Environmental Impact Assessment Report - Volume 2B Addendum

Appendix 10-5:
Underwater Noise Monitoring Experience – Supporting Information

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Environmental Impact Assessment Report - Addendum
Appendix 10-5: Underwater Noise Monitoring Experience – Supporting Information

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1 COVER NOTE

This document has been prepared in response to the Request for Further Information (RFI) made by An Coimisiún Pleanála (ACP)(formerly An Bord Pleanála) regarding the planning application (case reference ABP-319799-24) for the Oriel Wind Farm Project (hereafter referred to as "the Project").

In particular, RFI 9.F of Schedule – Further Information Request invited the Applicant to:

'*submit any details or monitoring/reporting available from previous experience of offshore development in other EU jurisdictions which demonstrates the efficacy of mitigation measures adopted (and proposed in the current application) in relation to underwater noise'.*

In response to this request, several documents outlining the Applicant's experience in implementing underwater noise mitigation measures have been provided as supporting documents. These documents give an overview of the procedures and outcomes of the underwater noise mitigation measures employed during the piling campaign of the Arcadis Ost windfarm in German economic waters. This wind farm has been constructed by Parkwind and is now fully operational.

Table 1A-1 lists the supporting documents which demonstrate the previous experience of the Applicant in implementing underwater noise mitigation measures. It also summarises the content of each document. The reports with document titles highlighted in bold are provided in full in section 2 of this appendix.

Table 1A-1: Titles and summaries of the documents that provide evidence of the Applicant's experience of underwater noise mitigation measures.

Document title	Summary of Document
MST Big Bubble Curtain (BBC)	This report describes the various phases of the installation of the BBC around the pile driving position of the vessel installing the monopile. It specifies the vessels crew and equipment needed. It provides a detailed description of the deployment of BBC system with step-by-step visuals.
MST Underwater Noise Monitoring	This report is a work method statement and outlines in detail the components of noise measurement devices and mooring systems. It provides work description of all devices with step-by-step procedure and visuals to supplement text.
MST PULSE R&D Underwater Monitoring	This report provides a description of the measurement set-up for the PULSE test R&D noise mitigation plan for evaluating the new hammer technology PULSE and to investigate possible ground coupling effects on the overall reduction of an applied Big Bubble Curtain system. The PULSE system is a noise mitigation system and the aim of the R&D project is to evaluate the overall achievable underwater noise reduction. The measurement concept consists of • Additional underwater noise measurements in different directions and distances to pile driving activity • Application of particle motion and particle velocity sensors and • Measurements of the water parameters temperature, salinity, water depth and sound velocity by a CTD probe sensor during each deployment and recovery per monopile installation.
Noise Mitigation Plan	This report outlines all noise mitigation measures used on Arcadis Ost 1 OWF to comply with German noise requirements. These measures include a combination of near field and far field state-of-the-art mitigation systems (Hydro Sound Dampening system - air filled balloons for noise reduction directly surrounding the monopile, and Double Big Bubble Curtain) and an adapted piling procedure (soft start procedure and noise optimising driving). A justification of noise mitigation systems is provided. Measures for marine mammal protection are also outlined including deterrence (ADD and soft start) and marine mammal detection prior to piling (MMO and PAM / C-POD). Airborne noise monitoring methodology is also mentioned.
Deviation report on noise protection USP Monopole	This report outlines an incident report where the outer ring of the deployed bubble curtain around the OSS did not have optimum structure. It also provides steps on how this was investigated and steps to take to ensure it is not repeated.

Document title	Summary of Document
Deviation report on noise protection monopile g4	This report outlines an incident report where pile-driving activity was interrupted for one monopile due to a problem with the live noise monitoring.
Underwater noise monitoring - Final technical report	This report summarises all underwater noise measurements carried out during the impact pile driving of monopiles for Arcadis Ost 1 OWF. The report covered deterrence, implementation, specification, measurement concept, realisation at sea, evaluation concept, measurement uncertainty, meteorological traceability, technical problems and failing of measuring systems, results and assessment. Noise protection value of 160$_{dBSEL}$ to be complied with by the 5% exceedance level of the single event level (SEL05) at a distance of 750m, could only be complied with at a single measurement position with a monopile installation. In contrast, the noise protection value of 190 dB, to be maintained by the peak level ($L_{p,pk}$) at a distance of 750m, was complied with at 27 foundation locations. The exceedance by the peak level is due to the reference monopile of the R&D project Based on the available measurement results, there is a sound reduction of approximately 4.5 dB per doubling of distance and a significantly stronger absorption factor in sound propagation even over shorter distances. This means that the impulse pile-driving sound has significantly shorter ranges than assumed in all previous forecasts. For example, the impulse pile-driving noise already increases over a distance of 5,000 m due to propagation attenuation. Based on measurement experience and literature data for propagation attenuation, a noise reduction of approximately 12 dB up to 5,000 m was to be expected.
Airborne noise monitoring - final technical report	This report outlines the results of the onshore noise monitoring campaign.
C-POD DATA - final technical report	This report presents the results of the analysis of data from C-POD devices deployed during the installations of the monopiles. The data shows how effectively harbour porpoises were driven away from the vicinity of the pile-driving work by the deterrence measures and whether and when animals returned to the area after the work ceased.
Underwater noise during percussive pile driving: Influencing factors on pile-driving noise and technical possibilities to comply with noise mitigation values - Experience report on pile-driving noise with and without technical noise mitigation measures - Paper written by itap GmbH*	This research paper discusses 'itap GmbH's' experience providing noise mitigation measures for the pile-driving campaign of Arcadis Ost 1 OWF.

* itap GmbH is the *Institut für technische und angewandte Physik GmbH* who were commissioned to carry out all necessary underwater noise measurements.

The efficacy of mitigation measures adopted on Arcadis is set out in the report titled 'Underwater noise monitoring – Final technical report', which examines the implementation of BBC and 'C-POD data – Final technical report', which reports on the use of ADD. The mitigation measures proposed by the Applicant include for implementation of the following include:

- Marine Megafauna Mitigation Plan (MMMP). The MMMP sets out the measures to apply in advance of and during piling activity, including the implementation of a mitigation zone, and monitoring by MMOs and Passive Acoustic Monitoring (PAM);
- During piling operations, soft starts will be used, following NPWS (2014) guidelines.
- Implementing a phased piling alongside other adjacent offshore wind farms in the western Irish Sea as part of a Piling Strategy.

In addition to the above measures, similar to Arcadis an ADD which (as outlined in chapter 10: Marine Mammals and Megafauna, EIAR volume 2B) has been shown to be effective in deterring marine mammals from proximity to piling which may result in injury (McGarry et al., 2017; Gordon et al., 2019) will be implemented as part of the MMMP, subject to discussion with stakeholders.

Despite the assessment of injury and disturbance to marine megafauna from underwater noise during pile driving concluding no significant impact, the Project is committed to the using a noise abatement system for the purpose of reducing sound levels from construction piling as outlined in the MMMP.

2 SUPPORTING DOCUMENTS

2.1 Noise Mitigation Plan

Arcadis Ost 1

Foundations EPCI

A01D-DO-ENG-PLN-2095

A01-DO-ENG-PLN-00006

Contract Number: 5868

Noise Mitigation Plan

Current Revision 02

Employer: Parkwind Ost GmbH	Main Contractor: DEME Offshore

Document approval status

Action	Name	Function	Signature	Date
Approved by	Mathieu Holvoet	Project Director		7/09/2021
Checked by	Tobe Possemiers	T&I Manager		7/09/2021
Checked by	Marie Vrielinck	Lead Engineer		7/09/2021
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ABBREVIATIONS & DEFINITIONS

Abbreviation	Definition
ADD	Acoustic Deterrence Device
AO1	Arcadis Ost 1 OWF
BBC	Big Bubble Curtain
BImSchG	Bundes-Immissionsschutzgesetz (engl. Federal Immission Control Act)
BSH	Bundesamt für Seeschifffahrt und Hydrographie (engl. Federal Maritime and Hydrographic Agency)
C-POD	Cetacean-Porpoise Detector
DBBC	Double Big Bubble Curtain
HLV	Heavy Lift Vessel
HSD	Hydro Sound Damper
DO	DEME Offshore
NMS	Noise Mitigation System
MST	Method Statement
OWF	Offshore Wind Farm
SEL	Sound Exposure Level
StALU	Staatliches Amt für Landwirtschaft und Umwelt (Engl. State Office for Agriculture and the Environment)

Term	Definition
PROJECT	Arcadis Ost 1
EMPLOYER	Parkwind Ost GmbH
CONTRACTOR	DEME Offshore

1 INTRODUCTION

1.1 GENERAL PROJECT OVERVIEW

For detailed information regarding project content, location and involved parties, reference is made to the Project General Information Plan [1].

1.2 OBJECTIVE & SCOPE

The Federal Maritime and Hydrographic Agency (BSH) is the regulatory and monitoring authority for offshore projects in the German exclusive economic zone. In the course of the approval procedures for the construction of Offshore Wind Farms (OWFs), the exposure to the ocean caused by piling noise takes over a crucial role, since underwater noise caused by pile driving during the installation of offshore foundations is potentially harmful to marine life.

Considering this potentially harmful effect, the BSH established in 2008 a dual sound level value criterion at a distance of 750m from the point of emission during pile driving works:

- Sound Exposure Level SEL_{05}[1] = 160 dB and
- Peak Level $L_{p,pk}$ = 190 dB

In addition, it is required to perform measurements of waterborne sound at pre-defined distances from the sound source and document them during pile driving [2] [3].

As the Arcadis Ost 1 OWF falls within the 12 nautical mile zone and is therefore within the territorial zone of Germany, the criteria and requirements with respect to noise will be set out by the StALU (State Office for Agriculture and the Environment). Note that the StALU will follow the national regulations set out by the BSH.

On the Arcadis Ost 1 (AO1) OWF, in order to comply with the above-mentioned noise requirements, the following noise mitigation measures are used:

- A combination of state-of-the-art noise mitigation systems (NMS) will be deployed and operated during pile driving works namely:
    - Hydro Sound Damper (HSD) net
    - Double Big Bubble Curtain (DBBC).
- An adapted piling procedure, considering the noise aspect and limiting the energy when possible.

With this document Contractor would like to substantiate on the proposed and most appropriate noise mitigation equipment to be in compliance with the German regulations for the installation of the 28 monopile (MP) foundations for the Arcadis Ost 1 OWF by the Heavy Lift Vessel (HLV) Orion.

[1] Note that SEL_{05} corresponds to the 95% percentile of overall SEL values or in other words 5% of the measured SEL values over the pile driving duration can exceed the imposed limit of 160 dB

2 NOISE PROGNOSIS

For AO1, noise emissions during the pile driving of the 28 MPs with the IQIP S-4000 hammer are estimated not to be constant. Based on the driveability analysis [4], the hammer energy required to bring the pile to final depth varies per location (with a max. hammer energy of 4000 kJ). Since the emitted noise is dependent on the pile diameter[2] and the applied hammer energy, the estimated sound peak levels and sound exposure levels will differ for each location.

As the MP diameter and embedment depths at AO1 are outside measured experience, numerical modelling was done with site specific information. Specialist company Jasco Applied Sciences (Jasco) has been consulted by the Employer to perform site specific noise prognosis calculation for the AO1 project. The noise prognosis model of Jasco is an advanced numerical model that considers the physical properties of the AO1 hammer and MP (up to 9.2m diameter). The model fulfils the requirements for hydro sound modelling from regulators in Germany. Reference is made to Jasco's prognosis report [5] in which all input data and model assumptions are clearly described and details on the model are provided. The latest pile design also includes diameters up to 9.4m (WTG) and 9.6m (OSS). Simulations were done confirming the unmitigated noise levels modelled in the Jasco prognosis.

The assessment considers the predicted noise levels at two AO1 locations (A04 and G04) from two hammer models (Menck and IQIP), at full piling energies. As IQIP's hammer S-4000 has been selected to perform the driving activities on AO1, only the results with the IQIP's hammer model are presented in Table 1 for the scenario without NMS. Jasco's noise prognosis shows that a large proportion of energy is expected to propagate through the soft sediment layers, with the harder glacial till and chalk layers present on the AO1 site reflecting energy back into the water column. As there is an uncertainty to what extent the soft soils will lead to damping or tunneling, the empirically measured efficiency of noise mitigation measures has been considered. Further details on the effect of the soil conditions can be found in [5].

Scenario	Received SEL at 750 m (dB re 1 µPa²·s)	Received $L_{p,pk}$ at 750 m (dB re 1 µPa)
A04 IQIP S-4000, 4000 kJ (no NMS)	175.0	196.1

Table 1: Results from Jasco's noise prognosis excluding noise mitigation systems [5]

The presented SEL and $L_{p,pk}$ values in Table 1 are related to the listed blow energy. In other words, this value represents the sound energy for every single blow by using this blow energy.

The expected max. hammer energy required to drive the pile to depth has been calculated by means of a driveability analysis. The results of this analysis together with the expected noise level are summarized in Table 2.

[2] The bigger the sound-emitting surface (or thus pile diameter) in the water, the bigger the sound entry.

The noise levels per hammer energy range have been scaled based on the Jasco prognosis result in Table 1, using following formula:

$$SEL_{e2} = SEL_{e1} + 10 * \log_{10}(\frac{e_2}{e_1})$$

With e_1 = hammer energy related to SEL_{e1} (reference for scaling)

e_2 = hammer energy related to SEL_{e2}

SEL_{e1} = SEL linked to the hammer energy e_1

SEL_{e2} = SEL linked to the hammer energy e_2

Hammer energy [kJ]	Hammer energy [%]	No* of locations	Expected SEL at 750m	Expected $L_{p,pk}$ at 750m
0 - 1000	0 - 25 %	0	139 - 169	160.1 - 190.1
1000 - 2000	25 - 50 %	5	169 - 172	190.1 - 193.1
2000 - 3000	50 - 75 %	5	172 - 173.8	193.1 - 194.9
3000 - 4000	75 - 100 %	18	173.8 - 175	194.9 - 196.1

Table 2: Expected hammer energy & scaled noise levels [6]

3 NOISE MITIGATION CONCEPT

In order to reduce the emitted noise as much as possible, the following noise mitigation measures will be implemented during the AO1 foundation installation campaign:

- A noise optimised piling procedure with the hammer
- Near field NMS: HSD net designed and built by Offnoise-Solutions.
- Far field NMS: DBBC designed and built by HydroTechnik Lübeck (HTL).

From the point of view of the industry and the German regulatory authorities, the above-described technical noise mitigation systems are state-of-the-art, after years of development and application in the construction of offshore wind farms

This Section will further elaborate on these noise mitigation measures and finally conclude on the expected noise reduction and an update of the AO1 noise prognosis including the effect of the listed NMS.

3.1 NOISE OPTIMISED PILE-DRIVING PROCEDURE

Since the emitted noise during pile driving is heavily dependent on the applied hammer energy, a possibility for underwater noise reductions is minimising the applied blow energy. Empirically, the acoustic parameters decrease with approx. 2.5 dB, when the blow energy is halved [7] .

3.1.1 Soft start procedure

Reference is made to Section 4.1.2.

3.1.2 Noise optimised driving

The noise optimised pile driving procedure is based upon the usage of energy to a level that the pile still penetrates at acceptable speed without using more energy than needed. A higher piling frequency can be used under certain conditions, in order to reach the target depth.

More specifically, this translates into the following addition to a normal piling procedure (where blowcount is normally limited to 30 – 50 blows/25cm):

- If during pile driving it is noticed that the noise threshold (measured by the online underwater noise monitoring system) is reached at a certain energy level, and it is expected that the pile can be driven to final penetration at this energy setting, energy can be kept constant at this level.
- At set energy level and increasing soil resistance, blowcount will rise.
- Only if a blowcount of 80 blows/25cm is reached, energy will need to be gradually increased to keep blowcount at 60-80 blows/25 cm.

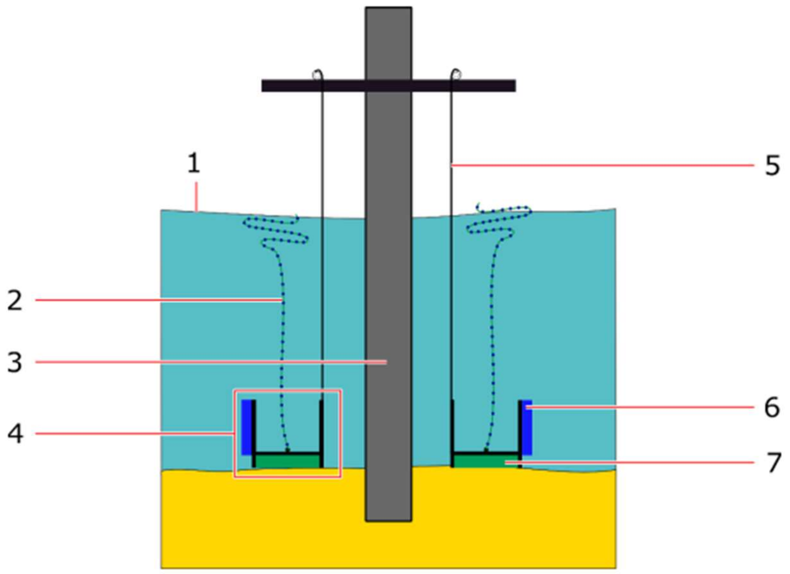
The application of a noise optimised pile driving procedure depends significantly on the soil resistance value and will be conducted based upon the local soil conditions, and the live noise measurements (see Section 5).

The noise-optimized pile-driving procedure represents an effective method for reducing the sound source. Experiences from previous OWF projects in Germany have shown that the blow energy could in some cases be reduced to half of the predicted maximum blow energy.

Acoustic parameters decrease with approx. 2-3 dB, when the blow energy is halved [8]. This measure is thus effectively applied to comply with the noise mitigation value criterion.

3.2 HYDRO SOUND DAMPING SYSTEM

The HSD system is a near field noise mitigation method with effective noise reductions near the emission source. The HSD system is developed by Offnoise-Solutions GmbH and has been successfully deployed on various projects. The system consists of three components: (1) a lowering- and lifting system with winches, (2) a 'net' with integrated HSD elements and (3) a ballast box (HSD-box on the figure).



ID	Description
1	Highest astronomical tide
2	Main HSD net
3	Monopile
4	Ballast box
5	Carrying wire
6	Ballast box outer net
7	Ballast box bottom net

Figure 1: HSD System general concept

3.2.1 Working Principle

The HSD system uses special air-filled balloons for noise reduction by scattering and reflection of underwater sound waves, and additional foam elements of materials with high damping effects. Each HSD element needs to be tuned to the desired frequencies and water depths of the Arcadis Ost 1 site.

All these noise-reducing HSD elements are fixed to a net that will surround the pile. The HSD system consists of multiple nets fitted with HSD elements, a steel ballast box in which the net is stored/released from and lastly a winch frame and steel wires to lift and sink the ballast box down to the seabed. The main net is unfolded around the pile during lowering of the ballast box. Other nets are also fitted directly to the ballast box to reduce noise radiated by the net basket itself and / or reflected by the seabed.

Figure 2: Top view of previous project HSD system deployed around a pile (left: net being deployed with ballast box underwater, right: net being retrieved in the ballast box)

In previous applications of the HSD system, the noise reduction achieved by the system was constant and reliable, but mostly focused on low frequencies. The system is therefore best suitable for combined use with a BBC system [8].

3.2.2 HSD Net layout

shows the expected configuration of the HSD net for AO1. The net will consist of seven layers:

- Three "inner" layers with HSD elements:
    - Two layers with foam elements
    - One layer with air-filled balloons
- Two protective net layers on the in- and outside enclosing the net layers with HSD elements

Note that further project specific updates can be made to HSD net design shown in .

3.2.3 Enhanced HSD Net

On AO1, an enhanced HSD net consisting of a higher ratio of HSD elements relative to previous projects will be used. Relative to the Arkona OWF, the buoyancy and therefore the air volume in the water will be more than doubled (ref. SEQ Table * ARABIC 3). The doubling in air volume can be achieved because of an increased mass of the ballast box relative to previous projects. In addition, the number of foam elements can be increased significantly and used for concentrated damping in known high energy regions. The increase in HSD elements will be applicable on the three inner nets of the full construction (see). According to Offnoise-Solutions (HSD net supplier), an additional 2 to 3 dB noise level reduction may be expected with this enhanced HSD net relative to the achieved reduction with the HSD net in previous OWF construction projects.

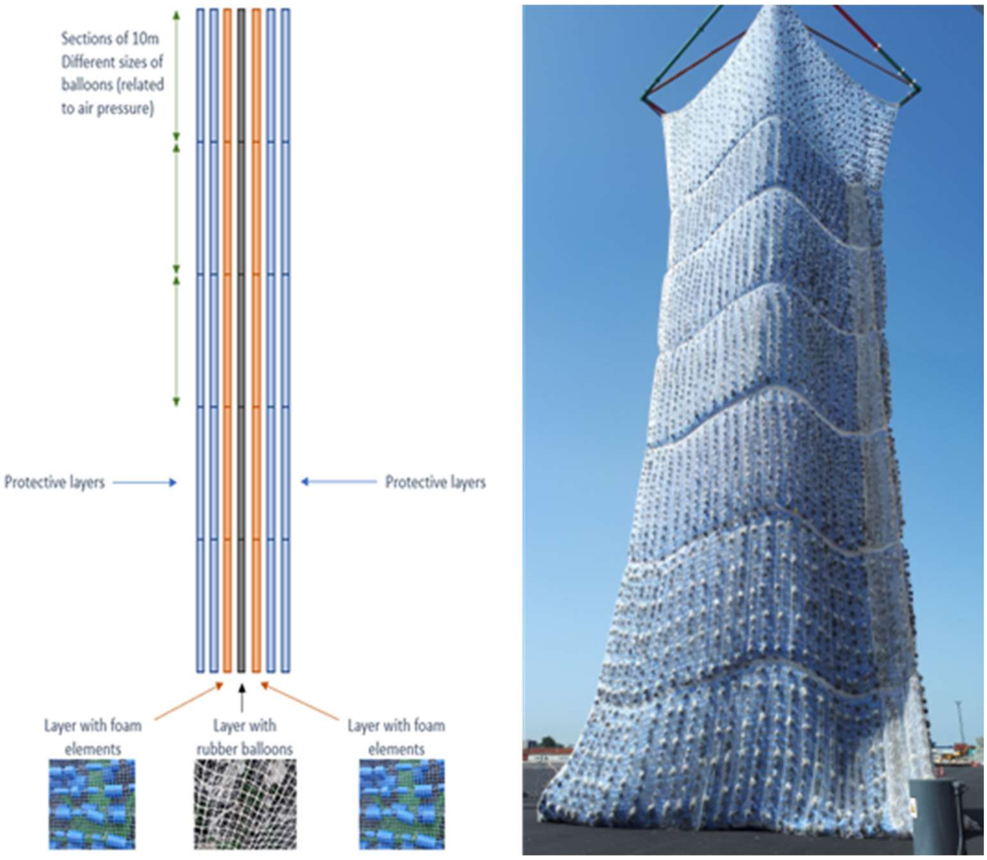


Figure 3: Envisaged HSD net configuration for Arcadis Ost 1

Project	Arkona	Borssele	Arcadis (Enhanced)
Max. water depth in m	38	39	45
Buoyancy at max. water depth (air volume)	29	32	60
Dimension of net in m²	2280	2184	3290

Table 3: HSD Net data Arkona & Borssele vs. expected on Arcadis Ost 1

3.2.4 Operational procedure

The HSD net deployment happens in parallel with lifting of the hammer on the MP, as it does not interfere with any operation on deck. The HSD net is deployed by lowering down the ballast box fitted underneath the pile gripper system. Lowering of the ballast box is done by paying out on the winches that are mounted on the pile gripper and connected to the ballast box.

Once below the water level, the buoyancy of the net elements causes the HSD-net to unfold on its own during lowering of the ballast box. Once the ballast box has reached the seabed, the HSD net surrounds the MP until the water surface. This is visualised in **Figure 4**.

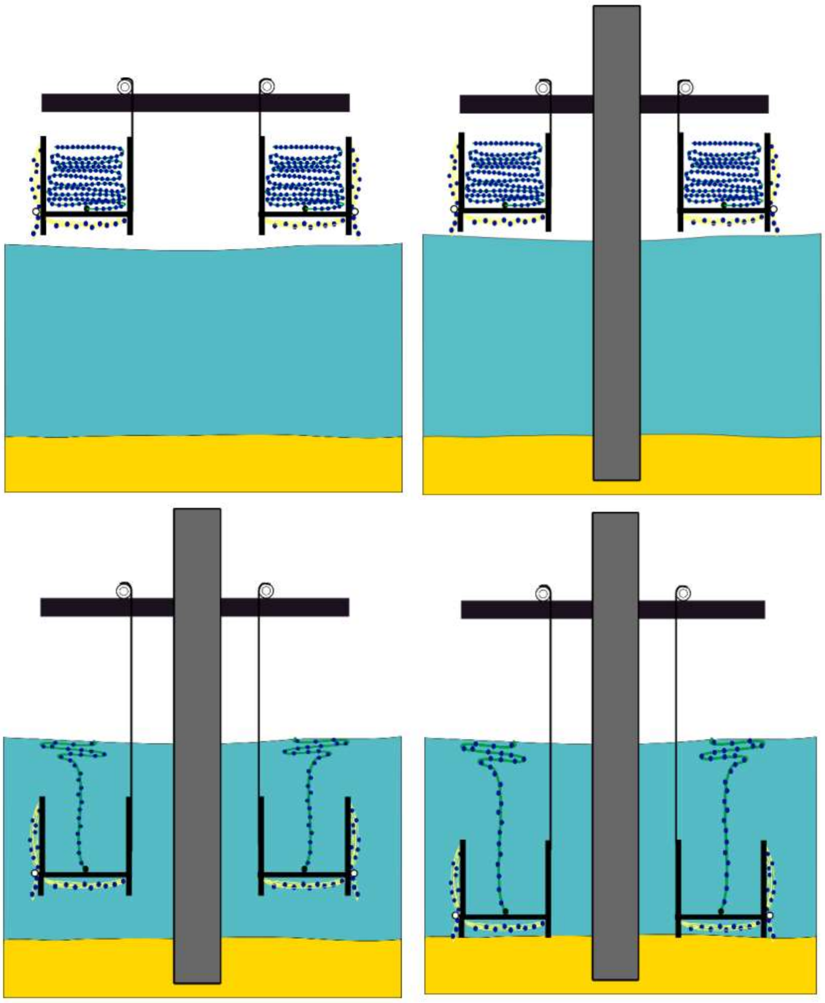


Figure 4: Lowering procedure HSD-net

3.3 BIG BUBBLE CURTAIN

One of the noise mitigation systems most practicable and currently applied for most MP foundation installations is the Big Bubble Curtain (BBC). Bubble curtains consist of perforated hoses that are deployed around the piling location by a support vessel in a pre-determined layout on the seafloor. These hoses are then connected to the supply vessel carrying air compressors. Compressed air is forced through the perforated hoses generating air bubbles through the water column.

In order to maximise the noise reduction, a DBBC will be deployed and operated on Arcadis Ost 1. The DBBC is provided and operated by HTL.

3.3.1 Layout

Figure 5 shows the base case DBBC layout around the HLV Orion.

The average current on site is around 0.2 m/s. Assuming an average ascent speed of 0.3 m/s of an air bubble [8], the drift-off over the max. water depth is expected to be:

$$L_{drift.} = \left(\frac{Depth_{w.}}{v_{bubble\ ascent}}\right) * v_{current} \approx \left(\frac{45.2\ m}{0.3\frac{m}{s}}\right) * \ 0.2\frac{m}{s} \approx 30\ m$$

The distance between the inner and outer curtain on the DBBC layout corresponds to the max. water depth present on site (i.e., 45 m). The distance between MP and the inner curtain is min. 70 metres, which is much larger than the expected air bubble drift-off.

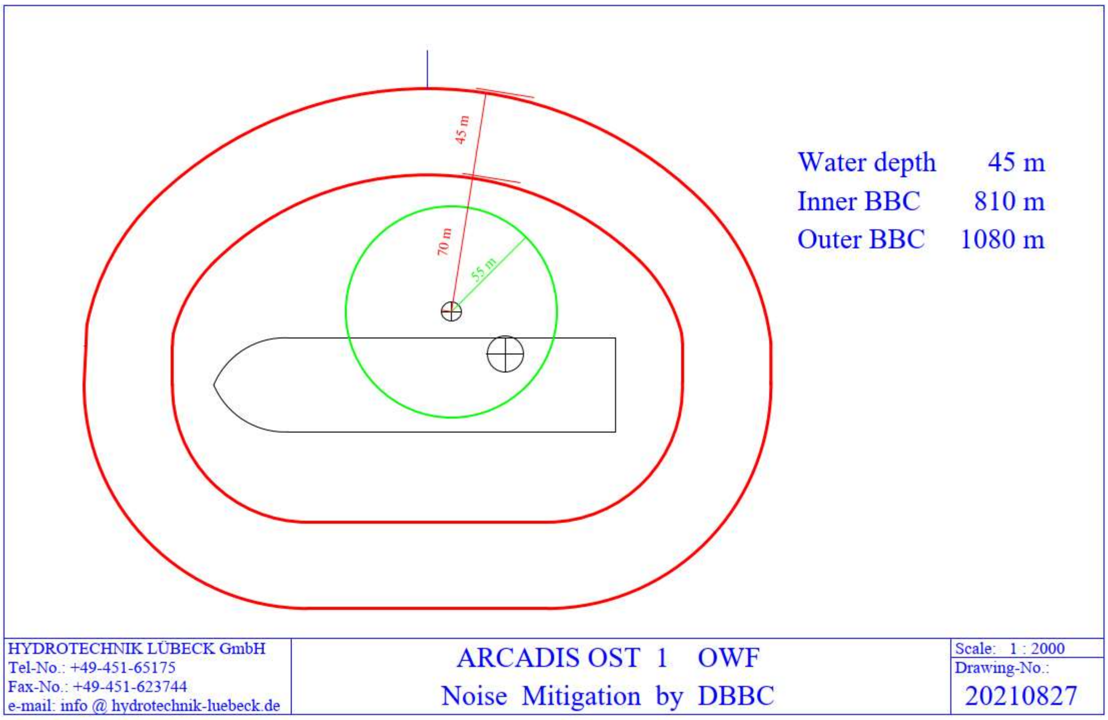


Figure 5: DBBC layout

The following DBBC system guidelines (based on experience from previous pile driving projects) will be considered in the final DBBC configuration [8]:

- Nozzle hose hole size and hole spacing: resp. 1 – 2 mm Ø and 20 – 30 mm
- Applied air volume inside hoses: ≥ 0.5 m³/(min*m)
- An overpressure of 2-3 bar relative to the static water pressure at each air outlet of the nozzle hose needs to be present to ensure a uniform air outlet. This translates itself into an operational pressure of approximately 9 – 10 bars for the compressors on Arcadis Ost 1.

Considering the above, the min. number of compressors ($n_{compressors}$) required to operate the envisaged DBBC configuration on AO1 can be calculated as follows:

$$n_{compressors} \geq \frac{L_{DBBC,tot} * 0.5 \frac{m^3}{min * m}}{FAD_{compr,9-10bar}}$$

With $FAD_{compr,9-10bar}$ = compressor free air delivery at working pressure of 9-10 bars

$L_{DBBC,tot}$ = total nozzle hose length of DBBC, envisaged to be 1890m (see Figure 5)

Assuming the compressors used on AO1 will have a min. FAD of approximately 40 m^3/min at a working pressure of 9 – 10 bars, the min. required number of compressors is:

$$n_{compressors} \geq 24$$

3.3.2 Operational Procedure

The DBBC equipment consists of perforated nozzle hoses, non-perforated supply air hoses, a deployment & recovery system and the compressors. The full DBBC spread is stored on a separate supply vessel as indicated on Figure 7. The supply vessel deploys the nozzle hoses on the seabed and connects them afterwards to the air supply hoses on deck (see Figure 6), through which air is forced by the air compressors on deck. Due to the pressure differences inside and outside the nozzle hoses, the air exits through air outlets in the nozzle hoses and the air bubbles rise towards the water surface.

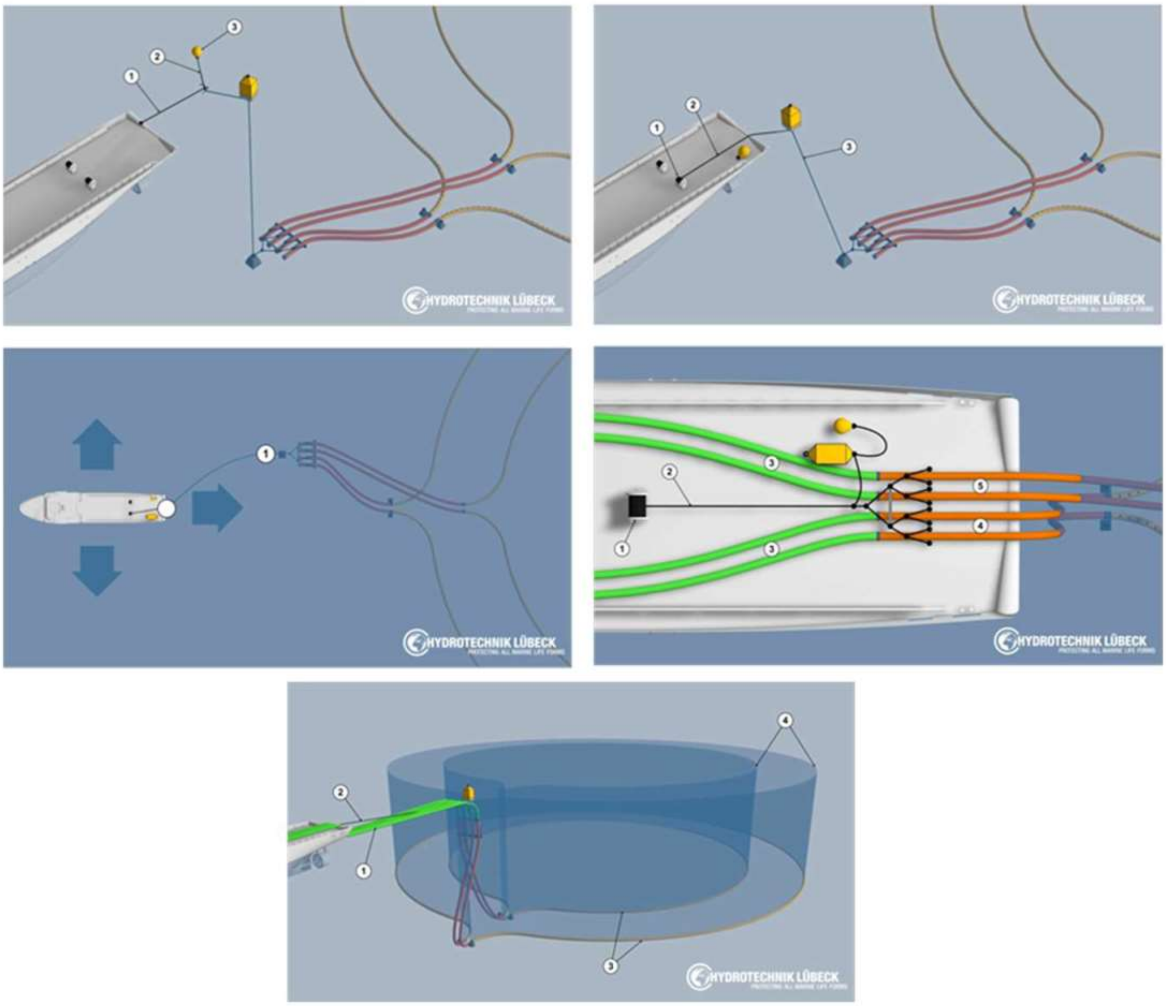


Figure 6 : Connection of hoses for a DBBC

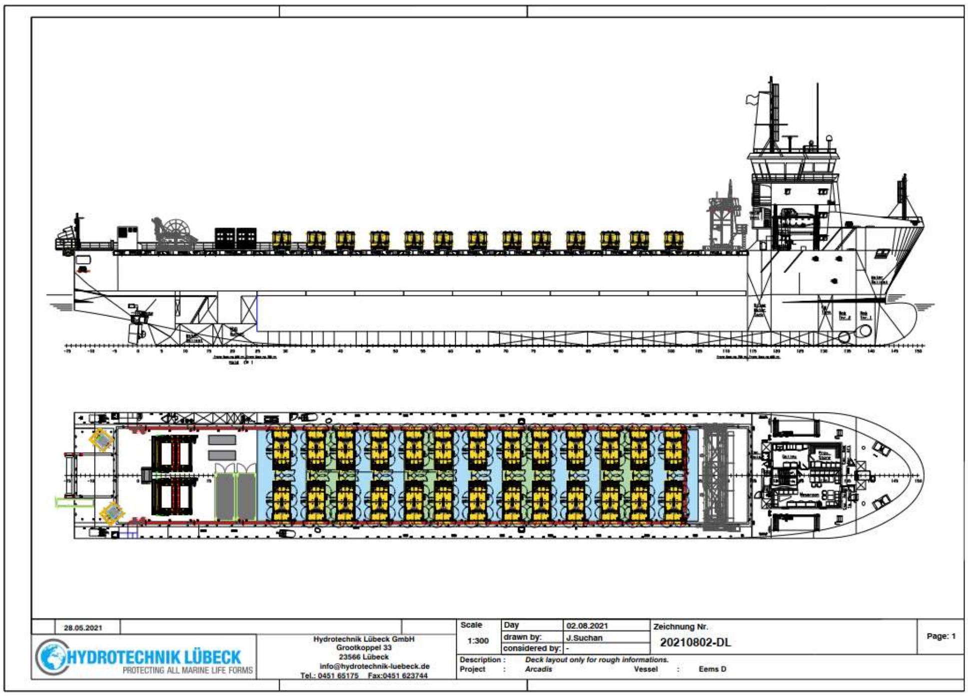


Figure 7: Indicative DBBC supply vessel deck layout

Prior start of the MP installation campaign, the DBBC supply vessel will have deployed and tested the DBBC on the two first locations on site. Once the MP installation vessel starts pile driving activities on the first location, the DBBC supply vessel will generate the DBBC on that respective location. After finalization of piling operations the DBBC vessel shall (partially) retrieve the hoses from that respective location (location N) and prepare the location (location N+2) which is following the next planned piling location (location N+1).

3.4 JUSTIFICATION NOISE MITIGATION SYSTEMS

In the past, the application of the HSD net combined with a DBBC has achieved a noise reduction of 18 to 19 dB, excluding the reduction gained from implementing a noise optimised pile driving procedure, in the North Sea with currents of up to 0.75 m/s and a sandy soil [8].

On a previous project in the Baltic Sea (i.e., Arkona OWF) with water depths between 20 and 40 metres, the combination of a noise optimised piling procedure (NOPP), a DBBC and HSD net resulted in a noise reduction in SEL between 15 and 28 dB [7] [8]. The large variances can be allocated to technical problems or dysfunctions of the respective noise mitigation system. On Arkona OWF there is very low current compared to the North Sea, as well as large diameter MPs, and relatively high-water depth (up to 37m). Arkona OWF is one of the most recent projects in the Baltic Sea using latest, state-of-the-art noise mitigation measures with successful outcome and therefore is considered as a valid reference project.

Table 4 points out that the achieved overall noise reduction of the applied optimized DBBC was higher in the Baltic Sea than in the North Sea due to the low current leading to no or little drifting effects of the air bubbles.

Noise mitigation systems	Location	Water depth [m]	DBBC air flow [m³/(min*m)]	Sound reduction in SEL at 750m	No° of MP
NOPP	n/a	n/a	n/a	~ 2 - 3 dB per halving of blow energy	
HSD + DBBC	North Sea	~ 40	≥ 0.5	18 - 19 dB	> 30
NOPP + HSD + DBBC	Baltic Sea	20 - 40	≥ 0.5	15 - 28 dB	> 50

Table 4: Achieved noise reduction with NOPP, HSD & DBBC [8]

The achieved noise reductions in Table 4 do not consider the enhancement of the net on AO1 and its expected additional reduction effect on noise of 2 to 3 dB (ref. 0).

Considering the achieved noise reductions in previous OWF projects, it can be concluded that with a max. expected SEL at 750m of 175 dB (at 4000 kJ as per Table 2) and with the worst-case noise reduction value of 15 dB resulting from HSD and DBBC (as per Table 4), the SEL shall comply with the SEL sound level value criterion of 160 dB at a distance of 750m. In other words, the selected noise mitigation systems are evaluated to be sufficient to comply with the SEL limit of 160 dB. Note that this does not consider the additional noise reduction effect expected from the enhancements of the HSD net.

Finally, it has been shown in all German construction projects in Germany that if the Sound Exposure Level (SEL_{05}) limit at a distance of 750 m of max. 160 dB is complied with, the zero-to-peak Sound Pressure Level ($L_{p,pk}$) limit of 190 dB was also complied to [8].

4 MARINE FAUNA PROTECTION

German authorities require the following measures to be implemented (within the 750m zone around the sound source) to prevent & reduce marine mammal impairment:

- Marine mammal deterrence by means of acoustic measures and a soft start procedure
- Marine mammal (more specifically porpoise) detection before start of piling works by visual monitoring (during the day) and passive acoustic monitoring (during day and night)

4.1 DETERENCE

Even with the noise mitigation measures in operation, the sound level could exceed 160 dB in the vicinity (< 750 m) of the sound source. This sound level is potentially harmful to marine mammals, in particular to seals and harbour porpoises. A two-step approach is chosen to deter marine mammals from the vicinity of the construction location up to a distance of 750m:

1. An acoustic deterrence device (ADD) is deployed from the installation or noise monitoring vessel prior start of pile driving
2. Use of soft start in piling procedure

4.1.1 Acoustic deterrence device

Contractor foresees to use the FaunaGuard or a combination of seal scarer and pinger as acoustic deterrence device. These devices produce underwater sound in order to deter porpoises from potentially hazardous areas before driving activities start. Contractor deploys the deterrent device 30 minutes prior commencement of piling from the installation vessel. Immediately after start of piling, the device(s) are recovered back to deck.

4.1.2 Soft Start Procedure

Single blows at low impact energy (10-15%) are applied which function as a deterrence mechanism for marine mammals.

After the single blows, the impact energy is slowly built up for continuous pile driving. According to local soil conditions and penetration of the pile, the number of the soft blows is decided during operation. After a pile driving stop, the ability to restart with a soft start may depend on the stage of piling and the pile/soil behaviour. Under some circumstances it may not be technically possible to re-commence the piling with a soft start procedure due to ground conditions and equipment limitations.

4.2 DETECTION

A two-steps approach is chosen to detect marine mammals in the vicinity of the construction location:

1. Acoustic monitoring by means of a cetacean-porpoise detector (CPOD)
2. Visual observation from the installation vessel

4.2.1 CPOD

The acoustic monitoring of porpoises is performed by using a cetacean-porpoise detector (CPOD). The CPOD is deployed at 750m from the sound source by the noise monitoring vessel prior commencement of piling. The CPOD is mounted onto the same mooring system as the underwater noise measurement devices (see Section 5). The CPOD is an offline device, meaning that the measured data at the time of piling is post-processed by specialist company Itap. The measurements data recorded on all 28 MP foundations and a detailed analysis of the data will be captured in a report three months after completion of pile driving activities on the AO1 site.

4.2.2 Marine mammal observation

For a 20-minute period prior commencement of pile driving, a trained staff or crew member [PT2]on board of the installation vessel visually monitors (with the aid of binoculars) the 750m zone around the construction location for presence of porpoises. The visual observation will take place from an optimal vantage point on the vessel that provides 360° visual coverage on the surroundings area (e.g., the bridge).

In a scenario where a marine mammal is spotted, the following actions are taken depending on the scenario:

- Spotting of mammal during acoustic deterrence period
  Continue visual search until there has been no visual detection for 15 minutes and extend the deterrence period until the end of this period. Pile driving activities will only start after reaching 15 minutes of no marine mammal observation.
- Spotting of mammal during piling
  Pile driving activities continue and the acoustic deterrence device (ADD) is redeployed for a period of 15 minutes.

Reference is made to Section 4.1.1 for details on the ADD procedure. The ADD will remain available on deck for use during the pile driving activities.

5 UNDERWATER NOISE MONITORING METHODOLOGY

During pile driving operations Contractor performs real-time underwater noise monitoring activities. The underwater monitoring, led by expert company Itap[3], is performed at two measurement positions:

- Real-time monitoring and data transmission at a position 750m away from the piling point;
- Measurement and data post-processing at a position 2000 m away from the piling point.

[3] Itap GmbH has an accredited quality management system (QMS) according to DIN EN ISO/IEC 17025 for emission and immission (pollution) measurements of vibrations as well as for measurements and forecasts of underwater noise (impulse and continuous noise).

The monitoring stations are deployed from the noise monitoring vessel under supervision of Itap personnel. Due care will be taken for accurate geospatial location of the measurement points.

This section specifies the envisaged instrument configuration and necessary reporting to meet the Permit requirements.

5.1 INSTRUMENTATION OVERVIEW

All underwater noise measurement devices are equal or comparable to the devices, which are currently being used in several other European OWFs and fulfil the StUK4 and other BSH requirements. The measurement set-up will consist of:

- One real-time position 750m away from the piling location. Contractor intends to use a buoy;
- Acoustic recorder watered at 2000m away from the piling point. The data collected by this acoustic recorder is post-processed after recovery from water.

For the underwater noise monitoring, mobile mooring systems are used. These moorings are suitable for mounting both an underwater noise monitoring device (i.e., hydrophones) and a CPOD to them. Reference is made to Annex A for a datasheet of the typical type of hydrophone used for the underwater sound monitoring.

For each measurement position a set of one measurement device and two spare devices will be provided. In case turnover times (from one to the next installation) are too short to recover or maintain the measurement devices or the noise monitoring/BBC vessel requires to leave the measurement devices in the water a second set is ready to be deployed for the next foundation installation.

5.1.1 Online acoustic monitoring system

At 750m Contractor intends to utilize a combination of a connected real-time acoustic buoy and a web-based application. The buoy can be deployed and moved easily to follow the installation vessel on each location. The buoy will be deployed, moved around and retrieved by the noise monitoring/BBC vessel. This has following advantages:

- Noise level monitoring: continuous measurement of peak-to-peak, sound pressure levels and sound exposure levels;
- Real-time reporting and analysis: all processed data are stored in a database which also enables post-analysis and semi-automatic periodic reports;
- Easy and quick implementation: its light weight and medium size just requires light means to operate it.

Underwater noise is picked up by a high-quality wideband hydrophone, specially selected and set up for measurement of piling activities in a noisy area. This hydrophone is calibrated before and after deployments and can be calibrated anytime thanks to a filed calibration case.

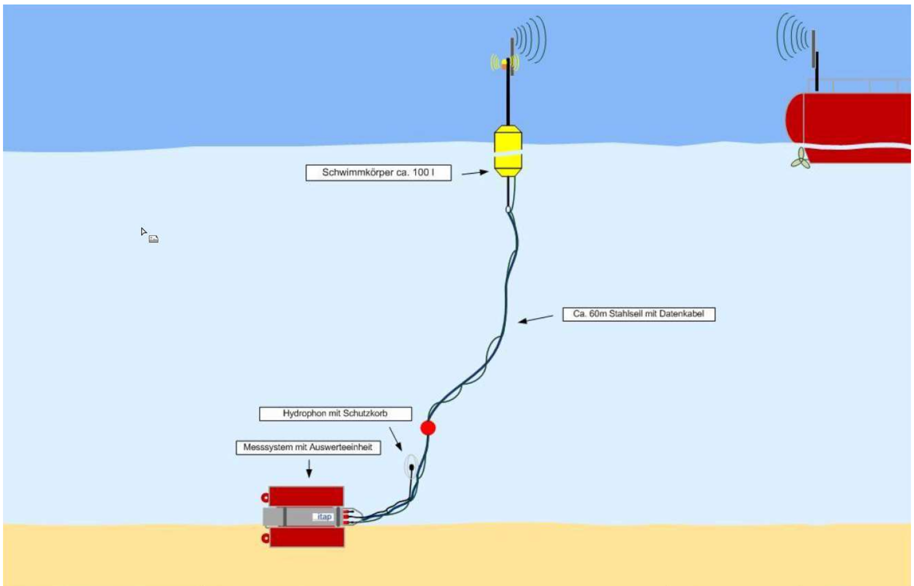


Figure 8: Schematic diagram of an online hydroacoustic monitoring system

5.1.2 Offline acoustic monitoring system

For the 2000m position that only requires offline measurements, the deployment will be done with a system made of an autonomous recorder equipped with a hydrophone installed in a seabed acoustic frame. This frame is stable and does not represent any obstacle to operations and navigation.

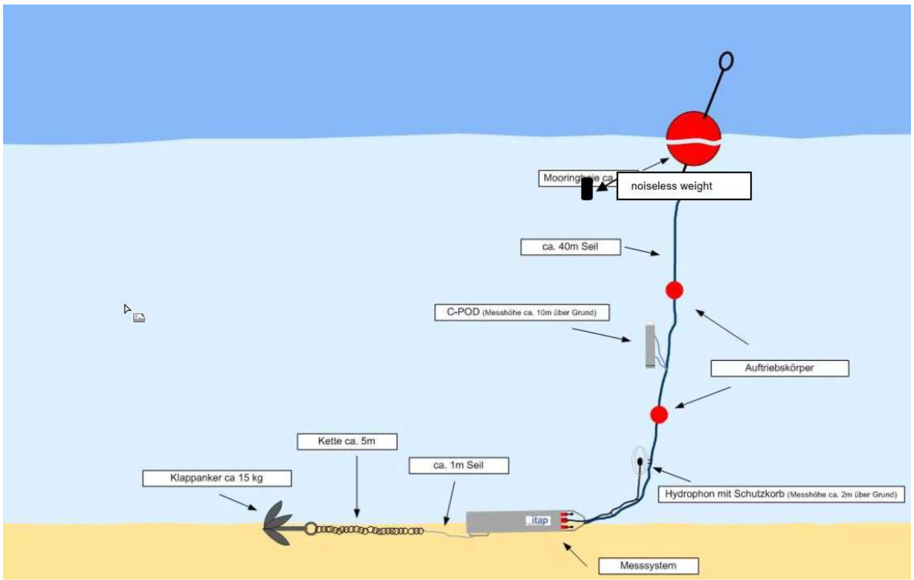


Figure 9: Schematic diagram of an offline hydroacoustic monitoring system

5.2 UNDERWATER NOISE REPORTING

The results of the baseline study and monitoring will be submitted to the relevant authorities in the form of comprehensible reports. The following reporting shall be provided:

- Preparation of a short report of underwater noise in accordance with BSH standards and best practice including the post-processed results of both measurement positions (750 and 2,000 m) delivered within 24 hours.

  In line with previous German OWF construction projects, short reports for the first 3 MPs are required. After this and in case of no exceedance of noise mitigation values the results of 3 MPs can be summarized in one short report. The results of the OSS MP will be summarized in a separate short report so that in total 12 short reports underwater noise will be provided.

- Preparation of a final technical report after the end of the measurement campaign including the quality control records, all post-processed data, list of defects (if any) and an evaluation of the applied noise mitigation concept (if possible).

6 AIRBORN NOISE MONITORING METHODOLOGY

Airborne noise measurements are required on the island of Rügen at Kap Arkona only during night (between 20:00 and 7:00) and pile-driving activities. The airborne noise at the measurement location shall not exceed the emission guide value of 40 dB(A). For the first five pile-driving activities performed within the night window, the airborne noise measurements are post-processed and evaluated daily by an accredited[4] company. At the end of the measurement campaign, a final technical report is provided which fulfils the requirements from BImSchG.

Based on the pile-driving plan it is not foreseeable if and when pile-driving activities may be conducted within the period 20:00 and 7:00 h. Therefore, it is planned to perform a monitoring during the complete construction phase at one standalone, unmanned measurement position at Kap Arkona (remote-controlled device) during each night.

The envisaged monitoring device will be a class 1 sound level meter which is DKD calibrated in accordance with ISO 17025 and fulfill the requirements of BImSchG.

[4] Accredited in accordance with DIN EN ISO/IEC 17025.

7 REFERENCES

[1] AO1-DO-PMT-PLN-00006, Project General Information Plan.

[2] BSH, Offshore Wind Farms: Measuring instruction for Underwater Sound Monitoring, 2011.

[3] BSH, Offshore Wind Farms: Measuring Specification for the Quantitative Determination of the Effectiveness of Noise Control Systems (stUK 4), 2013.

[4] AO1-DO-ENG-RPT-02201, MP Driveability Analysis.

[5] AO1-PWO-ENG-RPT-00008, Modelling of Underwater Acoustics Emissions from Piling.

[6] AO1-DO-ENG-TNO-00003, Evaluation of Driveability for Noise Prognosis Purposes.

[7] Itap, Arcadis Ost 1 - Modelling of underwater noise emissions during Construction pile-driving work.

[8] M. A. Bellmann, Underwater noise during percussive pile driving: Influencing factors on pile-driving noise and technical possibilities to comply with noise mitigation values, 2020.

[9] AO1-DO-ENG-MST-02104, MST Noise Mitigation.

