential to ensure, that the coupling is force-locked.

However, there is no mandatory national or international measurement regulation for the recording of such a continuous noise input. Furthermore, there are currently no evaluation criteria for continuous noise levels on the marine environment. In this field, there is a considerable need for research on the installation method (feasibility in the offshore range), the noise emission and transmission in shallow water, as well as the impact of this continuous noise exposure on marine life.

The vibro-piling is not appropriate for each project and also requires an single assessment regarding pile-design, soil conditions and site stability.

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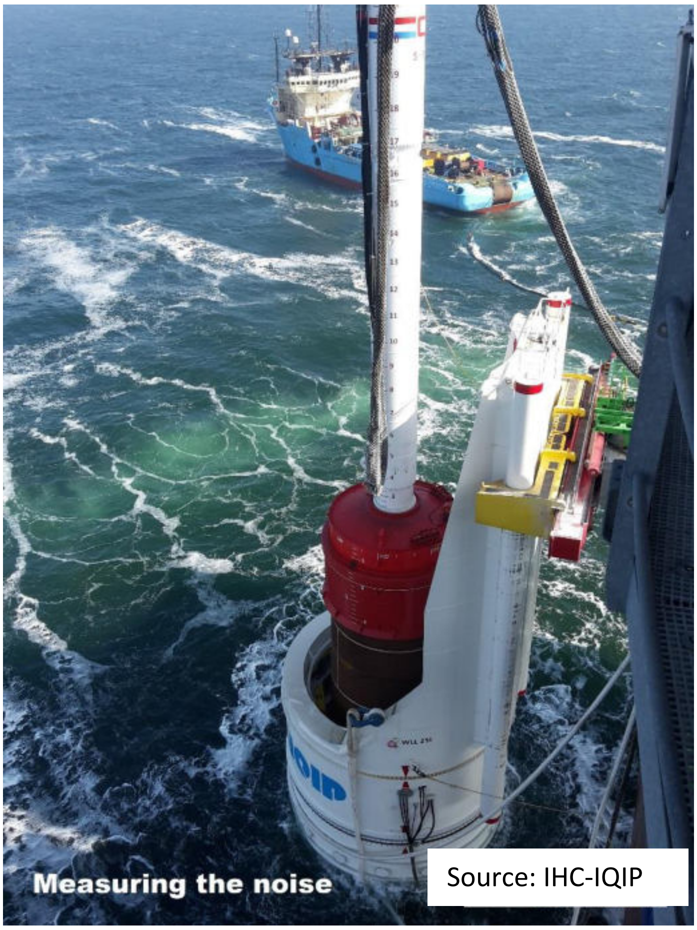
9. Appendix

Appendix A: Profiles for each offshore-suitable Noise Abatement System

Noise Mitigation Screen of the company *IHC-IQIP* (IHC-NMS)



Source: IHC-IQIP

- pipe-in-pipe system (impedance difference)
- near-to-pile Noise Abatement System
- applications until 40 m and pile diameters of ≤ 8,0 m
- several hundred offshore applications

Noise reduction is independent of:
- current (until 0.75 m/s)
- direction
- water depth / bathymetry

Advantages:
- pile-sleeve integrated
- inclination measurement of the pile possible
- positioning tool integrated

Disadvantages:
- size and mass (logistics)
- soil couplings
- applications in variable water depths?

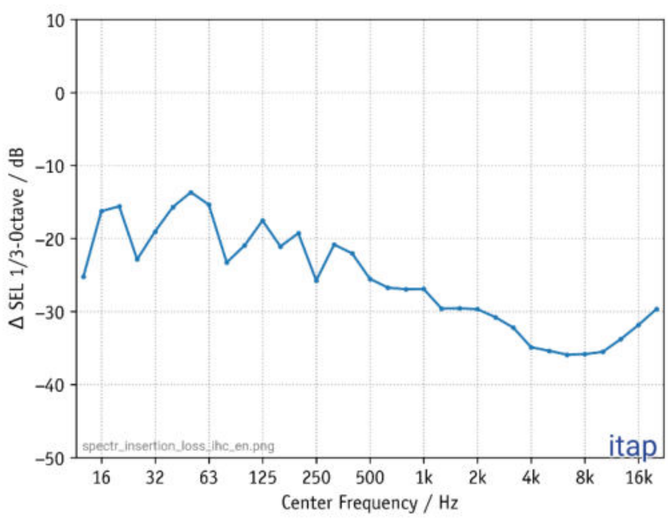
Offshore-suitable Noise Abatement System.