ANNEX A – DATASHEET NOISE MONITORING DEVICES

Configuration of the mooring system for online underwater noise measurement devices

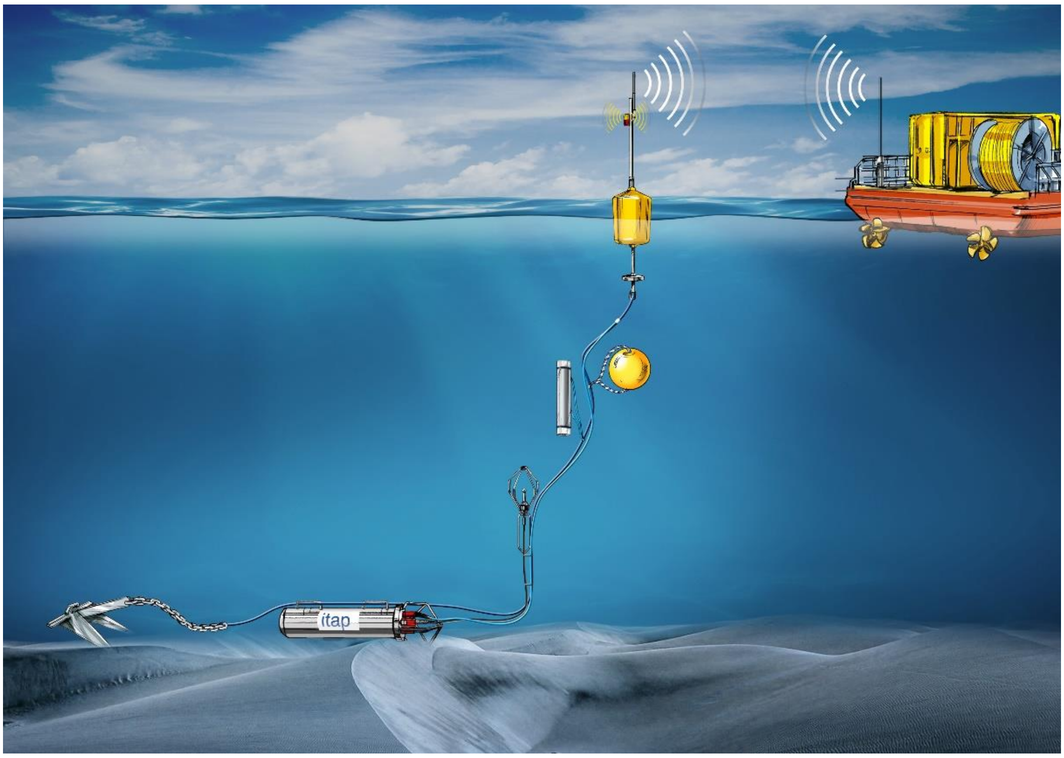


Figure 1: Schematic drawing of the measurement device with mooring and bouy incl receiver unit

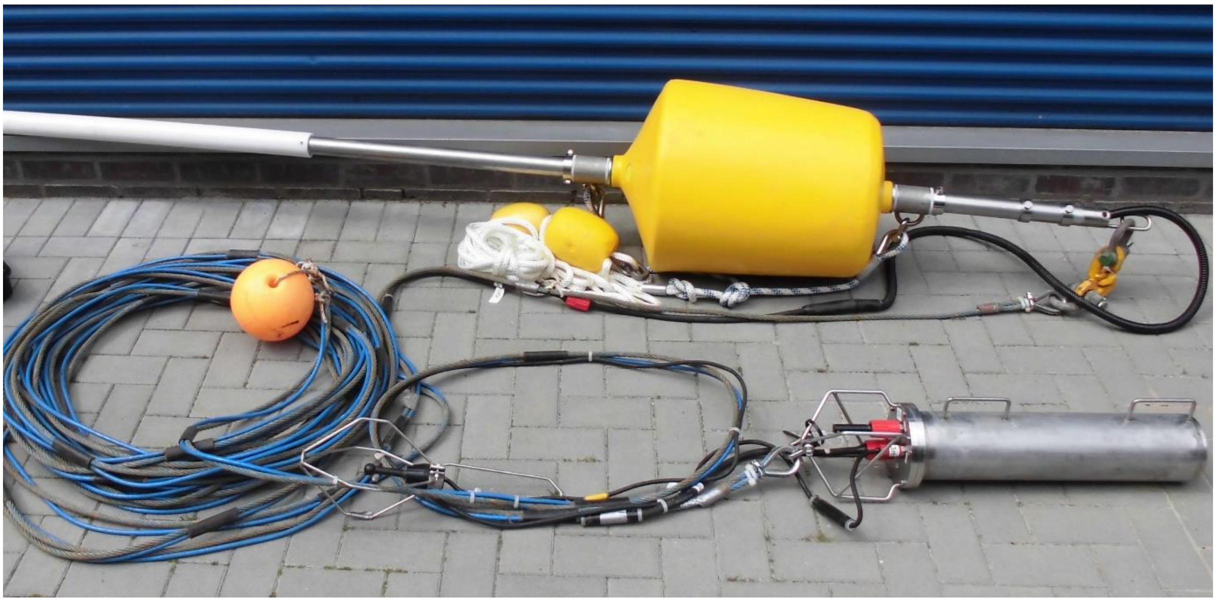


Figure 2: Picture of the measurement device with data cable and bouy

Item	Description
Stockless anchor	plate- and weight anchor combined with a weight of 40 kg; provides a good holding force in mud and sand
Measurement device	steel tube with a weight of approx. 30 kg (functions as an additional weight-anchor); with hydrophone and data transmission cable attached
Steel-rope	60 m length and 12 mm diameter with loops for connecting measurement device, hydrophone and floatation body; data transmission cable attached to steel-rope
floatation body	diameter 20 cm, buoyancy of 3.23 kg
buoy	100 l surface buoy with flashing light (frequency 1.5 s), 8 m messenger line with additional floatation body (buoyancy of approx. 630 g) and data transmission cable;

Configuration the online underwater noise measurement device

Underwater noise online device		
Details	Power supply	Battery (rechargeable)
	Sampling frequency	Lossless in 24 bit resolution. PCM WAVE data format, 44.1 kHz sampling rate.
	Charge amplifier	0.1 mV/pC
	Frequency range (Recorder)	10 Hz – 20 kHz
	Recording time / storage capacity	400 h
	Running time / battery capacity	120 h
Hydrophone	Number	1
	Type	RESON TC4033

	Frequency range (Hydrophone)	1 Hz – 140 kHz (Analogue Bandwith)
	Sensitivity	-203 dB re 1V/µPa at 250 Hz
	Measuring height	2-2.5 m above sea floor

Receiver Unit

The receiving unit consists of an antenna with cable, router, charger and laptop. The transmission is based on the Wi-Fi-standard (IEEE 802.11) with WPA2 encryption.

Figure 3: Parts of the receiver unit.

Configuration of the mooring system for offline underwater noise measurement devices

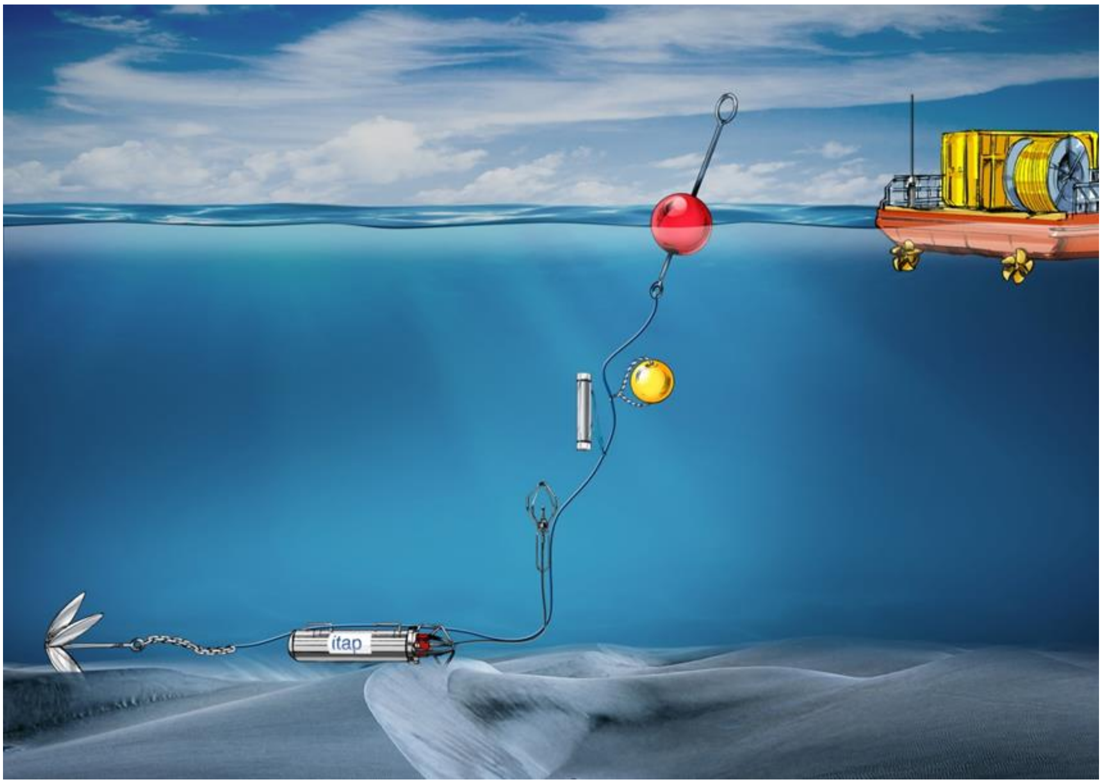


Figure 4: Schematic drawing of the offline underwater noise measurement device

Item	Description
Stockless anchor	plate- and weight anchor combined with a weight of 40 kg; provides a good holding force in mud and sand and a additional weight
Measurement device	steel tube with a weight of approx. 30 kg (functions as an additional weight-anchor); with hydrophone attached
Rope	60 m length and 16-18 mm diameter with loops for connecting measurement device, hydrophone and floatation body
floatation body	diameter 20 cm, buoyancy of 3.23 kg
buoy	60 l surface buoy with flashing light (frequency 1.5 s) and 8 m messenger line with additional floatation body (buoyancy of approx. 630 g)

Configuration the offline underwater noise measurement device

Underwater noise offline device		
Details	Power supply	Battery (nonrechargeable)
	Sampling frequency	Uncompressed, 24-bit PCM WAV, 44.1 kHz sampling frequency
	Charge amplifier	0.1 mV/pC
	Frequency range (Recorder)	10 Hz – 20 kHz
	Recording time / storage capacity	30 h
Hydrophone	Number	2
	Type	RESON TC4033
	Frequency range (Hydrophone)	1 Hz – 140 kHz (Analogue Bandwith)
	Sensitivity	-203 dB re 1V/µPa at 250 Hz
	Measuring height	2-2.5 m above sea floor and the half of the watercolumn

The underwater noise measurement devices fulfill all requirements of the ISO 18406:2018 and measurement guideline of BSH:2011.

Calibration procedure and measurement uncertainty of the underwater measurement device

The general measurement uncertainty of the whole measurement chain (speaking of the measurement device, including hydrophone, charge amplifier, recorder etc.) is about +/- 1 dB. The uncertainty of the measurement device itself (excluding hydrophone) is +/- <1 dB.

The calibration has to be divided into three different procedures which are all in accordance to ISO 17025:2017 and ISO 18406:2018.

A) The calibration of the used hydrophone sensors itself. This is performed on an annual basis for only the hydrophones. For example: According to the German measurement guideline it is required to perform such calibration every two years.

B) The calibration of the complete measurement chain (measurement device including all parts and the hydrophone) in full frequency- and amplitude range. Such calibrations are performed every time before a measurement device will be delivered to the project and additionally when it comes back from a project.

C) The single frequency calibration of the measurement device (excluding hydrophone). This will be performed within a so called factory acceptance test (FAT) before each deployment of a measurement device offshore. During the FAT the overall functioning of the measurement device is checked on single frequencies in accordance to ISO 17025:2017, ISO 18406:2018 and BSH 2011.

After recover of the measurement devices the measured data recorded on the device will be copied to a hard drive and post-processing will be performed to evaluate the measurement data. For quality control of the measurement data, they are correlated with the hammerlog during post-processing.

Each measurement device has installed a real-time clock with UTC time to assign the recoded data to an exact time stamp. This time stamp is also assigned to the data within the real-time monitoring interface.

C-POD

Software:	CPOD.exe carries out objective automated data analysis to find click trains in the data and identify those produced by dolphins, porpoises and all echo-locating cetaceans except sperm whales. It also provides fast display and export of data and enables users to change C-POD settings. Provided free, with free upgrades. The software and *C-POD Software Guide* can be downloaded here.
Working depth:	C-POD: At least 100 m. A single C-POD has been tested to destruction and failed at 220 m. DeepC-POD: At least 2 km.
Autonomous operation time:	Maximum running times seen are 200-212 days and depend on battery quality. With good quality, high capacity D-cells, more than 4 months can be expected.
Housing:	C-POD: Polypropylene. DeepC-POD: Aluminium.
Dimensions:	C-POD: Length: 670 mm. Diameter: 90 mm DeepC-POD: Length: 680 mm. Diameter: 100 mm
Weight:	C-POD: 2.1 kg without batteries, 3.5 kg with batteries. DeepC-POD: 7.15 without batteries, 8.6 kg with batteries.
Buoyancy:	C-POD: Approximately 0.7 kg. This makes C-PODs self-orientating and increases the chance of recovery if the mooring fails. A web link engraved on the outside has enabled many PODs to be returned to their owners by people who have found them on sea shores, sometimes more than 2,500 km from home. DeepC-POD: -3.1 kg, not buoyant.
Mooring:	C-POD: 3 x 10 mm holes in the lid. DeepC-POD: 1 x 12 mm hole in the lid.
Hydrophone:	20 kHz to 160 kHz, omni-directional hydrophone in a large-diameter housing to reduce surface noise. The transducer mounting and housing design gives high resistance to impact damage.
Memory:	Removable 4GB SD card. Two SD cards are supplied with each C-POD.
Batteries:	Battery packs hold 10 alkaline D-cells. The battery housing is sprung to reduce battery damage from end impacts.
Detection range:	Maximum detection range for porpoises is approximately 400 metres. Dolphins may be detected at >1 km.

Figure 5: Specification of the C-POD

The C-POD is provided by the company BioConsult-SH. All devices are calibrated. Furthermore, a factory acceptance test (FAT) will be performed before and after each offshore trip.

References

BSH (2011): Offshore wind farms - Measuring instruction for underwater sound monitoring – current approach with annotations. Application instructions. Project number 0327689A.

ISO 17025:2017: General requirements for the competence of testing and calibration laboratories.

ISO 18406:2018: Underwater acoustics -- Measurement of radiated underwater sound from percussive pile driving.

2.2 Underwater noise monitoring - Final technical report

Arcadis East 1

Foundations EPCI

AO1D-DO-T&I-REP-2248

AO1-DO-ENG-RPT-02025

Contract Number: 5868

Underwater noise monitoring - Final technical report

Current Revision 00

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Employer: Parkwind Ost GmbH	**Main Contractor: DEME Offshore**

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Measurement of underwater noise immissions at the *Arcadis Ost 1* offshore wind farm

Final report of the ordered efficiency control marine mammals

Project number: 3796
Version 1

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List of changes

Version	date	Change details
Version 1	15.09.2022	First draft

The current version of the report completely replaces all previous versions.

Table of contents

List of illustrations

List of tables

List of abbreviations

APD ....Acoustic Porpoise Deterrent

EEZ ....Exclusive Economic Zone

BSH ....*Federal Maritime and Hydrographic Agency*

DAkkS ....*German Accreditation Body*

DGBS ....Double Big Bubble Curtain (DBBC)

DKD ....*German Calibration Service*

HSD ....Hydro Sound Damper

HSD-GBS ....HSD bubble curtain

OWT ....Offshore wind turbine

OWP ....Offshore wind farm

StALU..*State Office for Agriculture and the Environment*

TGBS ....Tripple Big Bubble Curtain

UBA..*Federal Environment Agency*

1. Summarised assessment

Parkwind NV (hereinafter referred to as *Parkwind*) is currently constructing the *Arcadis Ost 1* offshore wind farm (OWF) in the German Baltic Sea. The *Arcadis Ost 1* OWP will be located approx. 19 km off the coast of Rügen within the 12 nautical mile zone of Germany in the federal state of Mecklenburg-Western Pomerania. Between 7 June 2022 and 24 July 2022, installation work took place at the *Arcadis Ost 1* offshore wind farm (OWP) to erect the foundation structures (monopiles) for the 27 offshore wind turbines (OWTs) and the transformer station using the impulse pile driving method. The offshore wind turbines are being installed on XL monopiles with a pile diameter of 9.4 metres and the transformer station (OSS) on an XL monopile with a diameter of 9.6 metres. The monopiles were driven into the sediment at water depths of 39 to 45 metres using an *IQIP B.V.* S4000 pile driving hammer. The embedment depths were 39 and 63 metres. The uppermost soil layer consists of a soft sediment layer with a thickness of up to 34 metres, followed by a layer of boulder clay and chalk.

In order to monitor the noise-intensive construction activities and the effectiveness of the noise mitigation measures used (efficiency control of marine mammals), *itap - Institut für technische und angewandte Physik GmbH* was commissioned to carry out all necessary underwater noise measurements (hydro noise). All work was carried out in accordance with the requirements of the planning approval decision and in accordance with StUK4 (StUK 4 2013) and the BSH measurement regulations for underwater noise measurements (BSH 2011) as well as ISO 18406 (2017).

This final report "Efficiency monitoring of marine mammals" summarises all underwater noise measurements carried out during the impact pile driving of all 27+1 monopiles. The measurement data collected for the presence and reactions of harbour porpoises to impulse pile driving noise (visual observations and C-POD measurements) are summarised in a separate final report.

In coordination with the authorities and companies involved in the construction, a research and development project R&D PULSE (M. Bellmann 2021) was planned and carried out on nine of the first 12 foundation installations to test the new hammer technology PULSE unit. These so-called R&D monopiles were founded in the period between 7 June 2022 and 2 July 2022 using the impulse pile driving method. The PULSE unit acts as an impulse extension unit or spring-damper unit between the impulse pile hammer and the anvil. The aim of this new hammer technology is to extend the ramming impulse while simultaneously reducing the transmission of peak forces. This impulse extension unit therefore has the following effects as a noise reduction measure, i.e. the source strength or source level is reduced. The results of the R&D project are summarised in detail in a separate report (Bellmann, Brüers, et al. 2022). The main results are also briefly summarised in this final report on efficiency control.

The underwater noise measurements during the impulse pile driving revealed the following results:

Efficiency control marine mammals - underwater sound measurements

- Despite the difficult ground conditions, all 28 monopiles were successfully driven to the final depth using the impulse driving method.
- All underwater noise measurements ordered at distances of 750 and 2,000 m (in accordance with the planning approval decision) were summarised promptly after each impulse pile driving in the form of a short underwater noise report in tabular form and in graphs (28 in total).
- The noise protection value of 160 $_{dBSEL}$, to be complied with by the 5% exceedance level of the single event level ($_{SEL05}$) at a distance of 750 m, could only be complied with at a single measurement position with a monopole installation. In contrast, the noise protection value of 190 dB, to be maintained by the peak level ($L_{p,pk}$) at a distance of 750 m, was complied with at 27 foundation locations. The exceedance by the peak level is due to the reference monopile of the R&D project.
- The noise protection systems used (i) optimised double bubble curtain (DGBS) and (ii) optimised hydro sound damper system (HSD) achieved significantly lower overall noise reductions in this construction project than was to be expected from previous construction projects (Bellmann et al., 2020). This is presumably due to the very difficult ground conditions and some of the technical challenges involved in using these state-of-the-art noise protection systems, e.g. the nozzle hoses sinking into the seabed. In addition, impulse pile driving of XL monopiles with a diameter of up to 9.6 metres was installed for the first time in this construction project using a floating installation vessel using the dynamic positioning method.
- The installation time per monopile, including soft start and deterrence, took longer than the required 180 minutes on three monopiles. There were brief interruptions to the pile-driving process during the installation of the OSS monopile; in conjunction with the maximum embedment depth of 63 m, the total pile-driving time was 4 hours 23 minutes. The test and reference monopiles G02 and C03 were each interrupted for several hours due to technical challenges in the pile-driving process. Due to these long

The acoustic deterrence was repeated before the restart during the two pile-driving interruptions. Each of these two pile-driving sections per monopile lasted less than 180 minutes.

- The new PULSE hammer technology unit had to be completely demobilised after the first nine monopile installations as a precautionary measure due to safety concerns regarding possible damage to the system and was therefore no longer available as an additional noise protection measure for the remaining 18 monopiles. For this reason, an additional bubble curtain in the HSD system (HSD-GBS) and five new system configurations of a project-specific, customised large bubble curtain were used within this construction project. A triple bubble curtain (TGBS) was used for the first time under real offshore conditions. In addition, so-called XL-DGBS systems with nozzle hose lengths of up to 1.8 km (as individual hoses; in combination up to 3.3 km in length) were designed and operated for the first time under real offshore conditions by two separate bubble curtain support vessels. These bubble curtain system configurations were designed on a project-specific basis based on numerical modelling (*JASCO*) in order to be able to capture any ground coupling occurring due to the difficult ground conditions in this construction project. All of the technical additions made to the noise protection systems used have contributed to a piecemeal improvement in the noise reduction achieved, but have not resulted in compliance with the noise protection value 160 $_{dBSEL05}$.
- Based on the daily underwater noise measurement data, additional underwater noise measurements were carried out for the last 12 monopile installations in particular at distances of up to 10 km to determine the project-specific propagation attenuation The project-specific propagation attenuation is significantly higher than expected in this construction project. For example, noise reductions of 9 to 13 dB were measured for a doubling of the distance instead of the expected 4 to 5 dB. This could be due to the difficult ground conditions in and around the OWP *Arcadis Ost 1* with a non-load-bearing, upper soft sediment layer, followed by boulder clay and chalk.
- At three R&D monopiles and another monopile (A01), the noise protection value of 160 dB was exceeded at a distance of 2,000 metres. In the case of the three R&D monopiles, this is due to the planned, reduced noise protection measures; at monopile A01, there were technical challenges with the noise protection systems used.

- It was also shown that despite exceeding the noise protection values by up to 10 dB at 750 m, no pile-driving noise could be measured in the water at a distance of 10 km due to the high project-specific propagation attenuation.
- The results regarding the application of novel system configurations of the large bubble curtain and the new hammer technology PULSE unit represent a major gain in knowledge for future construction projects in the German North Sea and Baltic Sea.

PULSE R&D project

- All of the monopiles analysed using the PULSE unit (configurations $P0_{,50,100\%}$) could be fully installed down to the final depth despite boulder clay and chalk layers.
- Pile monitoring was carried out on three R&D monopiles. The following effectiveness and transfer factors were found between the driving energy in the pile hammer and in the monopile head:
    - PULSE unit $_{P0\%}$= 97%
      This means that the transfer factor for an S4000 pile hammer with and without the PULSE unit switched off is comparable.
    - PULSE unit $_{P50\%}$= 85%
    - PULSE unit $_{P0\%}$= on average 70%
      (Measurements on two monopiles showed values between 64 and 76%)
- The maximum ram energies used per R&D monopile varied between 658 kJ (using the PULSE configuration $_{P50\%}$) and 3,213 kJ ($_{P0\%}$ and $_{P100\%}$) in the R&D monopile installations shown here.
- Using the new hammer technology PULSE unit results in noise reductions for the single event level $_{SEL05}$ of 4 to 6 dB ($_{P100\%}$) and 3 to 5 dB ($_{P50\%}$). Slightly higher values result for the peak level.
- A comparison of the monopile installations with the PULSE unit in various system configurations ($P0_{,\ 50,\ 100\%}$) and without additional sound insulation systems indicates a slight broadening of the impact sound spectrum towards higher and lower frequencies. Typically, the sound input for large monopiles is between 80 and 160 Hz. In this case, the frequency range is between 50 and 125 Hz when the PULSE unit ($_{P0\%}$) is switched off. When the PULSE unit is switched on ($_{P100\%}$), the frequency range widens to 32 to 200 Hz.

- As expected, the results of the evaluation of the new hammer technology PULSE unit indicate an addition of the noise reductions achieved by the combination of sound insulation systems and the PULSE unit.
- The impact sound spectrum of the reference measurement indicates a spectral shift to lower frequencies due to the large monopole.

Edited by Josef Poppitz
Project manager

Reviewed by Dr Michael A. Bellmann
Managing director and head of department

2. General introduction and objectives

DEME Offshore B.V. is currently constructing the *Arcadis Ost 1* offshore wind farm (OWP) in the German Baltic Sea for *Parkwind NV* (hereinafter referred to as *Parkwind*). The *Arcadis Ost 1* OWP will be located approx. 19 km off the coast of Rügen within the 12 nautical mile zone of Germany in the federal state of Mecklenburg-Western Pomerania. On 7 June 2022, installation work began at the *Arcadis Ost 1* offshore wind farm (OWP) to erect the foundation structures (monopiles) for the offshore wind turbines (OWTs) using the impulse pile driving method.

The impulse pile driving work during the foundation work results in noise emissions in the water that could potentially harm marine mammals, especially harbour porpoises (Kastelein, et al. 2015). For these reasons, a noise protection concept was developed from offshore-tested noise protection systems, consisting of the use of a near-pile (Hydro Sound Damper, HSD) and a far-pile (double large bubble curtain, DGBS) noise protection system as well as a noise-optimised pile-driving method.

The construction and operation of the *Arcadis Ost 1* OWP was authorised by the StALU. The approval documents required the use of noise reduction systems for the noise-intensive construction activities - e.g. foundation work using the impulse pile driving method - as well as simultaneous measurements of underwater noise immissions at 750 and 2,000 metres in one spatial direction.

In order to monitor the noise-intensive construction activities and the effectiveness of the noise reduction measures used (efficiency control), *itap - Institut für technische und angewandte Physik GmbH* was commissioned to carry out all necessary underwater noise measurements (hydro noise) within the construction area. In coordination with the approval authority, the State Office for Agriculture and the Environment (StALU) and the companies involved in the construction, a research and development project including a project description called R&D-PULSE (M. Bellmann 2021) was planned and carried out on nine of the first 12 foundation installations to test the new hammer technology PULSE unit. In this R&D project, test and reference measurements in accordance with DIN SPEC 45653 (2017) as well as further underwater noise measurements in different spatial directions and at distances of 250 m to 10,000 m from individual foundation installations were carried out in coordination with the StALU in addition to the arranged underwater noise monitoring of the arranged efficiency control marine mammals in 750 and 2,000 m in one direction. All work by *itap - Institut für technische und angewandte Physik GmbH* was carried out in accordance with the specifications of the (StUK 4 2013) and the

Measurement specification for underwater noise measurements of the BSH (BSH 2011) and ISO 18406 (2017).

This report summarises all available measurement results from the underwater noise measurements carried out on all 28 foundation installations in accordance with requirement 3 of the planning approval decision on efficiency control. The results of the R&D project were summarised in two separate reports (Bellmann, Brüers, et al. 2022). The main results from this research project are also briefly summarised in this report.

3. Local conditions and planned project

The *Arcadis Ost 1 (AO1)* offshore wind farm (OWP) is located in the Baltic Sea within the German 12 nautical mile zone off Rügen. A total of 27 OWTs, consisting of 9.5 MW wind turbines, and a substation (OSS/USP) will be installed; Figure 1.

The WTGs and the offshore supply station (OSS) are founded on monopile foundations with a diameter of 9.4 metres (WTG) and 9.6 metres (OSS). The length of the individual R&D monopiles varies from 97 m to 110 m with a water depth of between 39 m and 45 m. The embedment depth of the R&D monopiles in the seabed varies between 42 m and 63 m. The seabed consists mainly of non-load-bearing soft sediments (sand and mud or silt and clay) with a layer thickness of up to 34 metres. Beneath the sediment layers lies hard clay and boulder clay with a thickness of around 4 to 5 metres. The thickness of this layer varies greatly between locations and can reach up to 15 metres.

Beneath the hard clay is a layer of chalk, which is less firm over the first 4 to 5 metres.

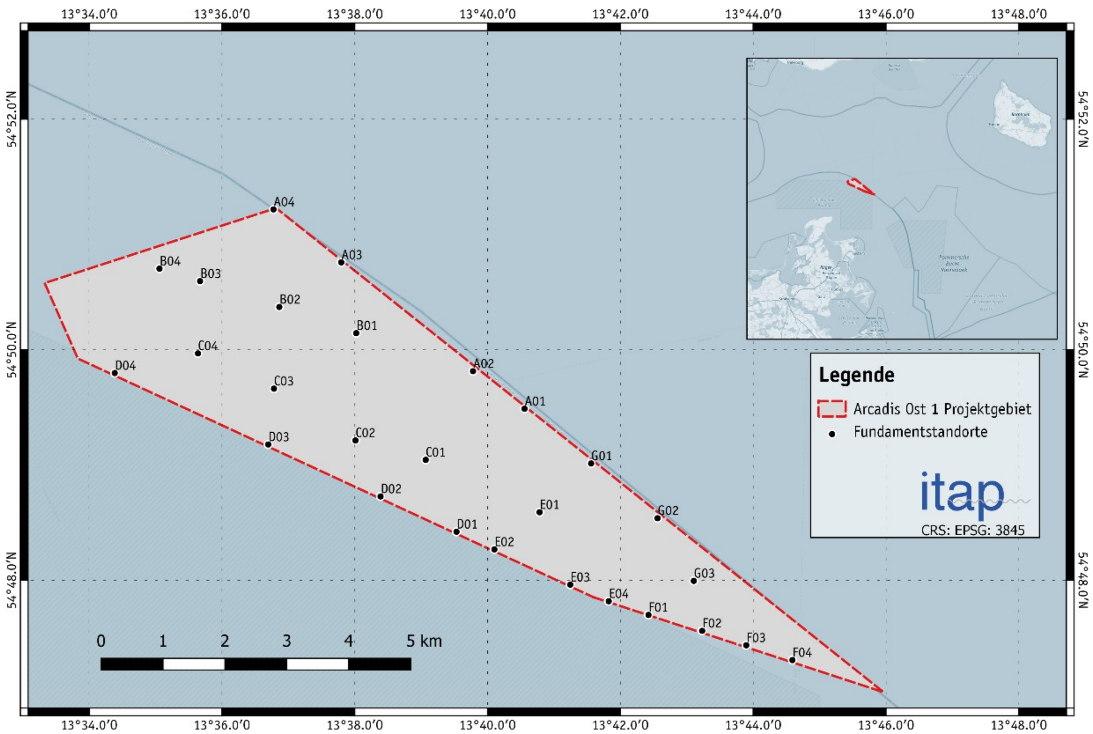


Figure 1: ***Location of the Arcadis Ost 1 project area in the Baltic Sea within the German 12-Nautical mile zone off Rügen.***

DEME Offshore B.V. used the installation vessel *ORION* to install all foundation structures using the impulse pile driving method with the S4000 impulse pile hammer from *IQIP B.V.* In addition, the new PULSE impulse extension unit from *IQIP B.V.* was used for the first seven of the nine R&D PULSE R&D monopiles.

The *ORION* installation vessel is a so-called floating vessel (floating unit) and installs the R&D monopiles with the aid of a dynamic positioning system.

Based on the planning approval decision, measurements of the noise emissions at 750 m and 2,000 m were carried out for each pile-driving operation as part of the efficiency control (underwater noise measurements), which were also included in the following evaluation for the R&D project.

4. Noise protection measures

Noise reduction measures are required to comply with the noise protection values during impulse pile driving with the *ORION* installation vessel. Two independent noise abatement systems are used in the *Arcadis Ost 1 OWP*: the Hydro Sound Damper (HSD) in combination with a double large bubble curtain (DGBS) plus a noise-optimised pile-driving process. A detailed description of the noise protection systems used can be found in the noise protection implementation plan (Van Es, et al. 2021). The systems used are briefly described below.

4.1 Hydro Sound Damper (HSD)

A Hydro Sound Damper (HSD) system from *Offnoise Solutions GmbH* was used as a **near-pile noise protection system** from the installation vessel. The HSD system consists of a net with HSD elements, a ballast box and a lifting and lowering device. The HSD net encloses the entire length of the monopile within the water column. The lifting and lowering device is located directly below the pile gripper. All individual components have been customised for this project and the respective installation vessel.

Furthermore, as an additional measure, an integrated bubble curtain was installed in the ballast box, which could also be put into operation with compressed air from the *ORION* installation vessel as required (HSD-GBS). Due to the low current in the Baltic Sea, a small bubble curtain forms directly around the monopile.

4.2 Large bubble veil (DGBS)

A double large bubble curtain (DGBS) from *Hydrotechnik Lübeck GmbH* (*HTL*) was installed around the respective foundation position as a **noise protection system away from the pile** using the pre-laying method. The large bubble curtain consists of two nozzle hoses (inner and outer ring), which are laid out on the seabed around the respective foundation locations using a corresponding ship. Compressors on board this escort vessel provide compressed air, which is fed into the nozzle hoses on both sides. The compressed air can escape via holes in the nozzle hoses located on the seabed and two separate large bubble curtains are formed in the water column.

PTS 1600 compressors from Atlas Copco were preferably used. Due to the high demand, identical PTS-916 models were also used.

A total of 24 compressors plus two spare compressors were available on board the escort vessel *Sar Brage*.

For the double large bubble curtain (DGBS), two sets of nozzle hoses (1 & 2) were mobilised and used, each numbered and noted in the respective bubble curtain protocols; see Table 1.

In coordination with the StALU, a third large bubble curtain and two double large bubble curtains with increased hose lengths were also deployed and tested for the first time in the German Baltic Sea using a second BBC escort vessel (*Eems Dundee*); see Table 1. A further 19 compressors plus a replacement were available on the *Eems Dundee*.

The actual number of compressors used, the exact nozzle hose length and the nozzle hose set number per monopole installation were recorded in bubble curtain logs. Chapter 10.5 contains a list of all nozzle hose configurations actually used, including the number of compressors used.

Table 1: System configuration of the deployed large bubble curtains (DGBS), the triple large bubble curtains (TGBS) and the two enlarged large bubble curtains ($XL1_{2,3\text{-}DGBS}$) for the impulse pile driving in the OWP Arcadis Ost 1 with the installation vessel ORION.

No.	Designation	Nozzle hose length [m]	Minimum distance to the Monopile [m]	Number of compressors	Air volume [m3/(min*m)]
Standard double large bubble veil (DGBS)					
1	Inner Bubble veil	810	~ 128	24 Compressors in the Use plus 2 reserve	0,5
2	Outer large bubble veil	1.080	~ 170		
Shortened double large bubble veil (DGBS)					
3	Inner bubble curtain	810	~ 128	24 Compressors in use plus 2 reserve	0,5
4	Outer large bubble veil	930	~ 148		
Triple large bubble veil (TGBS)					
5	Inner bubble curtain	810	~ 128	Up to 46 compressors are available	0,5
6	Outer large bubble veil	930	~ 148		
7	Outer large bubble veil	1.080	~ 170		
Enlarged double bubble curtain #1 (XL1-DGBS)					
8	Inner large bubble curtain	1.020	~ 162	Up to 46 compressors are available	0,5
9	Outer large bubble veil	1.260	~ 200		
Enlarged double bubble curtain #2 (XL2-DGBS)					
10	Inner large bubble curtain	1.020	~ 162	Up to 46 compressors are available	0,5
11	Outer large bubble veil	1.560	~ 250		
Enlarged double bubble curtain #3 (XL3-DGBS)					
12	Inner large bubble curtain	1.560	~ 200	Up to 46 compressors are available	0,5
13	Outer large bubble veil	1.800	~ 285		

4.3 Sound-optimised pile-driving process

Based on experience from previously completed construction projects in the German EEZ, a correspondingly large, latest-generation impact pile hammer was used in this construction project (IQIP hydraulic hammer S-4000). For noise-related reasons, an attempt was made to minimise the pile-driving energy used, so that the pile-driving hammer only had to be used with a total capacity of up to 70% if necessary. In addition, each impulse pile driving was carried out with a soft start (approx. 10% capacity of the pile hammer), based on individual impacts, followed by a so-called ramp-up procedure (simultaneous increase in pile driving energy and impact repetition frequency). Simultaneous underwater noise measurements in real time at a distance of 750 metres from the construction site enable active feedback of the hammer deployment and the resulting noise emissions.

Note: Due to the research nature of the project, the noise-optimised pile-driving process was not used for most of the new R&D monopile installations in order to be able to investigate the effectiveness of the new PULSE hammer technology at higher pile-driving energies. An attempt was made to keep the maximum pile-driving energy used comparable for all R&D monopile installations as long as the pile-driving process permitted this.

4.4 Soft start

With a soft start, pile-driving is carried out at approx. 10% of the pile-driving capacity for approx. 10 minutes before continuous pulse pile-driving is carried out to the final depth. The soft start ensures a two-stage deterrence concept for the noise-intensive construction activities.

4.5 PULSE system

The most common installation method currently used for offshore foundations is impulse driving using a hydraulic hammer. In this process, individual blows (impulses) are applied to the pile head by the pile hammer, which are used to drive the pile into the ground. However, part of this transferred energy is also emitted from the pile as sound into the surrounding water (so-called pile driving sound).

In the so-called blue piling concept, the energy transmission is extended in time and the peak amplitude is reduced, i.e. the same energy transmission, only in a different time.

The hammer transmits a significantly longer time to the pile head. Colloquially, you could say that the pile is not driven in, but rather "pressed in". By reducing the (peak) amplitudes, the sound input from the pile to be driven in the water is also significantly lower. However, an initial offshore test has shown that this hammer technology is more suitable for very large piles (diameter > 10 metres) and that the technology is not yet fully operational under offshore conditions. The principle of the blue piling hammer was subsequently adopted by the impulse pile hammer manufacturer *IQIP B.V.* and is currently undergoing further development.

Independently of this, *IQIP B.V.* has developed a type of spring-damper unit for its currently largest hydraulic hammer (S4000 pile hammer) - the PULSE unit. This additional hammer technology is integrated between the pile hammer and the anvil and has the effect of reducing the amplitude of the blow and simultaneously lengthening it. It is therefore a comparable technology to blue piling, except that the reduction of the (peak) amplitude and the pulse extension with the PULSE unit will not be as pronounced as is expected with blue piling. The PULSE spring-damper unit can be configured by adding water and can therefore actively influence the pulse lengthening to be achieved (and thus also the resulting sound reduction). At a water level of 100%, corresponding to a water level of 80 cm, the pulse lengthening should be maximised.

The PULSE unit with the S4000 hydraulic hammer is ready for use, but has not yet been tested offshore, so there are no reliable statements regarding the noise reduction that can be achieved with this new hammer technology. It is also likely that the spring-damper unit will cause losses in the pile-driving energy produced by the hammer as the water level increases (spring-damper ratio).

5. deterrence

To ensure that no marine mammals are harmed by the pile-driving noise in the vicinity of the foundations, they must be deterred from an area of at least 750 metres around the construction site before the installation work begins (in this case by means of impulse pile-driving).

In this construction project, Acoustic Porpoise Deterrent (APD) devices from the company *SEAMARCO* from on board the *ORION* installation vessel.

Note: The companies Van Oord Offshore B.V. and Seamarco have jointly developed and tested a deterrent device specifically for harbour porpoises, fish, seals and turtles with different frequencies and sound levels. With the help of these modules, individual animal species can be specifically deterred from an endangered area based on the selected frequency ranges and sound levels. Van Oord Offshore has transferred the rights to this deterrent device to ACE Aquatec, which offers this system on the market as FaunaGuard Porpoise. The company Seamarco sells a comparable deterrent device called Acoustic Porpoise Deterrent (APD).

The frequencies generated by both of the above-mentioned harbour porpoise deterrent devices range from 40°kHz to 120°kHz. The sound power is gradually increased in the first five minutes to give the animals the opportunity to move away from the noise source in good time (at least 750°m) before the maximum sound power of the deterrent devices is reached. The signals emitted by the device in all directions are not constant sounds, but more complex noises with different lengths and varying distances. This is intended to prevent the animals from quickly becoming accustomed to the disturbing noise. In accordance with the state of the art on the part of the BSH, deterrence was carried out for 30 minutes prior to installation using pulse ramming.

The bubble curtain used for impulse pile driving may only be switched on approx. 10°min. before the soft start so that the amplitude of the high-frequency sound input from the deterrent device is not reduced by the bubble curtain. The deterrent device must be deactivated no later than 5°min. after the soft start during impulse pile driving to avoid further adaptations. In addition, the discouragement measure was documented.

If pile-driving is interrupted for more than 40°min., the BSH requires a new deterrent measure to be taken before pile-driving is resumed.

For the three R&D monopiles C03, G03 and C04 using only the new hammer technology PULSE unit, a SealScarer from *ORION* was also introduced into the water in addition to the APD system in order to increase the displacement radius of the deterrent during the three test and reference measurements.

6. Measurement concept and implementation

6.1 Specification of the measuring devices used

Different types of measuring system were used to record the noise input into the water during the impulse pile driving, which are explained in more detail below.

All underwater sound recordings were carried out in accordance with standards within this arrangement using a hydrophone at a height of around 2°m above the seabed (BSH, 2011) and (ISO 18406, 2017).

Underwater noise measuring devices of the "WiFi-Online" type

Underwater noise online monitoring: Real-time monitoring was carried out during the pile-driving work. For this purpose, an autonomous online underwater noise measuring device was used at a distance of approx. 750 m and 2,000 m from the pile-driving site with a hydrophone (approx. 2°m above the seabed) and a transmitter unit. During monitoring, the single event level (SEL) and the peak level ($L_{p,pk}$) were calculated for each pile-driving impact and communicated to the installation vessel (Figure 2 and Figure 3).

Figure 2: Hydroacoustic online monitoring system.

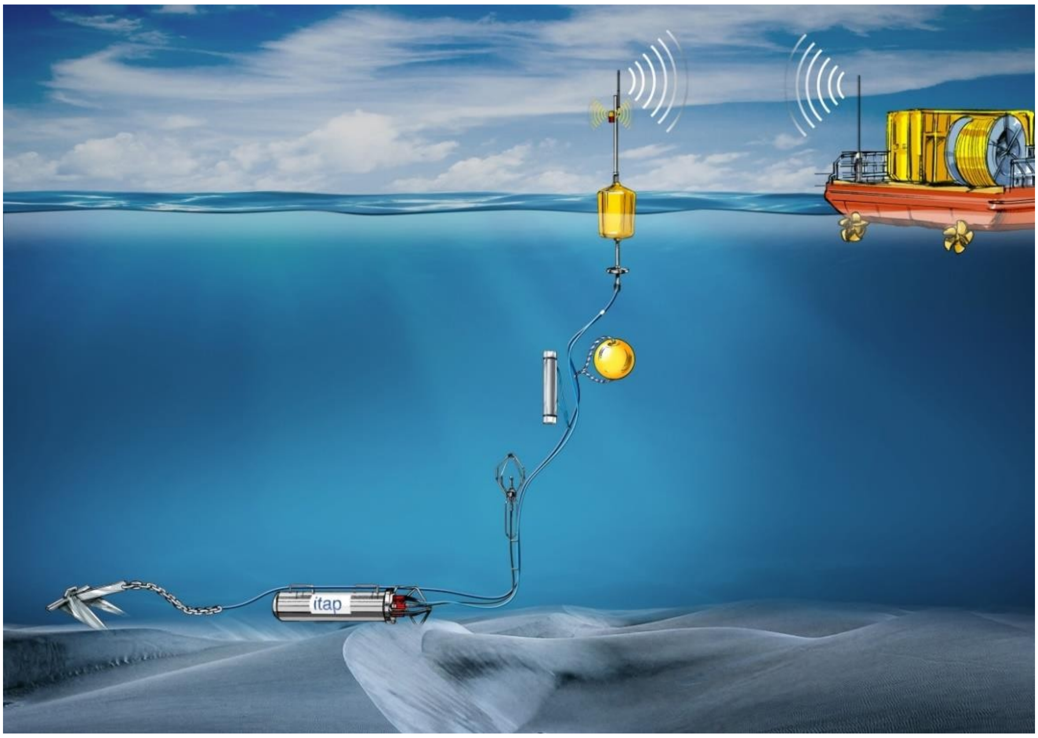


Figure 3: Schematic drawing of an online monitoring system combined with a C-POD. The measuring tube of the system lies on the seabed and the hydrophone and the C-POD are held at the intended height by floats. The buoy is connected to the measuring tube via a signalling cable.

Underwater noise measuring devices of the "Offline" type

The underwater sound recording is carried out within this arrangement using a hydrophone at a height of around 2 metres above the seabed. The measuring height is based on (ISO 18406 2017). The autonomously operating measuring devices for recording underwater sound were developed and built *by itap GmbH.*

The entire measuring sensors and power supply for the underwater sound measuring devices are located in the respective submersible body, which also serves as a weight anchor. Connected to this is the hydrophone, which is held about 2 metres above the seabed by a floating body. All underwater sound measuring devices used continuously record the time signals (in relation to the sound pressure curve) of the underwater sounds (hydro sound) and are stored uncompressed in PCM WAVE format or compressed in MPEG1 audio layer 3.

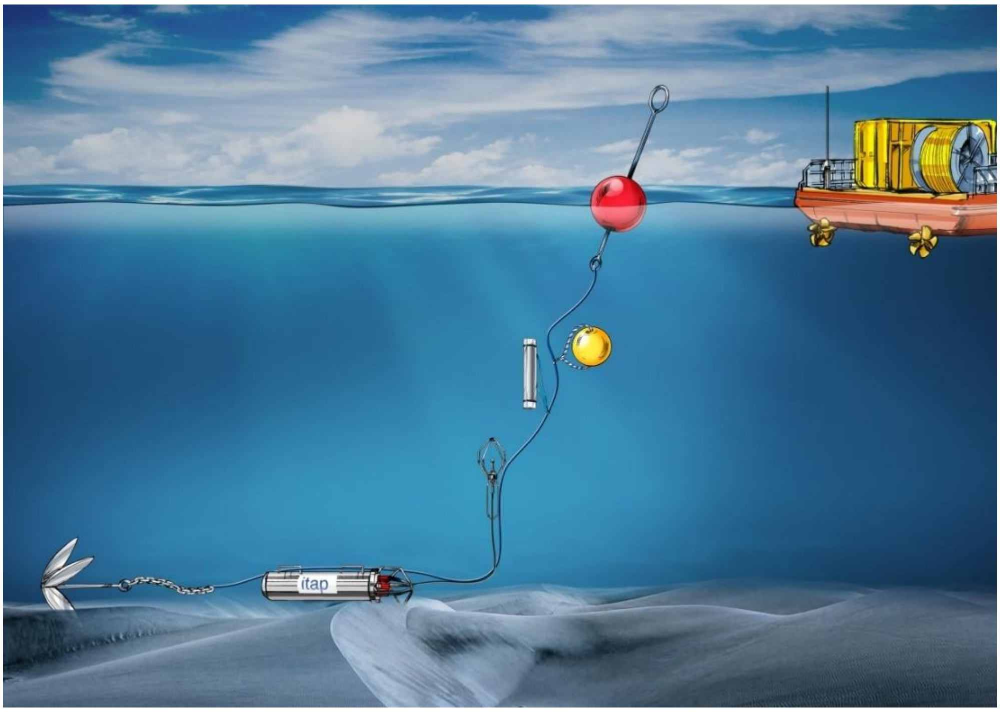


Figure 4: Schematic diagram of an offline recorder system with a small anchor. The hydrophone and a C-POD are held at the intended height on the cable by a float.

List of measuring devices

Table 2 lists all the devices used for this measurement project. All systems listed fulfil the requirements of (ISO 18406 2017) and (DIN 45653 2017).

Table 2: Devices used for the underwater sound measurements incl. calibration devices.

Device	**Manufacturer**	**Relevant technical info**	**Comments**
Underwater measuring device "online"	itap	Frequency range: 10 Hz - 24 kHz	Sampling frequency: 48 kHz 24 bit
Underwater measuring device "offline"	itap	10°Hz - 22°kHz	Sampling frequency: 44.1 kHz 24 bit
Pressure chamber for calibrating the hydrophones	itap	250 Hz, 154 and 171 dB re 1µPa adjustable	
GRAS 46AG: According to ISO/IEC 17025 (DAkkS) calibrated microphone as Reference in pressurised chamber	G.R.A.S.	13.55 mV/Pa @ 250 Hz	Calibration according to IEC 17025
U1610A: DKD-calibrated digital multimeter + Oscilloscope	Agilent		

6.2 Measurement concept

Standard measurements according to BSH measurement regulations (2011)

The underwater noise measurements were carried out and analysed for all impulse pile driving of the monopiles in accordance with the planning approval decision in accordance with the measurement regulations for underwater noise (BSH 2011), (ISO 18406 2017) and the planning approval decision.

The measurement concept comprises in detail

- One hydrophone each at a distance of 750 m and 2,000 m from the respective pile-driving site (mobile measuring positions). These hydrophones are deployed before the start of installation by means of impulse pile driving and before the deterrence measures are deployed and ends immediately after installation.

Test and reference measurements according to DIN SPEC 45653 (2017)

Test and reference measurements in accordance with (DIN 45653 2017) and (BSH 2013) were planned and carried out in coordination with the responsible authorities to evaluate the noise protection systems used and the PULSE unit noise reduction measure as part of the R&D project. In addition to the two mobile underwater noise measurement systems, up to four further systems were deployed within a radius of up to 2,000 metres. The total of six underwater sound measuring devices were deployed in four different spatial directions to the monopile in order to be able to analyse the directional effect of sound propagation (see Figure 5 for an example).

Determination of the project-specific propagation attenuation

To determine the project-specific propagation attenuation, additional underwater noise measurements were carried out at distances of between 250 m and 10,000 m from the respective R&D monopile (see Figure 6 for an example).

In addition, additional C-POD and underwater sound measurements were carried out at the last 12 monopile installations at intervals of 750 to 5,000 and 10,000 metres.

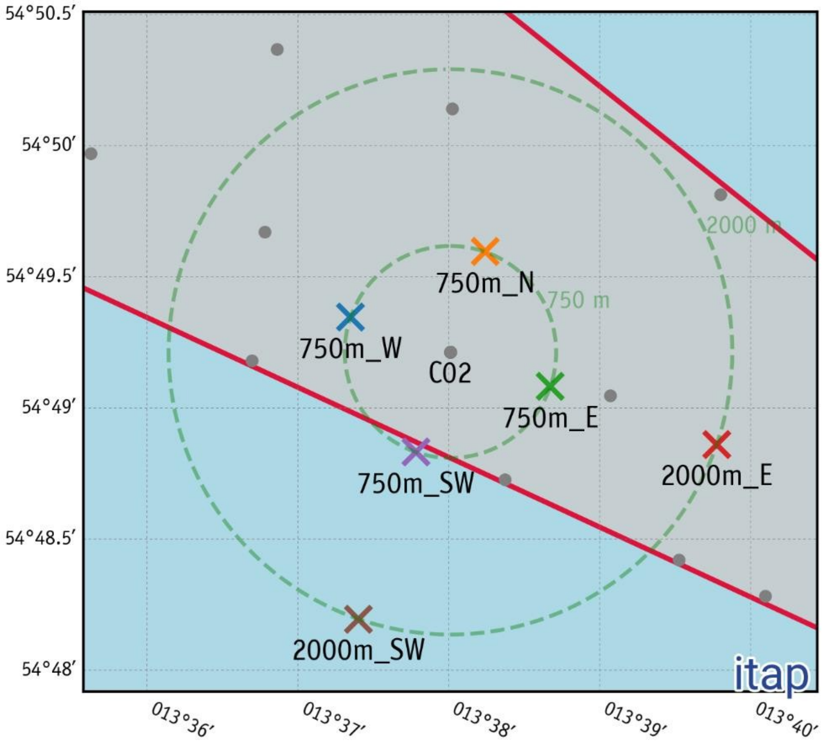


Figure 5: ***The measurement positions of the measurement systems are shown at a distance of 750 m and 2.000 m to the foundation C02.***

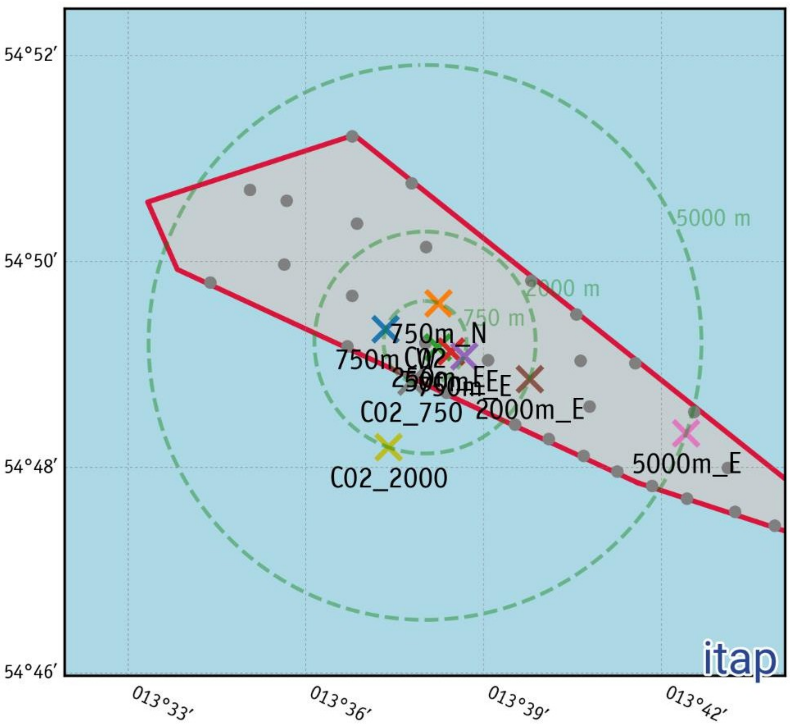


Figure 6: ***The measurement positions of the underwater noise measurement systems are shown at a distance of 250 m***

up to 5,000 m to the R&D foundation C02 to determine the project-specific propagation attenuation.

6.3 Realisation at sea

The hydro-sound emissions were recorded during the pile-driving work at a distance of 750 m and 2,000 m at a height of approx. 2 m above the ground using autonomous, remote measuring systems. The measurements required for efficiency control at 750 and 2,000 metres in one spatial direction were deployed and recovered by employees of *itap GmbH* from the DGBS escort vessel *Sar Brage*. The additional measurement systems for the R&D campaign were designed and the measurement data analysed by the research vessel *Viking Energy* by employees of *itap GmbH*. For the additional measurements at the last 12 monopile installations, additional measuring systems (underwater sound and C-PODs - not part of this report) were deployed and recovered by *itap GmbH* employees from the escort vessel *Arne Tiselius*.

The measurement positions and the remote hydro sound measurement devices fulfil the requirements of StUK4 (Standard, Investigation of the effects of offshore wind turbines on the marine environment, 2013), the measurement regulations for underwater sound measurements of the Federal Maritime and Hydrographic Agency (BSH, 2011) and DIN SPEC 45653 (2017).

The positions of the foundations and the times at which they were driven can be found in Table 7 in the Appendix, Chapter 10.1. The pile-driving times given refer to the times recorded by the measuring systems. Synchronisation with the clock of the pile hammer was not carried out. In addition, the coordinates of the hydro sound measurement systems used are summarised.

6.4 Evaluation concept

All hydrophone signals are available as single-channel time signals (MPEG1 audio layer 3 or PCM WAVE files). They were recorded by the autonomous, remote measuring systems with a sampling frequency of f_S = 44.1 kHz or 48 kHz.

The individual event levels were determined in a single impact analysis in accordance with the specifications of the measurement regulations for underwater noise (BSH, 2011), in which each pulse is analysed individually as soon as the signal-to-noise ratio is greater than 10 dB. For the presentation of the results, the one-third octave spectra are limited to the frequency range from 12.5 Hz to 16 kHz.

For documentation purposes, the following parameters are listed in accordance with the BSH measurement specifications (2011):

- $_{SPL5s}$= Energetic mean value of the continuous sound level over 5 seconds.
- $_{SEL90}$ or $_{L90}$ = percentile level of the single impact analysis of the single event level that was exceeded in 90% of all pile driving impacts over the time interval under consideration.
- $_{SEL50}$ or $_{L50}$= % level of the single impact analysis of the single event level that was exceeded in 50% of all pile-driving impacts over the time interval under consideration.
- $_{SEL05}$ or $_{L05}$ = Percentile level of the single impact analysis of the single event level that was exceeded in 5% of all pile-driving impacts over the time interval under consideration.
- $Lp_{,pk}$= Maximum peak level (zero-to-peak in magnitude) of the single beat analysis.

All analyses were carried out using the company's own audited software from *itap GmbH.* "IONIS" (vers. 0.6.2).

Note: Based on the requirements of the BSH, pile-driving with an interruption of at least 40 minutes is divided into individual pile-driving intervals and analysed separately.

6.5 Measurement uncertainty and measurement variance

According to the BSH's measurement concept for underwater noise measurements (BSH, 2011) and (ISO 18406, 2017), only measurement systems whose entire measurement chain has a maximum sensitivity deviation of ± 1 dB may be used. The measuring systems used fulfil these requirements and have a high reproducibility of ≤ ± 1 dB with regard to the hydrophones and the electrical measuring chain. Furthermore, the hydrophones used are regularly subjected to an internal calibration.

As a rule, however, an unsystematic measurement uncertainty in the range of ≥ 2 dB is to be expected for field measurements in the offshore area, even in calm seas (unpublished measurement data from *itap GmbH* from recent years). A systematic study on this topic is currently not available.

During the construction phase, it became apparent that the measured single event levels (SEL) over the driving of a pile sometimes differed considerably from one another. These differences are not due to systematic or unsystematic measurement uncertainties, but can be attributed in part to the driving energy used.

Measurement results from the construction monitoring of other offshore wind farms show that the stratification and the components of the sediment can also have a significant influence on the underwater noise emitted. Whether and to what extent other parameters have an influence is being investigated. These differences in the measurement results are therefore to be regarded as measurement variance and not as measurement uncertainty.

6.6 Metrological traceability

To ensure valid measurement results, it is necessary that the measurement systems used are calibrated at fixed intervals using reference standards that can be traced back to international or national measurement standards. In addition, a functional test of the measurement systems is necessary before and after each offshore measurement deployment in order to rule out defects during the measurements.

Taking into account the accreditation according to ISO/IEC 17025, a DKD (German Calibration Service) compliant calibration of the entire underwater sound measurement chain (hydrophone + amplifier and memory electronics, sound card) is carried out using a pressure chamber (measured variable: sound pressure level) in combination with a reference microphone. The reference microphone is traced back to the national standard (DKD calibration). All hydrophones used in the underwater sound measurements are calibrated at regular intervals in accordance with (ISO 17025 2017). In addition to this DKD-compliant calibration, the hydrophones used undergo a functional check in the form of electrical impedance spectroscopy before and after each use (May 2018).

All measuring systems used were subjected to a visual inspection and an electrical function test before and after the individual offshore deployments. No unauthorised deviations were found.

The entire calibration procedure was recognised by the German Accreditation Body (DAkkS) in February 2019 as standard-compliant, metrological traceability in accordance with (ISO 17025 2017).

6.7 Technical problems and failures of measuring systems

Table 3 lists all measuring systems that showed anomalies before, during or after the measurement mission. These anomalies were identified by means of control tests before and after the measurements at sea or during the detailed analysis of the raw measurement data. Until final clarification of the data quality, the measurement data from the conspicuous measurement systems were classified as "not valid" and were therefore not

are included in the following analyses.

Table 3: List of measurement systems that were taken out of active operation for analysis at itap GmbH due to anomalies before, during or after measurement operation.

Measuring system	date	Type of defect	Analysis
MR-GD-B	01.07.2022	No raw data available.	Technical defect
MR-BT-5	17.06.2022	No raw data available.	Technical defect
MR-GY-F	17.06.2022	No raw data available.	Technical defect
MR-GC-4	05.07.2022	No raw data available.	Technical defect
MR-GQ-1	22.07.2022	No raw data available.	Technical defect

7. Results

7.1 General

The measurement is carried out and analysed in accordance with StUK4 (StUK 4 2013) and the measurement regulations for underwater noise measurements (BSH 2011) in accordance with the procedure described in chapter
6.4 evaluation concept described above.

7.2 Display of the measurement results in 750 and 2,000°m

As examples, Figure 7 to Figure 10 show the temporal progression of the acoustic parameters single event level (SEL), peak level ($Lp_{,pk}$) and continuous sound level ($_{SPL5s}$), the spectrogram of the continuous sound level ($SPL5s_{, 1/3\ octave}$) and the percentile levels resulting from the single event levels (SEL) in 1/3 octaves for a measurement position at approx. 750 m at foundation site OSS (foundation site #1) with the HSD system and the DGBS in conjunction with the PULSE unit ($_{P100\%}$). Such time histories, spectrograms and the frequency-resolved percentile levels were presented in separate brief reports for all measurement positions within the construction site (750 m and 2,000 m).

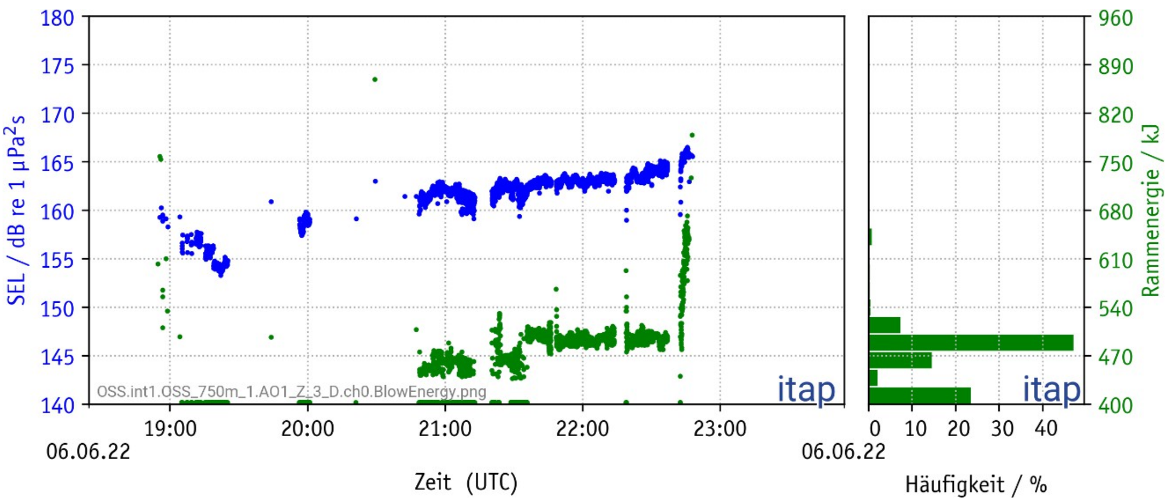


Figure 7: Time course of the single event level (SEL, blue) and the pile-driving energy (green) at the foundation OSS at a distance of approx. 750 metres. The distribution of pile-driving impacts is shown in a histogram on the right. Deviations in the times between the pile-driving log and the underwater sound measurement of a few minutes are possible due to the lack of time synchronisation.

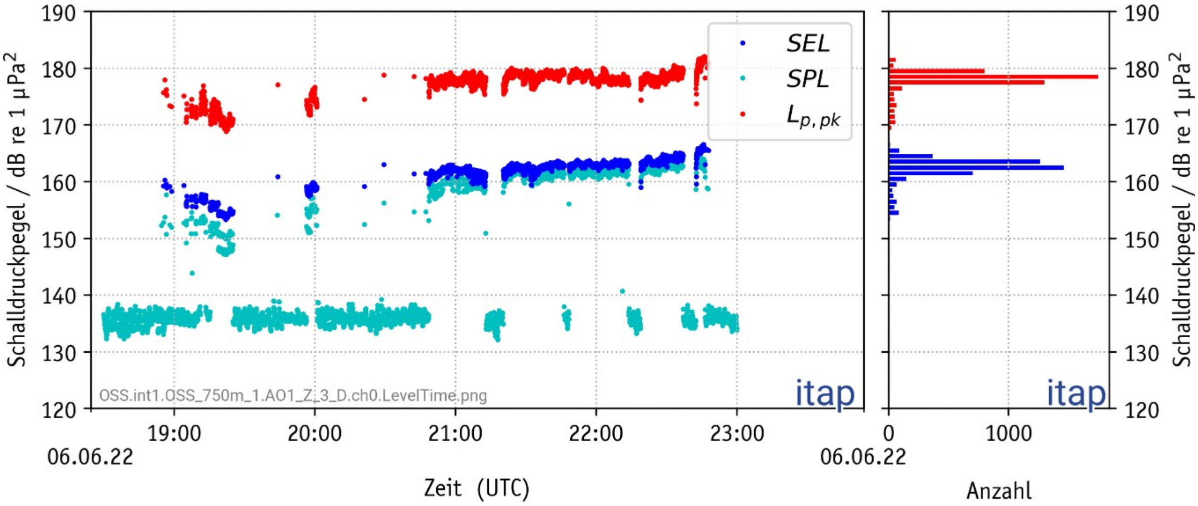


Figure 8: ***Time course of the sound pressure levels at a distance of approx. 750 m from the OSS blue foundation:***
Single event level (SEL), cyan: continuous sound pressure level (SPL5s) and red: peak level (Lp,pk). Right
the distributions of the single event level and the peak level are shown in a histogram.

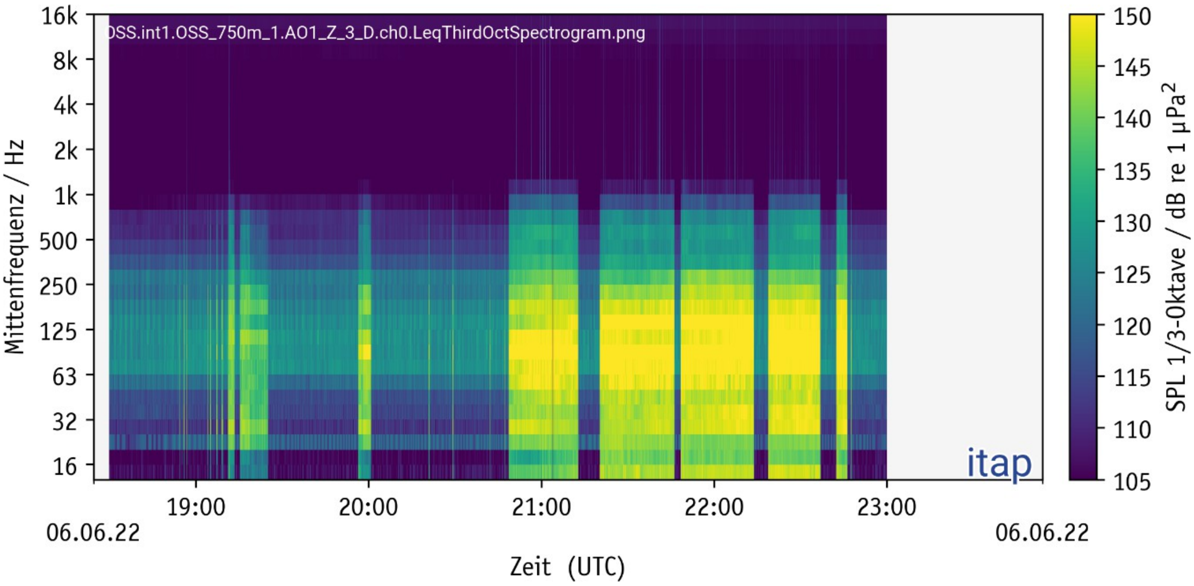


Figure 9: ***Spectrogram of the average sound pressure level (SPL5s) at the OSS foundation at a distance of approx. 750 m***
in 1/3 octaves.

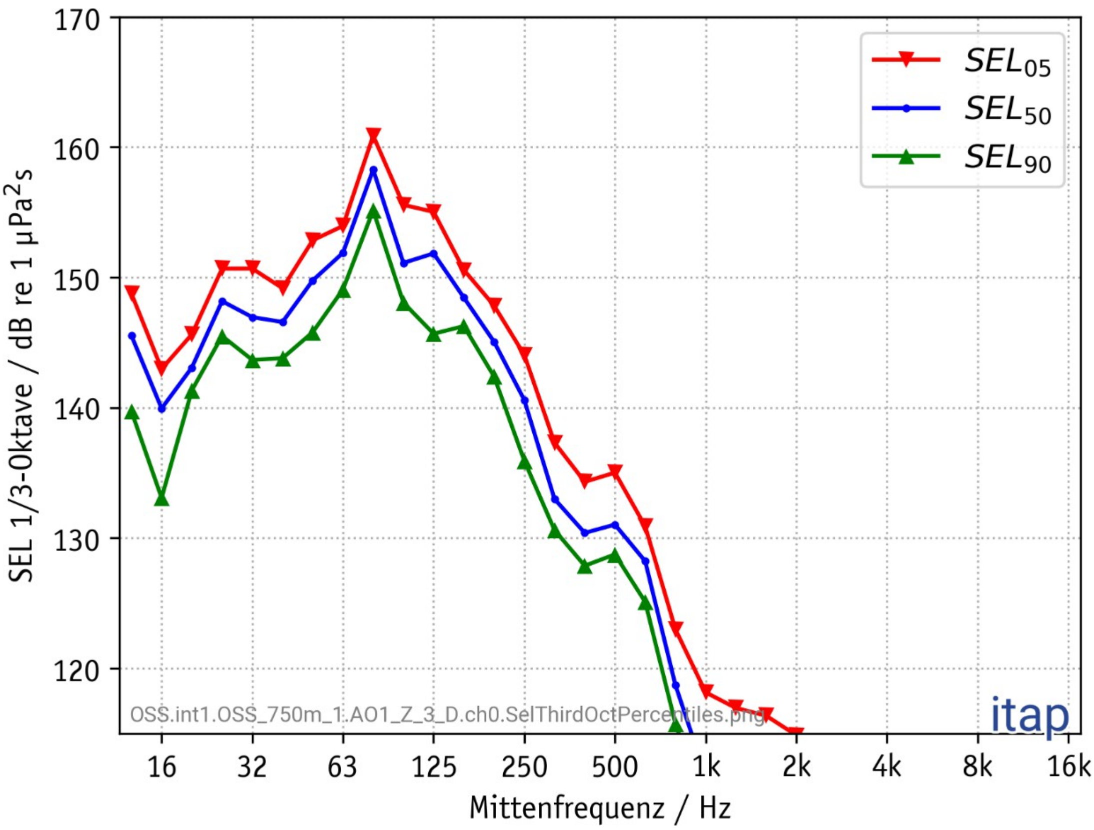


Figure 10: 1/3-octave representation (one-third octave spectrum) of the single event level at the OSS foundation at a distance of approx. 750 m.

Figure 11 shows the mean single event levels for the 95% exceedance percentile of the single event level at a distance of 750 m and Figure 12 for the 2,000 m measurement position. A more detailed overview including all level statistics is shown in Table 8 for all measurements at a distance of 750 m, Table 9 for all measurements at a distance of 2,000 m and Table 10 for all measurements at a distance of >2,000 m in the appendix. The time histories of the measured variables described can be found in the preceding brief reports for each monopole.

At the R&D monopile locations, so-called test and reference measurements were carried out in coordination with the responsible authorities without or with reduced noise reduction measures in accordance with DIN SPEC 45653; see concept Table 4 and results in the separate R&D report (Bellmann, Brüers, et al. 2022). For these locations, up to four measurement positions at 750 m and up to two measurement positions at
2,000 m in order to be able to analyse the directional dependency. If several measurement positions were deployed at 750 m, the mean value with variance is shown for the single event level and the peak level.

Table 4: Coordinated noise protection concept for the research project to test the new pile driving hammer technology R&D PULSE (Bellmann, 2021), including two R&D monopile installations within the research project (OSS, C01)(1).

R&D no.	Stake	PULSE	HSD	DGBS	Lin. BBC	Comment	Water depth [m]	Pile length [m]
0	OSS	Yes	Yes	Yes	No	Int. 1 PULSE 50% Int. 2 PULSE 0%	-44	110
1	C03	Yes	No	No	Yes	PULSE 0%	-44	107
2	G03	Yes	No	No	Yes	Int. 1: PULSE 50% Int. 2: PULSE 100%	-43	101
3	G02	Yes	No	Yes	No	PULSE 100%	-43	102
4	C04	Yes	No	No	Yes	PULSE 100%	-45	107
5	C01	Yes	Yes	Yes	No	PULSE 0%	-44	104
6	D04	Yes	No	Yes	No	Int. 1: PULSE 100% Int. 2: PULSE 50%	-45	108
7	B04	Yes	Yes	No	No	PULSE 100%	-45	107
8	F01	Yes	Yes	Yes	No	PULSE 100%	-43	101
9	C02[1]	No	Yes	Yes	No	–	-44	106
10	F03[1]	No	Yes	Yes	No	–	-43	100

[1]*Due to a technical defect in the PULSE unit, it was completely removed after seven of nine R&D monopiles for safety reasons. In addition, due to unexpected ground conditions at individual OWTG locations, the actual R&D PULSE pile-driving plan with and without noise protection systems had to be adapted to these new boundary conditions.*
be customised. However, this expansion of the PULSE unit offers the unique opportunity to make a comparison between a S4000 pile hammer and an S4000 pile hammer with PULSE unit $_{P0\%}$. In addition, for further applications of the PULSE unit, it is also essential to evaluate the mode of action of the PULSE unit in a medium setting ($_{P50\%}$). In order to evaluate these modified pile driving conditions, the impulse pile driving on the two non-R&D monopiles of the OSS and the OWTG C01 were also included. However, the pile-driving without PULSE unit at the foundation locations C02 and F03 were additionally carried out with increased measurement effort at 250, 500, 5,000 and 10,000 m for underwater noise. The pile-driving at C02 without a PULSE system installed will provide information in direct comparison with C01 (pile-driving with PULSE $_{P0\%}$, HSD and DGBS) and F01 (pile-driving with PULSE P100%, HSD and DGBS) on the influence of the PULSE unit both on the broadband pile-driving noise and on the spectral composition of the pile-driving noise.

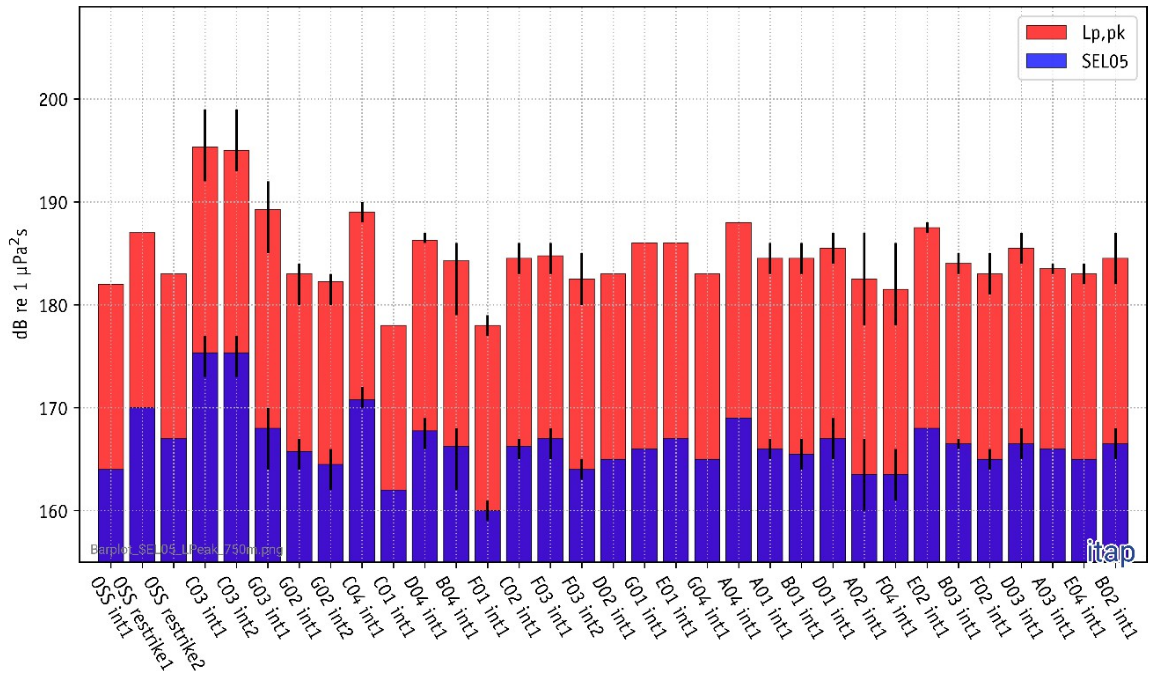


Figure 11: Results of the pulse ram method of efficiency control plus R&D projects and additional Measurements in the OWF Arcadis East 1 at a distance of 750 m. Indication of the mean values in $_{SEL05}$ and the $_{SEL05}$ minimum and maximum range for more than one measurement result per foundation. $Lp_{,pk}$ is shown in red and $_{SEL05}$ in blue.

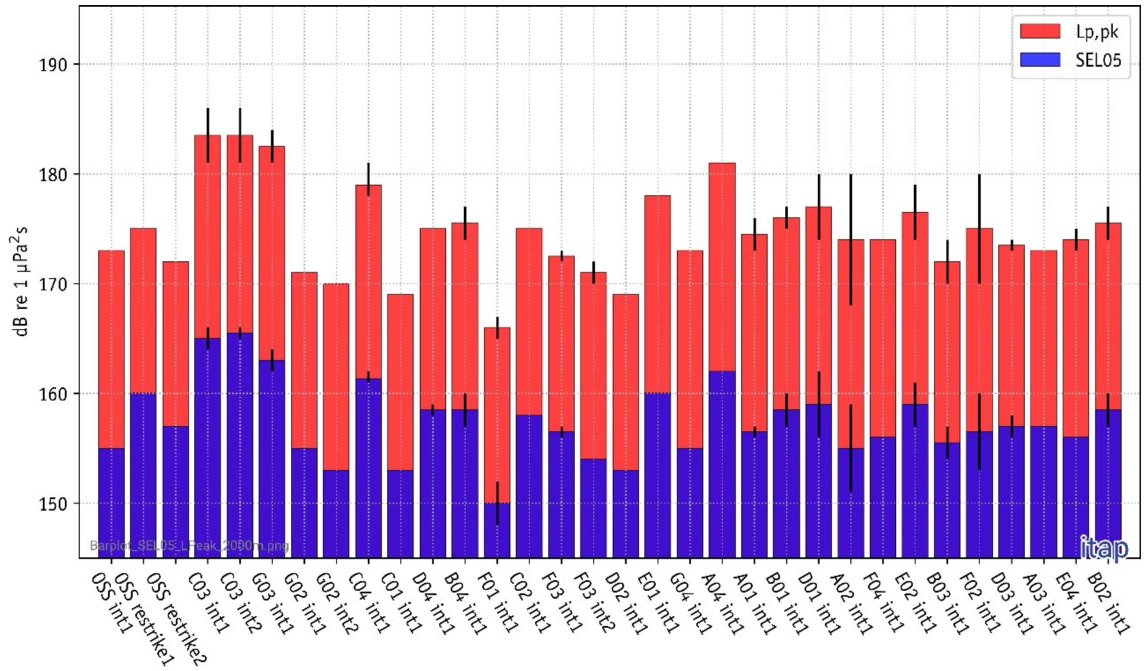


Figure 12: Results of the pulse ram method of efficiency control plus R&D projects and additional Measurements at OWF Arcadis East 1 at a distance of 2,000 m. Indication of the mean values in $_{SEL05}$ and the $_{SEL05}$ minimum and maximum range for more than one measurement result per foundation. $Lp_{,pk}$ is shown in red and $_{SEL05}$ in blue.

7.3 Project-specific propagation attenuation

As part of the PULSE R&D project and during the last 12 monopile installations, simultaneous underwater noise measurements were also carried out at distances of 250 m to 10,000 m in one direction from the pile-driving site.

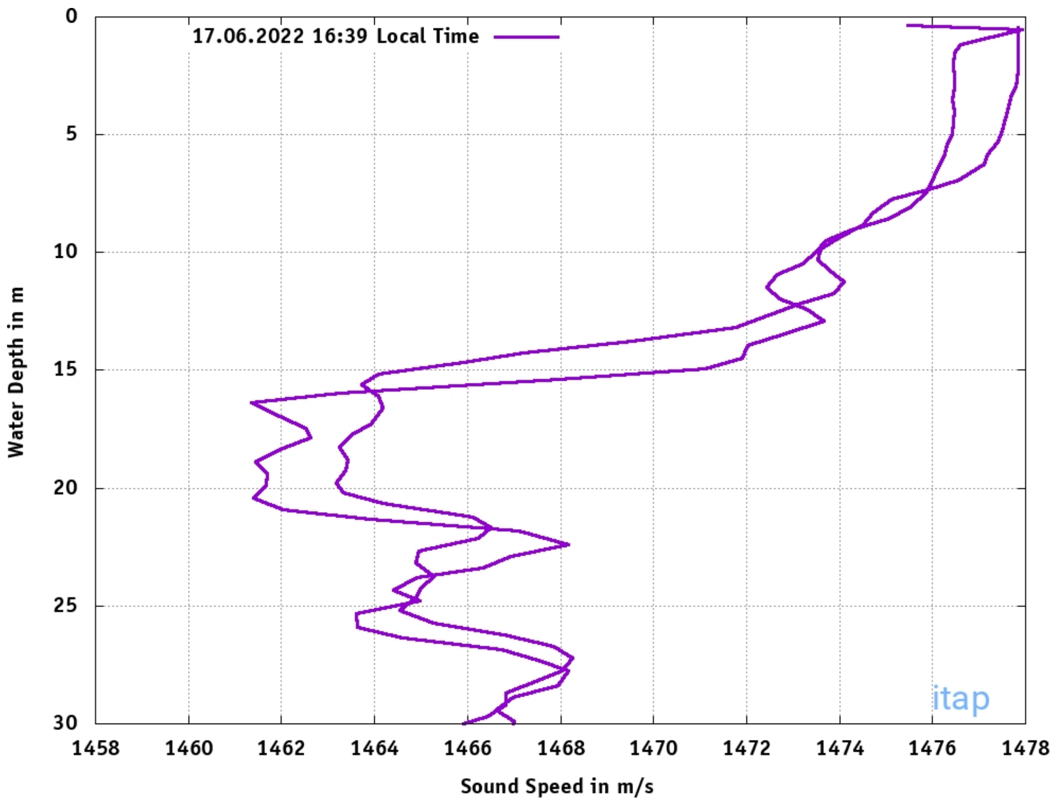
Based on the measurements along one transect per foundation installation at intervals of 250 m to max. 10,000 m, the project-specific sound propagation (transmission loss) in this part of the Baltic Sea is determined empirically. At the same time, the water temperature, water depth and salinity were measured at several measurement positions and over several days using a CTD probe and the sound velocity profile calculated from this; Figure 13.

The measurement data up to 10,000 m were used to determine the sound propagation attenuation and compared with those from the forecast (Bellmann, 2021b); see Figure 14.

A pronounced sound velocity profile is formed across the entire water column due to the long-lasting period of fair weather. As expected, such a sound velocity profile has no significant influence on low-frequency pile-driving noise (Bellmann et al., 2020).

Figure 14 clearly shows that the propagation attenuation in the *OWP Arcadis Ost 1* project area over distances of up to 5,000 m is significantly higher than known from the literature and from construction projects that have already been completed (e.g. Bellmann et al., 2020). I. d. R., a sound reduction per doubling of distance of approx. 4.5 dB (15*log10(distance)) can be expected up to a distance of approx. 8 km. In the case of sound propagation over greater distances, the additional absorption of the water also becomes apparent, so that the sound reduction becomes strongly non-linear at greater distances.

Based on the available measurement results, there is a sound reduction of approx. 4.5 dB per doubling of distance and a significantly stronger absorption factor in sound propagation even over shorter distances. This means that the impulse pile-driving sound has significantly shorter ranges than assumed in all previous forecasts. For example, the impulse pile-driving noise already increases over a distance of 5,000 m due to propagation attenuation. Based on measurement experience and literature data for propagation attenuation, a noise reduction of only approx. 12 dB up to 5,000 m was to be expected.



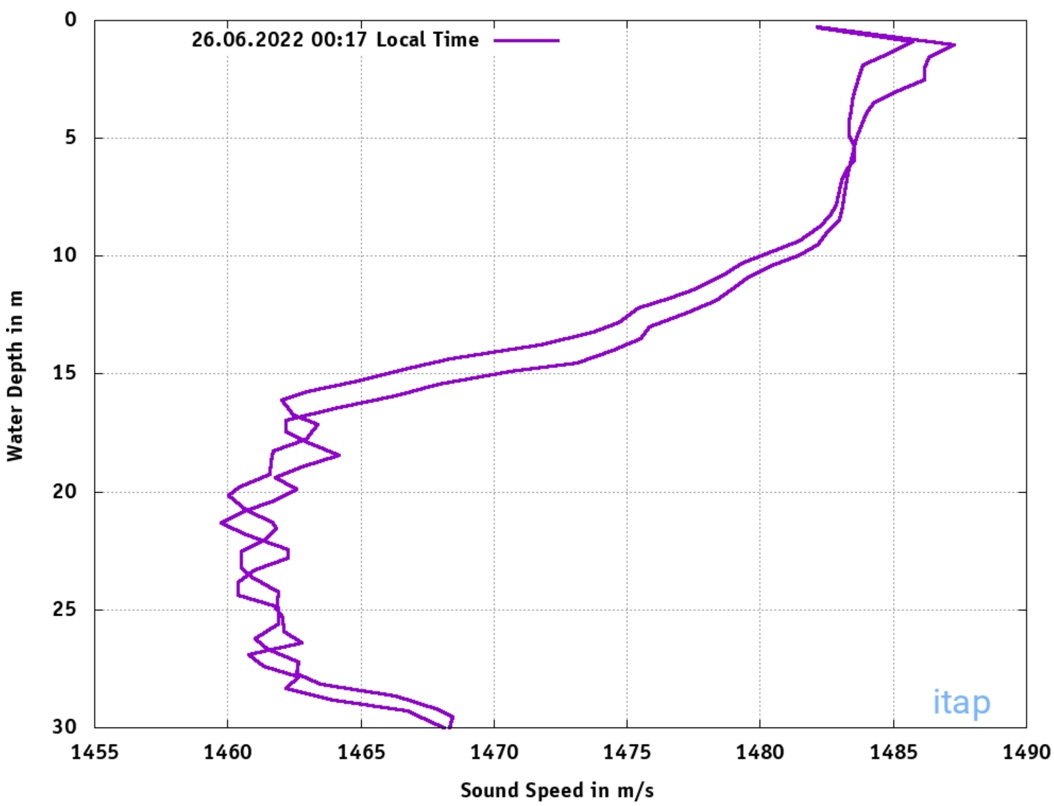


Figure 13: Sound velocity profiles measured at the measurement positions at 750 m with hydrophones in Water depths of 2, 10 and 20 m above the seabed: above: for G02 on 17 June 2022; below for B04 on 26 June 2022.

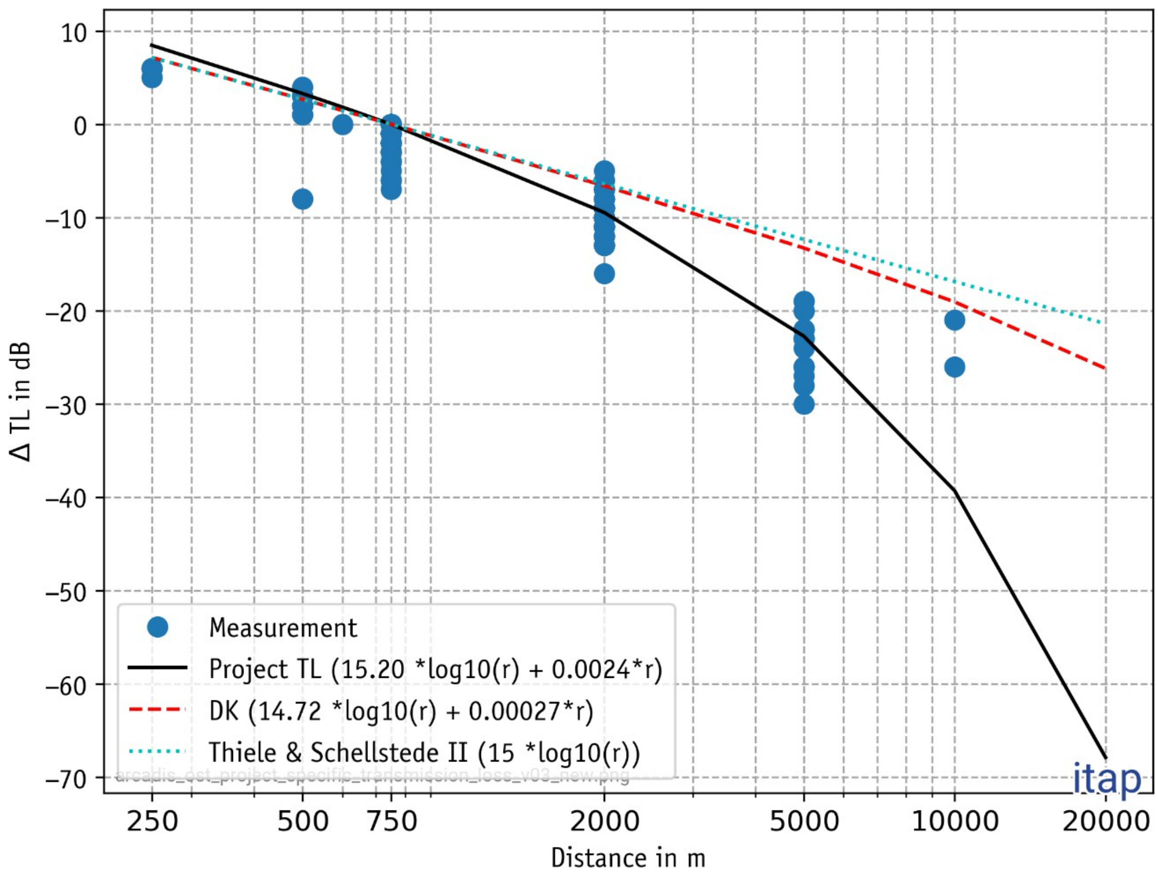


Figure 14: Illustration of the measurement results at distances between 250 m and 10,000 m and the project-specific sound propagation attenuation, based on all measurements carried out over the period of the project. This is compared with the validated propagation attenuations from the literature.

Interestingly, there are no further reductions in level between 5 and 10 km. For this reason, Figure 15 shows examples of the sound pressure levels over time at a distance of 5,000 m (top) and 10,000 m (bottom) from foundation F03.

At the measurement position at a distance of 5,000 m, each individual pile-driving impact still stands out clearly from the general background sound level (recognisable before and after the pile-driving by the SPL shown). A standard-compliant evaluation of the single event level SEL per pile-driving impact (SNR≥ 10 dB) is therefore possible. Although a few single event levels can be detected and calculated at the same time at a distance of 10,000 m, these can no longer be clearly linked to the pile driving. Based on the fluctuating background sound level (SPL), it can be assumed that one or more ships in the immediate vicinity passed the measurement position at the same time. This means that the impulse pile-driving noise in a distance of 10,000 m from the permanently present background noise level. It is therefore not possible to include the measurement results at a distance of 10 km when calculating the project-specific propagation attenuation.

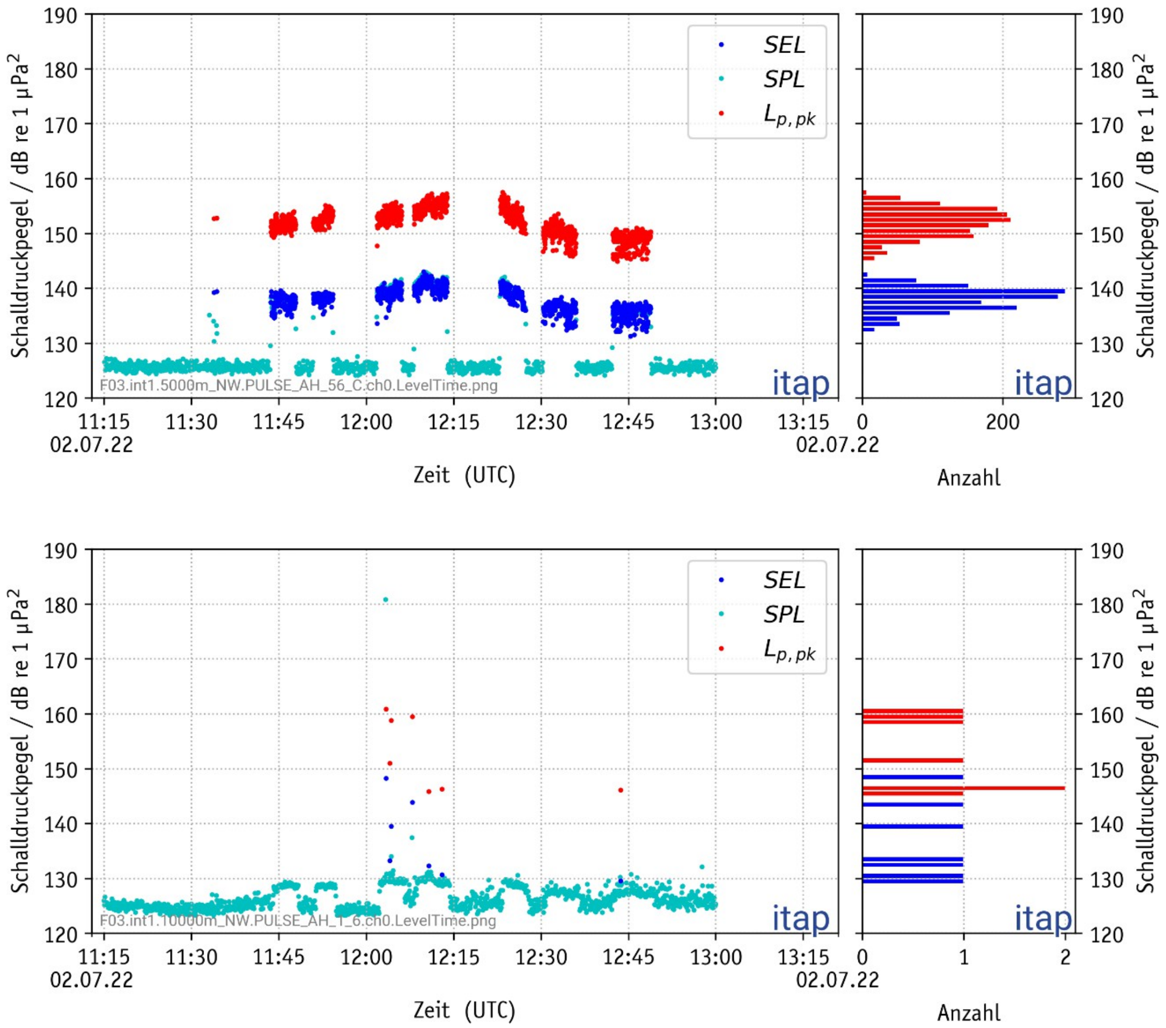


Figure 15: Time course of sound pressure levels at 5,000 m (top) and 10,000 m from the foundation F03: Blue: single event level (SEL), cyan: continuous sound pressure level ($_{SPL5s}$) and red: peak level ($Lp_{,pk}$). The distributions of the single event level and the peak level are shown in a histogram on the right.

7.4 Directionality

In some cases, there are differences of up to 5 dB in the measured underwater sound levels per monopile configuration and constant sound insulation configuration in different directions. As a rule, deviations in the measurement uncertainty range are not systematic and have already been measured in other, completed construction projects.

Figure 16 shows the direction-dependent, assessment-relevant single event levels SEL_{05} as relative level differences per monopile installation over several spatial directions for distances of 750 m and 2,000 m at a measurement height of 2 m above the seabed.

As expected, there are no systematic level differences in a single spatial direction, which could possibly be caused by the bathymetry.

In addition, an analysis was carried out to determine whether there were any shadowing effects from the *ORION* installation vessel on the impulse pile-driving noise. For this reason, the level differences at the same distance are summarised in Figure 17 as a function of the position of the *ORION*.

Figure 17 shows that, as expected, there is no particular accumulation of relative level differences at the measurement positions at 750 m and at 2,000 m in one spatial direction by the *ORION* installation vessel. The *ORION* has a draught of < 15 m with a water depth of at least 40 m.

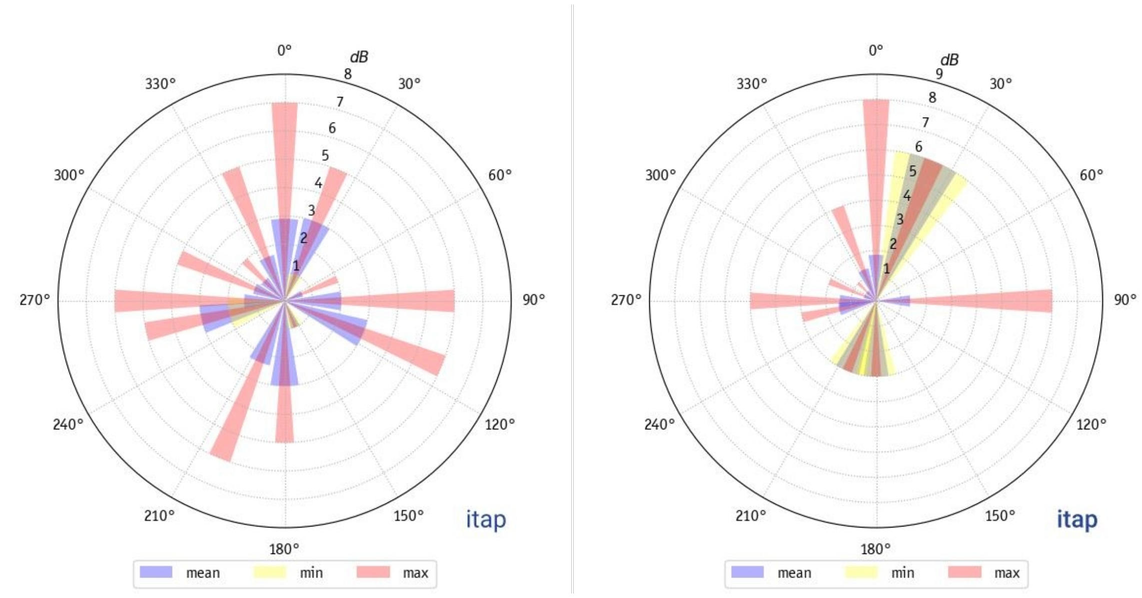


Figure 16: Direction-dependent, relative level differences (quietest direction per monopole installation and evaluated interval was taken as a reference) of the SEL05 relevant for the assessment for 750 m (left) and 2,000 m (right) measuring positions.

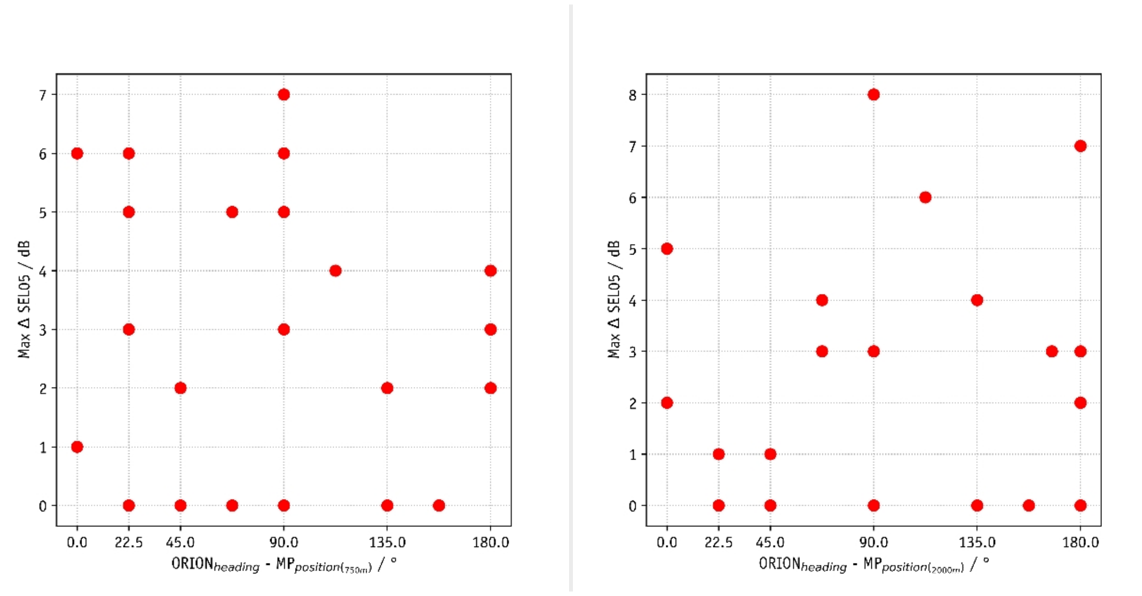


Figure 17: Max. relative level differences (quietest direction per monopole installation and analysed interval was taken as a reference), represented by the angular deviation between the installation vessel and the measurement position, for 750 m (left) and 2,000 m (right) measurement positions.

7.5 Ramming duration

Figure 18 shows the net pile-driving times for the individual foundations according to the pile-driving logs. The net pile-driving time describes the period in which the pile was actually driven.

The installation of the OSS took the longest, requiring almost 125 minutes net. With a diameter of 9.6 m and a embedment length of 67 m, this monopile was also by far the longest and heaviest monopile of the entire project. The OSS monopile also had to be installed in two sections to its final depth due to the difficult ground conditions and the first use of the PULSE unit at sea. The total time required to drive the other foundations was between 24 and 89 minutes.

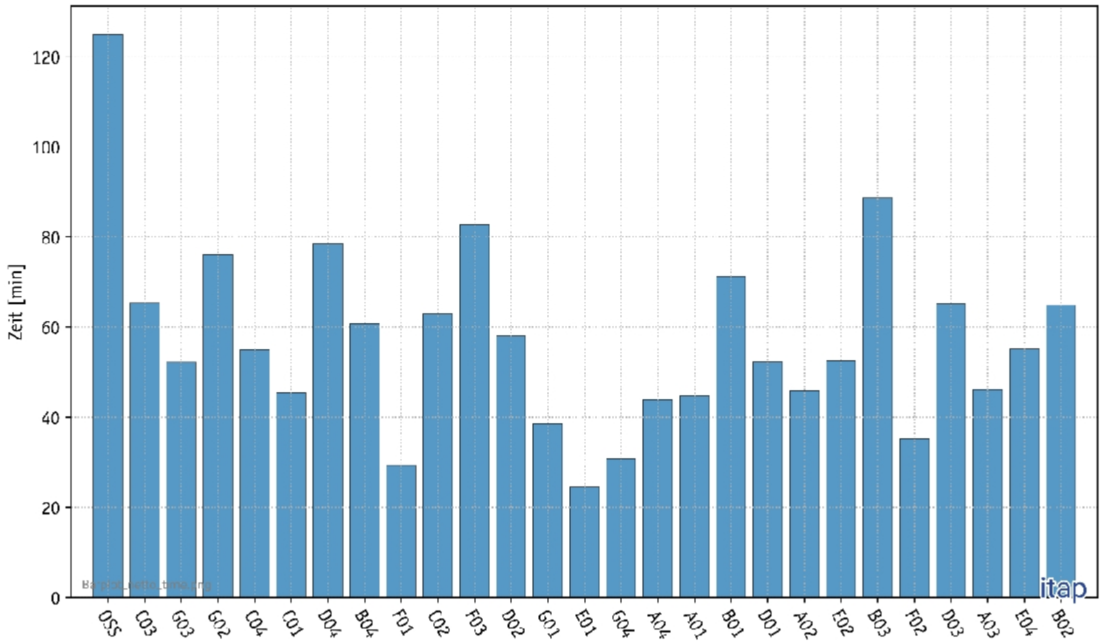


Figure 18: ***Net pile driving time (working time of the pile hammer without taking breaks into account).***

7.6 Ramming energy used

Due to isolated outliers in the pile-driving logs, the 99% percentile value of the pile-driving energy used was used for the following evaluation.

A so-called sound-optimised pile driving method was used for all impulse pile driving. The maximum pile-driving energy used and the $_{SEL05}$ levels measured are shown in Figure 19.

Particular attention was paid to the use of a noise-optimised pile-driving process after the demobilisation of the new PULSE unit hammer technology according to Monopfahl #9,
This means that the pile-driving energy was only increased gradually when a pile refusal was imminent due to the increased soil resistance.

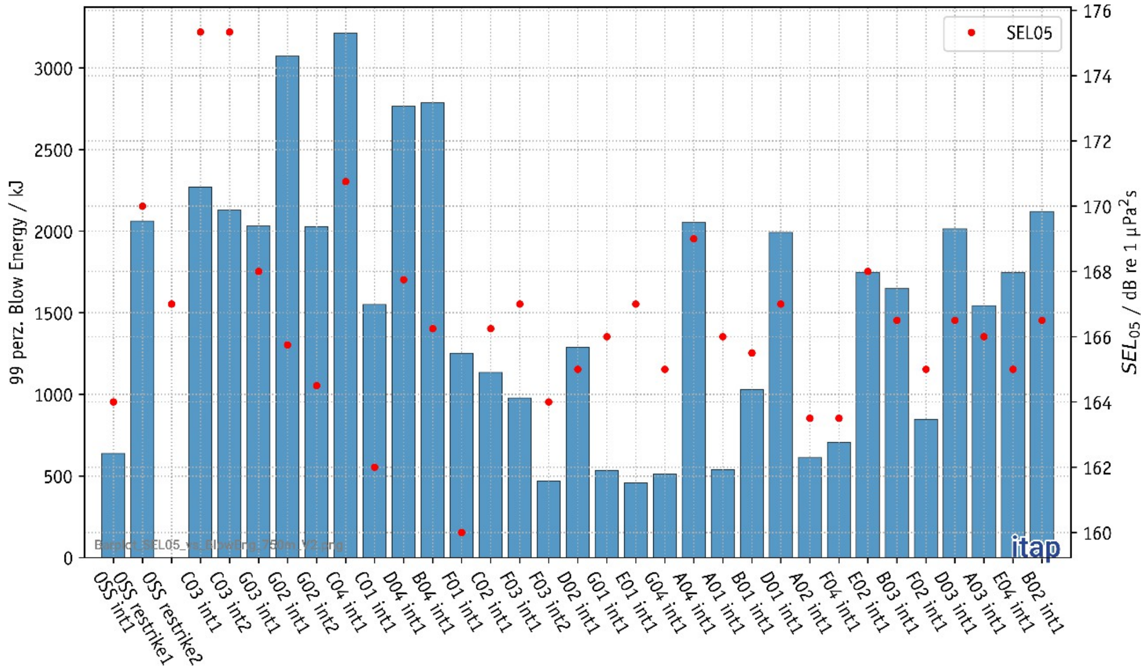


Figure 19: Illustration of the pile-driving energy with $_{SEL05}$ level at 750 m measurement position.

8. Assessment of the results of impulse pile driving

8.1 Assessment criteria

In order to protect marine fauna, it is necessary to minimise the noise input into the water during the noisy pile-driving work in order to avoid harming marine life through noise input. To this end, the BSH, with preliminary work by the Federal Environment Agency (UBA), set noise protection values for the single event level (SEL) of 160 $_{dBSEL}$ and for the peak level ($L_{p,pk}$) of 190 $dBL_{p,pk}$. These must be complied with at a distance of 750 metres from the piling site.

The 5% percentile level of the single event level ($_{SEL05}$) is decisive for compliance with the 160 $_{dBSEL}$ noise protection value, i.e. the $_{SEL05}$ must be≤ 160 dB at 750 m. These noise protection values have been developed in particular to protect harbour porpoises against temporary shifts in hearing thresholds. The noise protection value for the single event level $_{SEL05}$ is usually the more sensitive criterion during the installation of offshore wind turbines using the impulse pile driving method.

The pile-driving work should be completed within 180 minutes, including scaring and soft start per monopile installation (planning approval decision).

8.2 Compliance with the assessment criteria

The SEL05 levels measured at a distance of 750°m from the pile driving show that the noise protection value of 160°dB $_{SEL05}$ was exceeded for all impulse pile driving, except at F01 (159-161 dB at 750 m), with a combination of HSD system, different variants of double (DGBS), triple (TGBS) and enlarged (XL-DGBS) large bubble curtain and noise-optimised pile driving method as well as partial use of the new PULSE unit hammer technology.

The noise protection value for the peak level of 190 dB was met for all impulse pile driving, except for foundation C03 (R&D reference pile without noise protection).
At three R&D monopiles and another monopile (A01), the noise protection value of 160 dB was exceeded at a distance of 2,000 metres. In the case of the three R&D monopiles, this is due to the planned, reduced noise protection measures; at monopile A01, there were technical challenges with the noise protection systems used.

The net pile-driving time per OWTG monopile varied between 24 and 89 minutes including soft start and for the OSS monopile including soft start 125 minutes.

the OSS monopile could not be driven to its final depth within 180 metres. The monopiles C03 and G02 (reference and test monopiles) were each driven to their final depth in two sections. There were several hours between the two sections per monopile, which is why a separate 30-minute deterrence was carried out for each (pile-driving) section. Each individual (pile-driving) section complied with the 180-minute pile-driving time, but the overall installation of these two monopiles did not.

8.3 Comparison of the measurement results with the previous forecast

As the monopile diameter and the embedment depths for the *Arcadis Ost 1 OWP* are outside the measured empirical values (largest pile diameter installed to date in Germany 8.1 m; *Arcadis Ost 1:* 9.4 m for the OWTGs), numerical modelling was carried out with site-specific parameters. The specialist company *Jasco Applied Sciences* (Jasco) was commissioned by the licence holder to create a site-specific noise forecast. *Jasco*'s noise prediction model is an advanced numerical model that takes into account the physical properties of the impulse pile hammer used and the pile design. The model fulfils the requirements of the German supervisory authorities for waterborne noise modelling (BSH 2013). Reference is made here to the forecast report prepared by *Jasco* in the noise protection implementation plan (Van Es, et al. 2021), in which all input parameters and modelling assumptions are described and the details of the model are set out. The *Jasco* forecast also takes into account the special soil properties and the influences of various impact pile drivers.

Table 5: Results of Jasco's noise prediction without noise reduction systems (Van Es, et al. 2021).

Scenario	**Received SEL at 750 m (dB re 1µPa2s)**	**Received $L_{p,pk}$ at 750 m (dB re 1 µPa)**
A04 IQIP S-4000, 4000 kJ (no NMS)	175,0	196,1

Table 6: Predicted pile driving energy & scaled sound levels (Van Es, et al. 2021).

Ram energy [kJ]	Ram energy [%]	Number* of locations	SEL at 750 m [dB]	$Lp_{,pk}$ at 750 m [dB]
0 - 1.000	0 - 25%	0	139,0 - 169,0	160,1 - 190,1
1.000 - 2.000	25 - 50%	5	169,0 - 172,0	190,1 - 193,1
2.000 - 3.000	50 - 75%	5	172,0 - 173,8	193,1 - 194,9
3.000 - 4.000	75 - 100%	18	173,8 - 175,0	194,9 - 196,1

A comparison of the measured single event level (SEL) and the peak level ($Lp_{,pk}$) of the reference measurement (C03, $_{P0\%}$, without noise protection) with the predicted values from the forecast (Van Es, et al. 2021) shows a difference of up to 4 dB for the SEL and up to 6 dB for the $Lp_{,pk}$. The forecast underestimated the measured levels.

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10. Appendix

10.1 Underwater sound measurements: Locations and pile driving periods

Note: Due to the lack of time synchronisation of all construction site clocks, there may be deviations of a few minutes in the following times for different trades.

Table 7: Time and duration of the foundation installations by ORION. All times in UTC [dd.mm.yyyy HH:MM].