Achieved noise reduction for the Sound Exposure Level (SEL resp. L_E):

broadband insertion loss ΔSEL [dB]

Minimal	Median	Maximal
13	15	17

spectral insertion loss



Hydro Sound Damper (HSD) of the company *OffNoise Solutions GmbH*


Quelle: Offnoise Solution GmbH

- resonator system
- near-to-pile Noise Abatement System
- applications until 40 m and pile diameters of ≤ 8,0 m
- several hundred offshore applications

The noise reduction is independent of:
- current (until 0.75 m/s)
- direction
- water depth / bathymetry

Advantages:
- low mass
- application possible at very different water depths

Disadvantages:
- soil couplings
- lifting- and lowering device are currently project-specific unique pieces
- limited life-time of the HSD-elements according to the manufacturer
- noise reduction mainly in the low-frequency range

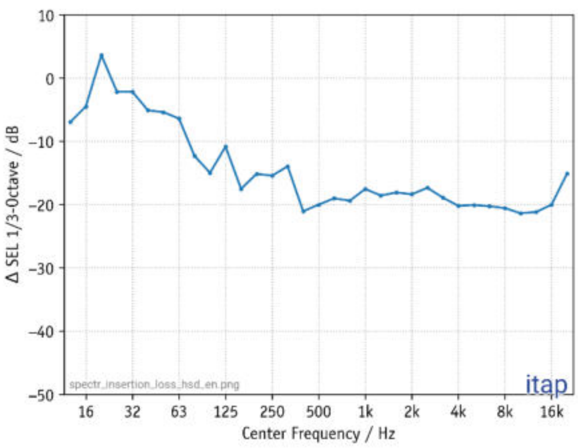
Offshore-suitable Noise Abatement System.

Achieved noise reduction for the Sound Exposure Level (SEL resp. L_E):

Broadband insertion loss ΔSEL [dB]

Minimal	Median	Maximal
10	11	12

spectral insertion loss



Single or double Big Bubble Curtain (BBC / DBBC)

Source: Trianel Lang

Source: Hydrotechnik Lübeck GmbH

- air-water-mixture (impedance difference)
- far-from-pile Noise Abatement System
- applications until 40 m and pile diameters of ≤ 8,0 m
- several hundred offshore applications

The noise reduction is dependent of:

- air volume
- current (until max. 0.75 m/s)
- water depth
- nozzle hose configuration and -length
- number of nozzle hoses
- offshore experience and maintenance status

Advantages:

- independent of foundation structure
- independent of the installation vessel

Disadvantages:

- separate vessel and compressors
- offshore logistics with vessels
- resulting noise reduction strongly depends on the system configuration
- requires project-specific optimization at the beginning of each construction project

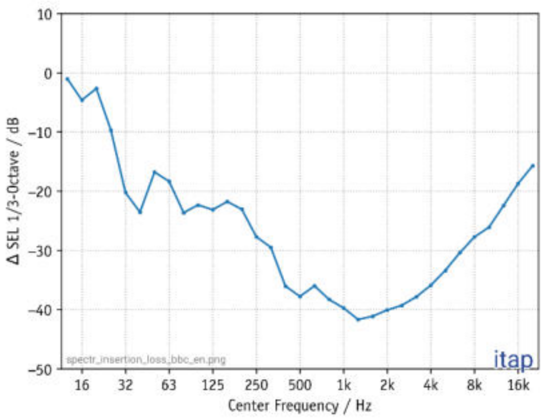
Offshore-suitable Noise Abatement System.

Achieved noise reduction for the Sound Exposure Level (SEL resp. L_E):

Broadband insertion loss

Systemkonfiguration	ΔSEL [dB]
Single Big Bubble Curtain - BBC (> 0,3 m^3/(min*m), water depth < 25 m)	11 ≤ 14 ≤ 15
Double Big Bubble Curtain - DBBC (> 0,3 m^3/(min*m), water depth < 25 m)	14 ≤ 17 ≤ 18
Single Big Bubble Curtain - BBC (> 0,3 m^3/(min*m), water depth ~ 30 m)	8 ≤ 11 ≤ 14
Single Big Bubble Curtain - BBC (> 0,3 m^3/(min*m), water depth ~ 40 m)	7 ≤ 9 ≤ 11
Double Big Bubble Curtain - DBBC (> 0,3 m^3/(min*m), water depth ~ 40 m)	8 ≤ 11 ≤ 13
Double Big Bubble Curtain - DBBC (> 0,4 m^3/(min*m), water depth ~ 40 m)	12 ≤ 15 ≤ 18
Double Big Bubble Curtain - DBBC (> 0,5 m^3/(min*m), water depth > 40 m)	~ 15 – 16

spectral insertion loss optimized DBBC



Appendix B: List of figures

Appendix C: List of tables