Foundation	WGS 84 [dd° mm, mmm']	Phase 1		Phase 2	
		Start	End	Start	End
OSS	54° 49,037′ N 013° 40,629′ E	06.06.2022 18:50	06.06.2022 22:47	Restrike: 10.06.2022 05:03	Restrike: 10.06.2022 05:24
C03	54° 49,672′ N 013° 36,780′ E	13.06.2022 14:15	13.06.2022 15:24	13.06.2022 23:45	14.06.2022 00:45
G03	54° 47,997′ N 013° 43,116′ E	15.06.2022 10:45	15:06:2022 13:00	-	-
G02	54° 48,542′ N 013° 42,553′ E	17.06.2022 07:07	17.06.2022 08:46	17.06.2022 13:06	17.06.2022 13:46
C04	54° 49,972′ N 013° 35,628′ E	19.06.2022 19:31	19.06.2022 20:46	-	-
C01	54° 49,048′ N 013° 39,068′ E	20.06.2022 19:51	20.06.2022 21:18	-	-
D04	54° 49,799′ N 013° 34,385′ E	22.06.2022 19:32	22.06.2022 21:24	-	-
B04	54° 50,698′ N 013° 35,049′ E	26.06.2022 02:30	26.06.2022 04:08	-	-
F01	54° 47,824′ N 013° 41,841′ E	27.06.2022 00:18	27.06.2022 01:12	-	-
C02	54° 49,214′ N 013° 38,011′ E	01.07.2022 04:35	01.07.2022 06:05	-	-
F03	54° 47,569′ N 013° 43,238′ E	02.07.2022 11:33	02.07.2022 12:49	02.07.2022 14:48	02.07.2022 15:23
D02	54° 48,727′ N 013° 38,372′ E	03.07.2022 11:36	03.07.2022 12:51	-	-
G01	54° 49,014′ N 013° 41,559′ E	05.07.2022 01:13	05.07.2022 02:03	-	-
E01	54° 48,596′ N 013° 40,783′ E	06.07.2022 00:10	06.07.2022 00:42	-	-
G04	54° 47,307′ N 013° 44,591′ E	06.07.2022 14:41	06.07.2022 15:52	-	-

Foundation	WGS 84 [dd° mm, mmm']	Phase 1		Phase 2	
		Start	End	Start	End
A04	54° 51,217′ N 013° 36,779′ E	08.07.2022 16:19	08.07.2022 17:18	-	-
A01	54° 49,488′ N 013° 40,562′ E	10.07.2022 17:10	10.07.2022 18:10	-	-
B01	54° 50,142′ N 013° 38,020′ E	11.07.2022 08:08	11.07.2022 10:54	-	-
D01	54° 48,420′ N 013° 39,525′ E	12.07.2022 06:39	12.07.2022 07:32	-	-
A02	54° 49,814′ N 013° 39,799′ E	14.07.2022 04:20	14.07.2022 05:11	-	-
F04	54° 47,438′ N 013° 43,912′ E	16.07.2022 16:31	16.07.2022 17:25	-	-
E02	54° 48,282′ N 013° 40,094′ E	17.07.2022 12:26	17.07.2022 13:22	-	-
B03	54° 50,596′ N 013° 35,670′ E	18.07.2022 21:37	18.07.2022 23:15	-	-
F02	54° 47,703′ N 013° 42,425′ E	19.07.2022 15:50	19.07.2022 16:32	-	-
D03	54° 49,181′ N 013° 36,694′ E	20.07.2022 14:25	20.07.2022 15:32	-	-
A03	54° 50,765′ N 013° 37,782′ E	22.07.2022 08:01	22.07.2022 08:50	-	-
E04	54° 47,964′ N 013° 41,246′ E	23.07.2022 00:37	23.07.2022 01:38	-	-
B02	54° 50,369′ N 013° 36,861′ E	23.07.2022 21:23	23.07.2022 22:37	-	-

10.2 Measurement results 2 m above the seabed at a distance of 750 m

Table 8: Assessment-relevant peak level ($Lp_{,pk}$) and statistical average level of the broadband single event level (SEL) of the foundation installations at a measurement distance of 750 m from the efficiency monitoring of marine mammals and the PULSE R&D project as well as the additional measurements at the last 12 monopile installations.

Funda-ment	Measuring position	Direction	Sound insulation system	Ramming phase	SEL_{05} [dB]	SEL_{50} [dB]	SEL_{90} [dB]	$Lp_{,pk}$ [dB]
OSS	750m	W	DGBS, HSD, PULSE 0-50%	1	164	163	161	182
	750m	W		Restrike	170	169	169	187
C03	750m	N	linear GBS, PULSE 0%	1	176	175	171	195
	750m	W			173	171	168	192
	750m	E			177	176	173	199
	750m	N		2	176	174	172	193
	750m	W			173	172	170	193
	750m	E			177	175	172	199
G03	750m	N	linear GBS, PULSE 50-100%	1	170	167	165	192
	750m	SSW			164	162	159	185
	750m	W			168	165	162	188
	750m	E			170	167	165	192
G02	750m	E	DGBS, PULSE 100%	1	166	164	162	184
	750m	N			166	164	161	184
	750m	S			167	165	161	184
	750m	W			164	162	159	180
	750m	E		2	165	164	162	183
	750m	N			165	164	162	183
	750m	S			166	164	162	183
	750m	W			162	160	158	180
C04	750m	E	linear GBS, PULSE 100%	1	172	170	166	190
	750m	NNE			171	169	165	190
	750m	W			170	168	165	188
C01	750m	WNW	DGBS, HSD, PULSE 0%	1	162	160	159	178
D04	750m	ENE	DGBS, PULSE 50-100%	1	168	165	162	187
	750m	ESE			166	164	161	186
	750m	WSW			168	166	162	186
	750m	WNW			169	166	162	186
B04	750m	ESE	HSD, PULSE 100%	1	168	166	163	186
	750m	NNE			167	165	163	186
	750m	WNW			162	160	156	179
	750m	SSW			168	166	164	186

Funda-ment	Measuring position	Direction	Sound insulation system	Ramming phase	SEL_{05} [dB]	SEL_{50} [dB]	SEL_{90} [dB]	$L_{p,pk}$ [dB]
F01	750m	E	DGBS, HSD, PULSE 100%	1	159	157	156	177
	750m	SSE			160	158	157	178
	750m	W			161	159	158	179
C02	750m	E	DGBS, HSD	1	167	165	163	184
	750m	NNE			167	166	164	185
	750m	W			165	164	163	183
	750m	SSW			166	165	164	186
F03	750m	ENE	DGBS, HSD	1	165	162	160	183
	750m	WNW			167	165	161	185
	750m	ESE			168	166	162	185
	750m	WSW			168	165	163	186
	750m	ENE		2	163	161	160	180
	750m	WNW			164	162	161	185
	750m	ESE			164	162	161	182
	750m	WSW			165	163	162	183
D02	750m	ENE	DGBS, HSD	1	165	164	162	183
G01	750m	ENE	DGBS, HSD	1	166	164	164	186
E01	750m	WNW	DGBS, HSD	1	167	166	166	186
G04	750m	WNW	DGBS, HSD, HSD-GBS	1	165	164	162	183
A04	750m	NE	DGBS, HSD, HSD-GBS	1	169	167	164	188
A01	750m	NW	DGBS, HSD, HSD-GBS	1	167	165	164	186
	750m	ENE		1	165	163	163	183
B01	750m	N	DGBS, HSD, HSD-GBS	1	167	165	164	186
	750m	E		1	164	162	161	183
D01	750m	NNE	TGBS, HSD, HSD-GBS	1	169	165	164	187
	750m	E		1	165	160	159	184
A02	750m	N	TGBS, HSD, HSD-GBS	1	167	167	166	187
	750m	E		1	160	159	158	178
F04	750n	E	TGBS, HSD, HSD-GBS	1	164	162	161	181
	750m	NNW		1	166	165	163	186
	750m	W		1	163	162	161	181
	750m	SE		1	161	160	159	178
E02	750m	E	TGBS, HSD, HSD-GBS	1	168	164	162	188
	750m	NNW		1	168	165	164	187
B03	750m	W	$_{XL1}$ DGBS, HSD, HSD-GBS	1	167	166	164	185
	750m	S		1	166	164	162	183
F02	750m	E	$_{XL1}$ DGBS, HSD, HSD-GBS	1	166	165	164	185

Funda-ment	Measuring position	Direction	Sound insulation system	Ramming phase	SEL05 [dB]	SEL50 [dB]	SEL90 [dB]	$L_{p,pk}$ [dB]
	750m	NNW		1	164	162	161	181
D03	750m	E	XL1 DGBS, HSD, HSD-GBS	1	168	166	164	187
	750m	N		1	165	164	161	184
A03	750m	E	XL2 DGBS, HSD, HSD-GBS	1	166	163	161	184
	750m	N		1	166	164	162	183
E04	750m	E	XL3 DGBS, HSD, HSD-GBS	1	165	163	161	184
	750m	NW		1	165	161	159	182
B02	750m	E	XL3 DGBS, HSD, HSD-GBS	1	168	167	165	187
	750m	N		1	165	163	161	182

10.3 Measurement results 2 m above the seabed at a distance of 2,000 m

Table 9: Assessment-relevant peak level ($L_{p,pk}$) and statistical average level of the broadband single event level (SEL) of the foundation installations at a measurement distance of 2,000 m from the efficiency monitoring of marine mammals and the PULSE R&D project as well as the additional measurements at the last 12 monopile installations.

Funda-ment	Measuring position	Distance [m]	Sound insulation system	Phase	SEL05 [dB]	SEL50 [dB]	SEL90 [dB]	$L_{p,pk}$ [dB]
OSS	2000m	W	DGBS, HSD, PULSE 0-50%	1	155	154	151	173
	2000m	W		Restrike	160	158	158	175
C03	2000m	NW	linear GBS, PULSE 0%	1	164	163	159	181
	2000m	E			166	165	162	186
	2000m	NW	linear GBS, PULSE 0%	2	165	163	161	181
	2000m	E			166	165	163	186
G03	2000m	E	linear GBS, PULSE 50-100%	1	164	162	160	184
	2000m	N			162	159	157	181
G02	2000m	W	DGBS, PULSE 100%	1	155	153	150	171
	2000m	W		2	153	152	149	170
C04	2000m_E	E	linear GBS, PULSE 100%	1	162	161	158	181
	2000m_W	W			161	159	155	178
C01	2000m_W	WNW	DGBS, HSD, PULSE 0%	1	153	150	149	169
D04	2000m_E	ENE	DGBS, PULSE 50-100%	1	158	155	152	175
	2000m_N	WNW			159	157	152	175
B04	2000m_E	ESE	HSD, PULSE 100%	1	157	155	152	174
	2000m_S	SSW			160	158	155	177
F01	2000m_N	NNW	DGBS, HSD, PULSE 100%	1	148	146	145	165
	2000m_W	W			152	149	147	167
C02	2000m_E	E	DGBS, HSD	1	158	156	154	175
F03	2000m_N	WNW	DGBS, HSD	1	156	153	149	173
	2000m_W	WSW			157	154	152	172
	2000m_N	WNW		2	154	151	151	172
	2000m_W	WSW			154	152	151	170
D02	2000m	ENE	DGBS, HSD	1	153	151	150	169
G01	2000m	N	DGBS, HSD	1	*1	*1	*1	*1
E01	2000m	WNW	DGBS, HSD	1	160	160	159	178
G04	2000m	WNW	DGBS, HSD, HSD-GBS	1	155	154	152	173
A04	2000m	NE	DGBS, HSD, HSD-GBS	1	162	161	157	181
A01	2000m	NW	DGBS, HSD, HSD-GBS	1	157	156	156	176
	2000m	ENE		1	156	154	153	173
B01	2000m	N	DGBS, HSD, HSD-GBS	1	160	158	157	177

Funda-ment	Measuring position	Distance [m]	Sound insulation system	Phase	SEL05 [dB]	SEL50 [dB]	SEL90 [dB]	Lp,pk [dB]
	2000m	E		1	157	155	153	175
D01	2000m	NNE	TGBS, HSD, HSD-GBS	1	162	158	157	180
	2000m	E		1	156	152	151	174
A02	2000m	N	TGBS , HSD, HSD-GBS	1	159	158	157	180
	2000m	E		1	151	149	147	168
F04	2000m	E	TGBS , HSD, HSD-GBS	1	156	154	152	174
E02	2000m	E	TGBS , HSD, HSD-GBS	1	157	153	152	174
	2000m	NNW		1	161	157	156	179
B03	2000m	W	XL1 DGBS, HSD, HSD-GBS	1	152	150	170	154
	2000m	S			154	152	150	170
F02	2000m	E	XL1 DGBS, HSD, HSD-GBS	1	160	159	157	180
	2000m	NNW		1	153	151	150	170
D03	2000m	E	XL1 DGBS, HSD, HSD-GBS	1	158	155	154	174
	2000m	N		1	156	153	150	173
A03	2000m	E	XL2 DGBS, HSD, HSD-GBS	1	*1	*1	*1	*1
	2000m	N		1	157	155	153	173
E04	2000m	E	XL3 DGBS, HSD, HSD-GBS	1	156	154	151	173
	2000m	NW		1	156	154	152	175
B02	2000m	E	XL3 DGBS, HSD, HSD-GBS	1	160	159	156	177
	2000m	N		1	157	156	153	174

*1No measurement data available.

10.4 Measurement results 2 m above the seabed at a distance of 5,000 m

Table 10: ***Assessment-relevant peak level ($Lp_{,pk}$) and statistical average level of the broadband single event level (SEL) of the foundation installations at the measurement distance 5,000 m from the efficiency monitoring of marine mammals and the PULSE R&D project as well as the additional measurements at the last 12 monopile installations.***

Funda-ment	Measuring position	Distance [m]	Sound insulation system	Phase (Events [%])	SEL05 [dB]	SEL50 [dB]	SEL90 [dB]	$Lp_{,pk}$ [dB]
G02	5000m	W	DGBS, PULSE 100%	1	141	139	137	156
				2	140	139	137	156
C04	5000m	E	linear GBS, PULSE 100%	1	150	149	145	167
F01*SNR	5000m	NNW	DGBS, HSD, PULSE 100%	1 (21%)	138	136	135	154
C02	5000m	E	DGBS, HSD, PULSE 100%	1 (100%)	144	143	141	160
F03	5000m	NW	DGBS, HSD	1 (100%)	141	138	135	158
				2 (100%)	139	136	135	155
A01	5000m	ENE	DGBS, HSD, HSD-GBS	1 (100%)	145	143	141	161
B01	5000m	E	DGBS, HSD, HSD-GBS	1 (100)	144	143	141	162
D01	5000m	E	TGBS	1 (100%)	146	142	140	163
A02	5000m	E	TGBS	1 (100%)	137	135	133	155
E02	5000m	NNW	TGBS	1 (100%)	148	144	143	167
B03	5000m	ESE	XL1 DGBS, HSD, HSD-GBS	1 (100%)	145	141	139	159
F02*SNR	5000m	NNW	XL1 DGBS, HSD, HSD-GBS	1 (6%)	138	136	135	153
D03	5000m	N	XL1 DGBS, HSD, HSD-GBS	1 (100%)	144	141	138	160
A03	5000m	E	XL2 DGBS, HSD, HSD-GBS	1 (100%)	147	144	142	162
E04	5000m	NW	XL3 DGBS, HSD, HSD-GBS	1 (100%)	145	142	140	161
B02	5000m	E	XL3 DGBS, HSD, HSD-GBS	1 (100%)	149	148	146	168

*SNR SNR between hammer sound and background sound< 10 dB. No sufficient registration of hammer blows.

10.5 Technical specifications of the bubble curtains used

Table 11: ***Technical specifications of the "Complog" bubble curtains from HTL.***
Hose set specification
with a single corresponds to single lin. coarse bubble veil= lin. GBS, two=DBGS, three=TGBS (triple GBS).

Fundament		Hose set	Designation g	Air volume q= [m³/(min*m)]	Quantity Compressors	Air pressure [bar]
1	OSS	I2 (810m) / O2 (1,080m)	DGBS	0,42	20	10,0 - 10,3
2	C03	O1 (1080m)	Lin. GBS	0,44	11	10,3
3	G03	O2 (1080m)	Lin. GBS	0,44	12	10,3
4	G02	I2 (810m) / O1 (1,080m)	DGBS	0,50	25	–
5	C04	O2* (1080m)	Lin. GBS	0,52	14	10,3
6	C01	I2 (810m) / O1 (1,080m)	DGBS	0,51	24	10,3
7	D04	I1 (810m) / O1 (1,080m)	DGBS	0,51	24	10,3
8	B04	No bubble veil	Test measurement HSD	–	–	–
9	F01	I2 (810m) / O1 (1,080m)	DGBS	0,51	24	10,3
10	C02	I1 (810m) / O1 (1,080m)	DGBS	0,51	24	10,3
11	F03	I2 (810m) / O2 (1,080m)	DGBS	0,53	25	10,3
12	D02	I2 (810m) / O2 (1,080m)	DGBS	0,51	24	10,3
13	G01	I2 (810m) / O2 (1,080m)	DGBS	0,51	24	9,1 - 9,5
14	E01	I1 (810m) / O1 (1,080m)	DGBS	0,48	23	10,3
15	G04	I1 (810m) / O1 (1,080m)	DGBS	0,51	24	10,3
16	A04	I2 (810m) / O2 (930m)	DGBS	0,55	24	10,3
17	A01	I2 (810m) / O2 (930m)	DGBS	0,55	24	10,3
18	B01	I2 (810m) / O1 (930m)	DGBS	0,55	24	10,3
19	D01	I2 (810m) / O2 (930m)	TGBS	0,55	24	10,3
		O3 (1080m)		0,31	9	10,3
20	A02	I1 (810m) / O1 (930m)	TGBS	0,55	24	10,3
		O3 (1080m)		0,48	13	10,3
21	F04	I1 (810m)/O1 (930m)	TGBS	0,55	24	10,3
		O3 (1080)		–	9	–
22	E02	I1 (810m)/O1 (930m)	TGBS	0,55	24	10,3
		O3 (1080m)		–	13	–
23	B03	I (1,020m) / E (1,260m)	XL1 DGBS	0,68	23+ 15	10,3
24	F02	I (1,020m) / E (1,260m)	XL1 DGBS	0,69	23+ N	10,3
25	D03	I (1,020m) / E (1,260m)	XL1 DGBS	0,67	24+ 14	10,3
26	A03	I (1,020m)/ E (1,560m)	XL2 DGBS	0,68	24+ 19	10,3
27	E04	I (1,560m) / E (1,800m)	XL3 DGBS	0,45	22+ 16	10,3
28	B02	I (1,560m) / E (1,800m)	XL3 DGBS	0,43	19+ 16	10,3

2.3 C-POD DATA - final technical report

Arcadis East 1

Foundations EPCI

AO1D-DO-T&I-REP-2250

AO1-DO-ENG-RPT-02027

Contract Number: 5868

C-POD Data - Final technical report

Current Revision 00

ARCADIS OST I OFFSHORE RENEWABLE ENERGY	DEME OFFSHORE
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OWP "Arcadis Ost 1" efficiency control report C-POD data

Effectiveness of harbour porpoise deterrence during foundation work

C-POD measurements at a distance of 750 m and 2,000 m from the construction sites

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Husum, September 2022

On behalf of itap GmbH

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LIST OF ABBREVIATIONS

Abbreviation	*Explanation*
APD	*Acoustic Porpoise Deterrent (deterrent)*
AWZ	*Exclusive economic zone*
BSH	*Federal Maritime and Hydrographic Agency*
C-POD	*Cetacean Porpoise Detector*
dB	*Decibel*
DPM	*Detection-positive minute, detection-positive minute (related to harbour porpoises)*
Lin. BBC	*Linear Big Bubble Curtain (linear single big bubble curtain)*
BBC	*Big Bubble Curtain (simple large bubble curtain)*
BBB	*Ballast Box Bubble Curtain (simple bubble curtain, integrated in ballast box)*
DBBC	*Double Big Bubble Curtain*
TBBC	*Triple Big Bubble Curtain (made up of BBC and DBBC)*
HSD	*Hydro silencer*
FEP	*Area development plan*
MW	*Megawatt*
OSS	*Transformer platform (offshore substation)*
WTG	*Offshore wind turbine, turbine*
OWP	*Offshore wind farm*
PAM	*Passive acoustic monitoring*
SEL	Single-event sound exposure level *(Sound Exposure Level)*
SPL	*Peak sound pressure level (Sound Pressure Level)*
UTC	*Coordinated Universal Time*

1 INTRODUCTION

Between the 06/06/2022 and the 23/07/2022 the offshore wind farm (OWP) was created.

"Arcadis Ost 1" of Parkwind Ost GmbH. "Arcadis Ost 1" is located in the southern German Baltic Sea within the 12 nm zone, 18.7 km north of Rügen (see Fig. 1.1). It is therefore located in the southern Arkona Sea, north-west of the Adlergrund and outside of Natura 2000 protected areas. The closest Natura 2000 protected area, "Westliche Rönnebank" (DE1249301), is located 12.8 km southwest of the OWP. At a distance of 13.5 km to the south-east of the OWP, directly bordering Rügen, is the Natura 2000 protected area "Extension Libben, cliffs and block grounds Wittow and Arkona" (DE1345301). The harbour porpoise is listed as a protected species in both areas. The Swedish bird sanctuary "Sydvästskånes utsjövatten" (SE0430187) begins in the north-west of the OWP, 22.9 kilometres away.

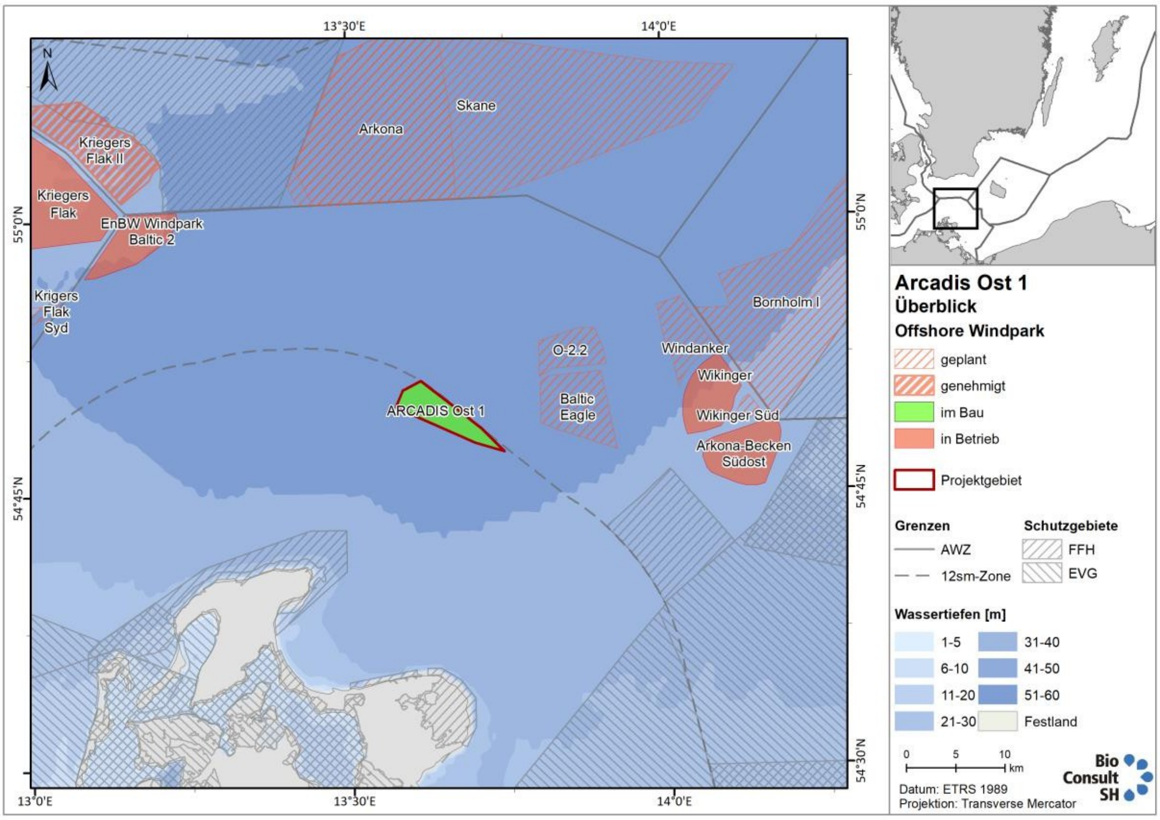

Fig. 1.1 Location of the "Arcadis Ost 1" wind farm in the Baltic Sea.

A total of 28 foundations (monopiles) for a total of 27 offshore wind turbines (OWT) and one transformer platform (OSS) were laid using the impulse pile driving method. The water depth in the project area is between approx. 43 m and 45 m. "Arcadis Ost 1" is to achieve a total capacity of 247 MW on an area of approx. 25.2 km².

The foundation method "impact pile driving" is associated with considerable emissions of pile-driving noise under water and therefore poses a risk to harbour porpoises. Lucke et al. (2009) were able to determine that harbour porpoises can suffer a temporary injury from a single-event sound exposure level (SEL) of 164 dB and an associated peak sound pressure level (SPL) of 199 dB.

suffer a shift in hearing thresholds. This can lead to limited use of echolocation, which is vital for harbour porpoises (Madsen et al. 2006, Kastelein et al. 2015a). The BMU therefore stipulated in the "Concept for the protection of harbour porpoises from noise pollution during the construction of offshore wind farms in the German North Sea" (in short: noise protection concept) that a SEL of 160 dB and an SPL of 190 dB must not be exceeded at a distance of 750 m from offshore construction work (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013). This concept is also applied in the associated approval notice for the OWP "Arcadis Ost 1" (StALU Vorpommern 2021).

The construction work on the OWP "Arcadis Ost 1" was carried out under conditions to protect harbour porpoises. On the one hand, this included deterring potentially nearby animals before the start of each foundation pile-driving operation, for which deterrence measures were carried out using an Acoustic Porpoise Deterrent (APD) system.

In addition, different combinations of a single big bubble curtain (BBC), a linear single big bubble curtain (lin. BBC from "linear big bubble curtain"), a double big bubble curtain (DBBC from "double big bubble curtain"), a triple big bubble curtain (TBBC from "triple big bubble curtain", consisting of BBC and DBBC), a single bubble curtain integrated in the ballast box (BBB from "ballast box big bubble curtain") and a hydro-sonic damper (HSD) were used to reduce the pile-driving noise emissions, which should minimise any damage to harbour porpoises caused by the pile-driving activities.

The effectiveness of the noise mitigation measures was measured during the construction work at a distance of 750 metres. At the same time, data on the presence of harbour porpoises was collected to monitor the effectiveness of the deterrence measures and the general impact of the construction activities on them. This was done with the help of so-called passive acoustic monitoring (PAM), in which the clicking sounds emitted by the harbour porpoises were recorded using specially developed devices (C-PODs). During the construction of the first 15 monopiles, a C-POD was deployed at a distance of 750 metres. From the 16th monopile (A04) onwards, additional measurements (ZSM) were carried out due to high noise levels during the first pile-driving operations. In addition to the C-POD at a distance of 750 m, four further C-PODs were deployed at a distance of 2,000 m for this purpose.

This report contains the results of the analysis of this data. It shows how effectively harbour porpoises were driven away from the vicinity of the pile-driving work by the deterrence measures and, if sufficiently long recording periods of the C-PODs near the construction site were available, whether and when animals returned to the area after the end of the work.

Unless otherwise stated, all times in this report are given in UTC format.

2 METHODOLOGY

2.1 Acoustic deterrence

To drive harbour porpoises away from a specific area ("deterrence"), so-called deterrence measures can be used. Prior to 2017, SealScarers were used in combination with pingers to deter harbour porpoises. Experimental studies on the effectiveness of SealScarers showed a clear avoidance reaction by harbour porpoises at distances of up to 7.5 km (Brandt et al. 2013, Rose et al. 2019, Voß et al. 2021). Due to the unnecessarily large scaring radius of the SealScarer/pinger combination, a deterrence system (APD, e.g. FaunaGuard) specially adapted to the hearing characteristics of harbour porpoises has been used since 2017 in the run-up to offshore pile-driving work. The scaring device reliably scares away harbour porpoises within a maximum radius of 1 km (Voß et al. 2021).

The deployment of an APD from the installation vessel is planned for the "Arcadis Ost 1" construction project. The APD system is to be deployed according to the following standard procedure:

- 40 minutes before the first pile-driving impact (soft start): APD system is lowered into the water;
- 30 minutes before the first ramming impact (soft start): Activation of APD system;
- 5 minutes after the first ramming impact (soft start): APD system is switched off and removed from the water.

If the pile-driving work is interrupted for more than 40 minutes, the pile-driving must be repeated according to the following procedure:

- 30 minutes before the next ramming: Activation of the APD system;
- 5 minutes after the first ramming impact of the new ramming: APD system is switched off and taken out of the water.

In addition to the APD, a SealScarer was also used when driving individual piles.

A briefing on deterrence using APD and SealScarer was held on 9 May on board the installation vessel, the "Orion", by employees of itap GmbH.

2.2 Passive acoustic monitoring using C-PODs

Harbour porpoises orientate themselves using echolocation with the help of short, high-frequency, narrow-band click sounds, which they emit almost continuously (Au et al. 1999, Akamatsu et al. 2007, Wisniewska et al. 2012, 2016). These can be single clicks or click trains consisting of several clicks emitted in succession. Individual clicks have an average duration of 77 µs and are most frequently emitted at frequencies of around 130 kHz at a volume of 157 to 169 dB re 1 µPa (p-p) (Teilmann et al. 2002, Villadsgaard et al. 2007). The hearing ability of harbour porpoises covers frequencies from 16 Hz to 140 kHz, with the best hearing ability between 100 kHz and 140 kHz (Kastelein et al. 2002, 2015b). Based on harbour porpoises use the reflected sound waves to assess their surroundings, detect their prey and communicate with each other (Koschinski et al. 2008, Verfuss et al. 2009, Clausen et al. 2011). However, relatively little is known about the communication between harbour porpoises (Sørensen et al. 2018). However, Clausen et al. (2011) showed that the short, high-frequency clicks used to locate prey can also be used to communicate with conspecifics.

For the passive-acoustic monitoring of harbour porpoises, C-PODs (Cetacean Porpoise Detector, Chelonia Ltd., UK; http://www.chelonia.co.uk; see Fig. 2.1) were used to detect the click trains of the harbour porpoises.

Fig. 2.1 C-PODs ready for deployment (left) and an opened C-POD (right).

The recorded C-POD data were checked for porpoise positive minutes (DPM; "detection positive minutes") and compared with the respective construction progress (deterrence/ramming). The C-POD data was processed using the C-POD.exe software (version 2.045). For this report, the two highest quality classes ("high", "moderate") were analysed with regard to the probability of a harbour porpoise origin of the signals. In addition, all harbour porpoise signals recorded during the deterrence or pile-driving were visually inspected and verified on the basis of an expert assessment. This is intended to prevent misclassifications ("false positives") from influencing the assessment of the deterrence.

2.3 Depicted ramming events

This report deals with the pile-driving of all 27 WTG foundations (pile numbers: see Table 2.1) and the OSS in the "Arcadis Ost 1" OWP. An overview of the locations of the individual foundations in the OWP is shown in Fig. 2.2.

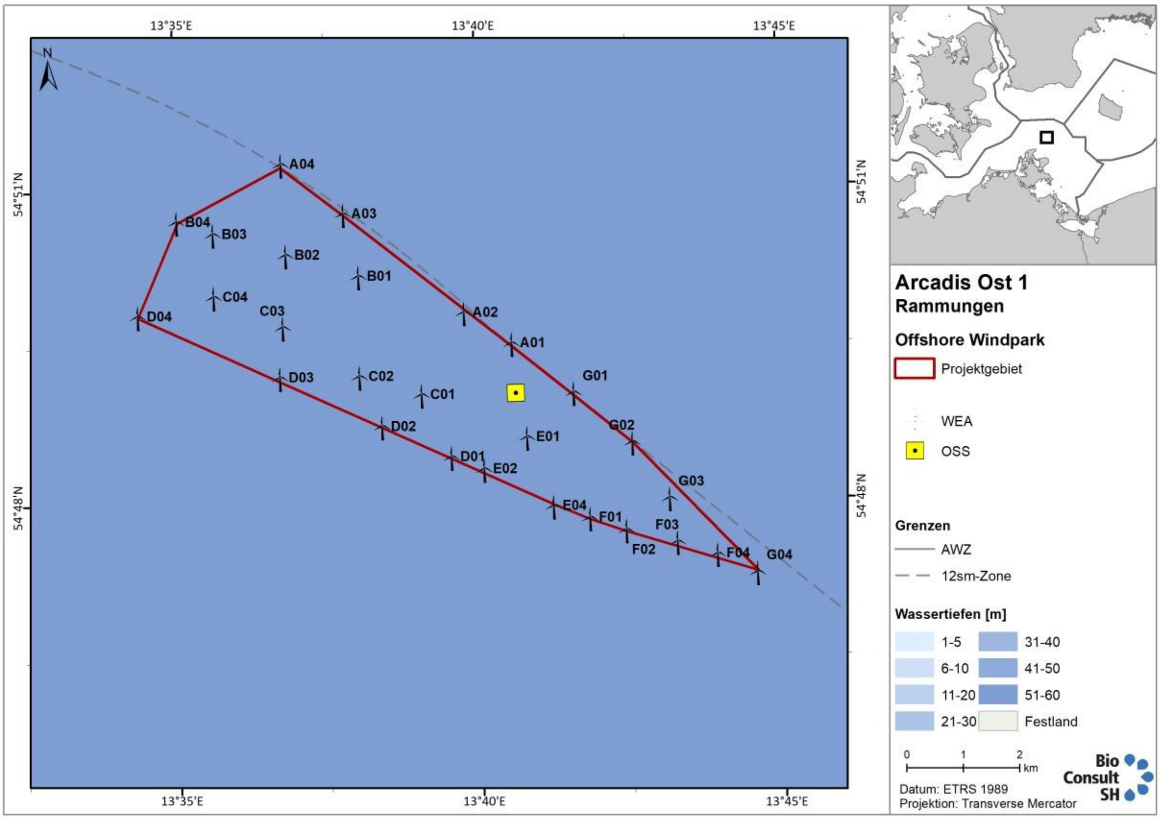

Fig. 2.2 Foundations installed in the "Arcadis Ost 1" OWP from 06/06/2022 to 23/07/2022 (27 WTGs + 1 OSS).

The duration of the C-POD recordings, the deterrence by an APD, the use of the noise protection systems (BBC, lin. BBC, DBBC, TBBC and HSD), as well as the pile-driving phases were visualised with the help of bar charts and thus put into temporal relation. The time axis of the illustrations was set to a period from 12 hours before the start of the first pile-driving phase to 12 hours after the end of the last pile-driving phase for a pile or the OSS.

Tab. 2.1 Information on driving times, the use of C-PODs at 750 and 2,000 metres, the use of the APD system and noise protection during construction work on "Arcadis Ost 1". MP = monopile (consecutive number of driven monopiles), pile: monopile designation, driving phase: piles were sometimes driven in several intervals, APDB vRB = APD start before driving begins, APDE nRB = APD end after driving begins, noise protection: HSD = hydro silencer, DBBC = double big bubble curtain, lin. BBC = linear big bubble curtain, TBBC = triple big bubble curtain (corresponds to the simultaneous use of DBBC and BBC), BBB = ballast box bubble curtain, vRB= before the start of pile driving, nRE = after the end of pile driving, ZSM = additional measurement, NA= no information; yellow markings emphasise information that deviates from the specifications. All times in UTC.

MP	Stake	Ramming phase	Start of pile driving	Ramming end	APDB vRB	APDE nRB	Sound insulation	C-POD Distance	750 m vRB	750 m nRE	2.000 m vRB	2.000 m nRE	ZSM1 vRB	ZSM1 nRE	ZSM2 vRB	ZSM2 nRE	ZSM3 vRB	ZSM3 nRE
1	OSS	OSS a1	06.06.2022 18:57	06.06.2022 20:01	01:58	00:59 vRB	HSD, DBBC	750	07:42	14:09								
1	OSS	OSS a2	06.06.2022 20:51	06.06.2022 22:49	NA	NA	HSD, DBBC	750	09:36	11:21								
1	OSS	OSS b	10.06.2022 05:29	10.06.2022 05:29	NA	NA	HSD, DBBC	750	07:16	02:25								
2	C03	C03 a	13.06.2022 14:20	13.06.2022 15:23	01:25	00:04	lin. BBC	750	08:04	11:34								
2	C03	C03 b	13.06.2022 23:50	14.06.2022 00:46	NA	NA	lin. BBC	750	17:34	02:11								
3	G03	G03	15.06.2022 10:42	15.06.2022 12:59	00:32	00:06	lin. BBC	750	10:21	01:56								
4	G02	G02 a	17.06.2022 07:10	17.06.2022 08:44	00:38	00:00	DBBC	750	05:46	08:25								
4	G02	G02 b	17.06.2022 13:07	17.06.2022 13:48	00:49	00:00	DBBC	750	11:43	03:21								
5	C04	C04	19.06.2022 19:36	19.06.2022 20:47	00:51	00:01	lin. BBC	750	05:33	10:19								
6	C01	C01	20.06.2022 19:54	20.06.2022 21:17	00:55	00:02 vRB	HSD, DBBC	750	19:31	20:00 vRE								
7	D04	D04	22.06.2022 19:32	22.06.2022 21:26	00:36	00:07	DBBC	-	NA	NA								
8	B04	B04	26.06.2022 02:33	26.06.2022 04:19	00:41	00:02 vRB	HSD	750	12:37	5:03 vRE								
9	F01	F01	27.06.2022 00:20	27.06.2022 01:12	00:32	00:00	HSD, DBBC	750	02:02	22:34 vRE								
10	C02	C02	01.07.2022 04:36	01.07.2022 06:04	00:34	00:09 vRB	HSD, DBBC	750	15:58	7:31 vRE								
11	F03	F03 a	02.07.2022 11:34	02.07.2022 12:49	00:44	00:00	HSD, DBBC	750	08:33	08:45								
11	F03	F03 b	02.07.2022 14:53	02.07.2022 15:26	00:26	00:02	HSD, DBBC	750	11:52	06:08								
12	D02	D02	03.07.2022 11:38	03.07.2022 12:52	00:40	00:00	HSD, DBBC	750	NA	NA								
13	G01	G01	05.07.2022 01:15	05.07.2022 02:04	00:36	00:00	HSD, DBBC	750	01:59	17:59 vRE								
14	E01	E01	06.07.2022 00:13	06.07.2022 00:44	00:35	00:00	HSD, DBBC	750	11:21	19:28								
15	G04	G04	06.07.2022 14:42	06.07.2022 15:53	00:37	00:00	HSD, DBBC, BBB	750	03:35	02:03								
16	A04	A04	08.07.2022 16:19	08.07.2022 17:18	00:30	00:00	HSD, DBBC, BBB	750,	04:37	01:48	05:12	02:30	01:30	01:30	00:49	00:49	16:49	61:18vRE
17	A01	A01	10.07.2022 17:11	10.07.2022 18:10	00:44	00:00	HSD, DBBC, BBB	750,	13:30	02:01	04:52	02:44	01:23	00:32	01:42	00:58	01:57	01:18
18	B01	B01	11.07.2022 08:13	11.07.2022 09:55	00:44	00:05 vRB	HSD, DBBC, BBB	750,	05:26	07:46	05:52	07:00	01:59	01:43	01:40	00:39	62:07nRB	15:47
19	D01	D01	12.07.2022 06:42	12.07.2022 07:32	00:41	00:02	HSD, TBBC, BBB	750,	12:04	02:27	12:09	03:01	05:13	00:44	NA	NA	05:42	01:16
20	A02	A02	14.07.2022 04:22	14.07.2022 05:12	01:10	00:02 vRB	HSD, TBBC, BBB	750,	18:08	4:12 vRE	17:35	02:29	05:51	01:10	06:30	01:38	06:14	02:00
21	F04	F04	16.07.2022 16:33	16.07.2022 17:25	00:39	00:02 vRB	HSD, TBBC, BBB	750,	10:30	21:56 vRE	11:00	02:41	03:27	01:16	03:38	01:33	03:54	95:02vRE
22	E02	E02	17.07.2022 12:27	17.07.2022 13:22	00:34	00:01 vRB	HSD, TBBC, BBB	750,	04:08	02:01	04:31	02:29	01:34	00:44	01:53	01:09	02:13	01:29
23	B03	B03	18.07.2022 21:40	18.07.2022 23:15	00:46	00:03 vRB	HSD, DBBC, BBB	750,	02:52	07:58	03:37	08:29	02:20	01:37	01:24	00:40	01:38	01:07
24	F02	F02	19.07.2022 15:52	19.07.2022 16:34	00:32	00:01 vRB	HSD, DBBC, BBB	750,	02:03	02:31	02:28	03:05	01:33	00:37	02:20	01:30	02:02	01:05
25	D03	D03	20.07.2022 14:27	20.07.2022 15:33	00:47	00:02 vRB	HSD, DBBC, BBB	750,	08:50	16:15 vRE	09:16	08:24	01:09	00:46	01:20	01:02	01:45	01:35
26	A03	A03	22.07.2022 08:00	22.07.2022 08:50	00:32	00:00	HSD, DBBC, BBB	750,	02:33	05:37	03:26	05:03	00:55	00:52	01:15	01:19	01:27	01:35
27	E04	E04	23.07.2022 00:40	23.07.2022 01:37	00:42	00:01 vRB	HSD, DBBC, BBB	750,	06:55	09:31	07:29	08:56	14:58	02:24	05:12	02:12	04:48	01:44
28	B02	B02	23.07.2022 21:26	23.07.2022 22:37	00:34	01:13 nRB	HSD, DBBC, BBB	750,	04:23	01:52	04:49	02:38	07:59	19:48	00:39	05:32	00:23	00:00

Table 2.2 Results of the noise measurements during pile driving at a distance of 750 m. SEL: average single event level (specification: max. 160 dB; BMU 2013), SPL: peak level (specification: max. 190 dB; BMU 2013); yellow markings emphasise results of the noise measurements that deviate from the specifications.

MP	Stake	Ramming phase	Average SEL 750m	min SEL 750m	Max SEL 750m	SPL 750 m
1	OSS	OSS a1	164	153	167	182
1	OSS	OSS a2	170	169	170	187
1	OSS	OSS b	167	166	167	183
2	C03	C03 a	177	171	177	199
2	C03	C03 b	177	171	177	199
3	G03	G03	170	162	174	192
4	G02	G02 a	164	156	166	180
4	G02	G02 b	162	157	162	180
5	C04	C04	170	133	171	188
6	C01	C01	162	156	164	178
7	D04	D04	169	161	170	186
8	B04	B04	168	161	169	186
9	F01	F01	161	156	163	179
10	C02	C02	166	162	168	186
11	F03	F03 a	168	161	168	186
11	F03	F03 b	165	161	166	183
12	D02	D02	165	159	166	183
13	G01	G01	166	163	168	186
14	E01	E01	167	165	168	186
15	G04	G04	165	161	166	183
16	A04	A04	169	162	170	188
17	A01	A01	167	163	168	186
18	B01	B01	167	163	167	186
19	D01	D01	169	161	170	187
20	A02	A02	167	164	169	187
21	F04	F04	164	160	165	181
22	E02	E02	168	161	169	188
23	B03	B03	167	162	168	185
24	F02	F02	166	162	167	185
25	D03	D03	168	162	168	187
26	A03	A03	166	157	166	184
27	E04	E04	165	159	166	184
28	B02	B02	168	163	169	187

3 RESULTS OF THE C-POD RECORDINGS

The mobile C-PODs were deployed at distances of 750 m and 2,000 m from the respective construction sites before the start of the noise mitigation measures and retrieved after the pile-driving work was completed, whereby the length of the deployment period could vary (Table 2.1). The recordings were made over the entire standard frequency range of the C-PODs from 20 kHz to 160 kHz. Detections of harbour porpoise signals are most likely in the higher frequency range.

In the case of the "Arcadis Ost 1" construction work, harbour porpoises were detected before and after the pile-driving. There were no harbour porpoise detections during the pile-driving. Detections are shown in Table 3.1 in the form of harbour porpoise positive minutes (DPM). If detections were made before the first deployment of the APD system or after the last pile-driving phase, a time interval was specified. A total of 29 harbour porpoise detections were recorded during the entire construction work.

Table 3.1 Harbour porpoise detections before, during or after pile driving of listed piles, as well as before or during the respective APD deployment. Foundations without harbour porpoise detections are not listed. V1.APD: Detection before the first deployment of the APD, APD: Detection during the deployment of the APD (also multiple APD deployments in the case of several pile-driving phases), Ramm: Detection during pile-driving, zwRamm: Detection between two pile-driving phases, nLRamm: Detection after the last pile-driving phase; Zeitabstand: Time interval between detections before and after the last pile-driving phase.
1st use of an APD and after the last ramming phase, Lmin: last minute; Emin: first minute.

Distance	Stake	DPM					Time interval (min.)	
		v1. APD	APD	Ramm	zwRamm	nLRamm	Lmin v1.APD	Emin nLRamm
750	MP02_C03	0	0	0	1	0	-	-
750	MP04_G02	1	0	0	0	0	269	-
750	MP16_A04	1	0	0	0	0	44	-
2.000	MP16_A04	1	4	0	0	0	1	-
2.000	MP21_F04	1	0	0	0	0	209	-
2.000	MP22_E02	4	0	0	0	0	37	-
2.000	MP23_B03	0	0	0	0	1	-	20
2.000	MP24_F02	0	0	0	0	2	-	109
2.000	MP28_B02	3	0	0	0	10	78	35

3.1 Transformer platform

The OSS was created on two days, 6 June 2022 and 10 June 2022, with a total of three pile-driving phases using the impulse pile-driving method (Fig. 3.1). The first pile-driving phase began on 6 June 2022 at 18:57 and ended on the same day at 20:01. For deterrence, an APD system was activated 1 h 58 min before the start of pile-driving, but deactivated again 59 minutes before the start of pile-driving (duration: 58 min). The second pile-driving phase began on 6 June 2022 at 20:51 and ended on the same day at 22:49. There was a fifty-minute break between the first and second pile-driving phase, which would have made another deterrence necessary. This was not carried out. According to the protocol, a DBBC and an HSD were used to minimise noise during the first two pile-driving phases. Only the deployment times of the DBBC are available (Fig. 3.1.)

The third pile-driving phase, the so-called "restrike", was carried out on 10 June 2022 at 5:29 a.m. with a single strike. No predetermined deterrence was carried out here either. According to the protocol, a DBBC and an HSD were used to minimise noise. There are no recorded deployment times for either of the two noise protection systems.

One C-POD was deployed during the first two pile-driving phases and another during the third pile-driving phase at a distance of 750 metres. The following average SEL values were determined at this distance: 1st pile-driving phase: 164 dB, 2nd pile-driving phase: 170 dB, 3rd pile-driving phase: 167 dB (Table 2.2). All three SEL values determined exceed the maximum level of 160 dB specified in the noise protection concept (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013). At 182 dB (1st pile-driving phase), 187 dB (2nd pile-driving phase) and 183 dB (3rd pile-driving phase), the average SPL values determined at this distance are just below the maximum peak level value of 190 dB specified in the noise protection concept (Table 2.2.)

In none of the three pile-driving phases were harbour porpoises detected at the position of the C-POD 750 m from the pile-driving event (Table 3.1).

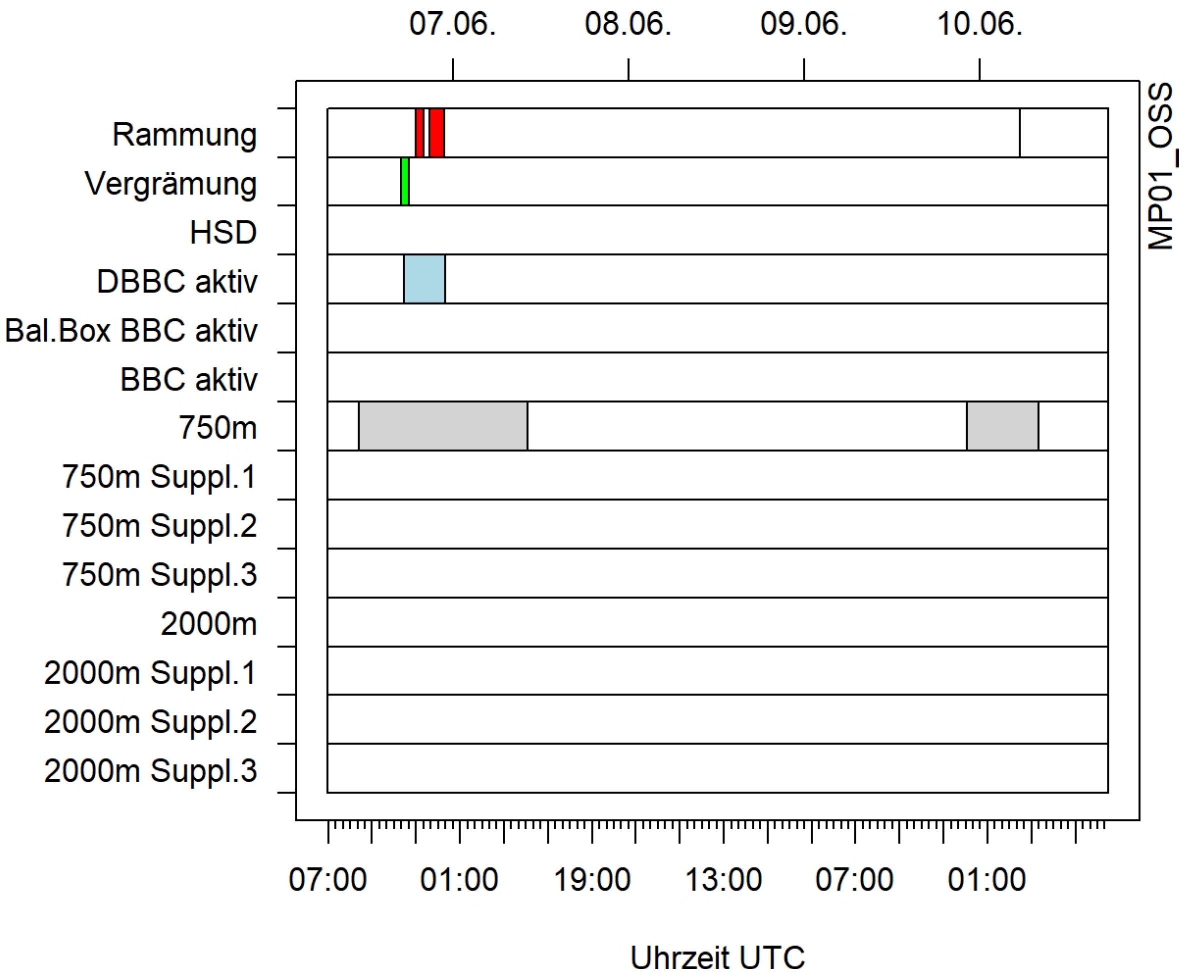

Fig. 3.1 OSS - Temporal representation of the pile-driving phases (red), the use of an APD system (green), the noise protection measures (HSD, DBBC active, Bal. Box BBC active and BBC active, blue) and C-PODs (grey). The pile-driving took place in three pile-driving phases over two days (06/10 June 2022). An APD system was only used before the first pile-driving phase; DBBC and HSD were used as noise protection, according to the protocol. The time period for the deployment of the DBBC on 10 June 2022 and the complete deployment period of the HSD is missing. Harbour porpoises were not detected before, during or after the pile-driving work. C-PODs are shown according to their distance (here: a C-POD at a distance of 750 m from the pile-driving). "Suppl." (supplementary) = additional measurements, only relevant for later pile-driving.

3.2 Monopile C03

Monopile C03 was founded on 13/06/2022 and 14/06/2022 in two pile-driving phases (Table 2.1). The first pile-driving phase lasted from 14:20 to 15:23 on 13 June 2022. An APD system was activated for burial 1 h 25 min before the start of pile driving and deactivated 4 minutes after the start of pile driving (duration: 1 h 29 min). A SealScarer was also used. Time data on the use of the SealScarer are not available in the protocol. Furthermore, as part of a research project, only a linear BBC was aligned in the direction of the FFH area for this and further pile-driving as a noise protection measure. This meant that there was no noise protection north of the pile-driving.

The second pile-driving phase began on 13 June 2022 at 23:50 and ended on 14 June 2022 at 0:46. There was a break of 8 h 27 min between the first and second pile-driving phase, so that a new deterrence would have been necessary. This was not carried out. As part of the research project, only a linear BBC was used for noise minimisation in the direction of the FFH area to the south.

A C-POD was continuously deployed for both pile-driving phases at a distance of 750 m (Table 2.1). The following average SEL values were determined at this distance: 1st pile-driving phase: 177 dB, 2nd pile-driving phase: 177 (Table 2.2). The SEL values determined exceed the maximum level value of 160 dB specified in the noise protection concept (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013). At 199 dB, the average SPL values are also above the specified maximum peak level values of 190 dB (Table 2.2).

During the break between the two pile-driving phases, harbour porpoises were detected at the POD station 750 m from the construction site (Table 3.1.)

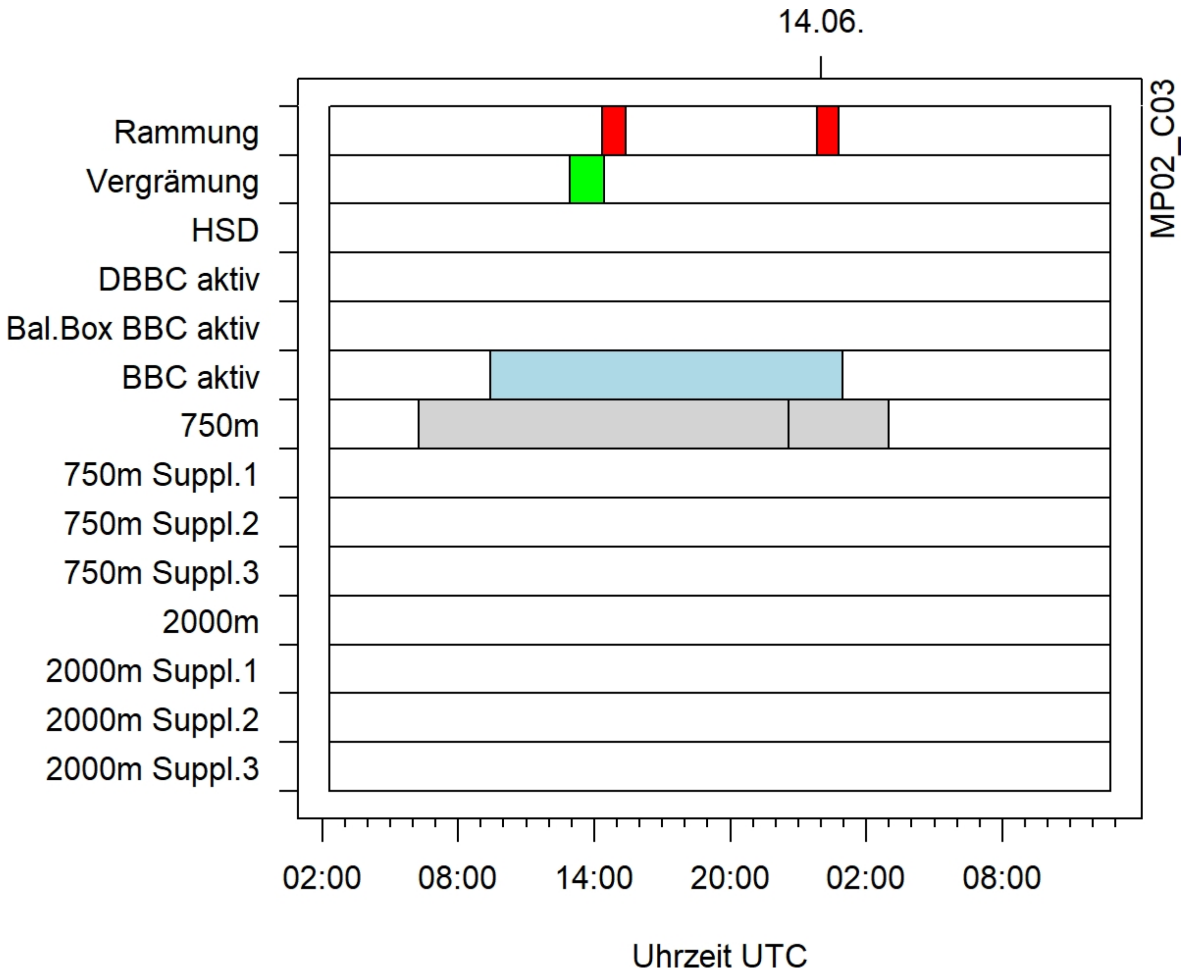

Fig. 3.2 C03 - Chronological representation of the pile-driving phases (red), the use of an APD system (green), noise protection measures (HSD, DBBC, Bal. Box BBC active and BBC active, blue) and C-PODs (grey). The pile-driving took place in two pile-driving phases on two days (13/14 June 2022). An APD system was only used before the first pile-driving phase; in addition, a Se- alScarer was used, for which there are no collated deployment times. A linear BBC (here: BBC) was used as noise protection in the direction of the FFH area to the south. C-PODs are shown by their distance from the pile-driving (here: one C-POD at 750 m), harbour porpoise detections in the same field are shown as a vertical line. Harbour porpoises were detected between the two pile-driving phases. "Suppl." (supplementary) = additional measurements, only relevant for later pile-driving.

3.3 Monopile G03

The monopile G03 was set up on 15 June 2022 from 10:42 to 12:59 (Table 2.1). An APD system was activated 32 minutes before the start of pile-driving and deactivated 6 minutes after the start of pile-driving (duration: 38 minutes). A SealScarer was also used. Time data on the deployment are not available in the protocol. Furthermore, as part of a research project, only a linear BBC was aligned in the direction of the FFH area for this and further pile-driving as a noise protection measure. This meant that there was no noise protection north of the pile-driving.

A C-POD was installed at a distance of 750 m (Table 2.1). At this distance, an average SEL value of 170 dB was determined and exceeds the maximum level value of 160 dB specified in the noise protection concept (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013). The average SPL value of 192 dB is also above the specified maximum peak level value of 190 dB (Table 2.2).

No harbour porpoises were detected at the POD station at a distance of 750 m from the pile-driving event (Table 3.1).

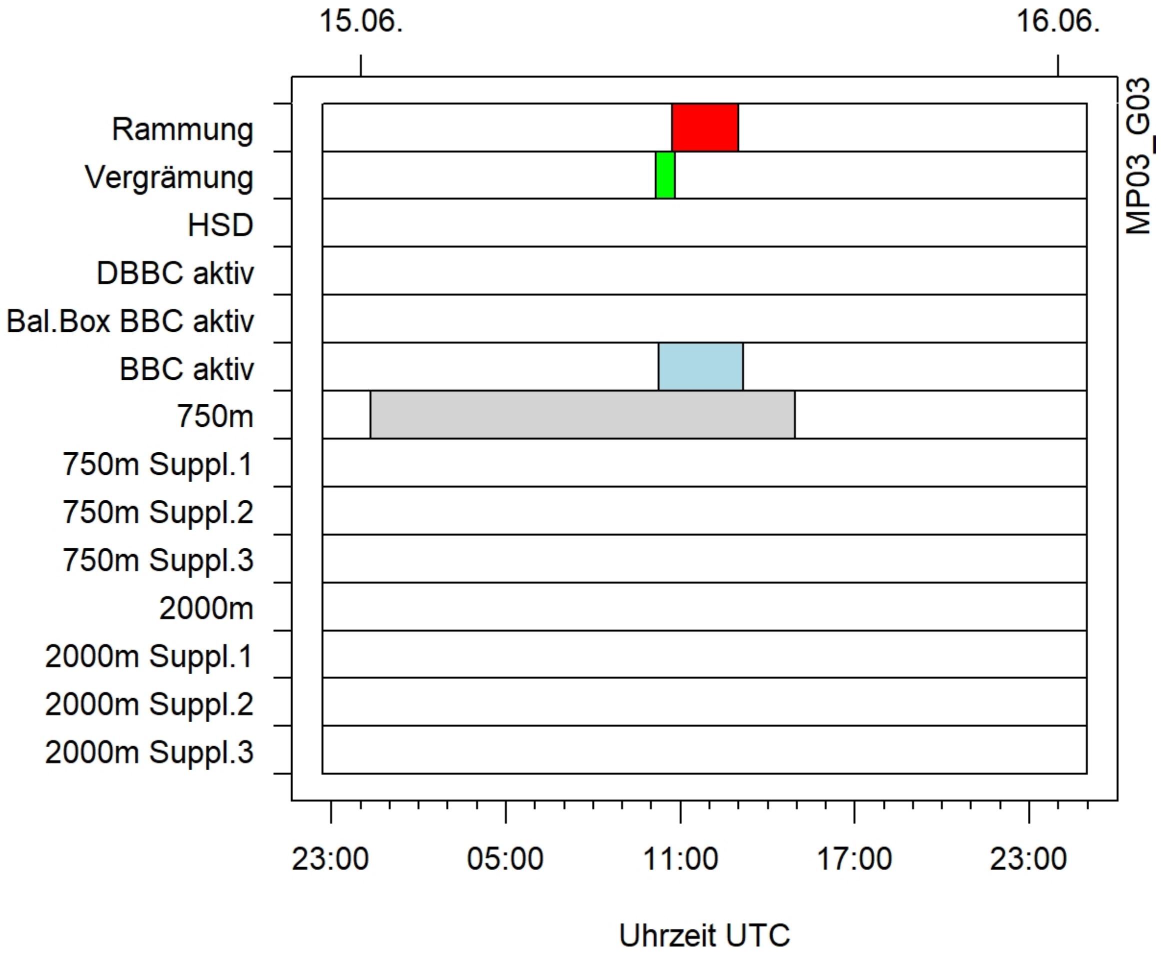

Fig. 3.3 G03 - Temporal representation of the pile-driving phase (red), the use of an APD system (green), noise protection measures (HSD, DBBC, Bal. Box BBC active and BBC active, blue) and C-PODs (grey). The pile-driving took place on 15/06/2022. In addition to the APD system, a SealScarer was also used. No recorded deployment times are available for this. A lin. BBC (here: BBC) was only used as noise protection in the direction of the FFH area to the south. A C-POD was deployed at a distance of 750 metres. No harbour porpoises were detected before, during or after the pile driving. "Suppl." (supplementary) = additional measurements, only relevant for later pile-driving.

3.4 Monopile G02

The monopile G02 was founded on 17 June 2022 in two pile-driving phases (Table 2.1). The first pile-driving phase lasted from 07:10 to 08:44. For deterrence, an APD system was activated 38 minutes before pile-driving began and deactivated at the same time as pile-driving began (duration: 38 minutes). A DBBC was used to minimise noise.

The second pile-driving phase began at 13:07 and ended at 13:48. For deterrence, an APD system was activated 49 minutes before the start of pile-driving and deactivated at the same time as pile-driving began (duration: 49 minutes). A DBBC was used to minimise noise.

A C-POD was continuously deployed for both pile-driving phases at a distance of 750 m (Table 2.1). The following average SEL values were determined at this distance: 1st pile-driving phase: 164 dB, 2nd pile-driving phase: 162 dB (Table 2.2). The average SEL values determined exceed the maximum level value of 160 dB specified in the noise protection concept (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013). The average SPL value determined at a distance of 750 m is 180 dB, which is below the maximum specified peak level value of 190 dB (Table 2.2).

Harbour porpoises were detected approx. 4.5 h before the first deployment of the APD system at the POD station at a distance of 750 m from the pile-driving event (Table 3.1).

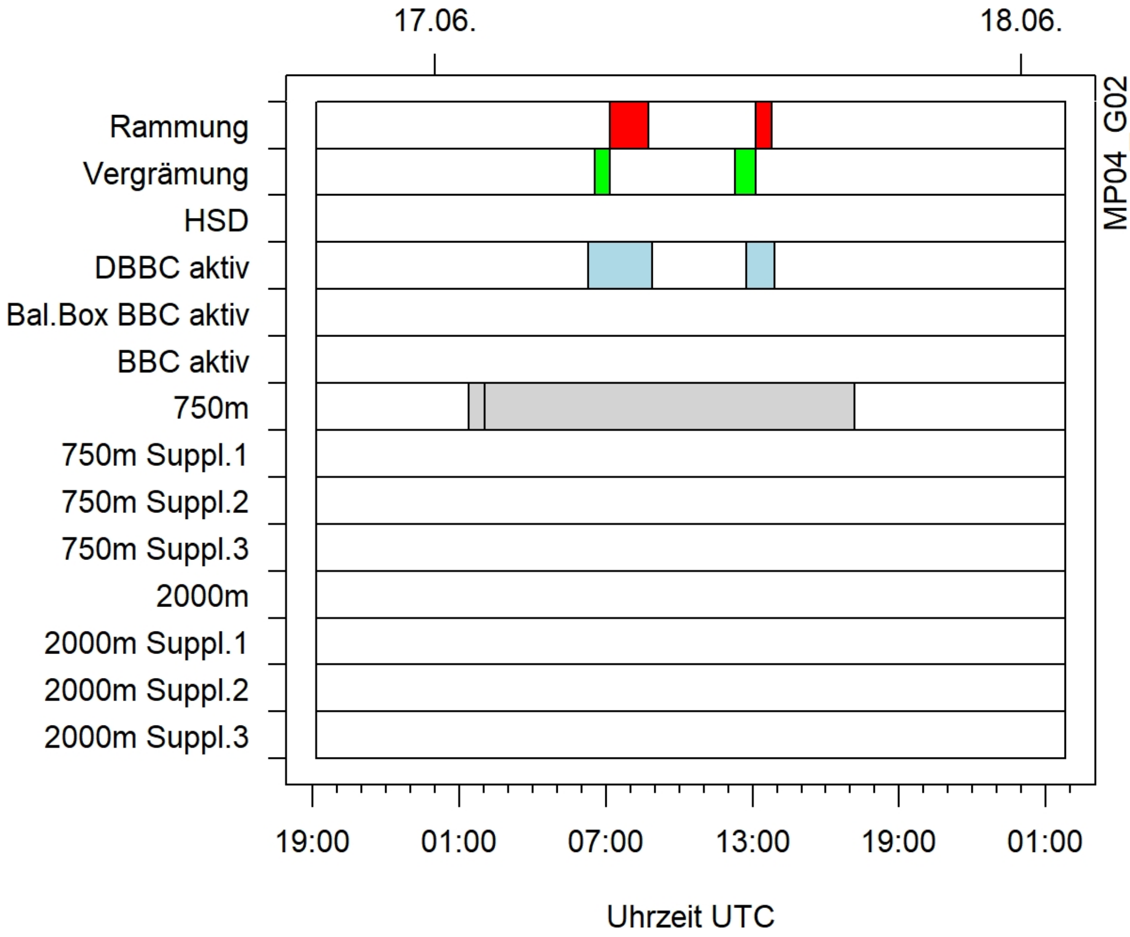

Fig. 3.4 G02 - Chronological representation of the pile-driving phases (red), the use of an APD system (green), noise protection measures (HSD, DBBC, Bal. Box BBC active and BBC active, blue) and C-PODs (grey). The pile-driving took place in two pile-driving phases on 17 June 2022. An APD system was used before each pile-driving phase. A DBBC was used as noise protection in each case. A C-POD was installed at a distance of 750 metres. Around 4.5 h before the first deployment of the APD system, harbour porpoises were detected at a distance of 750 m (vertical line). "Suppl." (supplementary) = additional measurements, only relevant for later pile-driving.

3.5 Monopile C04

Monopile C04 was set up on 19 June 2022 from 19:36 to 20:47 (Table 2.1). For deterrence, an APD system was activated 51 min before the start of pile-driving and deactivated one minute after the start of pile-driving (duration: 52 min). A SealScarer was also used. Time data on the deployment are not available. Furthermore, as part of a research project, only a linear BBC was installed as a noise protection measure in the direction of the FFH area to the south. This meant that there was no noise protection to the north of the pile driving.

A C-POD was installed at a distance of 750 m (Table 2.1). An average SEL value of 170 dB was determined at this distance; the maximum level value of 160 dB specified in the noise protection concept (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013) was exceeded (Table 2.2.)At 188 dB, the average SPL value determined is just below the maximum specified peak level value of 190 dB (Table 2.2).

No harbour porpoises were detected at the POD station 750 m from the pile-driving event (Table 3.1).

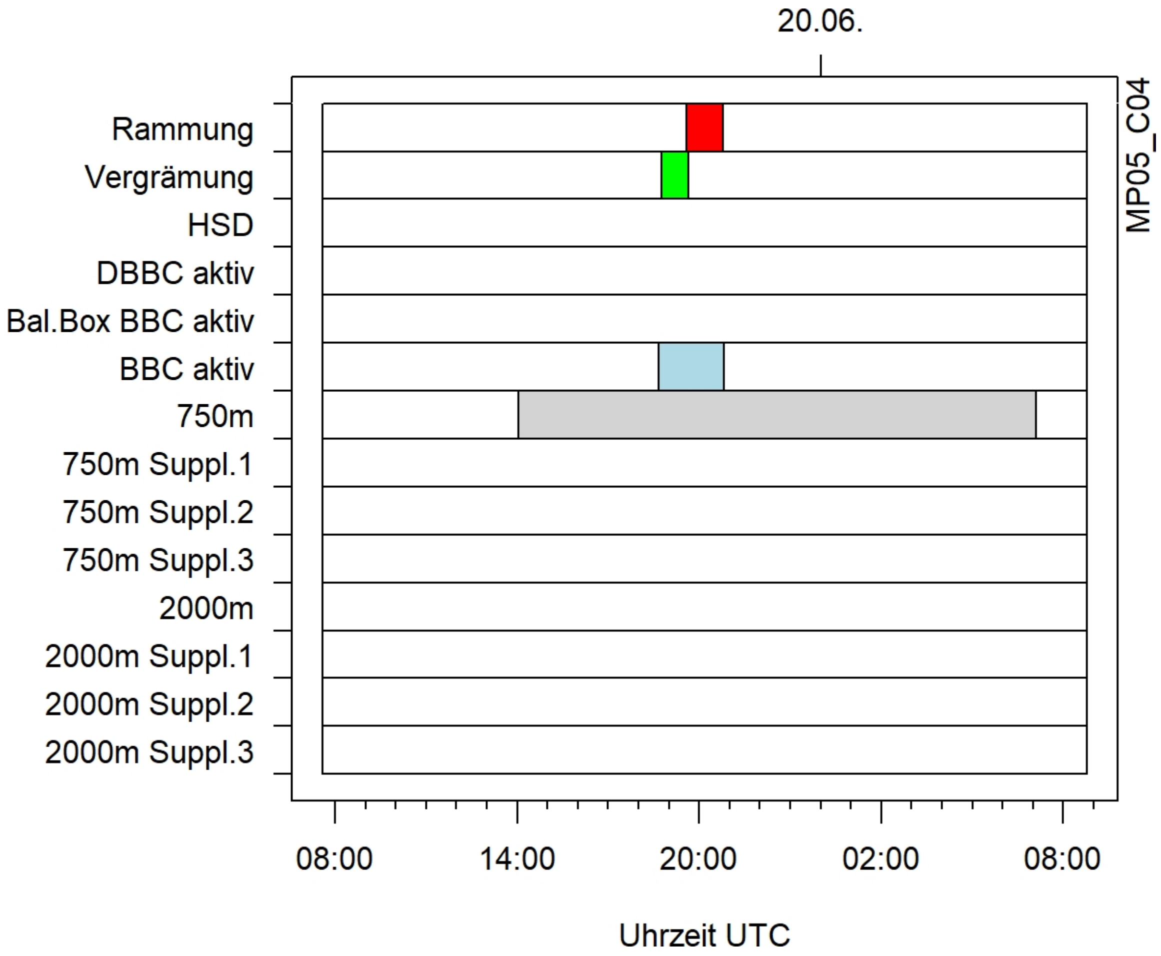

Fig. 3.5 C04 - Chronological representation of the pile-driving phase (red), the use of an APD system (green), noise protection measures (HSD, DBBC, Bal. Box BBC active and BBC active, blue) and C-PODs (grey). The pile-driving took place on 19/06/2022. In addition to the APD system, a Se- alScarer was also used. No deployment times are recorded for this. A lin. BBC (here: BBC) was only used as noise protection in the direction of the FFH area to the south. A C-POD was deployed at a distance of 750 metres. No harbour porpoises were detected before, during or after the pile driving. "Suppl." (supplementary) = additional measurements, only relevant for later pile-driving.

3.6 Monopile C01

Monopile C01 was set up on 20 June 2022 from 19:54 to 21:17 (Table 2.1). An APD system was activated for deterrence 55 minutes before pile-driving began, but deactivated two minutes before pile-driving began (duration: 53 minutes). A DBBC and an HSD were used to minimise noise.

A C-POD was deployed at a distance of 750 metres. According to the log, it was recovered 20 hours before the end of the pile-driving. A documentation or setting error is assumed. For better evaluation, the recovery time was adjusted accordingly (Fig. 3.6.)An average SEL value of 162 dB was determined at a distance of 750 m (Table 2.2). The maximum level value of 160 dB specified in the noise protection concept (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013) was exceeded. The average SPL value determined at a distance of 750 m was 178 dB, which is below the maximum specified peak level of 190 dB (Table 2.2).

Based on the available recordings, no harbour porpoises were detected at the POD station at a distance of 750 m from the pile-driving event (Table 3.1.)

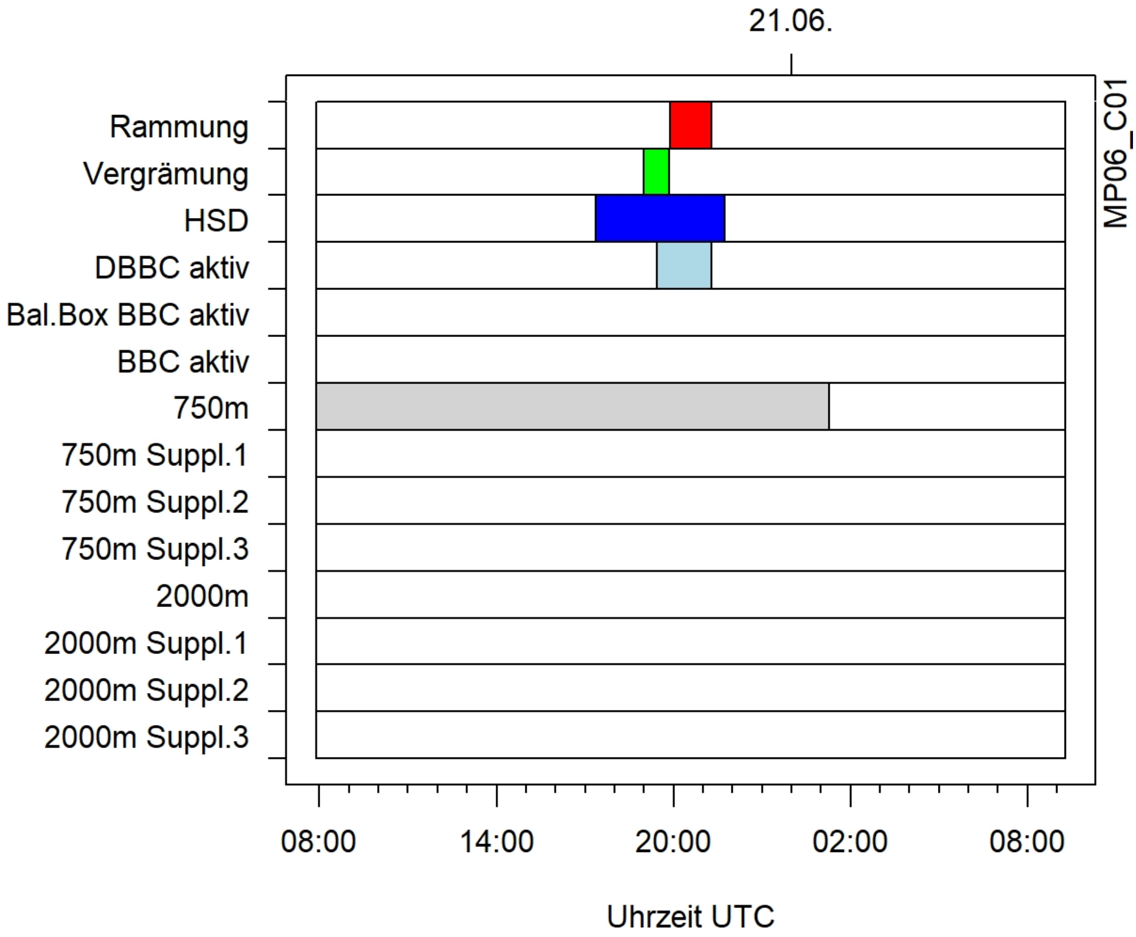

Fig. 3.6 C01 - Chronological representation of the pile-driving phase (red), the use of an APD system (green), noise protection measures (HSD, DBBC, Bal. Box BBC active and BBC active, blue) and C-PODs (grey). The pile-driving took place on 20/06/2022. An APD system was used before the pile driving. A DBBC and an HSD were used as noise protection. A C-POD was deployed at a distance of 750 metres. The logged deployment time ends 20 hours before the end of pile driving. A logging or setting error is assumed. The recovery time was reasonably adjusted for the evaluation. No harbour porpoises were detected on the basis of the existing recording. "Suppl." (supplementary) = additional measurements, only relevant for later pile-driving.

3.7 Monopile D04

The monopile D04 was set up on 22 June 2022 from 19:32 to 21:26 (Table 2.1). For deterrence, an APD system was activated 36 minutes before pile-driving began and deactivated 7 minutes after pile-driving began (duration: 44 minutes). A DBBC was used to minimise noise.

A C-POD was not deployed during this pile-driving (Table 2.1). It is therefore not possible to determine whether harbour porpoises were present in the surrounding area during the pile-driving.

An average SEL value of 169 dB was determined at a distance of 750 m (Table 2.2). The maximum level value of 160 dB specified in the noise protection concept (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013) was exceeded. The average SPL value of 186 dB determined at a distance of 750 m is just below the maximum specified peak level value of 190 dB (Table 2.2).

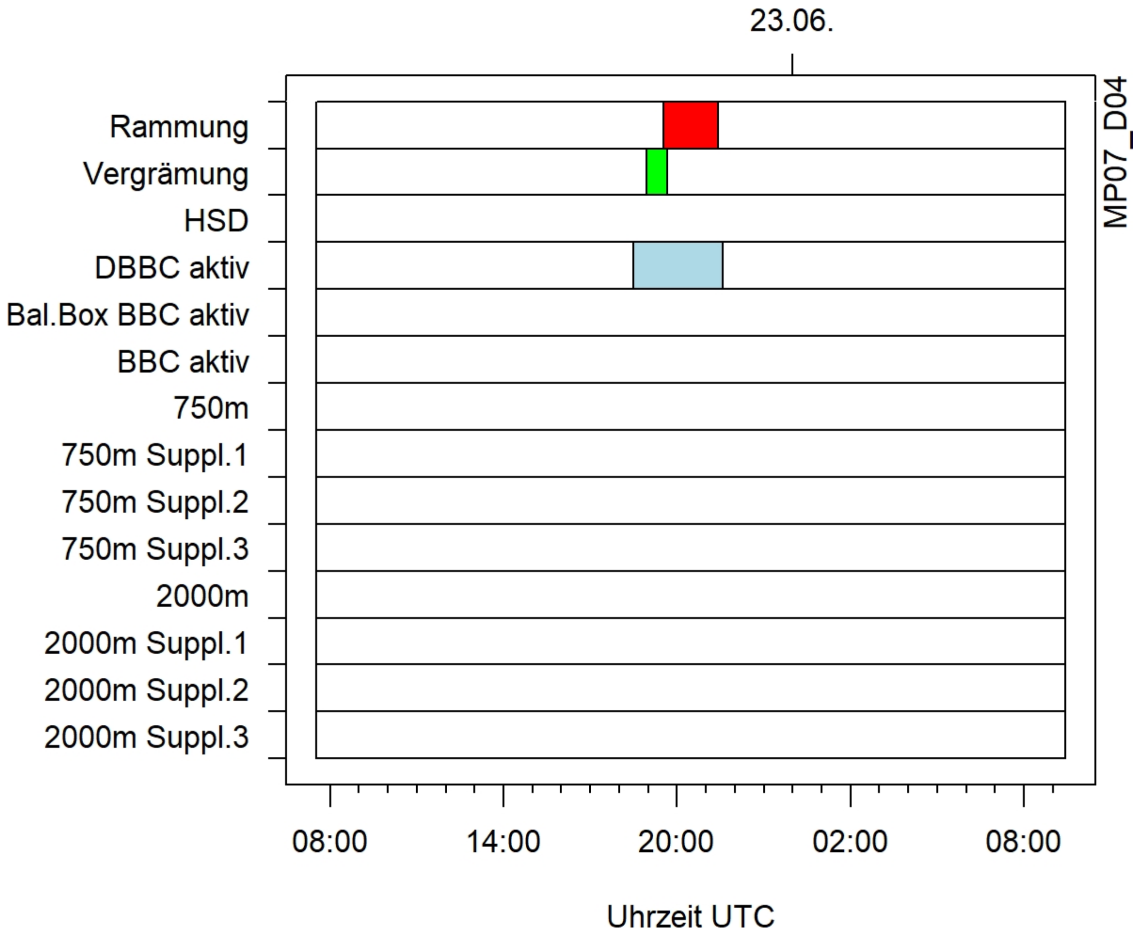

Fig. 3.7 D04 - Temporal representation of the pile-driving phase (red), the use of an APD system (green), noise protection measures (HSD, DBBC, Bal. Box BBC active and BBC active, blue) and C-PODs (grey). The pile-driving took place on 22/06/2022. An APD system was used before the pile driving. A DBBC was used as noise protection. A C-POD was not used during this pile-driving, so it is not possible to determine whether harbour porpoises were present in the vicinity of the pile-driving at the specified time. "Suppl." (supplementary)= Additional measurements, only relevant for later pile-driving.

3.8 Monopile B04

The monopile B04 was set up on 26 June 2022 from 02:33 to 04:19 (Table 2.1). An APD system was activated 41 minutes before the start of pile-driving for deterrence purposes, but deactivated again two minutes before the start of pile-driving (duration: 39 minutes). An HSD was used to minimise noise.

A C-POD was deployed at a distance of 750 m (Table 2.1). According to the protocol, it was recovered about 5 hours before the end of the pile-driving. It is assumed that this was a documentation or setting error. For better evaluation, the recovery time was adjusted accordingly (Fig. 3.8). An average SEL value of 168 dB was determined at a distance of 750 m (Table 2.2); the maximum level value of 160 dB specified in the noise protection concept (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013) was exceeded. The average SPL value of 186 dB determined at a distance of 750 m is just below the maximum specified peak level value of 190 dB (Table 2.2).

Based on the available recordings, no harbour porpoises were detected at the POD station at a distance of 750 m from the pile-driving event (Table 3.1).

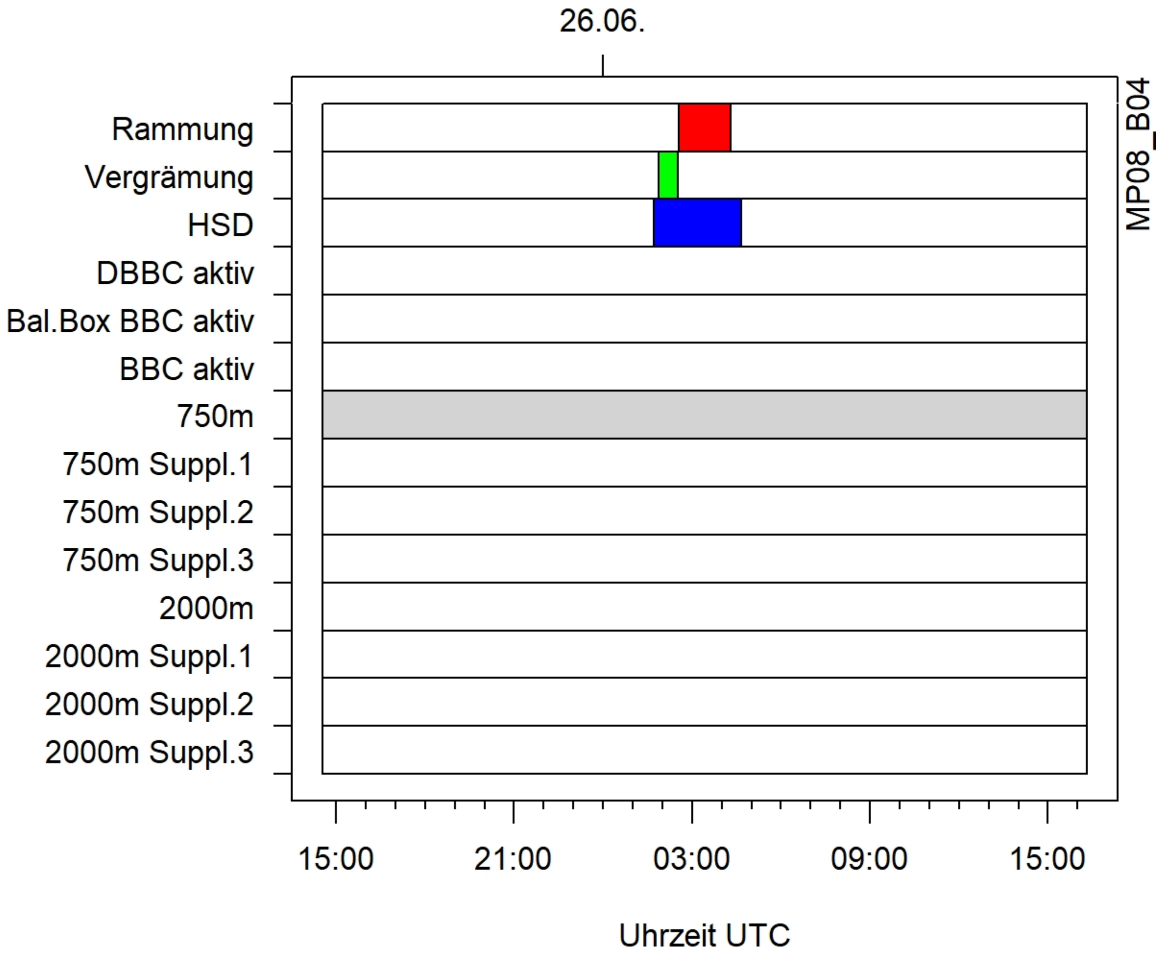

Fig. 3.8 B04 - Temporal representation of the pile-driving phase (red), the use of an APD system (green), noise protection measures (HSD, DBBC, Bal. Box BBC active and BBC active, blue) and C-PODs (grey). The pile-driving took place on 26/06/2022. An APD system was used before the pile driving. An HSD was used as noise protection. A C-POD was deployed at a distance of 750 m. The logged deployment time ends about 5 h before the end of pile driving. A logging or setting error is assumed. The recovery time was reasonably adjusted for the evaluation. No harbour porpoises were detected on the basis of the available recordings. "Suppl." (supplementary) = additional measurements, only relevant for later pile-driving.

3.9 Monopile F01

The monopile F01 was set up on 27 June 2022 from 00:20 to 01:12 (Table 2.1). An APD system was activated for deterrence 32 min before the start of pile-driving, but deactivated again as soon as pile-driving began (duration: 32 min). A DBBC and an HSD were used to minimise noise.

A C-POD was deployed at a distance of 750 m (Table 2.1). According to the protocol, it was recovered about 22.5 h before the end of the pile-driving. It is assumed that this was a documentation or setting error. For better evaluation, the time of recovery was adjusted accordingly (Fig. 3.9). An average SEL value of 161 dB was determined at a distance of 750 m (Table 2.2); the maximum level value of 160 dB specified in the noise protection concept (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013) was exceeded. At 179 dB, the average SPL value determined at a distance of 750 m is below the maximum specified peak level value of 190 dB (Table 2.2).

Based on the available recordings, no harbour porpoises were detected at the POD station at a distance of 750 m from the pile-driving event (Table 3.1).

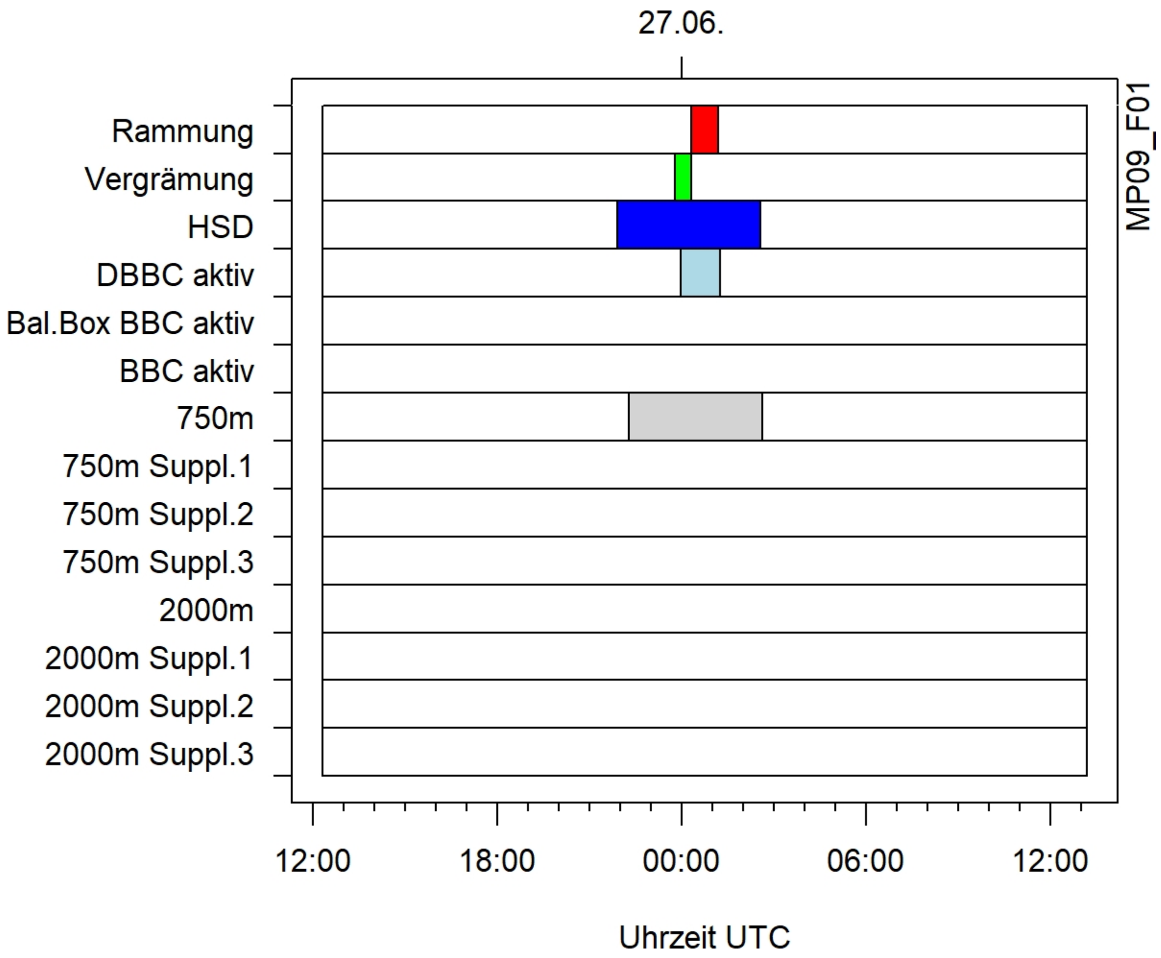

Fig. 3.9 F01 - Chronological representation of the pile-driving phase (red), the use of an APD system (green), noise protection measures (HSD, DBBC, Bal. Box BBC active and BBC active, blue) and C-PODs (grey). The pile-driving took place on 27/06/2022. An APD system was used before the pile driving. A DBBC and an HSD were used as noise protection. A C-POD was deployed at a distance of 750 metres. The logged deployment time ends around 22.5 h before the end of pile driving. A logging or setting error is assumed. The recovery time was reasonably adjusted for the evaluation. No harbour porpoises were detected on the basis of the existing recording. "Suppl." (supplementary) = additional measurements, only relevant for later pile-driving.

3.10 Monopile C02

The monopile C02 was set up on 1 July 2022 from 04:36 to 06:04 (Table 2.1.) An APD system was activated for deterrence 34 minutes before pile-driving began, but deactivated again nine minutes before pile-driving began (duration: 25 minutes). A DBBC and an HSD were used to minimise noise.

A C-POD was deployed at a distance of 750 m (Table 2.1). According to the protocol, it was recovered about 7.5 hours before the end of the pile-driving. A documentation or setting error is assumed. For better evaluation, the recovery time was adjusted accordingly (Fig. 3.10). An average SEL value of 166 dB was determined at a distance of 750 m (Table 2.2); the maximum level value of 160 dB specified in the noise protection concept (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013) was exceeded. The average SPL value of 186 dB determined at a distance of 750 m is just below the maximum specified peak level value of 190 dB (Table 2.2).

Based on the available recordings, no harbour porpoises were detected at the POD station at a distance of 750 m from the pile-driving event (Table 3.1).

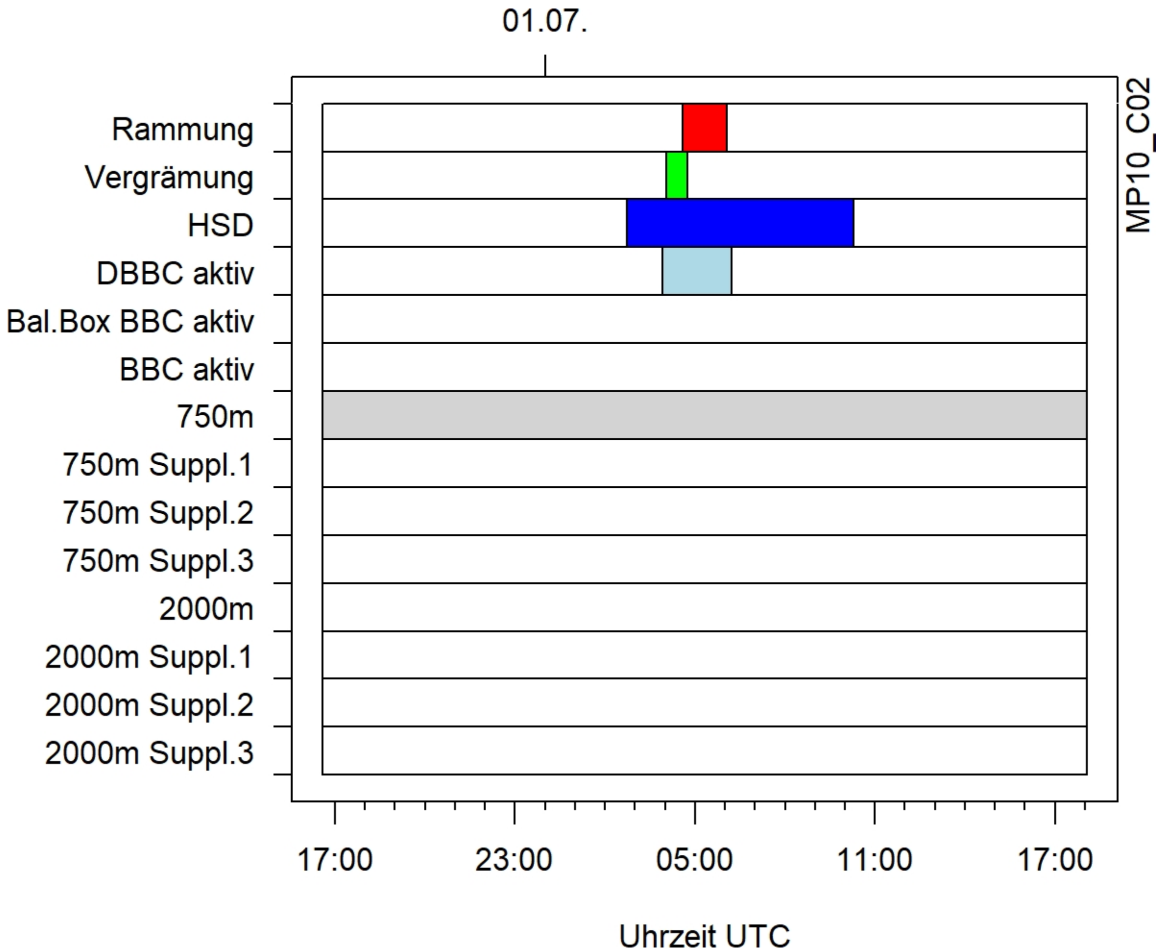

Fig. 3.10 C02 - Chronological representation of the pile-driving phase (red), the use of an APD system (green), noise protection measures (HSD, DBBC, Bal. Box BBC active and BBC active, blue) and C-PODs (grey). The pile-driving took place on 01.07.2022. An APD system was used before the pile driving. A DBBC and an HSD were used as noise protection. A C-POD was deployed at a distance of 750 metres. The logged deployment time ends around 7.5 h before the end of pile driving. A logging or setting error is assumed. The recovery time was reasonably adjusted for the evaluation. No harbour porpoises were detected on the basis of the existing recording. "Suppl." (supplementary) = additional measurements, only relevant for later pile-driving.

3.11 Monopile F03

The monopile F03 was founded on 2 July 2022 in two pile-driving phases (Table 2.1). The first pile-driving phase lasted from 11:34 to 12:49. For deterrence, an APD system was activated 44 minutes before pile-driving began and deactivated at the same time as pile-driving began (duration: 44 minutes). A DBBC and an HSD were used to minimise noise.

The second pile-driving phase began at 14:53 and ended at 15:26. An APD system was activated 26 minutes before the start of the pile-driving and deactivated just 2 minutes after the start of the pile-driving (duration: 28 minutes). A DBBC and an HSD were used to minimise noise.

A C-POD was continuously deployed for both pile-driving phases at a distance of 750 m (Table 2.1). The following average SEL values were determined at this distance: 1st pile-driving phase: 168 dB, 2nd pile-driving phase: 165 dB (Table 2.2). The average SEL values determined exceed the maximum level value of 160 dB specified in the noise protection concept (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013). The average SPL value determined at a distance of 750 m is 186 dB for the 1st pile-driving phase and 183 dB for the 2nd pile-driving phase, which is below the maximum specified peak level value of 190 dB (Table 2.2.)

No harbour porpoises were detected at the POD station 750 m from the pile-driving event (Table 3.1).

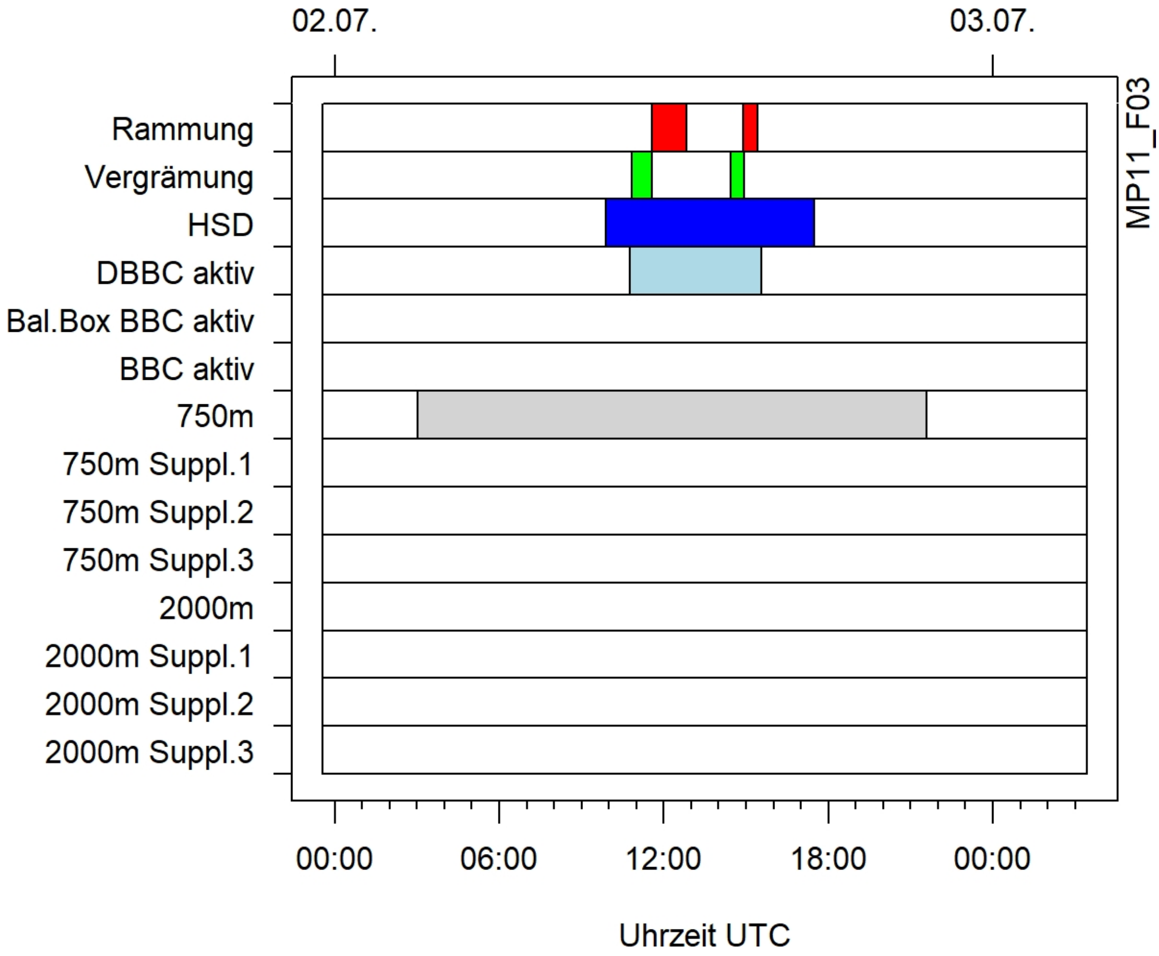

Fig. 3.11 F03 - Temporal representation of the pile-driving phases (red), the use of an APD system (green), noise protection measures (HSD, DBBC, Bal. Box BBC active and BBC active, blue) and C-PODs (grey). The pile-driving took place in two pile-driving phases on 2 July 2022. An APD system was used before each pile-driving phase. One DBBC and one HSD were used as noise protection. A C-POD was installed at a distance of 750 metres. No harbour porpoises were detected before, during or after the pile driving. "Suppl." (supplementary)= Additional measurements, only relevant for later pile driving.

3.12 Monopile D02

The monopile D02 was set up on 3 July 2022 from 11:38 to 12:52 (Table 2.1.)For deterrence, an APD system was activated 40 minutes before pile-driving began and deactivated again as soon as pile-driving began (duration: 40 minutes). A DBBC and an HSD were used to minimise noise.

A C-POD was deployed 750 metres away during this pile-driving. However, this was not set beforehand, so that no recordings were made. It is therefore not possible to determine whether harbour porpoises were present in the surrounding area during the pile-driving.

An average SEL value of 165 dB was determined at a distance of 750 m (Table 2.2); the maximum level value of 160 dB specified in the noise protection concept (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013) was exceeded. The average SPL value determined at a distance of 750 m is 183 dB, which is below the maximum specified peak level value of 190 dB (Table 2.2).

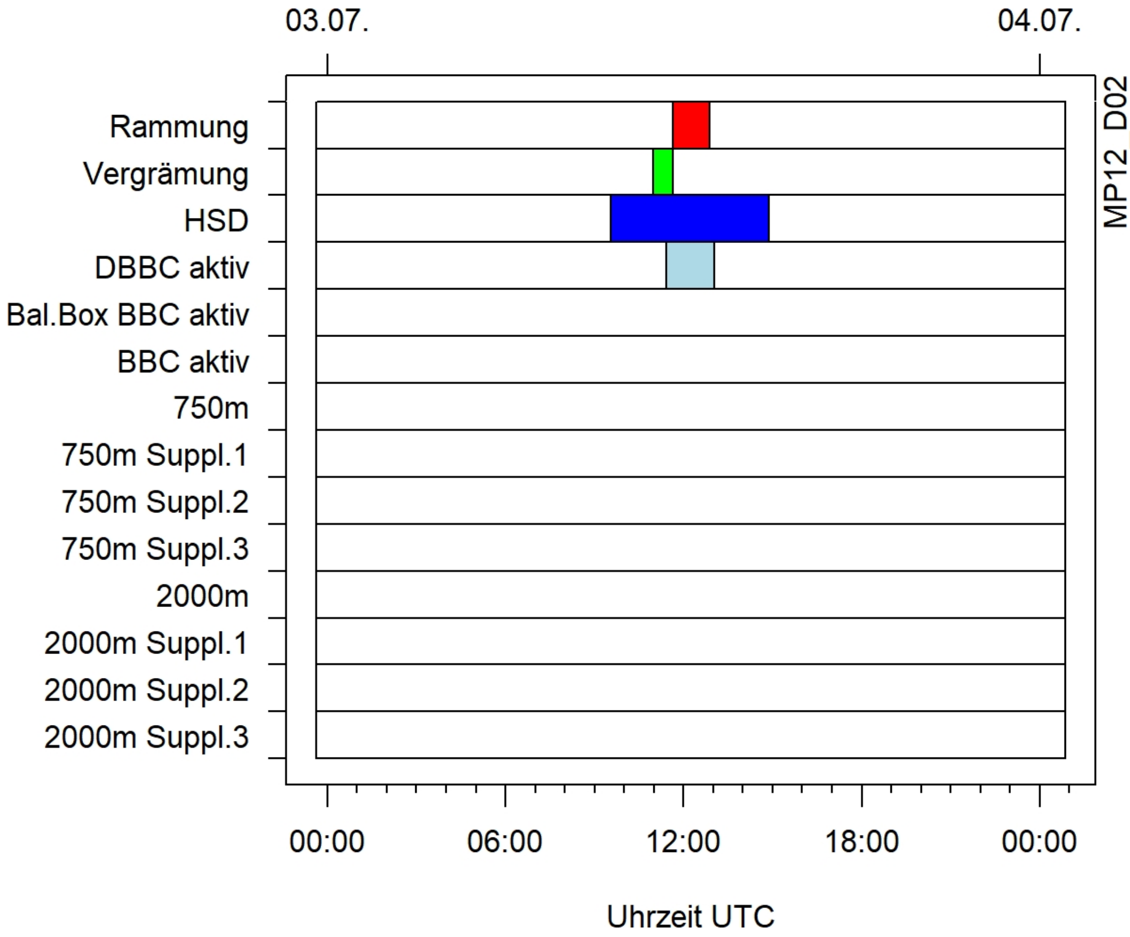

Fig. 3.12 D02 - Temporal representation of the pile-driving phase (red), the use of an APD system (green), noise protection measures (HSD, DBBC, Bal. Box BBC active and BBC active, blue) and C-PODs (grey). The pile-driving took place on 03/07/2022. An APD system was used before the pile driving. A DBBC and an HSD were used as noise protection. A C-POD was deployed at a distance of 750 m during this pile-driving, but no recordings were possible, so it is not possible to determine whether harbour porpoises were present in the vicinity of the pile-driving at the specified time. "Suppl." (supplementary)= Additional measurements, only relevant for later pile driving.

3.13 Monopile G01

The monopile G01 was set up on 5 July 2022 from 01:15 to 02:04 (Table 2.1). An APD system was activated for deterrence 36 min before the start of pile driving, but deactivated again at the start of pile driving (duration: 36 min). A DBBC and an HSD were used to minimise noise.

A C-POD was deployed at a distance of 750 m (Table 2.1). According to the protocol, it was recovered about 18 hours before the end of the pile-driving. A documentation or setting error is assumed. For better evaluation, the recovery time was adjusted accordingly (Fig. 3.13). An average SEL value of 166 dB was determined at a distance of 750 m (Table 2.2); the maximum level value of 160 dB specified in the noise protection concept (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013) was exceeded. The average SPL value of 186 dB determined at a distance of 750 m is just below the maximum specified peak level value of 190 dB (Table 2.2).

Based on the available recordings, no harbour porpoises were detected at the POD station at a distance of 750 m from the pile-driving event (Table 3.1).

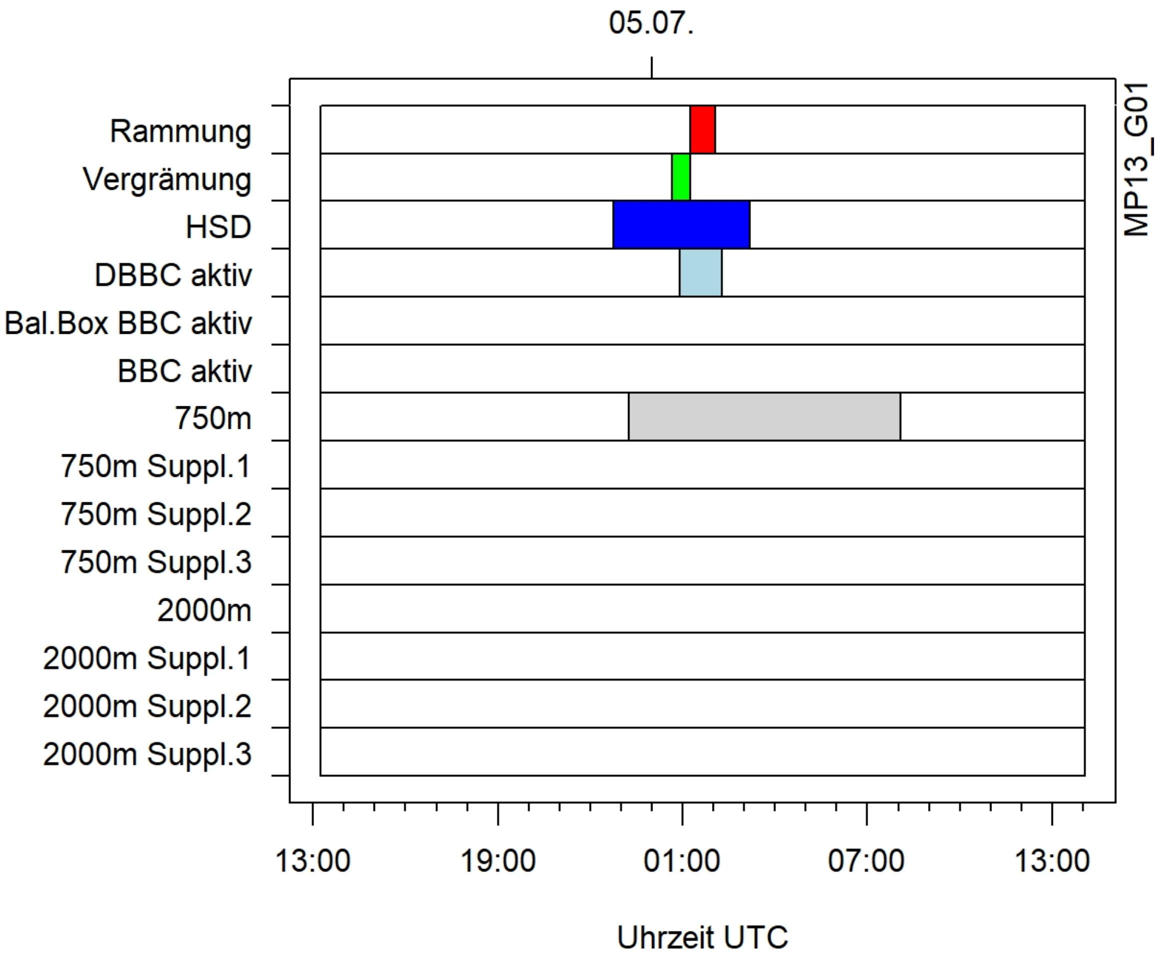

Fig. 3.13 G01 - Temporal representation of the pile-driving phase (red), the use of an APD system (green), noise protection measures (HSD, DBBC, Bal. Box BBC active and BBC active, blue) and C-PODs (grey). The pile-driving took place on 05.07.2022. An APD system was used before the pile driving. A DBBC and an HSD were used as noise protection. A C-POD was deployed at a distance of 750 metres. The logged deployment time ends around 18 hours before the end of pile driving. A logging or setting error is assumed. The recovery time was reasonably adjusted for the evaluation. No harbour porpoises were detected on the basis of the existing recording. "Suppl." (supplementary) = additional measurements, only relevant for later pile-driving.

3.14 Monopile E01

The monopile E01 was set up on 6 July 2022 from 00:13 to 00:44 (Table 2.1). For deterrence, an APD system was activated 35 minutes before pile-driving began and deactivated again as soon as pile-driving began (duration: 35 minutes). A DBBC and an HSD were used to minimise noise.

A C-POD was deployed at a distance of 750 m from the pile-driving position during this pile-driving (Table 2.1), but two recordings were detected with a large time interval. It is assumed that there was a documentation or setting error. For better evaluation, the time of the later recordings was sensibly adjusted to the pile-driving time available for E01. It is therefore not possible to conclusively determine whether harbour porpoises were present in the surrounding area during the pile-driving event.

At a distance of 750 m, an average SEL value of 167 dB was determined (Table 2.2); the maximum level value of 160 dB specified in the noise protection concept (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013) was exceeded. The average SPL value of 186 dB determined at a distance of 750 m is just below the maximum specified peak level value of 190 dB (Table 2.2).

Based on the available recordings, no harbour porpoises were detected at the POD station at a distance of 750 m from the pile-driving event (Table 3.1).

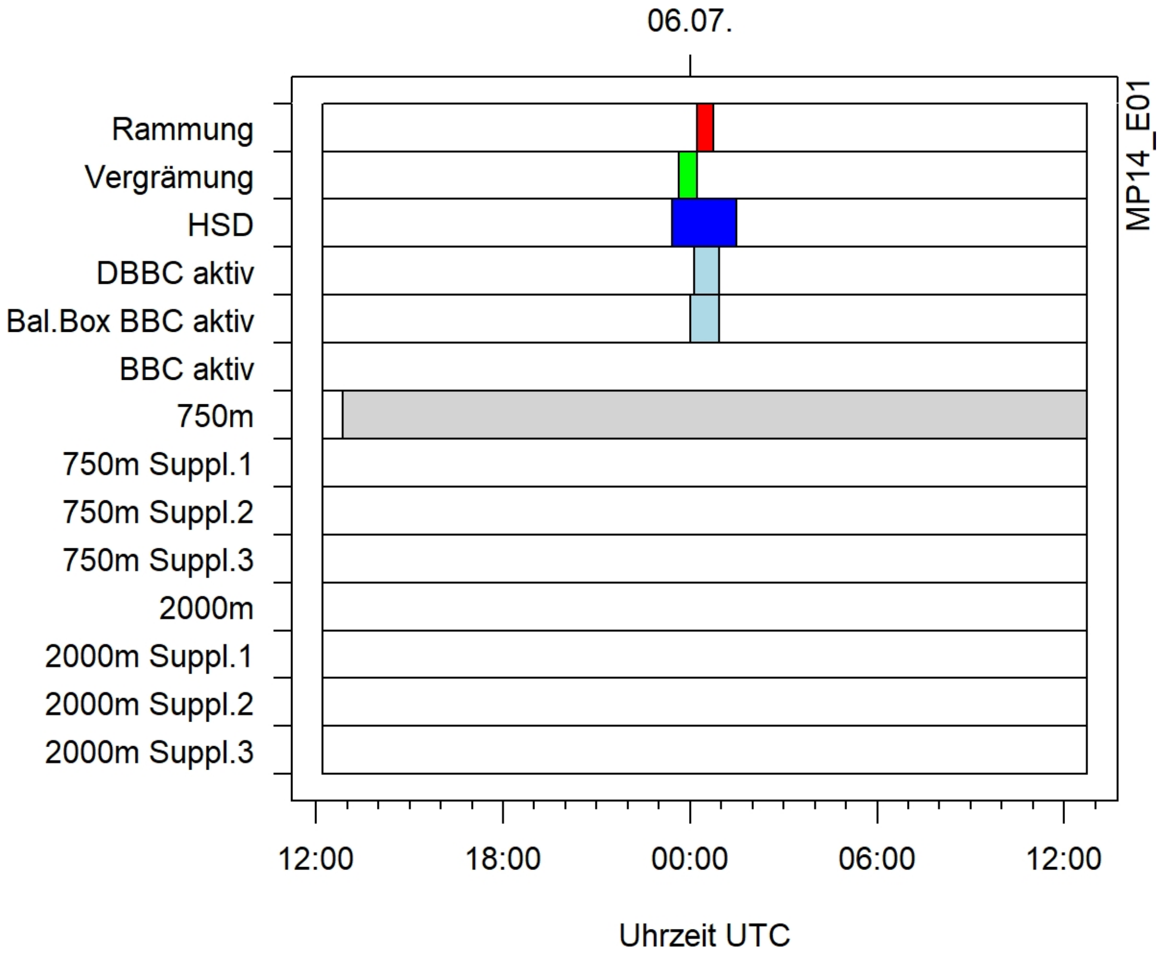

Fig. 3.14 E01 - Chronological representation of the pile-driving phase (red), the use of an APD system (green), noise protection measures (HSD, DBBC, Bal. Box BBC active and BBC active, blue) and C-PODs (grey). The pile-driving took place on 06.07.2022. An APD system was used before the pile driving. A DBBC and an HSD were used as noise protection. A C-POD was deployed at a distance of 750 metres. The recorded deployment time did not match the pile-driving time. A logging or setting error is assumed. The application time was sensibly adjusted for the evaluation. No harbour porpoises were detected on the basis of the existing recording. "Suppl." (supplementary) = additional measurements, only relevant for later pile-driving.

3.15 Monopile G04

The monopile G04 was set up on 6 July 2022 from 14:42 to 15:53 (Table 2.1). For deterrence, an APD system was activated 37 min before the start of pile-driving and deactivated again at the start of pile-driving (duration: 37 min). A DBBC, a BBB and an HSD were used to minimise noise.

A C-POD was deployed at a distance of 750 m (Table 2.1). At this distance, an average SEL value of 165 dB was determined; the maximum level value of 160 dB specified in the noise protection concept (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013) was exceeded. At 183 dB, the average SPL value determined at a distance of 750 m is below the maximum specified peak level value of 190 dB (Table 2.2).

No harbour porpoises were detected at the POD station 750 m from the pile-driving event (Table 3.1).

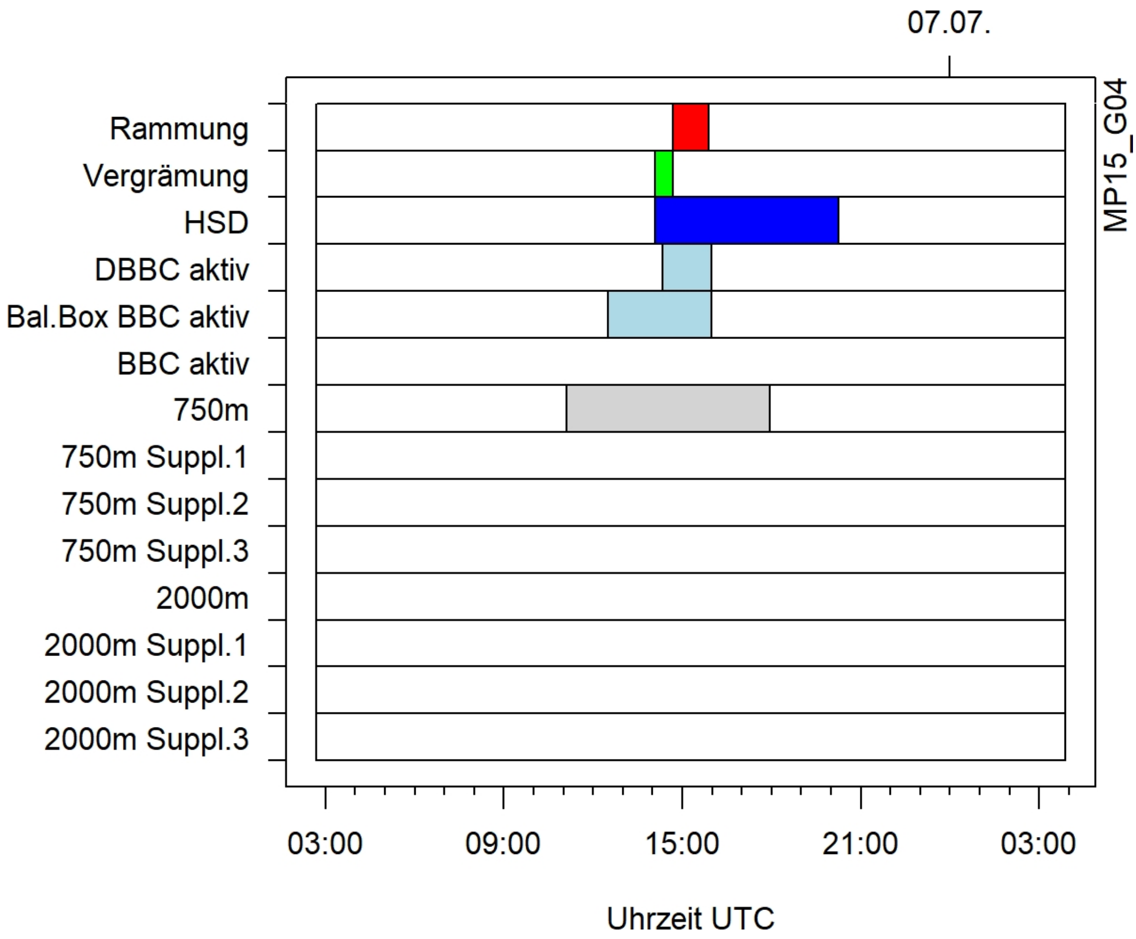

Fig. 3.15 G04 - Temporal representation of the pile-driving phase (red), the use of an APD system (green), noise protection measures (HSD, DBBC, Bal. Box BBC active and BBC active, blue) and C-PODs (grey) for the foundation of the monopile G04. The pile-driving took place on 06.07.2022. An APD system was used before the pile driving. A DBBC, a BBB and an HSD were used as noise protection. A C-POD was installed at a distance of 750 metres. No harbour porpoises were detected before, during or after the pile-driving. "Suppl." (supplementary)= Additional measurements, only relevant for later pile-driving.

3.16 Monopile A04

The monopile A04 was set up on 8 July 2022 from 16:19 to 17:18 (Table 2.1). For deterrence, an APD system was activated 30 min before the start of pile driving, but deactivated again at the start of pile driving (duration: 30 min). A DBBC, a BBB and an HSD were used to minimise noise.

One C-POD was deployed at a distance of 750 m and one at a distance of 2,000 m. Due to the fact that the maximum level values of previous pile-drivings were consistently exceeded, additional measurements were carried out for these and all further pile-drivings in the form of three additional C-PODs each in
2,000 m away. In total, one C-POD was deployed at a distance of 750 m and four C-PODs at a distance of 2,000 m for each pile-driving operation. According to records, one C-POD at a distance of 2,000 m from the pile-driving event was recovered approx. 61 h before the end of the pile-driving. A documentation or setting error is assumed. The deployment times were sensibly adjusted for the evaluation. An average SEL value of 169 dB was determined at a distance of 750 m (Table 2.2); the maximum level value of 160 dB specified in the noise protection concept (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013) was exceeded. At 188 dB, the average SPL value determined at a distance of 750 m is just below the maximum specified peak level value of 190 dB (Table 2.2).

Harbour porpoises were detected at the POD station at a distance of 750 m from the pile-driving event approximately 44 minutes before the APD system was deployed (Table 3.1). At a distance of 2,000 m from the pile-driving activity, harbour porpoises were detected one minute before the APD system was deployed and four times during the deployment of the APD system (Table 3.1.)

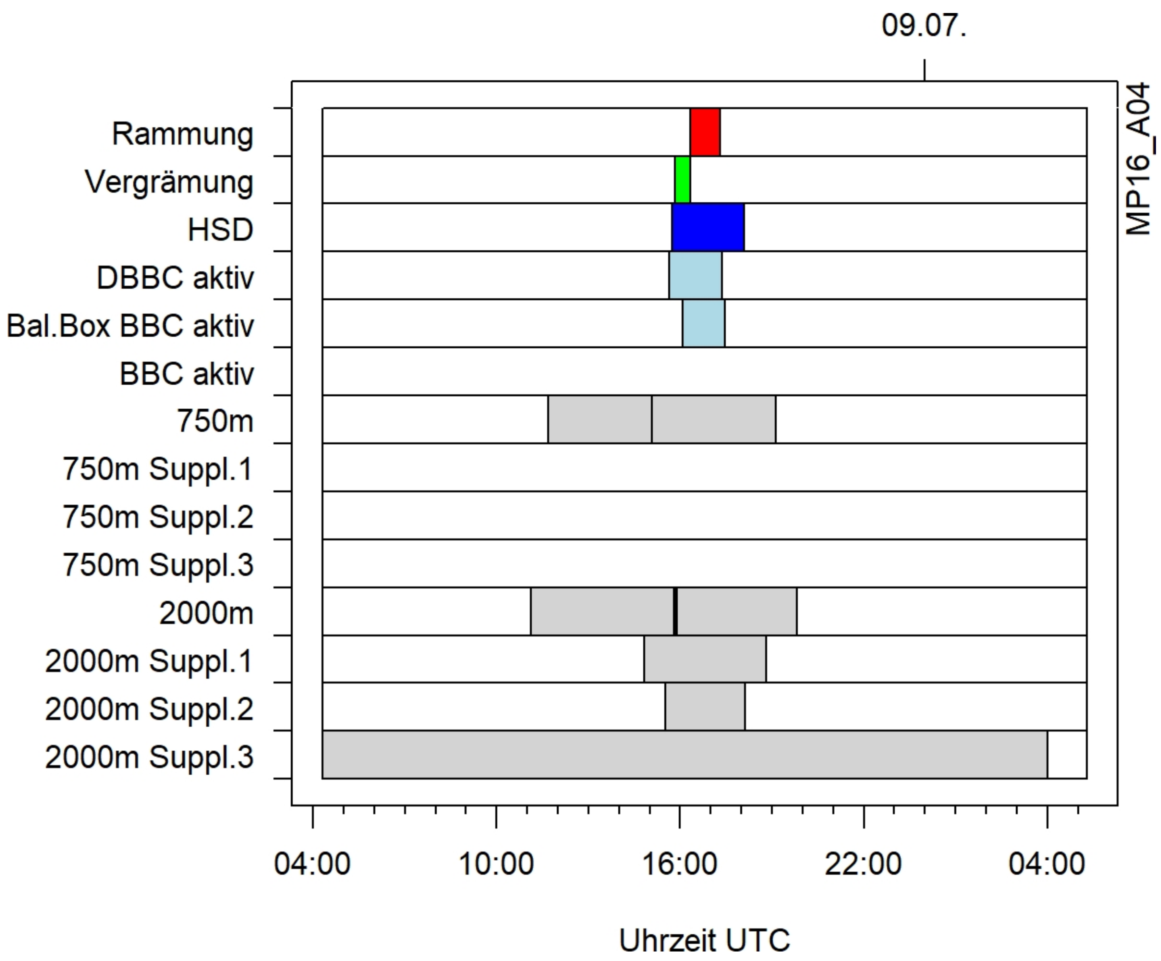

Fig. 3.16 A04 - Temporal representation of the pile-driving phase (red), the use of an APD system (green), noise protection measures (HSD, DBBC, Bal. Box BBC active and BBC active, blue) and C-PODs (grey). The pile-driving took place on 08/07/2022. An APD system was used before the pile driving. A DBBC, a BBB and an HSD were used as noise protection. C-PODs were deployed at 750 m and 2,000 m distance. The recorded deployment time of the C-PODs
"2,000 m Suppl. 3" ends about 61 h before the end of the pile-driving. A logging or setting error is assumed. The time of the recovery was sensibly adjusted for the evaluation. Harbour porpoises were detected both at a distance of 750 m and 2,000 m before and during the deployment of the APD system (vertical lines). "Suppl." (supplementary) = additional measurements.

3.17 Monopile A01

The monopile A01 was set up on 10 July 2022 from 17:11 to 18:10 (Table 2.1). For deterrence, an APD system was activated 44 min before the start of pile-driving, but deactivated again at the start of pile-driving (duration: 44 min). A DBBC, a BBB and an HSD were used to minimise noise.

One C-POD was deployed at a distance of 750 m and a total of four C-PODs at a distance of 2,000 m (Table 2.1). At a distance of 750 m, an average SEL value of 167 dB was determined; the maximum level value of 160 dB specified in the noise protection concept (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013) was exceeded. The average SPL value of 186 dB determined at a distance of 750 m is just below the maximum specified peak level value of 190 dB (Table 2.2).

No harbour porpoises were detected at the POD stations 750 m and 2,000 m from the pile-driving event (Table 3.1.)

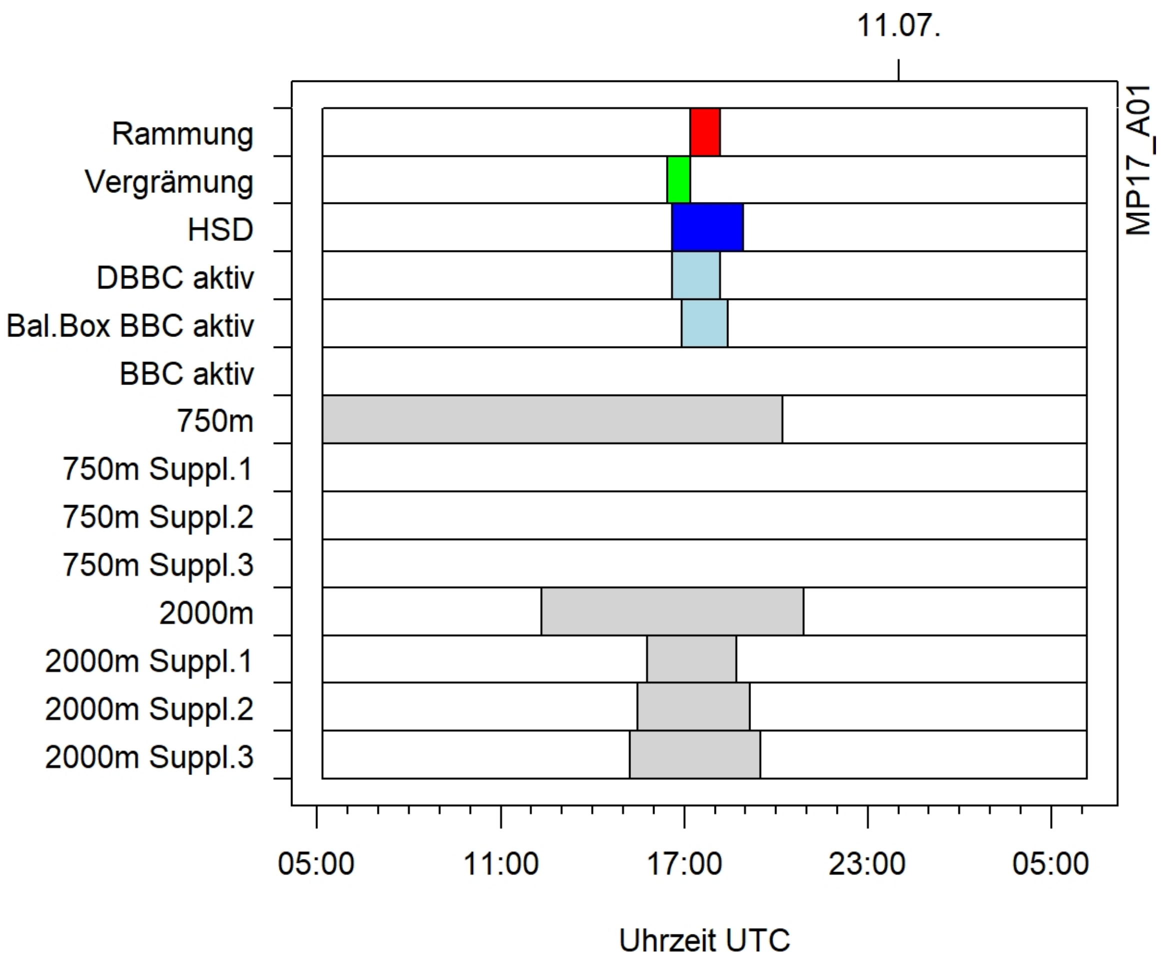

Fig. 3.17 A01 - Temporal representation of the pile-driving phase (red), the use of an APD system (green), noise protection measures (HSD, DBBC, Bal. Box BBC active and BBC active, blue) and C-PODs (grey). The pile-driving took place on 10/07/2022. An APD system was used before the pile driving. A DBBC, a BBB and an HSD were used as noise protection. C-PODs were deployed at 750 m and 2,000 m distance. No harbour porpoises were detected before, during or after the pile-driving. "Suppl." (supplementary) = additional measurements.

3.18 Monopile B01

Monopile B01 was set up on 11 July 2022 from 08:13 to 09:55 (Table 2.1). An APD system was activated 44 minutes before the start of pile-driving for deterrence purposes, but deactivated again five minutes before the start of pile-driving (duration: 39 minutes). A DBBC, a BBB and an HSD were used to minimise noise.

One C-POD was deployed at a distance of 750 m and a total of four C-PODs at a distance of 2,000 m (Table 2.1). According to the records, one C-POD at a distance of 2,000 m from the pile-driving event was recovered approx. 62 h before the end of the pile-driving. A documentation or setting error is assumed. The deployment times were sensibly adjusted for the evaluation. At a distance of 750 m, an average SEL value of 167 dB was determined (Table 2.2); the maximum level value of 160 dB specified in the noise protection concept (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013) was exceeded. The average SPL value of 186 dB determined at a distance of 750 m is just below the maximum specified peak level value of 190 dB (Table 2.2).

Based on the available recordings, no harbour porpoises were detected at the POD stations 750 m and 2,000 m from the pile-driving event (Table 3.1).

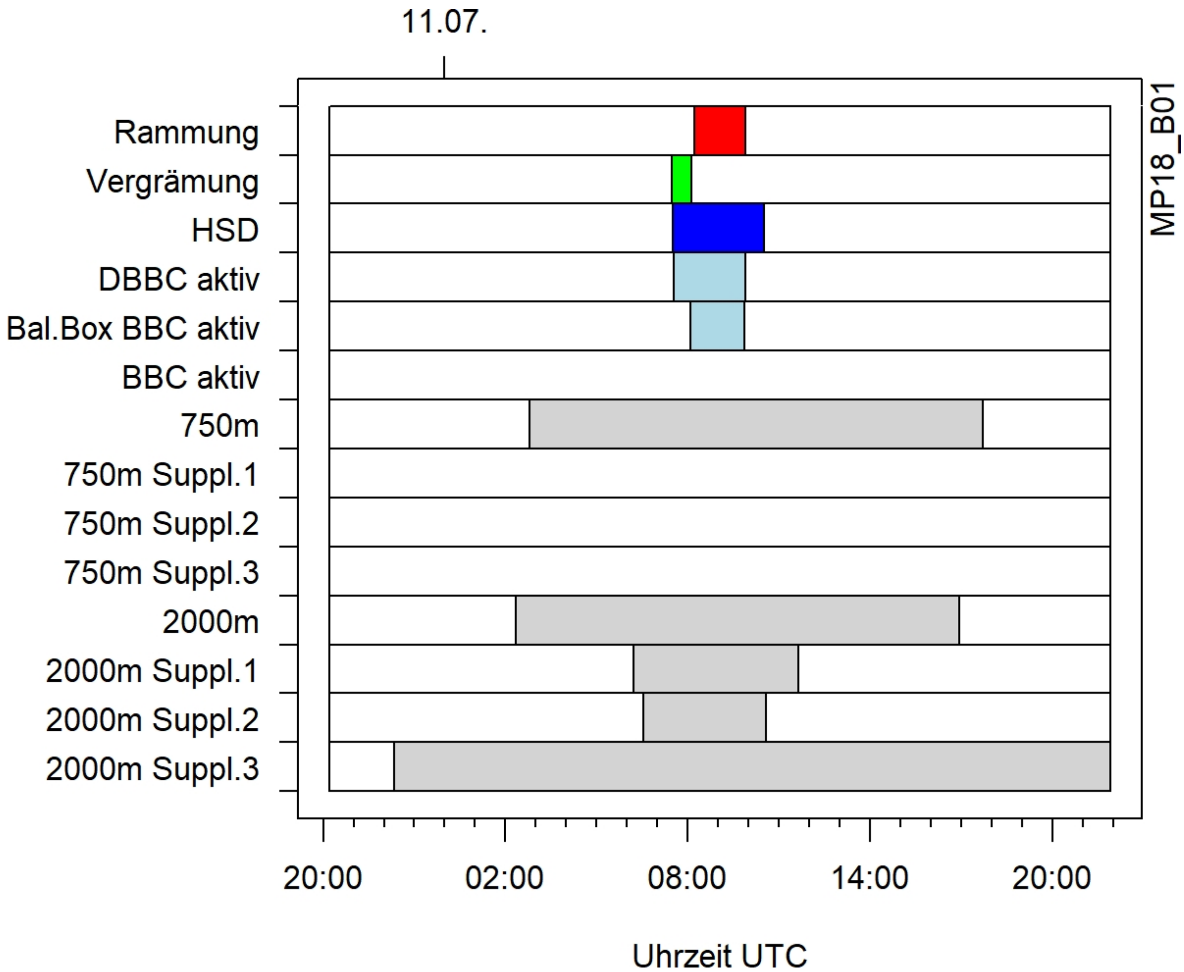

Fig. 3.18 B01- Temporal representation of the pile-driving phase (red), the use of an APD system (green), noise protection measures (HSD, DBBC, Bal. Box BBC active and BBC active, blue) and C-PODs (grey). The pile-driving took place on 11/07/2022. An APD system was used before the pile driving. A DBBC, a BBB and an HSD were used as noise protection. C-PODs were deployed at 750 m and 2,000 m distance. The recorded deployment time of the C-POD "2,000 m Suppl. 3" ends approximately 62 h before the end of pile driving. A logging or setting error is assumed. The recovery time was sensibly adjusted for the evaluation. No harbour porpoises were detected before, during or after the pile-driving. "Suppl." (supplementary) = additional measurements.

3.19 Monopile D01

The monopile D01 was set up on 12 July 2022 from 06:42 to 07:32 (Table 2.1.)For deterrence, an APD system was activated 41 min before the start of pile-driving, but deactivated again just two minutes after the start of pile-driving (duration: 43 min). A TBBC (DBBC + BBC), a BBB and an HSD were used to minimise noise.

One C-POD was deployed at a distance of 750 m and, in this case, only a total of three C-PODs were deployed at a distance of 2,000 m (Table 2.1.)At a distance of 750 m, an average SEL value of 169 dB was determined (Table 2.2); the maximum level value of 160 dB specified in the noise protection concept (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013) was exceeded. At 187 dB, the average SPL value determined at a distance of 750 m is just below the maximum specified peak level value of 190 dB (Table 2.2).

No harbour porpoises were detected at either the POD stations at 750 m or 2,000 m from the pile-driving event (Table 3.1.)

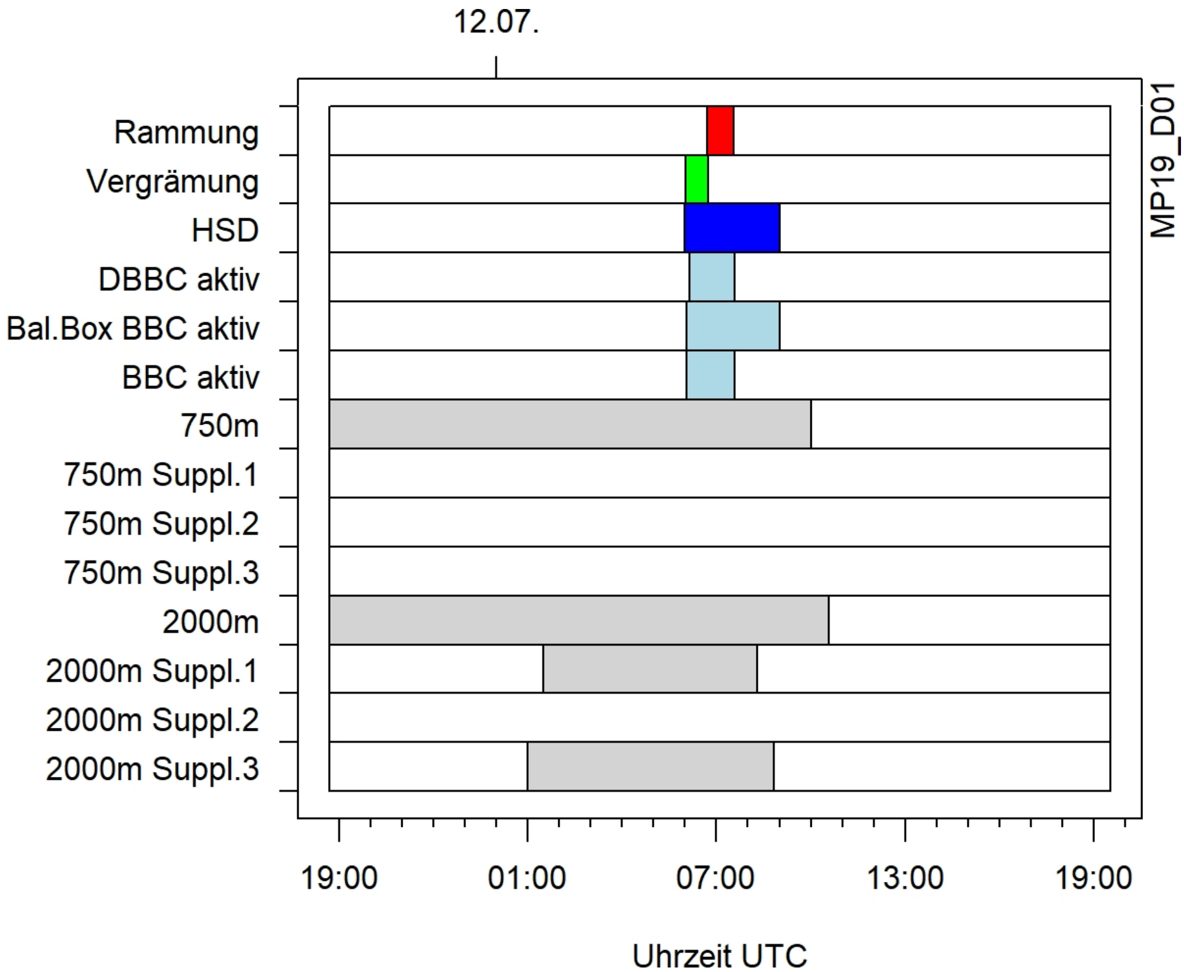

Fig. 3.19 D01 - Chronological representation of the pile-driving phase (red), the use of an APD system (green), noise protection measures (HSD, DBBC, Bal. Box BBC active and BBC active, blue) and C-PODs (grey) for the foundation of monopile D01. The pile-driving took place on 12/07/2022. An APD system was used before the pile driving. A TBBC (DBBC+ BBC), a BBB and an HSD were used as noise protection. C-PODs were installed at distances of 750 m and 2,000 m. No harbour porpoises were detected before, during or after the pile driving. "Suppl." (supplementary) = additional measurements.

3.20 Monopile A02

The monopile A02 was set up on 14 July 2022 from 04:22 to 05:12 (Table 2.1). For deterrence, an APD system was activated 1 h 10 min before the start of pile-driving and deactivated again two minutes before the start of pile-driving (duration: 1 h 8 min). A TBBC (DBBC + BBC), a BBB and an HSD were used to minimise noise.

One C-POD was deployed at a distance of 750 m and a total of four C-PODs at a distance of 2,000 m (Table 2.1). According to the records, the C-POD at a distance of 750 m from the pile-driving event was recovered approx. 4 h before the end of the pile-driving. A documentation or setting error is assumed. The deployment times were sensibly adjusted for the evaluation. An average SEL value of 167 dB was determined at a distance of 750 m (Table 2.2); the maximum level value of 160 dB specified in the noise protection concept (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013) was exceeded. At 187 dB, the average SPL value determined at a distance of 750 m is just below the maximum specified peak level value of 190 dB (Table 2.2).

Based on the available recordings, no harbour porpoises were detected at the POD stations 750 m and 2,000 m from the pile-driving event (Table 3.1).

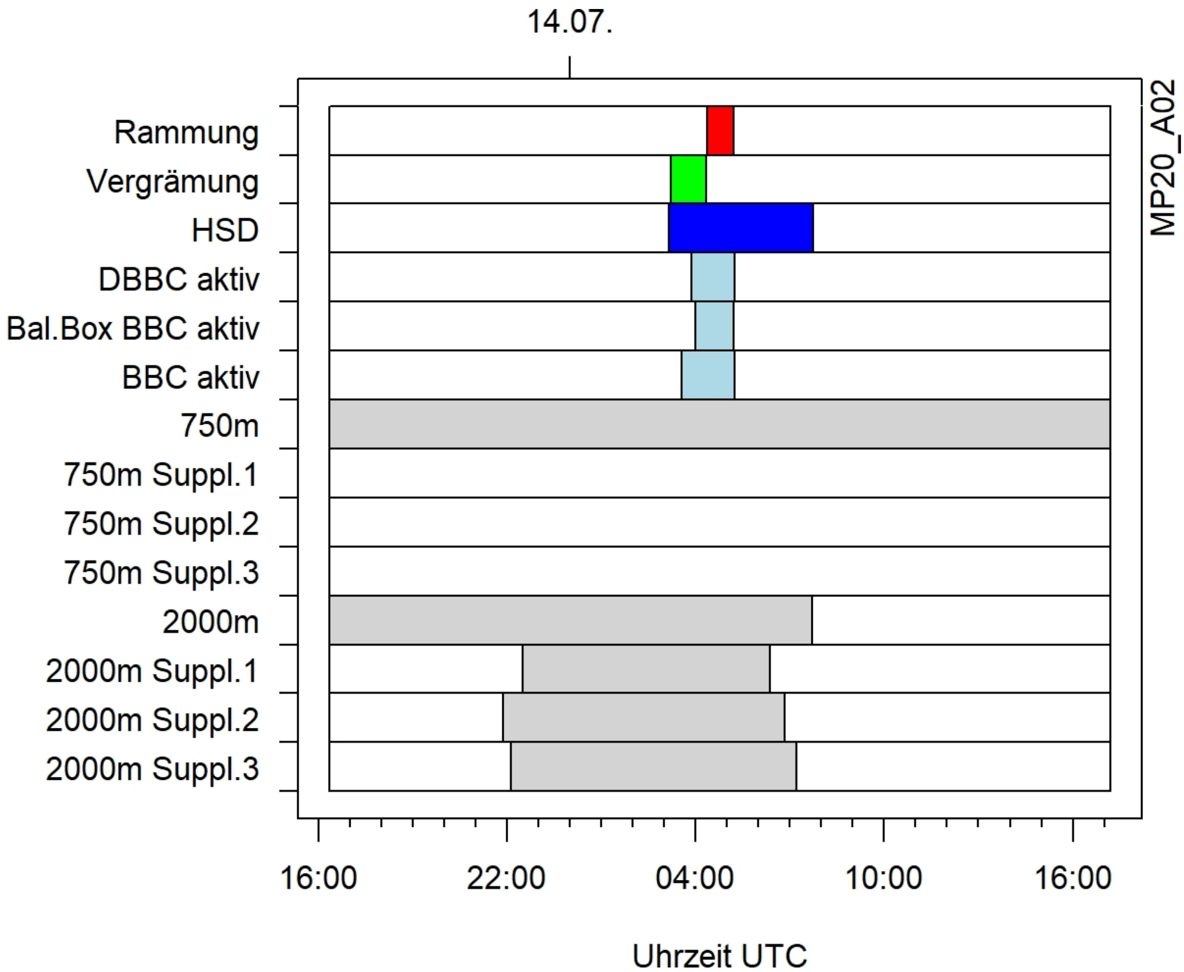

Fig. 3.20 A02 - Temporal representation of the pile-driving phase (red), the use of an APD system (green), noise protection measures (HSD, DBBC, Bal. Box BBC active and BBC active, blue) and C-PODs (grey). The pile-driving took place on 14/07/2022. An APD system was used before the pile driving. A TBBC (DBBC + BBC), a BBB and an HSD were used as noise protection. C-PODs were deployed at distances of 750 m and 2,000 m. The recorded deployment time of the C-POD at a distance of 750 m ends about 4 h before the end of pile driving. A logging or setting error is assumed. The recovery time was reasonably adjusted for the evaluation. No harbour porpoises were detected on the basis of the existing recording. "Suppl." (supplementary) = additional measurements.

3.21 Monopile F04

The monopile F04 was set up on 16 July 2022 from 16:33 to 17:25 (Table 2.1). An APD system was activated 39 minutes before the start of pile-driving for deterrence purposes and deactivated again just two minutes after the start of pile-driving (duration: 41 minutes). A TBBC (DBBC + BBC), a BBB and an HSD were used to minimise noise.

In this case, four C-PODs were deployed at a distance of 750 m and one C-POD at a distance of 2,000 m (Table 2.1.)According to the records, the C-POD at a distance of 750 m from the pile-driving event was recovered approx. 22 h before the end of the pile-driving. According to the records, the C-POD at a distance of 2,000 m from the pile-driving event was recovered approx. 95 h before the end of the pile-driving. A documentation or setting error is assumed. The deployment times were sensibly adjusted for the evaluation. At a distance of 750 m, an average SEL value of 164 dB was determined (Table 2.2); the maximum level value of 160 dB specified in the noise protection concept (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013) was exceeded. The average SPL value determined at a distance of 750 m is 181 dB, which is below the maximum specified peak level value of 190 dB (Table 2.2).

Around 3.5 h before the APD system was deployed, harbour porpoises were detected at the POD station at a distance of 2,000 m (Table 3.1).

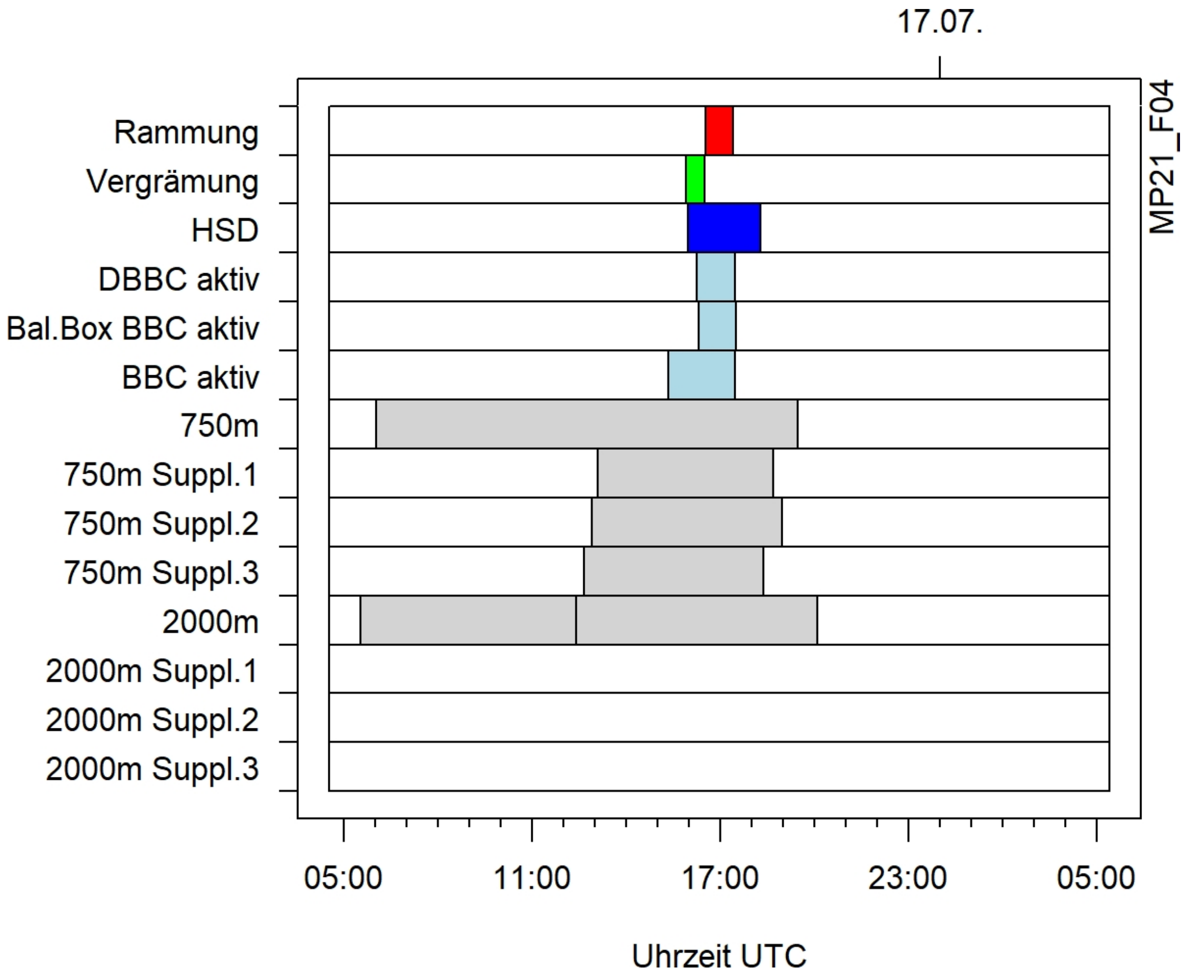

Fig. 3.21 F04 - Chronological representation of the pile-driving phase (red), the use of an APD system (green), noise protection measures (HSD, DBBC, Bal. Box BBC active and BBC active, blue) and C-PODs (grey). The pile-driving took place on 16/07/2022. An APD system was used before the pile driving. A TBBC (DBBC + BBC), a BBB and an HSD were used as noise protection. Four C-PODs were deployed at a distance of 750 m and one C-POD at a distance of 2,000 m. The recorded deployment time of the C-POD "750m" ends about 22 h, that of the C-POD "750m Suppl. 3" about 95 h before the end of pile driving. A logging or setting error is assumed. The deployment times were sensibly adjusted for the evaluation. Harbour porpoises were detected before the APD system was deployed (vertical lines). "Suppl." (supplementary) = additional measurements.

3.22 Monopile E02

The monopile E02 was set up on 17 July 2022 from 12:27 to 13:22 (Table 2.1). An APD system was activated for deterrence 34 minutes before pile-driving began, but deactivated again one minute before pile-driving began (duration: 33 minutes). A TBBC (DBBC + BBC), a BBB and an HSD were used to minimise noise.

One C-POD was deployed at a distance of 750 m and a total of four C-PODs at a distance of 2,000 m (Table 2.1). At a distance of 750 m, an average SEL value of 168 dB was determined (Table 2.2); the maximum level value of 160 dB specified in the noise protection concept (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013) was exceeded. At 188 dB, the average SPL value determined at a distance of 750 m is just below the maximum specified peak level value of 190 dB (Table 2.2).

At a POD station 2,000 metres away, harbour porpoises were detected a total of four times, the last time 37 minutes before the APD system was deployed (Table 3.1).

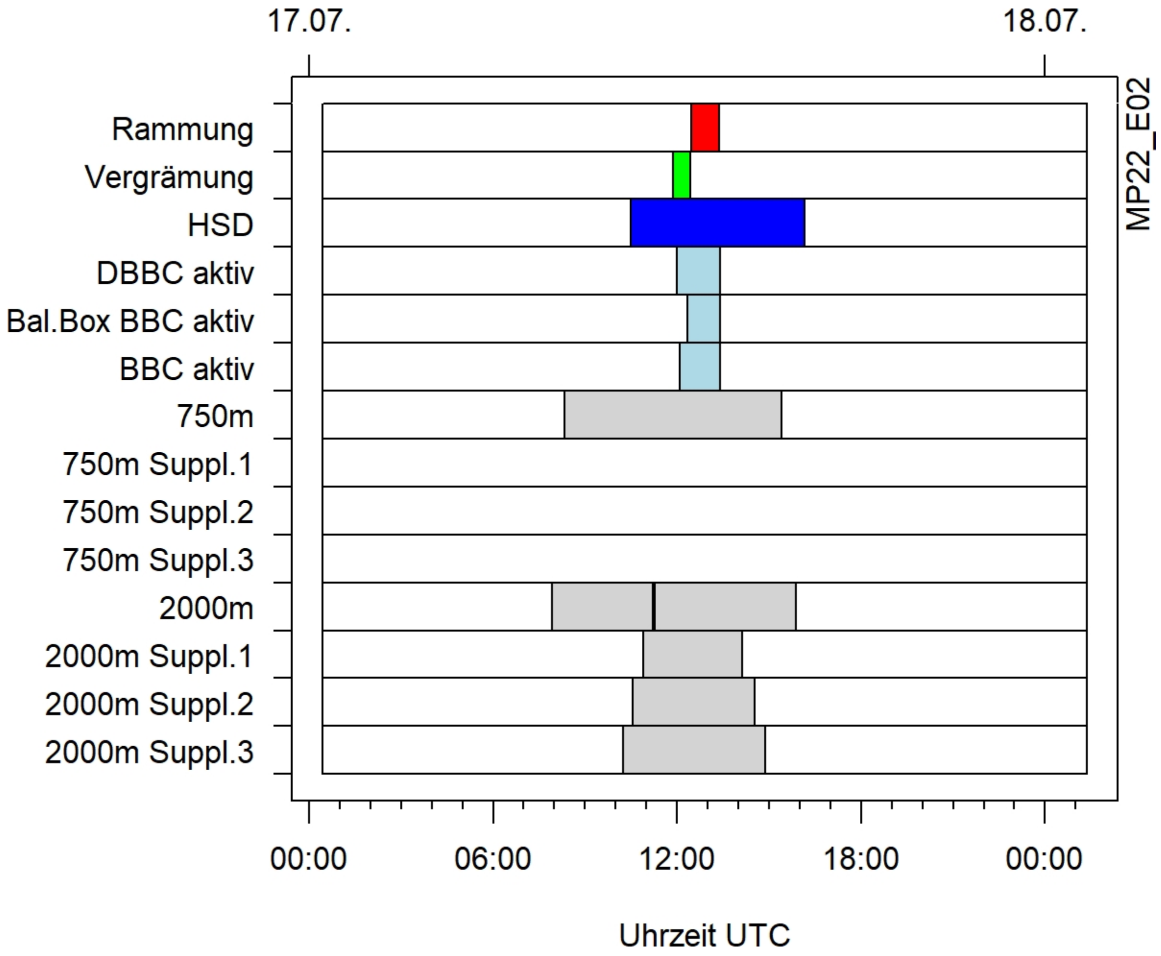

Fig. 3.22 E02 - Chronological representation of the pile-driving phase (red), the use of an APD system (green), noise protection measures (HSD, DBBC, Bal. Box BBC active and BBC active, blue) and C-PODs (grey). The pile-driving took place on 17/07/2022. An APD system was used before the pile driving. A TBBC (DBBC+ BBC), a BBB and an HSD were used as noise protection. C-PODs were installed at distances of 750 m and 2,000 m. Before the APD system was deployed, harbour porpoises were detected at a distance of 2,000 m from the pile driving (vertical lines).
"Suppl." (supplementary)= Additional measurements.

3.23 Monopile B03

The monopile B03 was set up on 18 July 2022 from 21:40 to 23:15 (Table 2.1). An APD system was activated 46 minutes before the start of pile-driving for deterrence purposes, but deactivated again three minutes before the start of pile-driving (duration: 41 minutes). A DBBC, a BBB and an HSD were used to minimise noise.

One C-POD was deployed at a distance of 750 m and a total of four C-PODs at a distance of 2,000 m (Table 2.1). At a distance of 750 m, an average SEL value of 167 dB was determined (Table 2.2); the maximum level value of 160 dB specified in the noise protection concept (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013) was exceeded. At 185 dB, the average SPL value determined at a distance of 750 m is just below the maximum specified peak level value of 190 dB (Table 2.2).

Harbour porpoises were detected at one of the POD stations at a distance of 2,000 m 20 minutes after the last pile-driving (Table 3.1).

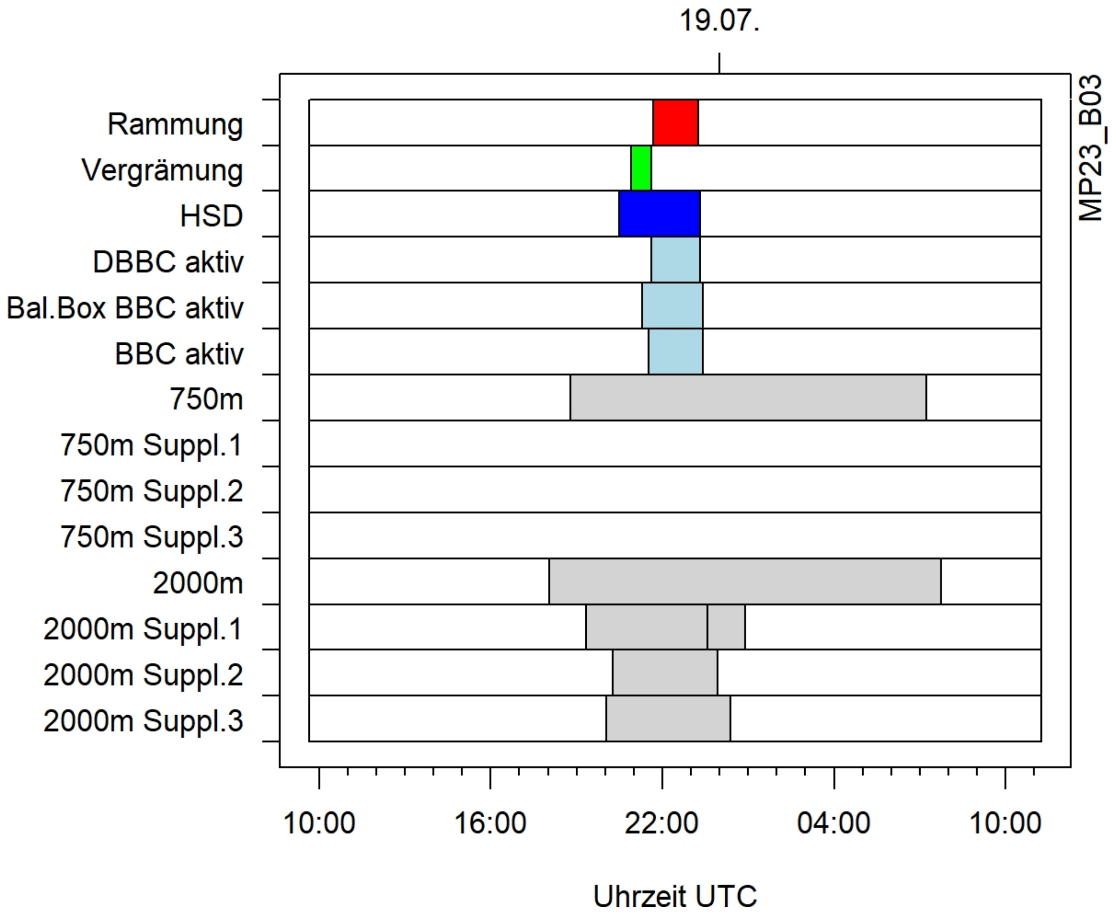

Fig. 3.23 B03 - Chronological representation of the pile-driving phase (red), the use of an APD system (green), noise protection measures (HSD, DBBC, Bal. Box BBC active and BBC active, blue) and C-PODs (grey). The pile-driving took place on 18/07/2022. An APD system was used before the pile driving. A DBBC, a BBB and an HSD were used as noise protection. C-PODs were deployed at 750 m and 2,000 m distance. After the last pile-driving, harbour porpoises were detected at a distance of 2,000 m from the pile-driving (vertical lines). "Suppl." (supplementary) = additional measurements.

3.24 Monopile F02

The monopile F02 was set up on 19 July 2022 from 15:52 to 16:34 (Table 2.1). For deterrence, an APD system was activated 32 minutes before the start of pile-driving, but deactivated again one minute before the start of pile-driving (duration: 31 minutes). A DBBC, a BBB and an HSD were used to minimise noise.

One C-POD was deployed at a distance of 750 m and a total of four C-PODs at a distance of 2,000 m (Table 2.1). At a distance of 750 m, an average SEL value of 166 dB was determined (Table 2.2); the maximum level value of 160 dB specified in the noise protection concept (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013) was exceeded. The average SPL value determined at a distance of 750 m is 185 dB, which is below the maximum specified peak level value of 190 dB (Table 2.2).

Harbour porpoises were detected at a POD station at a distance of 2,000 m 109 minutes after the last pile-driving (Table 3.1).

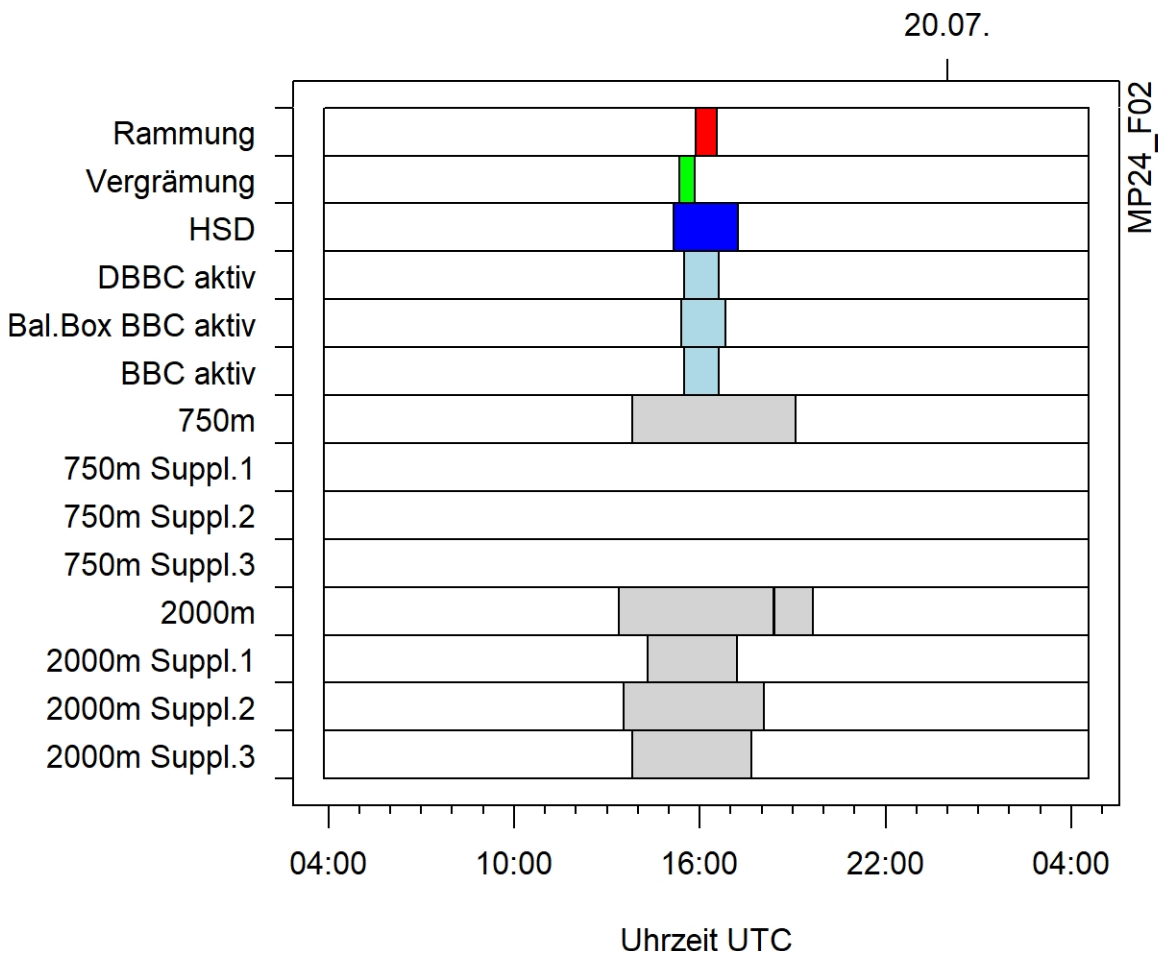

Fig. 3.24 F02 - Chronological representation of the pile-driving phase (red), the use of an APD system (green), noise protection measures (HSD, DBBC, Bal. Box BBC active and BBC active, blue) and C-PODs (grey). The pile-driving took place on 19/07/2022. An APD system was used before the pile driving. A DBBC, a BBB and an HSD were used as noise protection. C-PODs were deployed at 750 m and 2,000 m distance. After the last pile-driving, harbour porpoises were detected at a distance of 2,000 m from the pile-driving (vertical lines). "Suppl." (supplementary) = additional measurements.

3.25 Monopile D03

Monopile D03 was set up on 20 July 2022 from 14:27 to 15:33 (Table 2.1). An APD system was activated 47 minutes before the start of pile-driving for deterrence purposes, but was deactivated again two minutes before the start of pile-driving (duration: 45 minutes). A DBBC, a BBB and an HSD were used to minimise noise.

One C-POD was deployed at a distance of 750 metres and a total of four C-PODs at a distance of 2,000 metres. According to the records, the C-POD at a distance of 750 m from the pile-driving event was recovered approx. 16 h before the end of the pile-driving. A documentation or setting error is assumed. The deployment times were sensibly adjusted for the evaluation. An average SEL value of 168 dB was determined at a distance of 750 m (Table 2.2); the maximum level value of 160 dB specified in the noise protection concept (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013) was exceeded. The average SPL value of 187 dB determined at a distance of 750 m is just below the maximum specified peak level value of 190 dB (Table 2.2).

Based on the available recordings, none of the POD stations at 750 m or
harbour porpoises were detected at a distance of 2,000 m from the pile-driving event (Table 3.1).

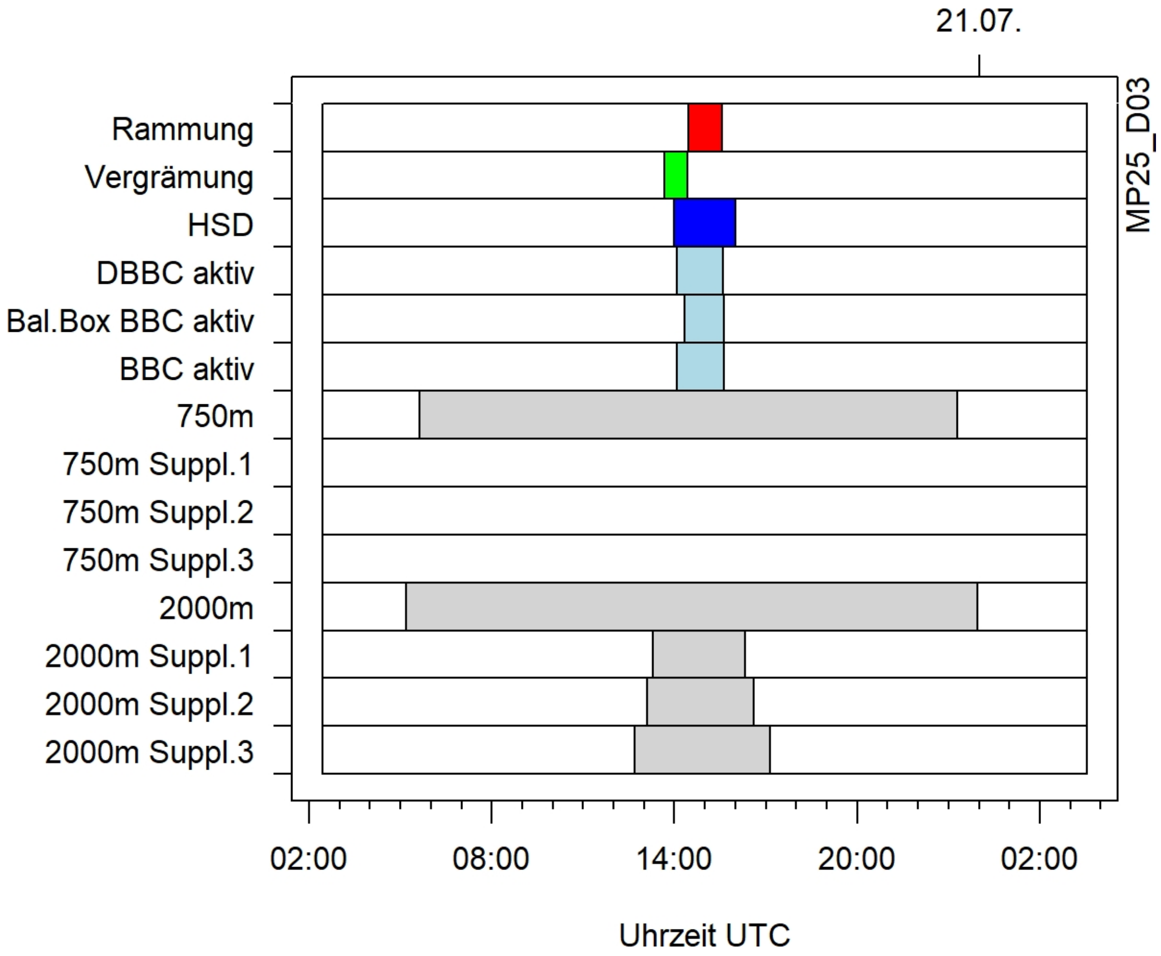

Fig. 3.25 D03 - Chronological representation of the pile-driving phase (red), the use of an APD system (green), noise protection measures (HSD, DBBC, Bal. Box BBC active and BBC active, blue) and C-PODs (grey). The pile-driving took place on 20/07/2022. An APD system was used before the pile driving. A DBBC, a BBB and an HSD were used as noise protection. C-PODs were deployed at 750 m and 2,000 m distance. No harbour porpoises were detected. "Suppl." (supplementary) = additional measurements.

3.26 Monopile A03

The monopile A03 was set up on 22 July 2022 from 08:00 to 08:50 (Table 2.1). For deterrence, an APD system was activated 32 minutes before the start of pile-driving, but deactivated again at the start of pile-driving (duration: 32 minutes). A DBBC, a BBB and an HSD were used to minimise noise.

One C-POD was deployed at a distance of 750 m and a total of four C-PODs at a distance of 2,000 m (Table 2.1). At a distance of 750 m, an average SEL value of 166 dB was determined (Table 2.2); the maximum level value of 160 dB specified in the noise protection concept (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013) was exceeded. At 184 dB, the average SPL value determined at a distance of 750 m is below the maximum specified peak level value of 190 dB (Table 2.2).

No harbour porpoises were detected at the POD stations 750 m and 2,000 m from the pile-driving event (Table 3.1.)

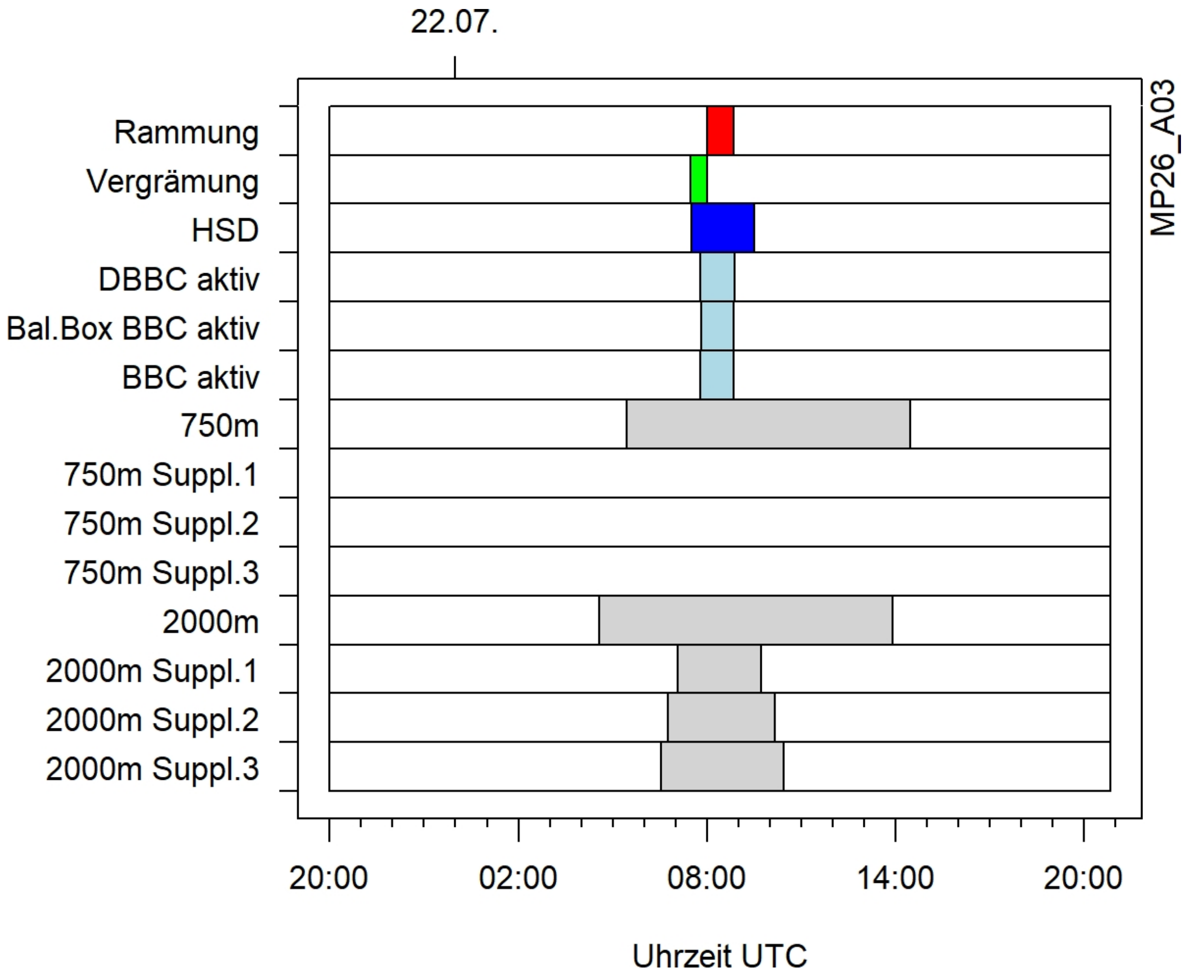

Fig. 3.26 A03 - Temporal representation of the pile-driving phase (red), the use of an APD system (green), noise protection measures (HSD, DBBC, Bal. Box BBC active and BBC active, blue) and C-PODs (grey). The pile-driving took place on 22/07/2022. An APD system was used before the pile driving. A DBBC, a BBB and an HSD were used as noise protection. C-PODs were deployed at 750 m and 2,000 m distance. No harbour porpoises were detected. "Suppl." (supplementary) = additional measurements.

3.27 Monopile E04

The monopile E04 was set up on 23 July 2022 from 00:40 to 1:37 (Table 2.1). An APD system was activated for deterrence 42 min before the start of pile-driving, but deactivated again one minute before the start of pile-driving (duration: 41 min). A DBBC, a BBB and an HSD were used to minimise noise.

One C-POD was deployed at a distance of 750 m and a total of four C-PODs at a distance of 2,000 m (Table 2.1). At a distance of 750 m, an average SEL value of 165 dB was determined (Table 2.2); the maximum level value of 160 dB specified in the noise protection concept (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013) was exceeded. The average SPL value determined at a distance of 750 m is 184 dB, which is below the maximum specified peak level value of 190 dB (Table 2.2).

No harbour porpoises were detected at the POD stations 750 m and 2,000 m from the pile-driving event (Table 3.1.)

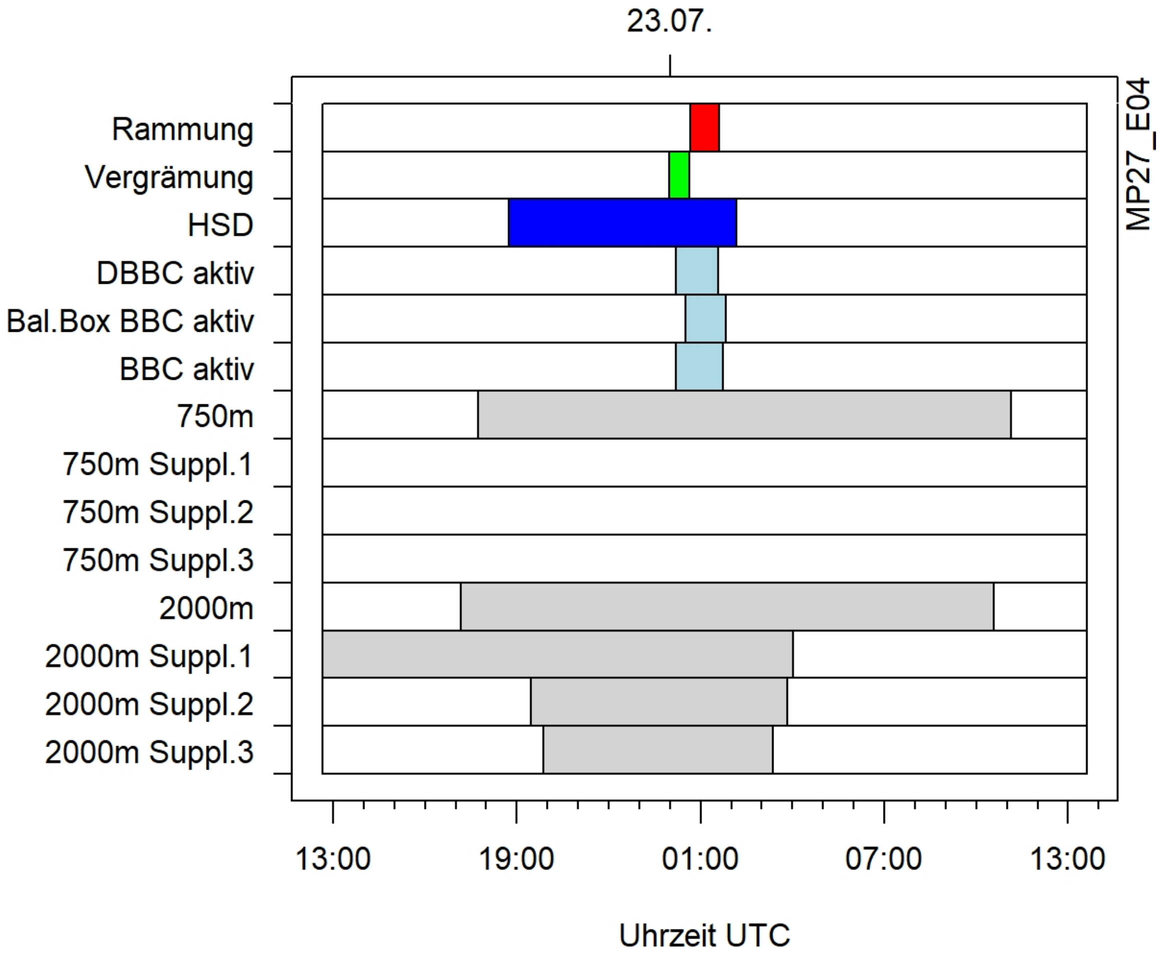

Fig. 3.27 E04 - Chronological representation of the pile-driving phase (red), the use of an APD system (green), noise protection measures (HSD, DBBC, Bal. Box BBC active and BBC active, blue) and C-PODs (grey). The pile-driving took place on 23 July 2022. An APD system was used before the pile driving. A DBBC, a BBB and an HSD were used as noise protection. C-PODs were deployed at 750 m and 2,000 m distance. No harbour porpoises were detected. "Suppl." (supplementary) = additional measurements.

3.28 Monopile B02

The monopile B02 was set up on 23 July 2022 from 21:26 to 22:37 (Table 2.1). For deterrence, an APD system was activated 34 min before the start of pile-driving, but only deactivated 1 h 13 min after the start of pile-driving (duration: 1 h 47 min). A DBBC, a BBB and an HSD were used to minimise noise.

One C-POD was deployed at a distance of 750 metres and a total of four C-PODs at a distance of 2,000 metres. According to records, one C-POD at a distance of 2,000 m from the pile-driving event was recovered approx. 20 h before the end of the pile-driving. A documentation or setting error is assumed. The deployment times were sensibly adjusted for the evaluation. An average SEL value of 168 dB was determined at a distance of 750 m (Table 2.2); the maximum level value of 160 dB specified in the noise protection concept (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013) was exceeded. The average SPL value of 187 dB determined at a distance of 750 m is just below the maximum specified peak level value of 190 dB (Table 2.2).

At one of the POD stations at a distance of 2,000 m, harbour porpoises were detected up to 78 minutes before the APD system was deployed; another POD station at a distance of 2,000 m recorded harbour porpoises from 35 minutes after the last pile-driving (Table 3.1.)

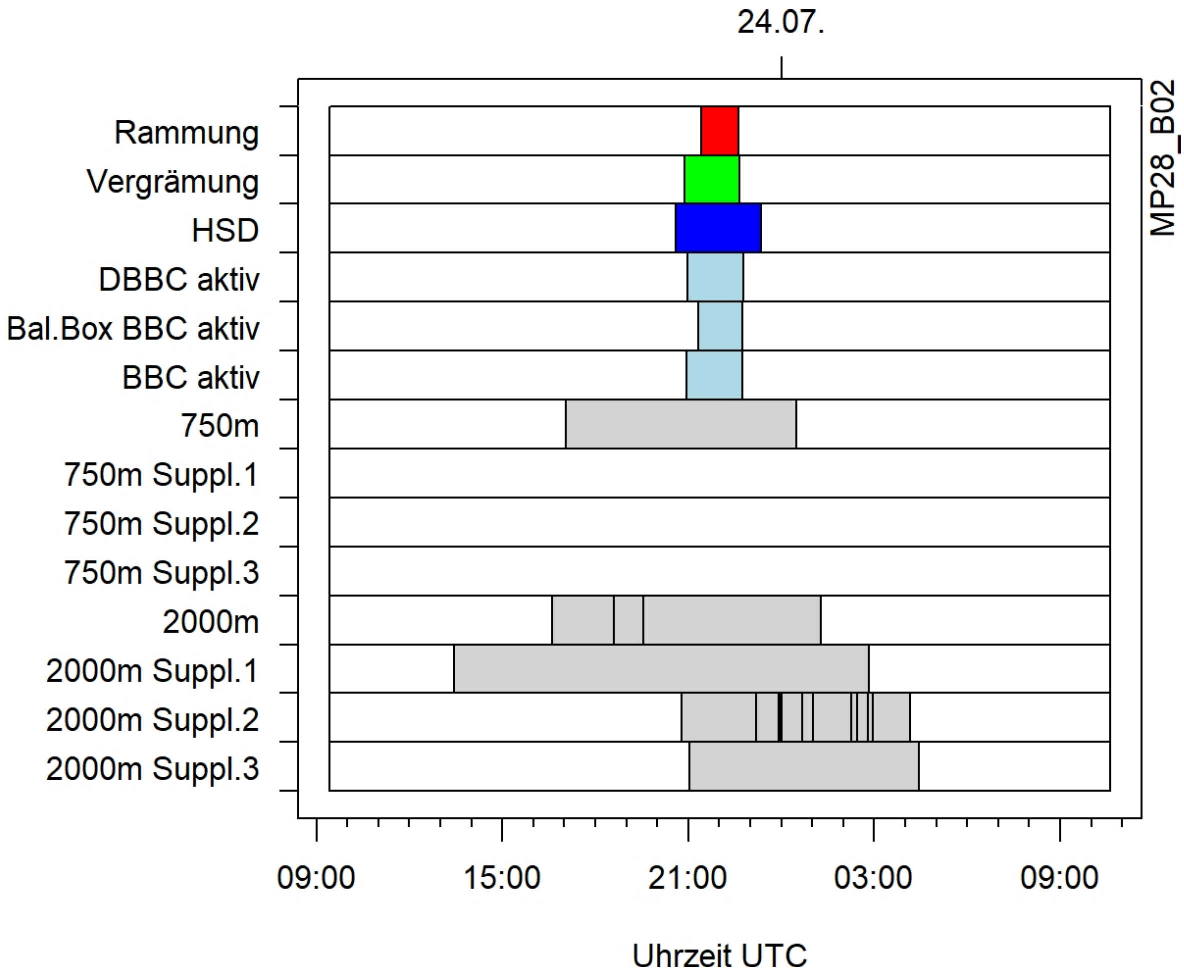

Fig. 3.28 B02 - Temporal representation of the pile-driving phase (red), the use of an APD system (green), noise protection measures (HSD, DBBC, Bal. Box BBC active and BBC active, blue) and C-PODs (grey). The pile-driving took place on 23 July 2022. An APD system was used before the pile driving. A DBBC, a BBB and an HSD were used as noise protection. C-PODs were deployed at 750 m and 2,000 m distance. The recorded deployment time of the C-PODs "2,000m Suppl. 1" ends about 20 h before the end of the pile-driving. A logging or setting error is assumed. The application time was sensibly adjusted for the evaluation. Harbour porpoises were detected several times both before the APD system was deployed and after the last pile-driving. "Suppl." (supplementary) = additional measurements.

4 SUMMARY

Between 6 June 2022 and 23 July 2022, a total of 28 monopiles (27 WTGs + 1 OSS) were installed for the "Arcadis Ost 1" OWP using the impulse pile driving method.

It should be noted that the recorded application times of the C-PODs often did not match the corresponding pile-driving times (C01, B04, F01, C02, G01, A02, F04, D03, B02, B01, A04, see yellow markings in Table 2.1). It was therefore necessary to adjust the application times during the evaluation. These adjustments are not valid; they are based on the assumption that dates and times were entered incorrectly or that time forms (UTC, UTC+2) were swapped. Reasonable assumptions were made on the basis of existing protocols, which were included in the subsequent analysis of the data. The results presented here, particularly in relation to harbour porpoise detections, must therefore be viewed critically.

C-PODs were deployed at a distance of 750 metres from the construction site during almost all pile-driving operations in the "Arcadis Ost 1" OWF as part of the ordered efficiency control. Exceptions to this are the work on monopile D04 (C-POD not deployed) and D02 (C-POD not deployed). From the 16th monopile (A04) onwards, four C-PODs were deployed at a distance of 2,000 m in addition to the C-POD at a distance of 750 m due to high noise levels during the first pile-driving operations. All deployed and functioning measuring devices provided analysable data. A scan limit for the maximum number of sound signals per minute was not set for the mobile C-PODs.

Overall, harbour porpoise detections were rare during the construction phase (Table 3.1). Three detections were recorded at close range, i.e. at a distance of 750 metres. Two harbour porpoise detections occurred before the APD system was deployed. One harbour porpoise detection took place during the pile-driving pause between the two pile-driving phases for the monopile C03. The pile-driving pause between the two pile-driving phases was 8 hours and 27 minutes; according to the standard procedure for the use of an APD system (see Chapter 2.1), a new deterrence should have been carried out. However, this was not done. This is to be regarded as critical, as complete noise protection was dispensed with during this pile-driving as part of a research project. No harbour porpoises were detected in the close range (750 m) during the other pile-driving operations. No harbour porpoises were detected returning to the recording range of the POD stations at a distance of 750 m from the pile-driving position after any of the pile-driving operations during the measurement period of the C-PODs (Table 2.1.)

A total of 26 detections were made within a distance of 2,000 metres. Six of the detections were more than one hour before the first deployment of an APD system or more than one hour after the last pile-driving impact (Table 3.1). During the construction of the monopile A04, a harbour porpoise was detected one minute before the ADP system was deployed and four more during the active phase of the deterrence, i.e. immediately before the pile-driving (Fig. 3.16). The visual inspection of MMOs present on board revealed no sightings of marine mammals before or during the pile-driving, so it can be surmised that the deterrence worked in the vicinity of the construction site, but did not deter animals further away in this case. After one of the four pile-driving operations in which harbour porpoises were detected at a distance of 2,000 m before or during the APD operation, harbour porpoises were also detected within 2,000 m of the construction site (B02) after the pile-driving. Here, harbour porpoises were detected just 35 minutes after the last pile-driving.

ten harbour porpoise detections were recorded. In two further cases, in which no detections could be seen before the pile-driving, a detection occurred 20 minutes and approx. 1h 50 min after the last pile-driving impact (B03, F02).

The extent to which the additional use of the SealScarer at pile-driving sites C03, G03 and C04 caused extensive deterrence of the harbour porpoises and thus resulted in no harbour porpoises being detected during the entire recording period, at least at sites G03 and C04, cannot be determined.

The aim is to prevent the risk of hearing damage to marine mammals, in particular harbour porpoises, with the help of prescribed deterrence procedures, visual monitoring and maximum noise levels. In the worst-case scenario, hearing damage to harbour porpoises can lead to starvation and/or stranding of the animals. During the construction work for "Arcadis Ost 1", three construction works were not carried out at all (2nd pile-driving phase OSS, Restrike OSS, 2nd pile-driving phase C03) or ended too early (25 out of 30 times, see Table 2.1). In the case of the first pile-driving work at the OSS substation, the APD system was, according to the protocol, activated approx. 2 h before the start of pile-driving, but also deactivated again approx. 1 h before the start of pile-driving. A deterrence benefit is unlikely due to the device being deactivated far too early. In this case, but also during deterrence for the construction work on monopile B02 (34 min vRB to 1 h13 min nRB), deterrence was carried out for too long, contrary to the normal procedure. Although attempts are being made to reduce possible habituation effects through the moderating mode of operation of the APD, these still cannot be completely ruled out. Accordingly, this can reduce the deterrent effect and make it more likely that harbour porpoises will return to the danger zone early. In addition, too long a deterrence by means of APD leads to an unnecessary shortening of the harbour porpoises' opportunity to use the habitat. The same applies to the significantly greater habitat disturbance caused by the SealScarer. However, the duration of use is unknown here due to a lack of logging.

The prescribed maximum level value for individual SEL events at a distance of 750 m from the construction site is 160 dB, the maximum peak level is 190 dB (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013, StALU Vorpommern 2021). During the construction work for "Arcadis Ost 1", the SEL was exceeded in every pile-driving procedure, in five cases even by 10 dB or more (Table 2.1). The SPL was also exceeded during the work for the C03 and G03 monopiles (Table 2.1). As part of a research project, these piles were only partially soundproofed in the form of a linear single large bubble curtain in the direction of the FFH area to the south. The noise measurements were carried out to the north-west of the pile-driving work and therefore correspond to a noise level without noise protection measures.

This report presents the efficiency of the deterrence and noise protection measures implemented during the construction work on the "Arcadis Ost 1" offshore wind farm. Overall, only a few harbour porpoises were detected in the vicinity of the construction sites and no harbour porpoises were recorded during the pile-driving work. However, it was also found that the harbour porpoises were not deterred as specified or possibly could not be tracked correctly due to the lack of logging in some cases. The noise measurements revealed non-compliance with the specified level values (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety 2013, StALU Vorpommern 2021); in addition, noise protection was suspended in parts due to a research project. According to the records, the protective measures were therefore not was observed throughout. Nevertheless, the number of harbour porpoise detections is low overall and no harbour porpoises were detected during the pile driving in particular, meaning that the animals were presumably deterred. Whether this deterrence was due to the deterrence measures or to other factors, such as the pile-driving noise or the ship traffic itself, cannot be clarified.

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2.4 Underwater noise during percussive pile driving: Influencing factors on pile-driving noise and technical possibilities to comply with noise mitigation values - Experience report on pile-driving noise with and without technical noise mitigation

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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Disclaimer: Chapter 3 describes the procedures of the regulatory authority for offshore-projects in the German EEZ of the North- and Baltic Sea and was provided by the Federal Maritime and Hydrographic Agency (BSH).

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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.

[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) ≤ 160 dB (re 1 µ Pa^2s) and • zero-to-peak Sound Pressure Level ($L_{p,pk}$) ≤ 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 Pa^2s (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.

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[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 mandatory restriction of the noise emissions 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 ≥ 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:

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

$$Z = \rho \cdot c$$ *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:

$$\text{SPL} = 10\log\left(\frac{1}{T}\int_0^T \frac{p(t)^2}{p_0^2}\,dt\right) \text{ [dB re 1 µPa}^2\text{]}$$ *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:

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

$$\text{SEL} = 10\log\left(10^{SPL/10} - 10^{L_{hg}/10}\right) - 10\log\frac{nT_0}{T} \text{ [dB re 1 µPa}^2\text{s]}$$ *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:

$$\text{SEL} \approx \text{SPL} - 10\log\frac{nT_0}{T} \text{ [dB re 1 µPa}^2\text{s]}$$ *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:

$$L_{p,pk} = 20\log\left(\frac{|p_{peak}|}{p_0}\right) \text{ [dB re 1 µPa]}$$ *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.

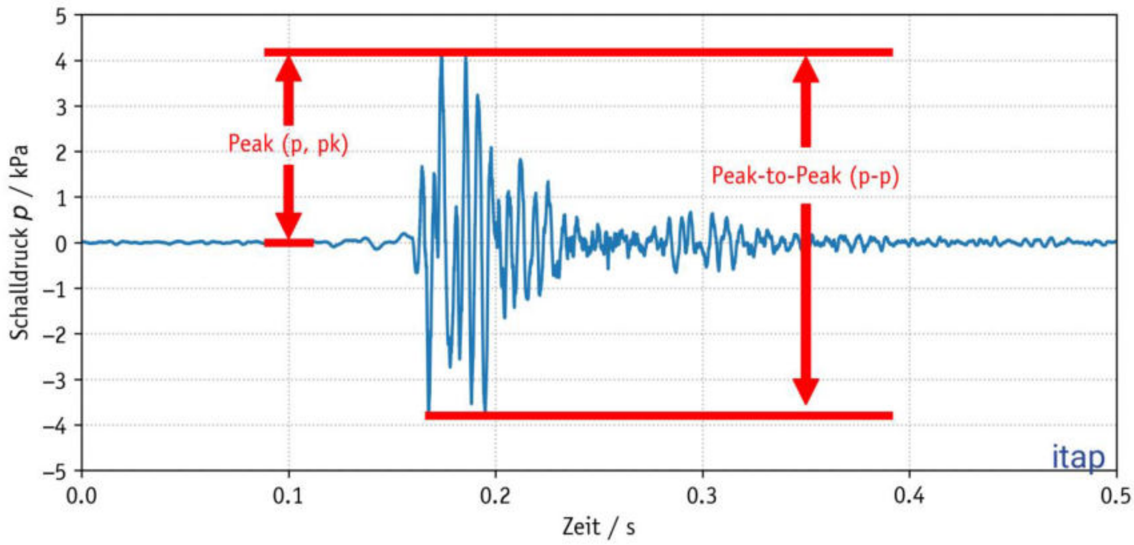

Figure 1: *Typical measured time signal of the underwater noise during pile-driving in a distance of several 100 m.*

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 singly 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.

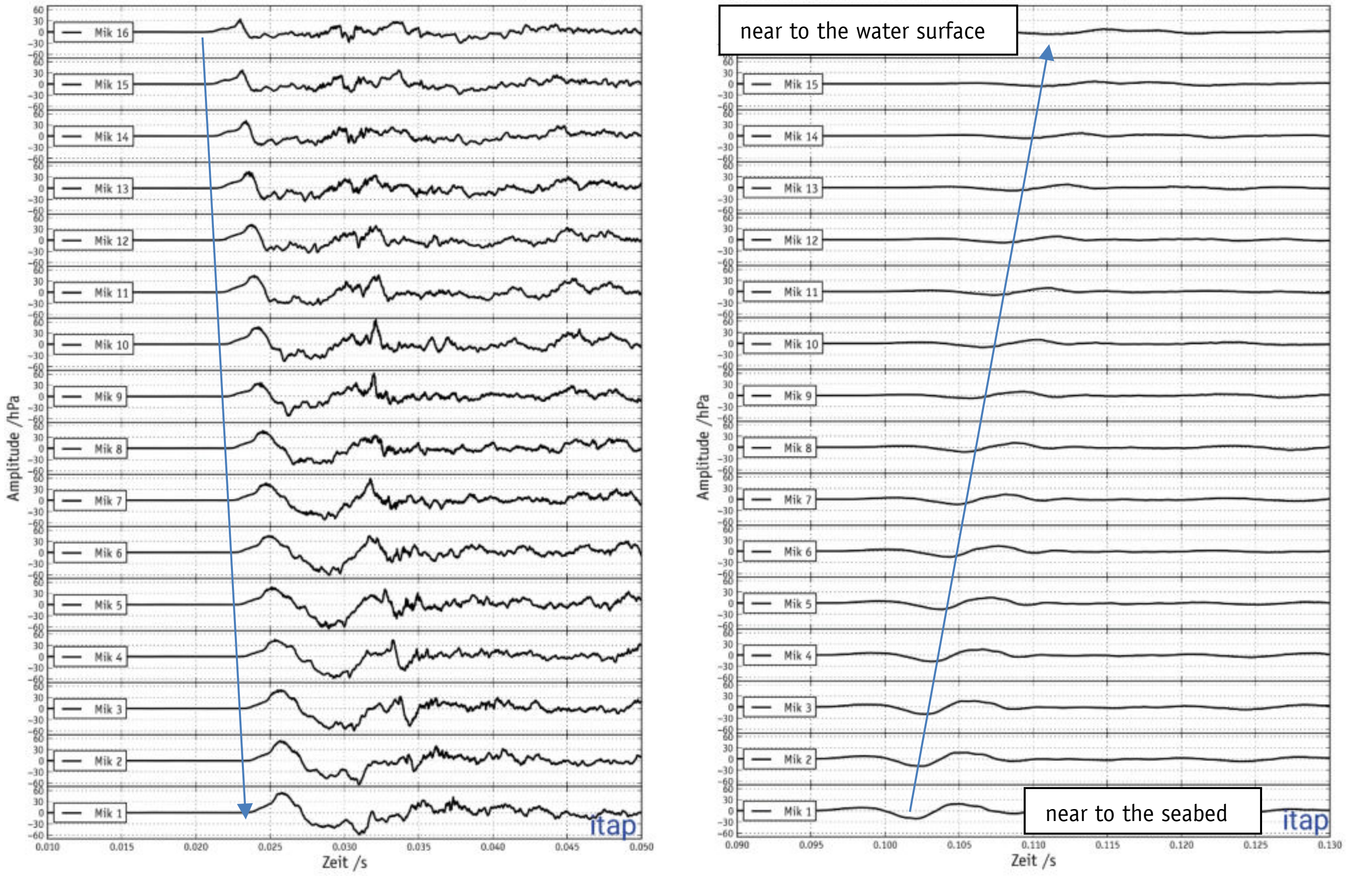

Figure 2: *Time course of a single strike at a monopile, measured in a distance of approx. 80 m with several hydrophones at different heights to the seabed without (left) and with (right) the use of a near-to-pile Noise Abatement System. Mik 1 marks the lowest hydrophone 2 m above the seabed, all further 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).

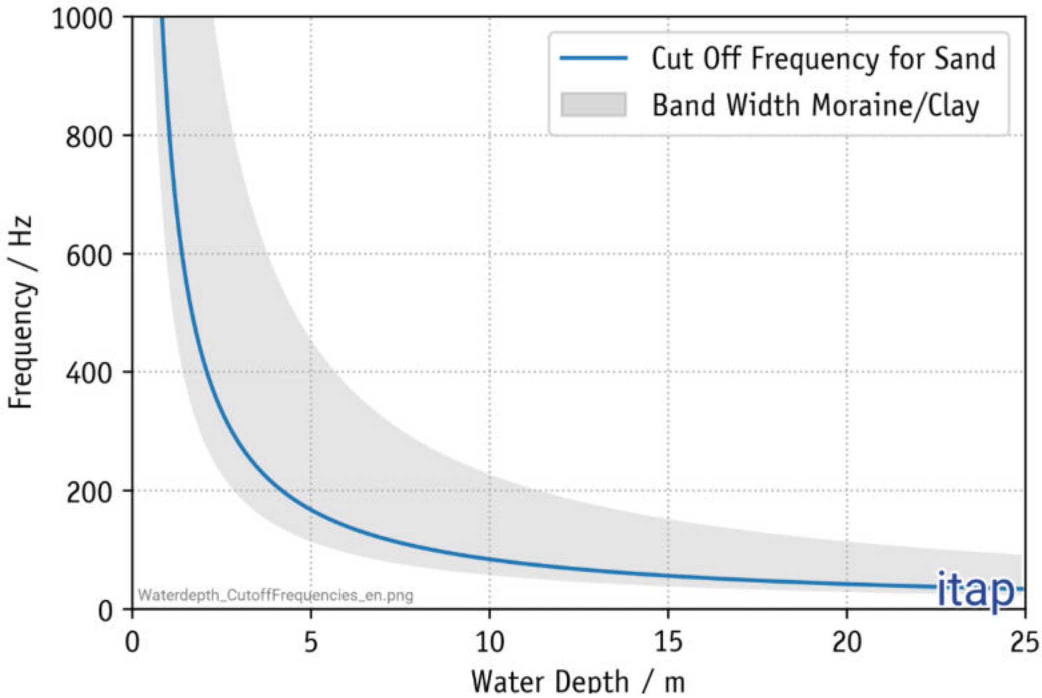

Figure 3: *Theoretical lower cut-off frequency f_g for an undisturbed sound propagation in the water for different soil layers: the blue line results assuming sandy soils and the grey shaded area sketches the influence of different soils, like clay and till (Urick, 1983; Jensen et al., 2010).*

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.

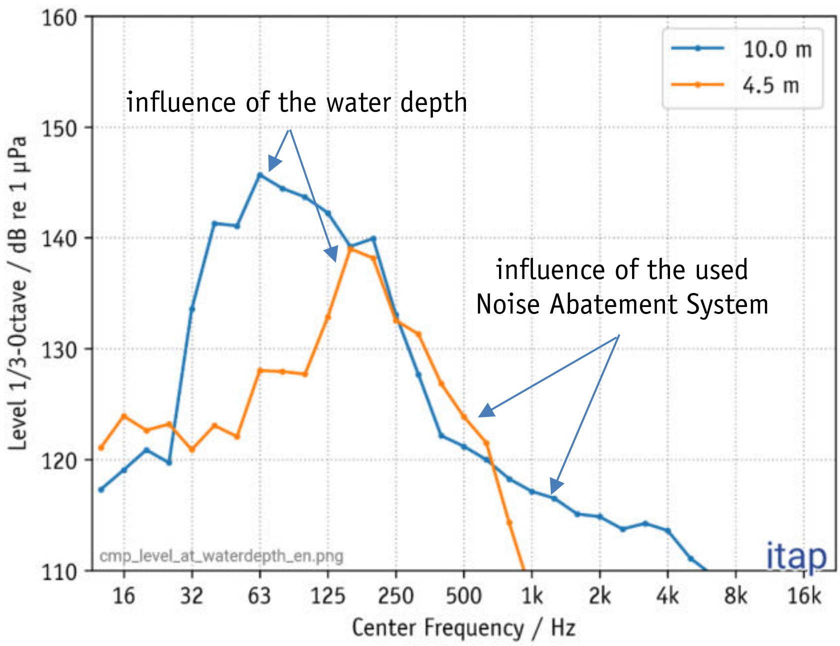

Figure 4: *Measured 1/3-octave-spectrum of a monopile installation in two different water depths (4.5 and 10 m water depth; sandy subsoil). Both installations were performed with comparable Noise Abatement Systems. (Source: Unpublished measurement data of the itap GmbH from a construction project not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

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

$$\mathrm{TL} = -k \cdot log_{10}(r/Meter) \text{ [dB]}$$ *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:

$$\mathrm{TL} = -14.72 \cdot log_{10} r + 0.00027 \cdot r \text{ [dB]}$$ *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:

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

with

F = *10 log(f/*[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.

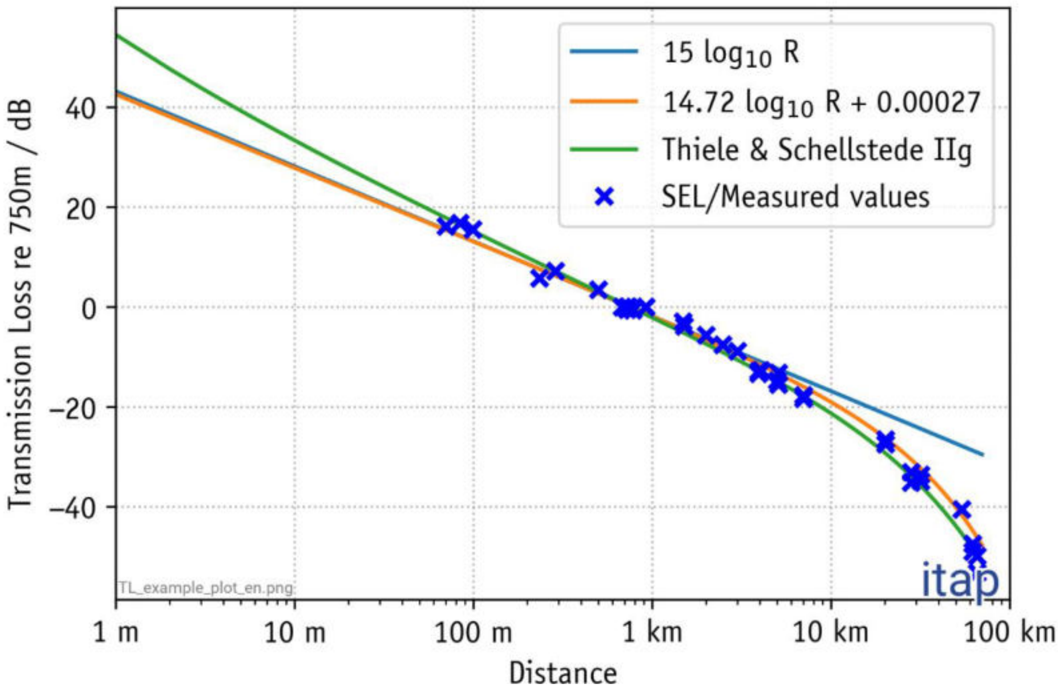

Figure 5: *Different, predicted transmission loss curves (continuous lines) for shallow waters: general, geometric transmission loss (conservative approach; 15 log R), semi-empiric approach defined in Danish Energy Agency (2016) (DK_log R) and semi-empiric approach of Thiele and Schellstede (1980) for 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.

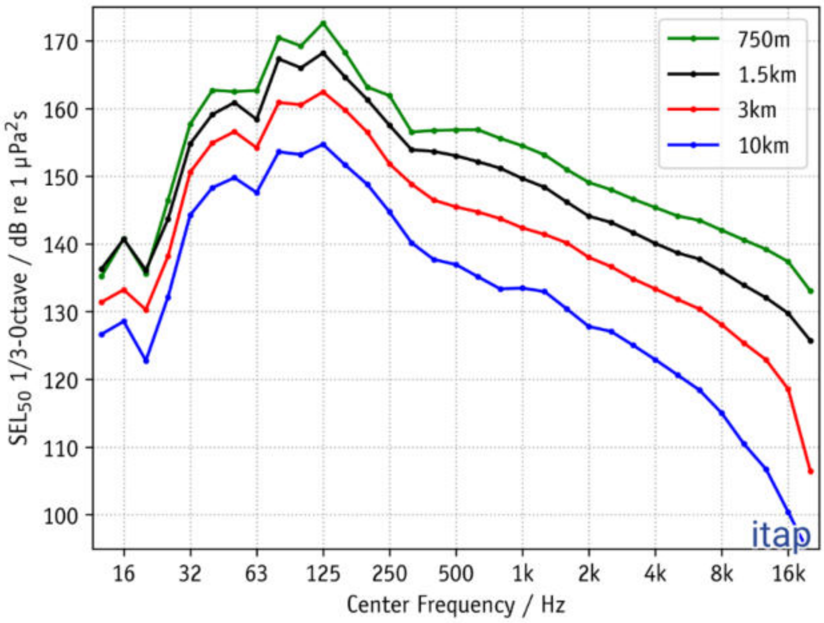

Figure 6: *Average 1/3-octave-spectra measured in different distances during the foundation construction of a monopile with the impact pile-driving method.*

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).

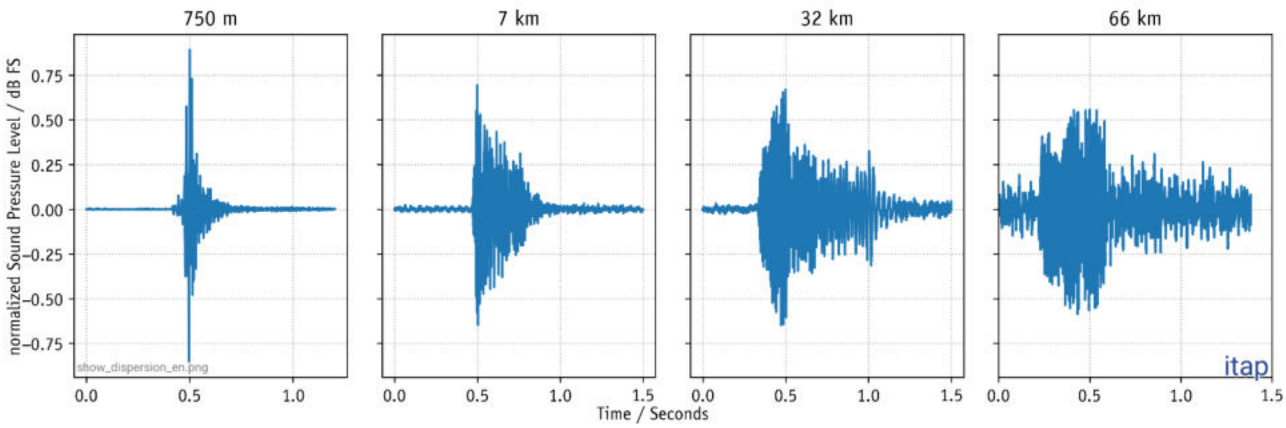

Figure 7: *Time signal of a single strike, measured in different distances to the pile-driving activity.*

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

[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).

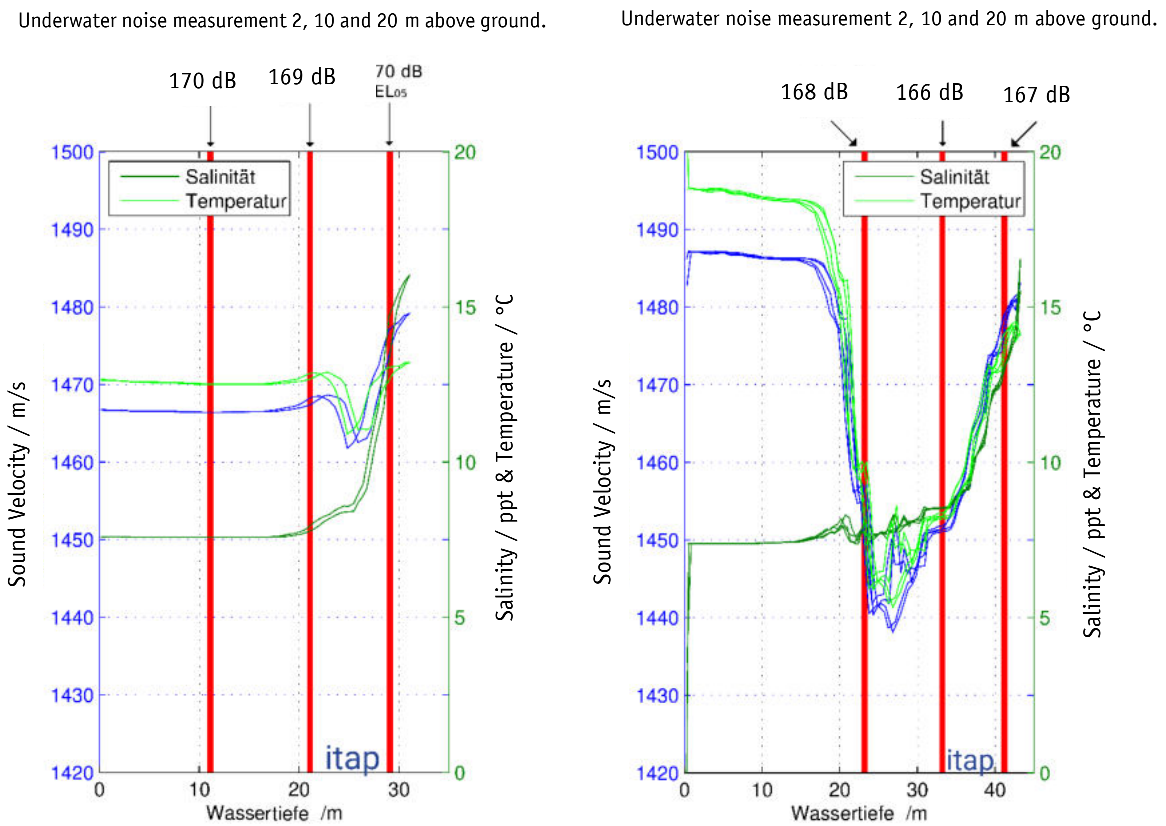

Figure 8: *Water depth-dependent sound velocity profiles measured in the Baltic Sea after a long-lasting good weather period (right) and after a complete mixing of the water column (left). Furthermore, during the pile-driving works, underwater noise measurements in three different hydrophone heights 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.

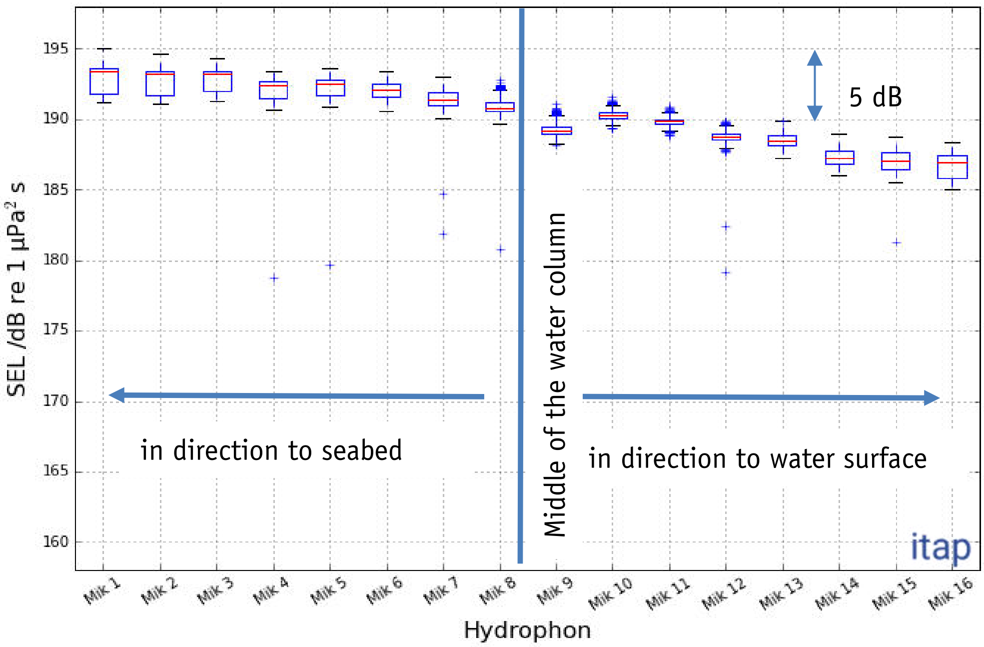

Figure 9: *Statistic presentation (boxplot) of the measured Sound Exposure Level (L_E resp. SEL) with 16 hydrophones of approx. 2 m above ground to the water surface during an impact pile-driving of a monopile without the application of a technical Noise Abatement System in a distance of approx. 80 m 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)*

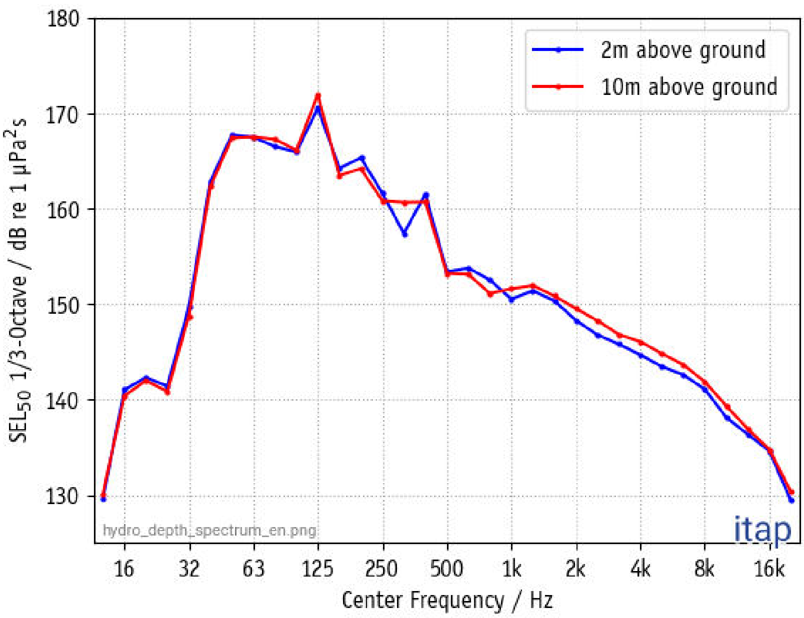

Figure 10: *Averaged 1/3-octave-spectrum of the Sound Exposure Level (SEL_{50}) of a monopile foundation by means of the impact pile-driving method, measured in 750 m in two different measurement heights (2 m and 10 m above ground at a water depth of larger 20 m).*

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.

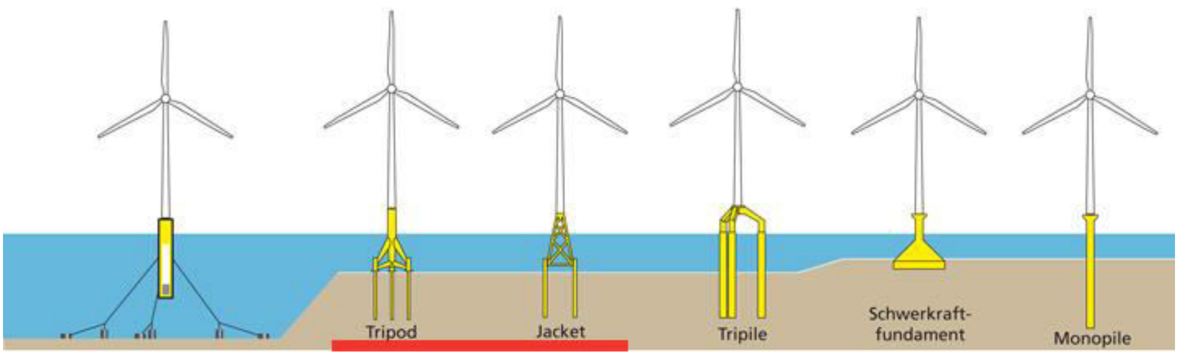

Figure 11: *Different foundation structures for OWTs (Source: Stiftung OFFSHORE-WINDENERGIE).*

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.

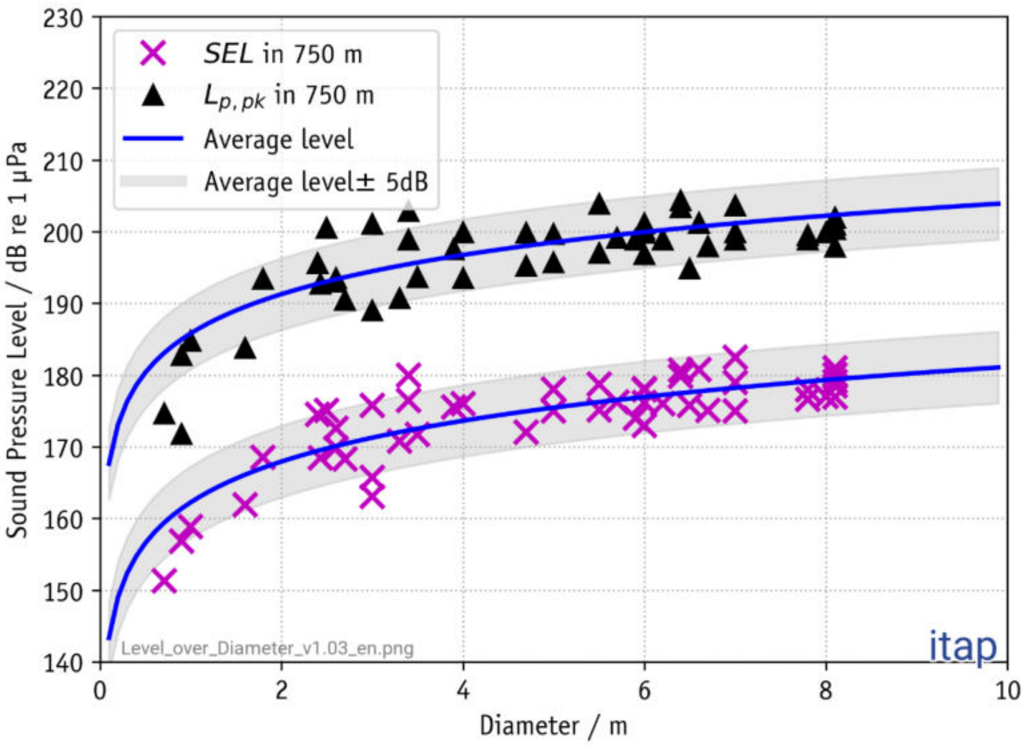

Figure 12: *Measured zero-to-peak Sound Pressure Levels ($L_{p,pk}$) and broadband Sound Exposure Levels (L_E resp. SEL_{05}) at foundation works at piles with a different foundation structure by the impulse pile-driving method of various OWFs as a function of the pile diameter. All pile-drivings were 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.

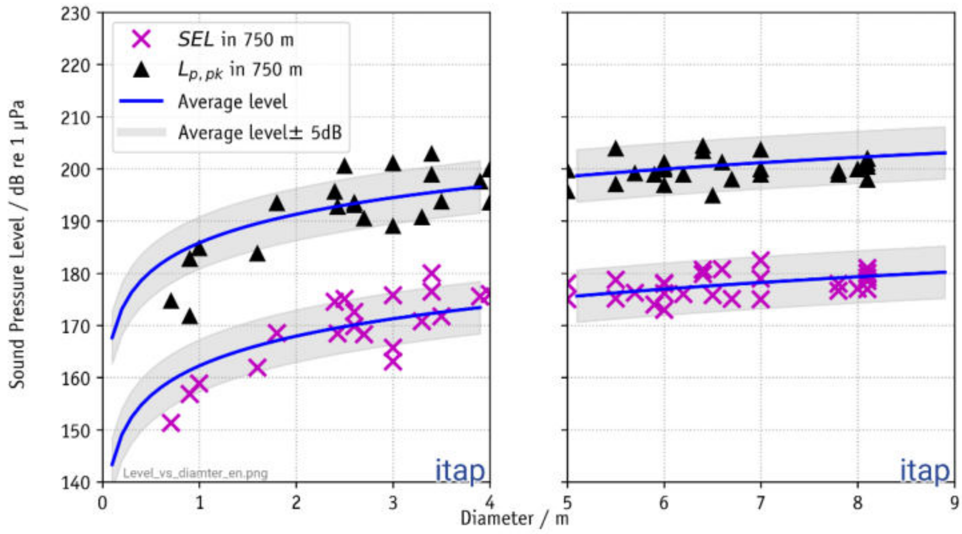

Figure 13: *Measured zsero-to-peak Sound Pressure Levels ($L_{p,pk}$) and broadband Sound Exposure Levels (L_E resp. SEL_{05}) at foundation works with the impulse pile-driving method of diverse OWFs as a function of the pile diameter. Left: different pile designs with pile diameters of up to 4 m. Right: 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.*

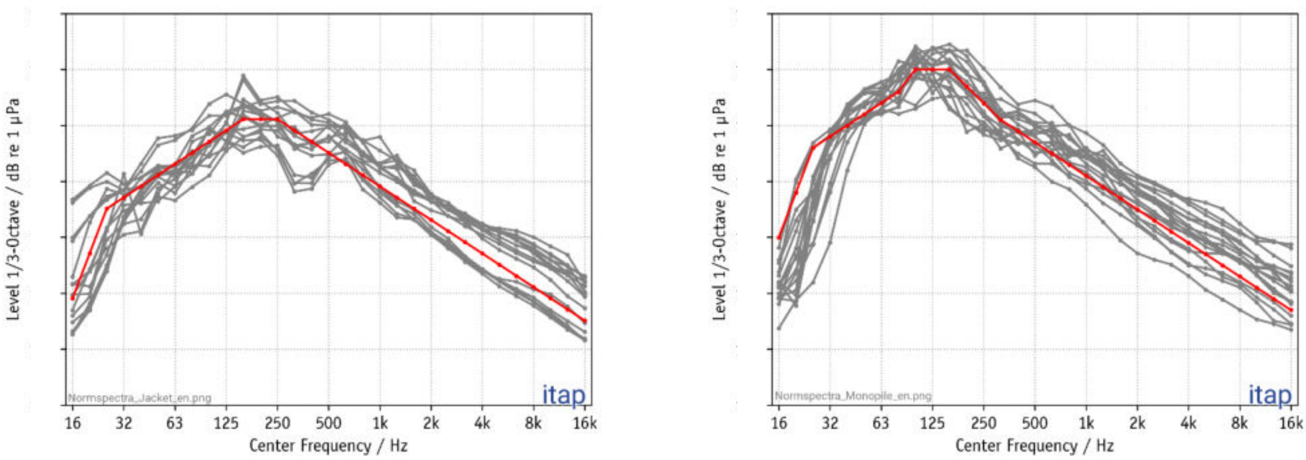

Figure 14: *1/3-octave-spectra of several impulse pile-drivings in different OWF construction projects, measured in 750 m distance. The pile-drivings were performed without the application of technical Noise Abatement Systems. Left: grey shaded lines mark the real measurement data of different pile diameters 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.

<u>Technical note:</u> 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.

<u>Technical note:</u> 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.

<u>Technical note:</u> 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.

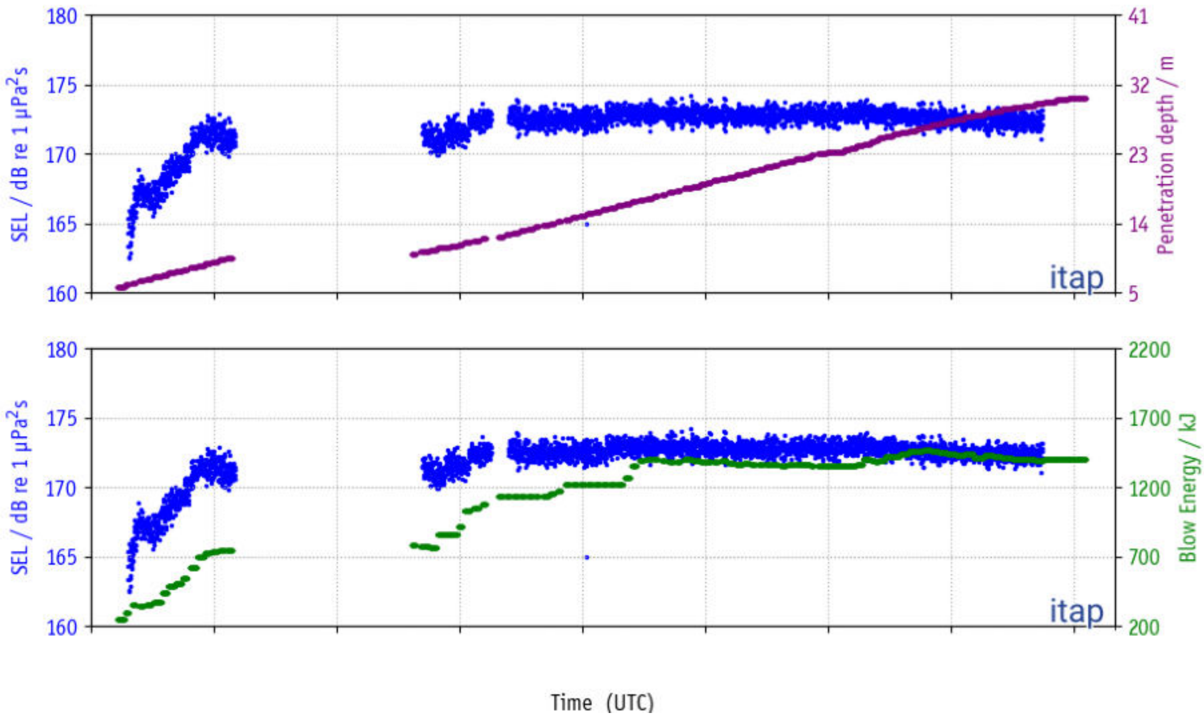

Figure 15: *Measured Sound Exposure Level (L_E resp. SEL) in 750 m during a monopile installation as a function of the time. The pile-driving was performed without the application of a technical Noise Abatement System. Additionally, the applied blow energy per blow (green) and the achieved embedding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

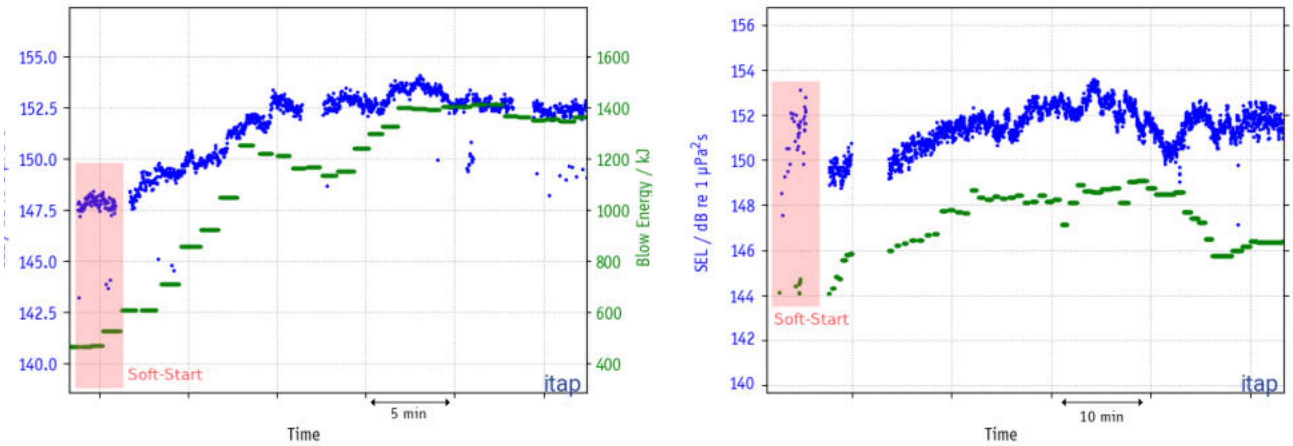

Figure 16: *The measured Sound Exposure Level (SEL resp. L_E) and the applied blow energy (green) during unmitigated monopile installations in a distance of 750 m as function of time. Left: The influence of the blow energy during the soft-start corresponds approximately to a level increase of 2 to 3 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.

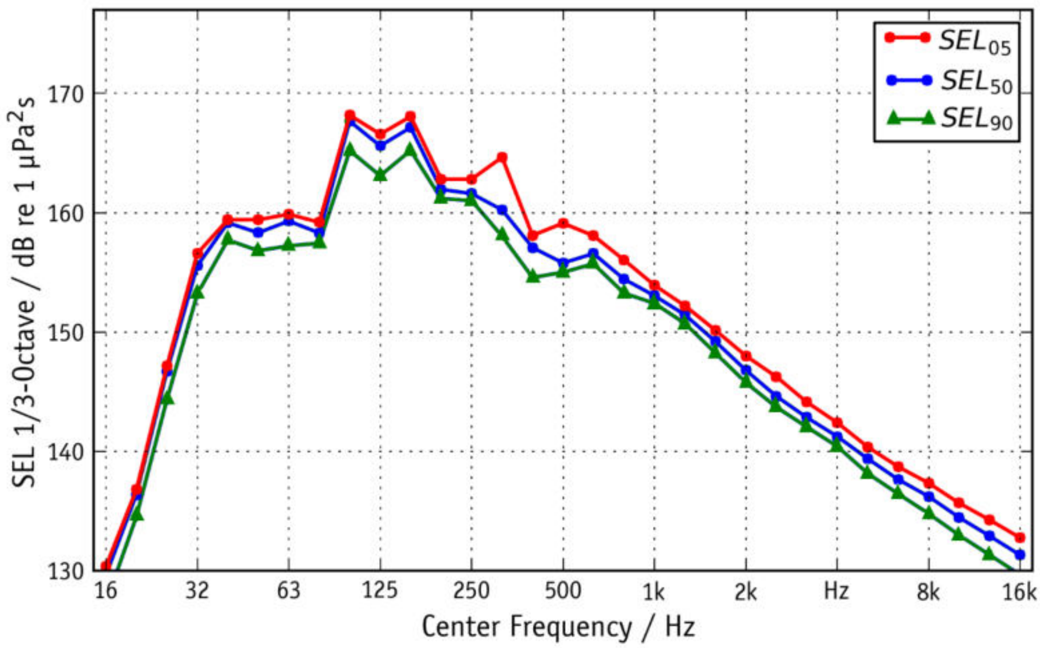

Figure 17: *1/3-octave-spectrum of the 5-, 50- and 90 % exceedance level of the Sound Exposure Level (L_E resp. SEL) in approx. 750 m distance during the foundation works of a monopile with an unmitigated impact pile-driving procedure. The SEL_{90}-level mostly characterizes the start of a pile-driving 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.

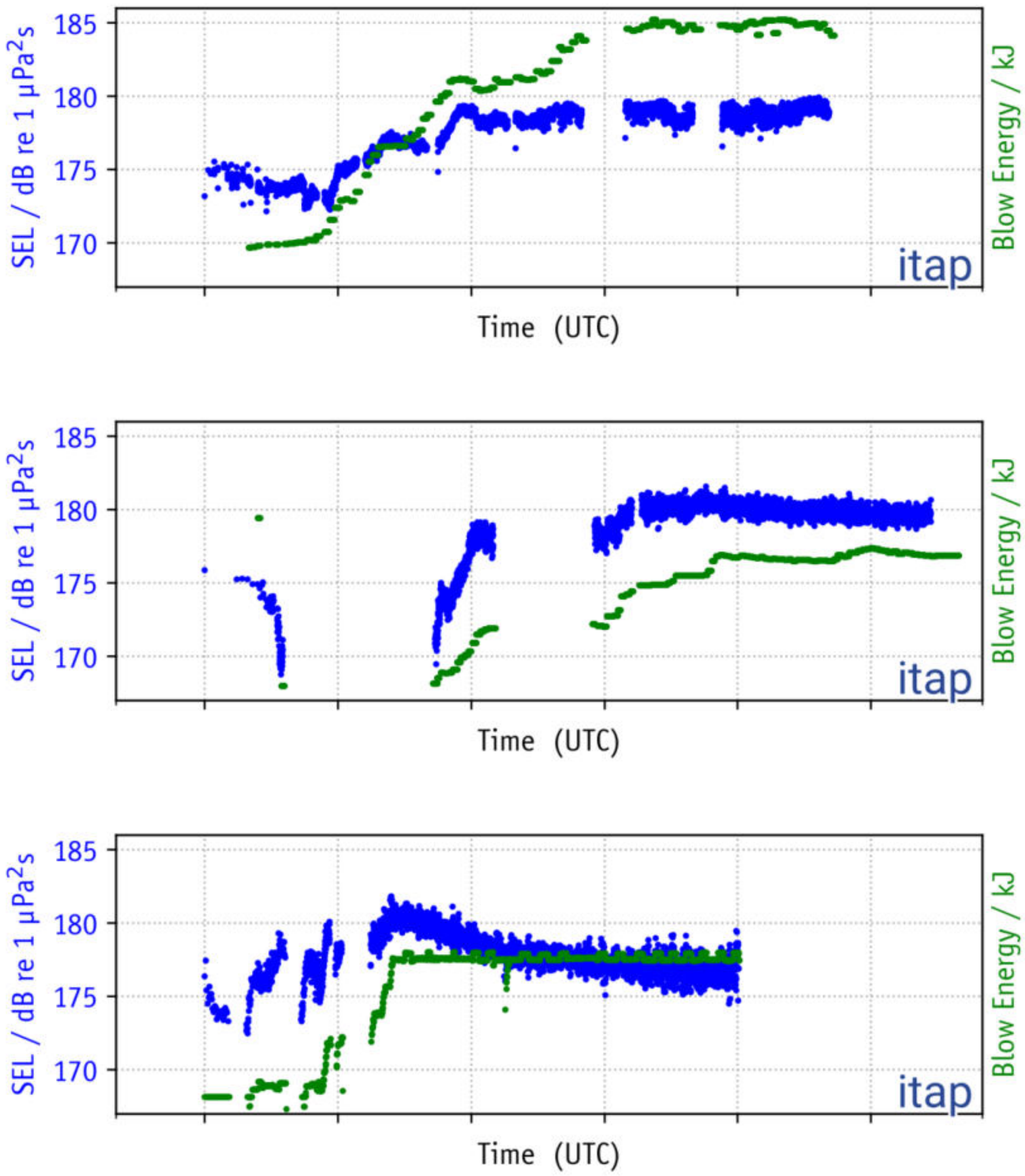

Figure 18: *Temporal course of the measured Sound Exposure Level (SEL resp. L_E, blue) and the applied blow energy (green) during monopile installations (diameter 5,5 to 7,5 m) in a distance of 750 m with three different impact hammer types in the German EEZ of the North Sea. All pile-drivings were performed 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).*

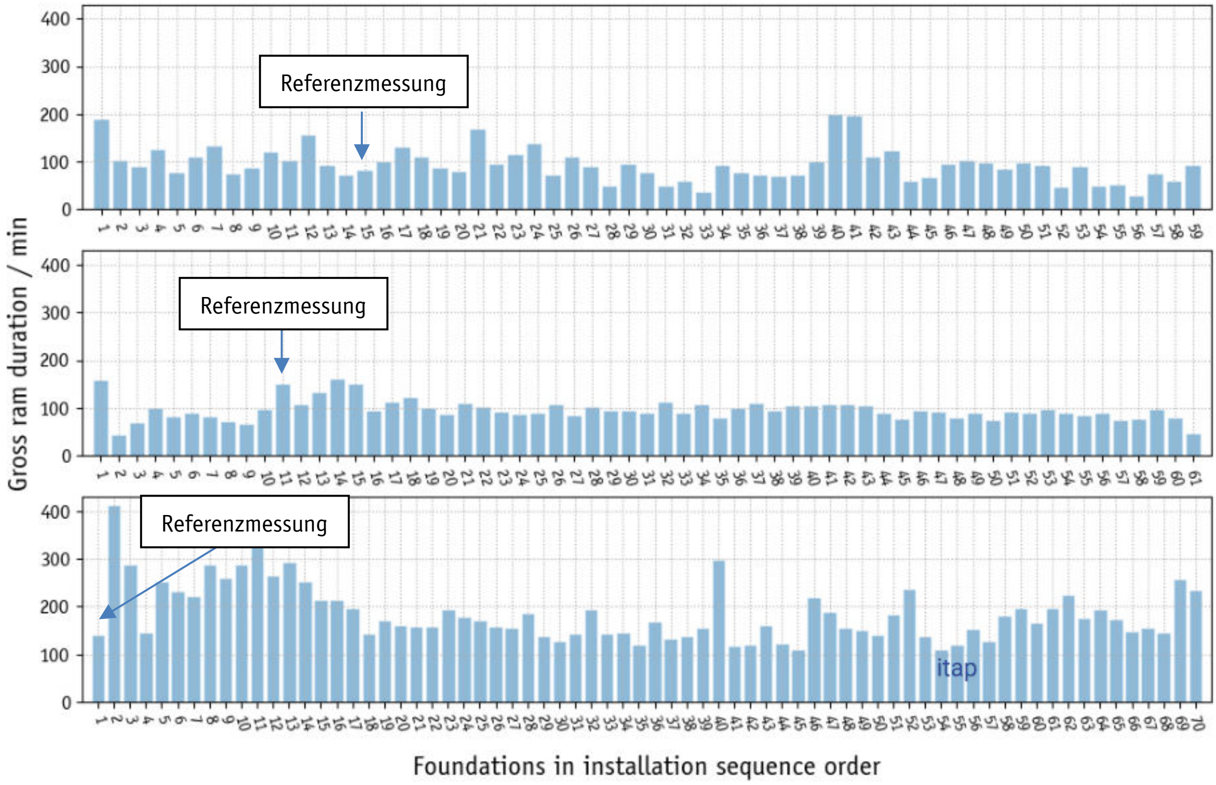

Figure 19: *Gross pile-driving duration per monopile installation with three different impact hammers, as described in Figure 18. For each construction project, only one monopile without noise abatement measure (reference measurement) was installed.*

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.

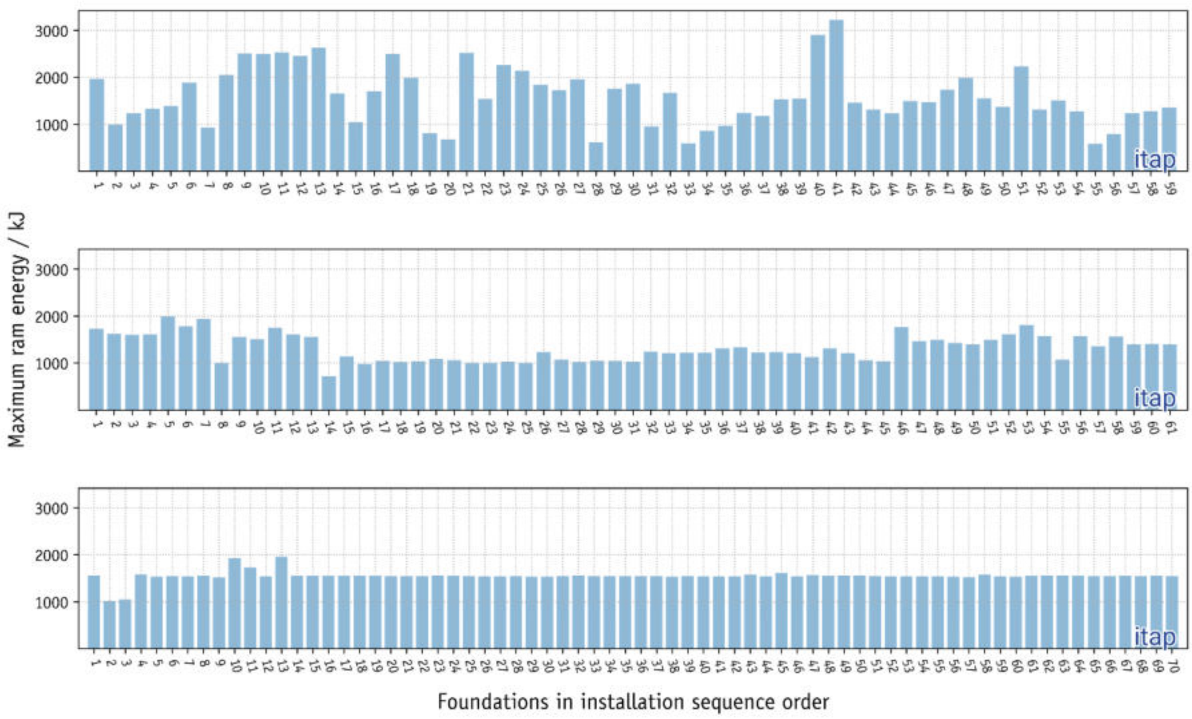

Figure 20: *Max. applied blow energy per monopile installation with three different impact hammers, as described in Figure 17. Above: large impact hammer of the newest generation with a noise-optimized pile-driving procedure, middle: small impact hammer with a not yet fully developed, noise-optimized 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.

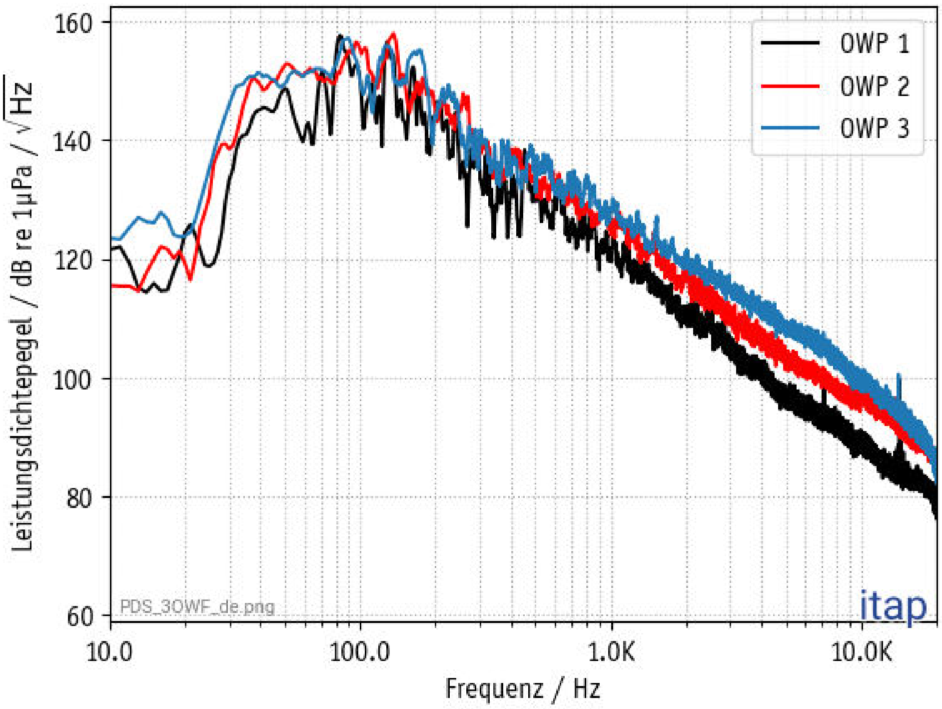

Figure 21: *Narrow band spectra of monopile installations with different impact hammers, as described in Figure 18. The measurement data were normalized regarding the applied blow energy and moreover, no Noise Abatement System was used.*

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.

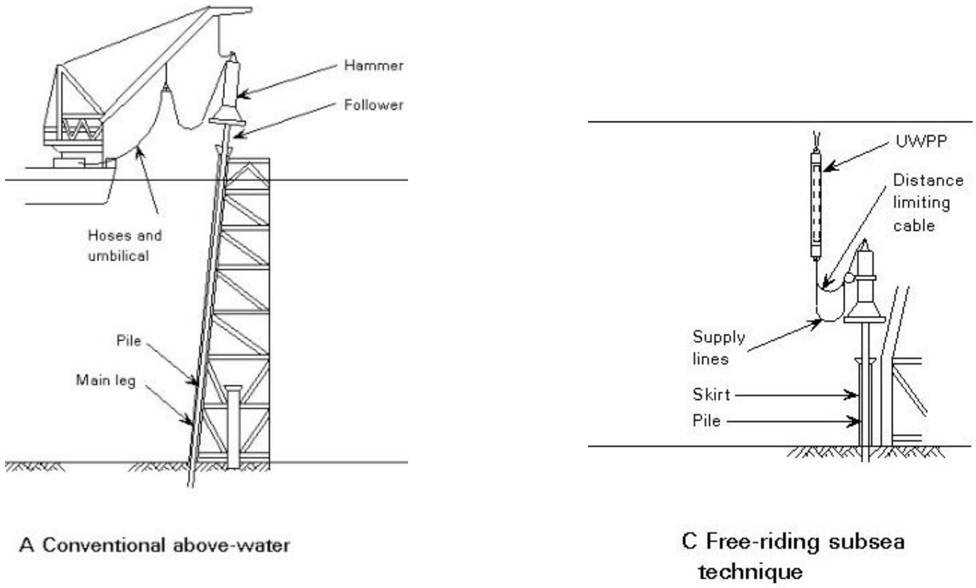

Figure 22: *Difference main- (left) and skirt-piles (right) as skirt-piles for Jacket-constructions. (Source: ESDEP Lecture note [WG15A] fgg-web.fgg.uni-lj.si).*

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.

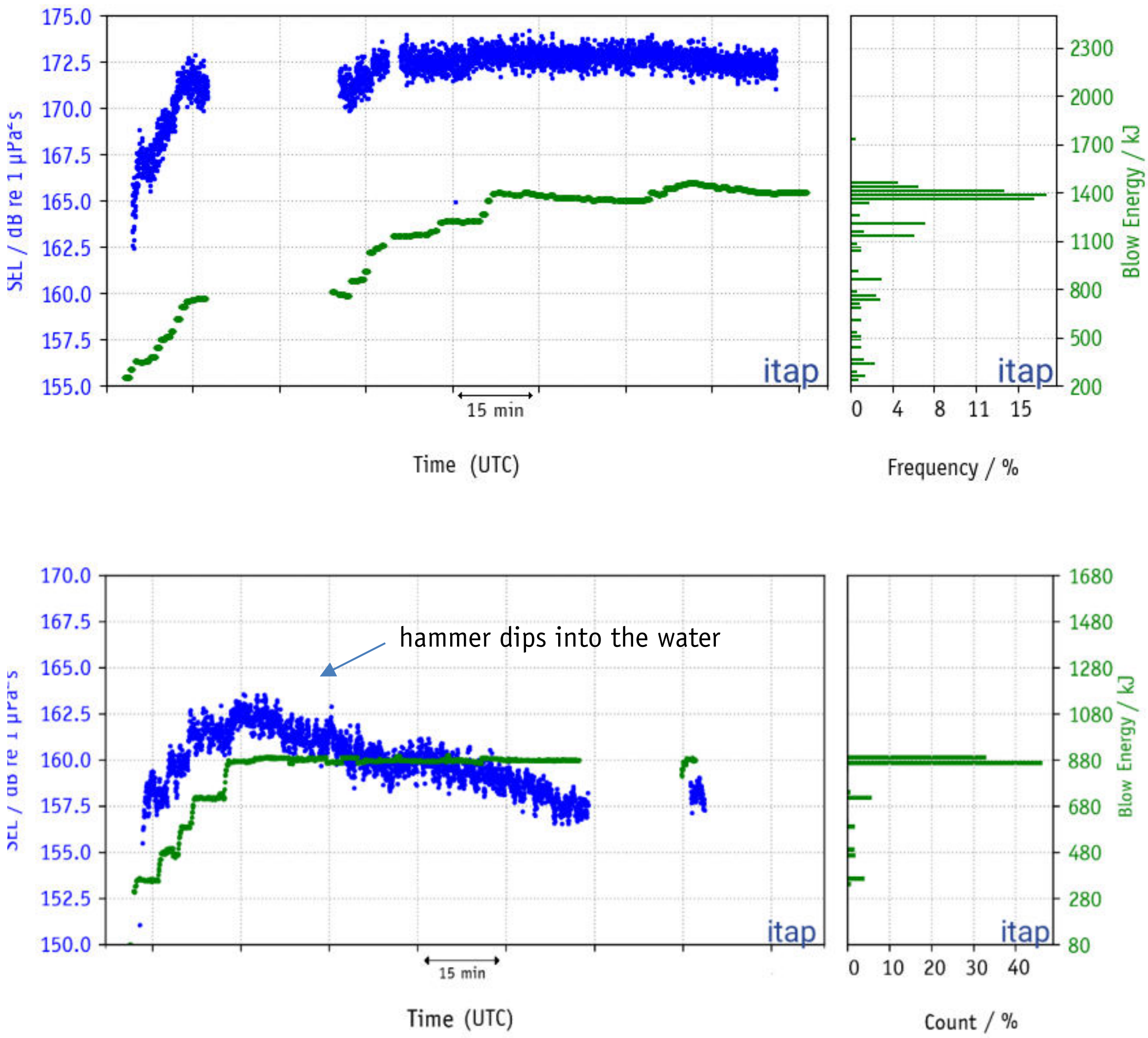

Figure 23: *Temporal course of the measured Sound Exposure Level (L_E resp. SEL) in 750 m distance and the blow energy applied. Both pile-drivings were performed without Noise Abatement System. Above: pile-driving of a monopile resp. main-pile (pile-drivings always above the water surface); below: pile-driving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

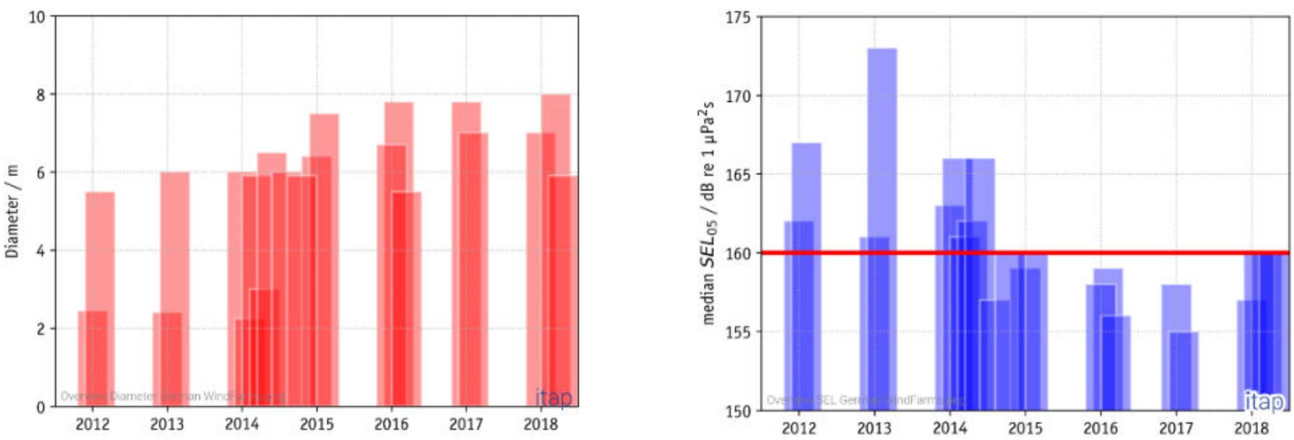

Figure 24: *Left: development of the pile diameters for foundation structures during the construction of OWFs in the German EEZ of the North- and Baltic Sea. Right: measured Sound Exposure Level (SEL_{05}) in a distance of 750 m when applying technical Noise Abatement Systems; the red line marks the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

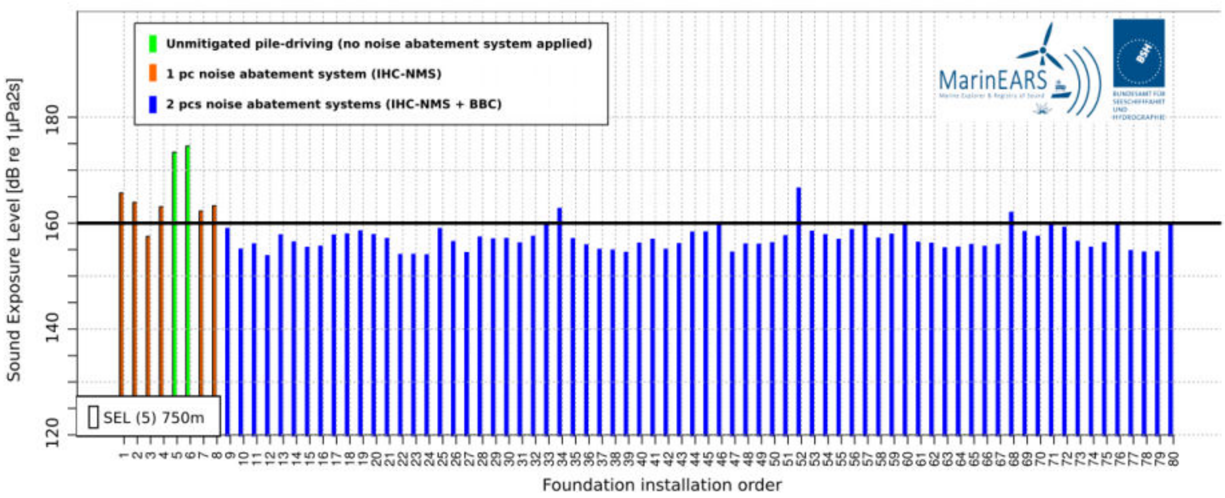

Figure 25: *Measured Sound Exposure Level resp. exceedance level (SEL_{05}) in 750 m distance to the respective monopile for all foundation installations of the OWF Butendiek in the North Sea with and without applications of Noise Abatement Systems. For this project, measurements in several spatial directions 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.

Technical note: 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.

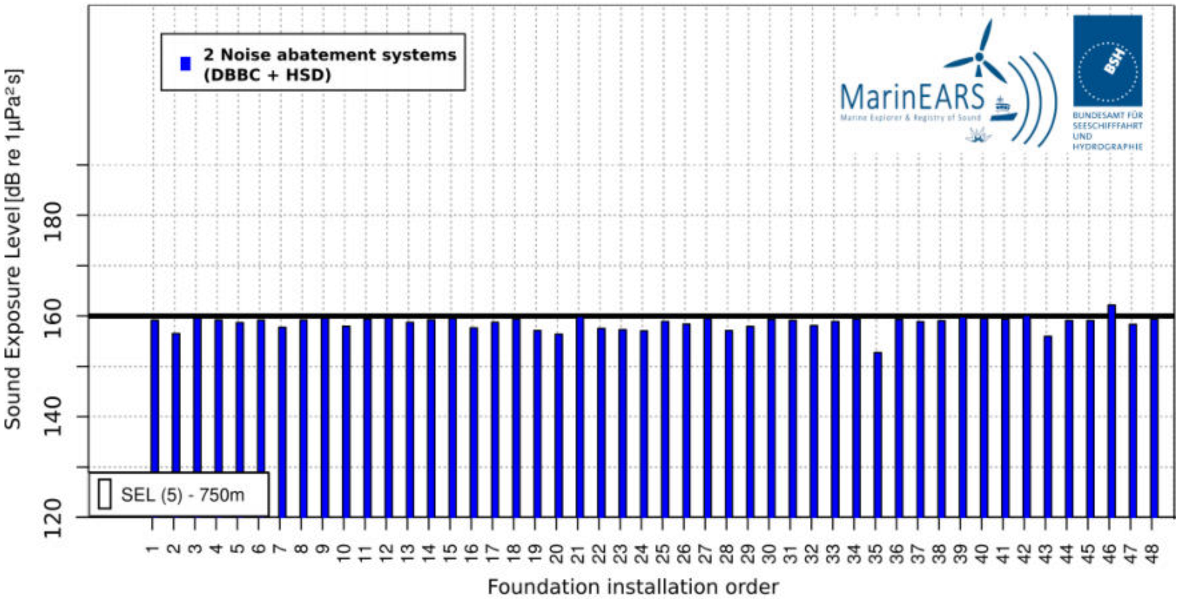

Figure 26: *Measured Sound Exposure Level resp. exceedance level (SEL_{05}) in 750 m distance to the respective monopile for all foundation installations of a later OWF construction project in the German EEZ of the North Sea with a near-to-pile and a far-from-pile Noise Abatement System and the application 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 ≤ 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 singlely 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.

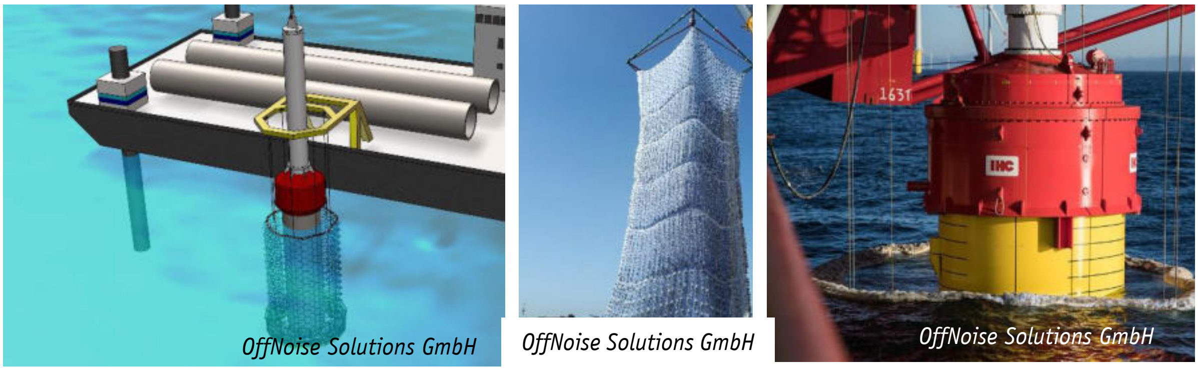

Figure 28: *Left: schematic drawing of a totally mobilized HSD-system, which hangs below a pile-sleeve system attached to the installation vessel. Middle: net with HSD-elements; HSD-system during a pile-driving. (Source: OffNoise Solutions GmbH)*

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

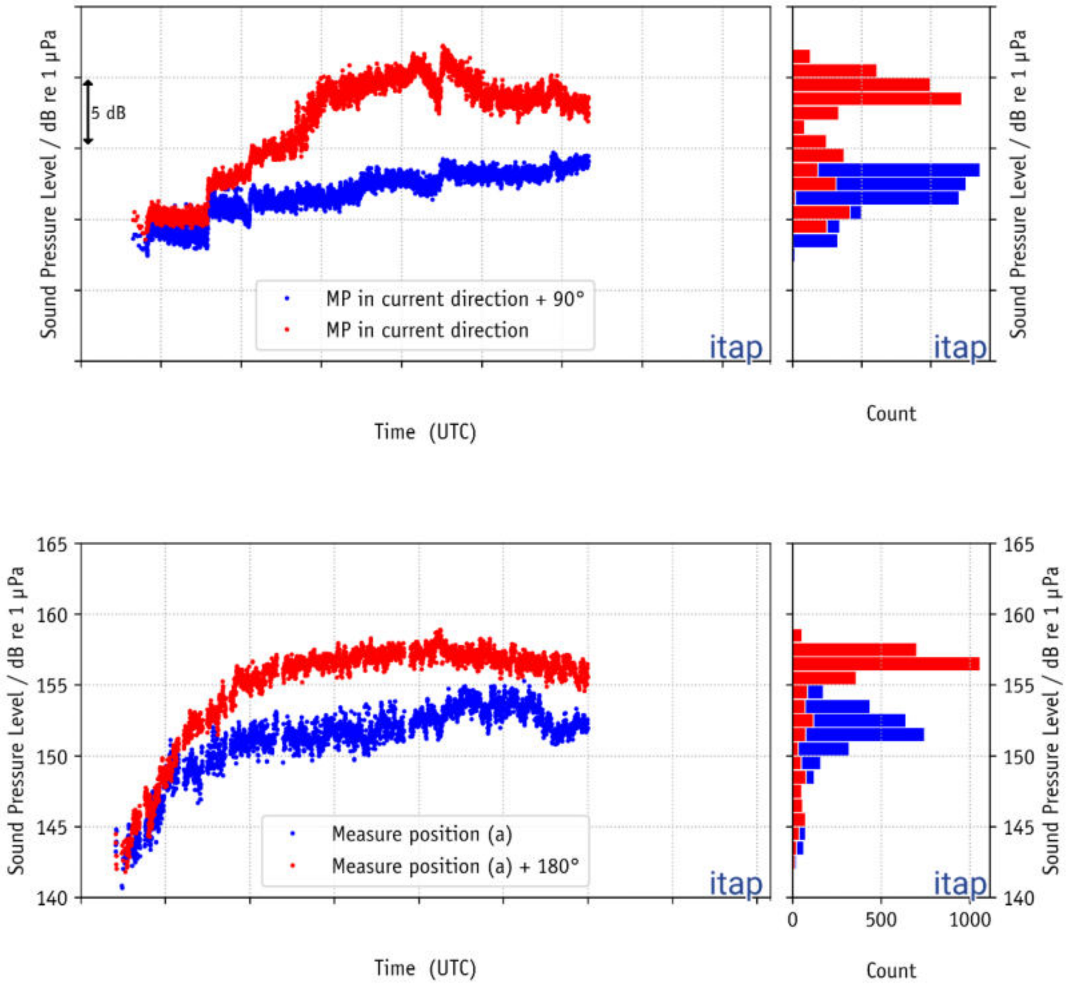

Figure 30: *The measured Sound Exposure Level at two measuring positions in 750 m in different spatial directions to the monopile installation with the application of a Big Bubble Curtain as secondary Noise Abatement System as function of time. Above: The difference between the two measuring positions 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 singlely 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·m), water depth < 25 m)	$11 \leq 14 \leq 15$	> 150
2	Double Big Bubble Curtain – DBBC (> 0.3 m^3/(min·m), water depth < 25 m)	$14 \leq 17 \leq 18$	> 150
3	Single Big Bubble Curtain – BBC (> 0.3 m^3/(min·m), water depth ~ 30 m)	$8 \leq 11 \leq 14$	< 20
4	Single Big Bubble Curtain – BBC (> 0.3 m^3/(min·m), water depth ~ 40 m)	$7 \leq 9 \leq 11$	30
5	Double Big Bubble Curtain – DBBC (> 0.3 m^3/(min·m), water depth ~ 40 m)	$8 \leq 11 \leq 13$	8
6	Double Big Bubble Curtain – DBBC (> 0.4 m^3/(min·m), water depth ~ 40 m)	$12 \leq 15 \leq 18$	3
7	Double Big Bubble Curtain - DBBC (> 0.5 m^3/(min·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.

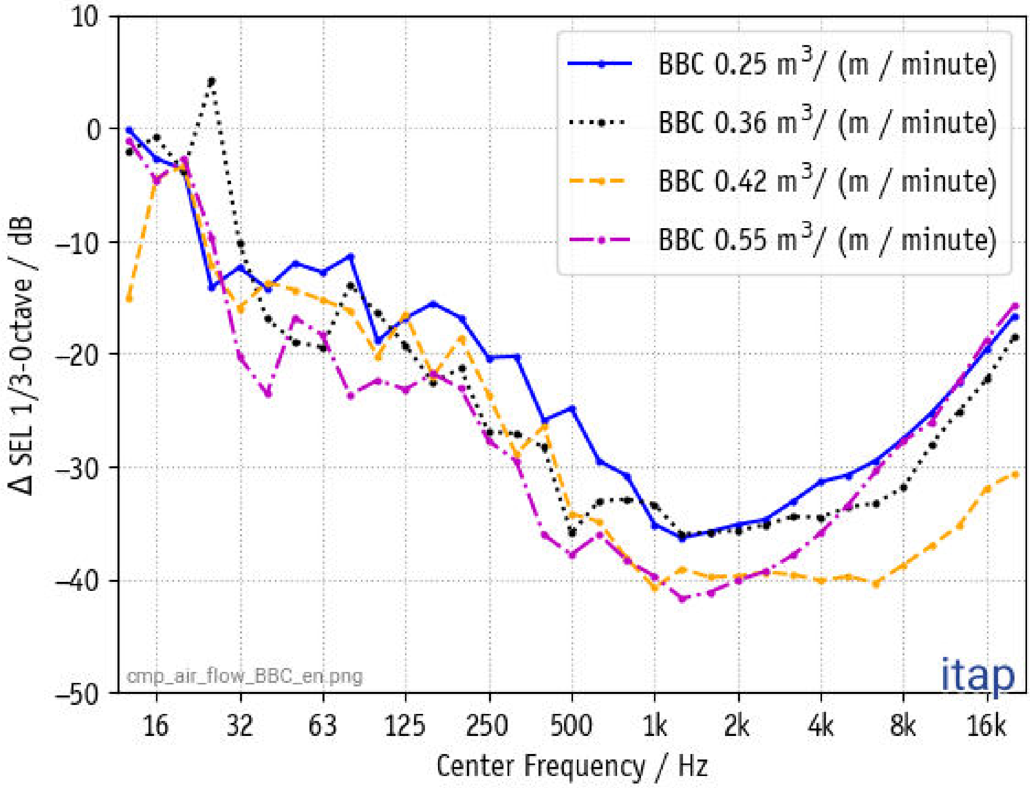

Figure 31: *Resulting averaged noise reduction (transition loss) from the test measurements according to the DIN SPEC 45653 (2017) with a double Big Bubble Curtain (DBBC) with different supplied air volumes.*

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)	$13 \leq 15 \leq 17$ dB IHC-NMS8000 $15 \leq 16 \leq 17$ dB	> 450 > 65
2	HSD (water depth up to 40 m)	$10 \leq 11 \leq 12$ 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)	$17 \leq 19 \leq 23$	> 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)	$19 \leq 21 \leq 22$	> 65
7	combination HSD + optimized BBC (> 0,4 m^3/(min m), water depth ~ 30 m)	$15 \leq 16 \leq 20$	> 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 ≥ 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.

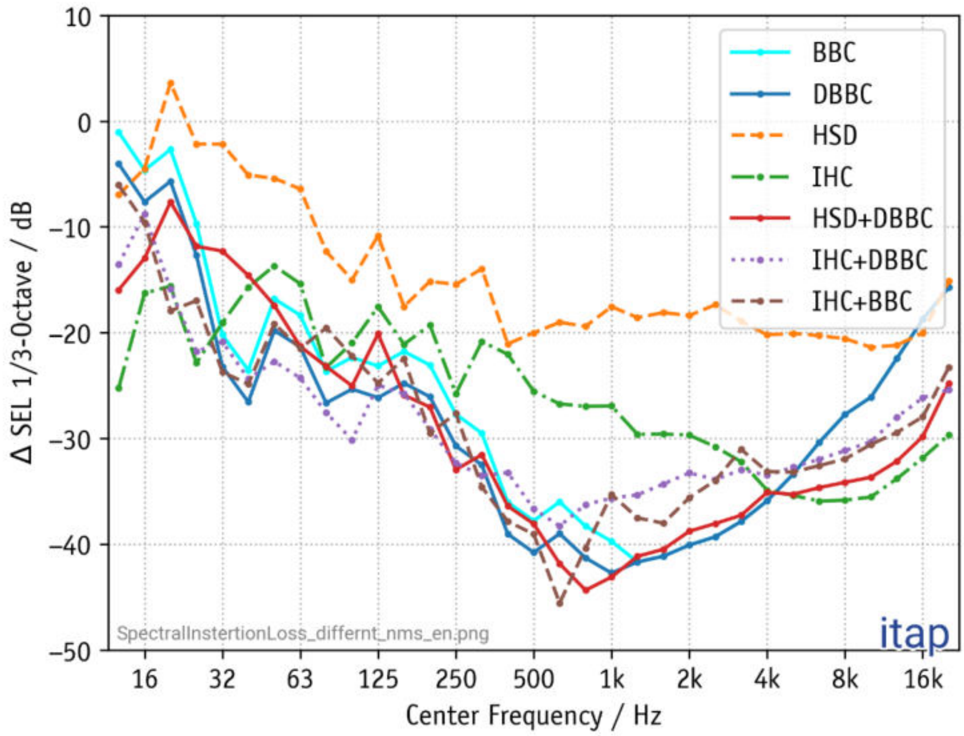

Figure 32: *Resulting noise reduction (transition loss) of the applied Noise Abatement Systems – IHC-Noise Mitigation Screen (NMS8000), Hydro Sound Damper (HSD) and optimized single/double Big Bubble Curtain (BBC/DBBC), averaged over all applications within the German EEZ of the North Sea. Note: The 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.

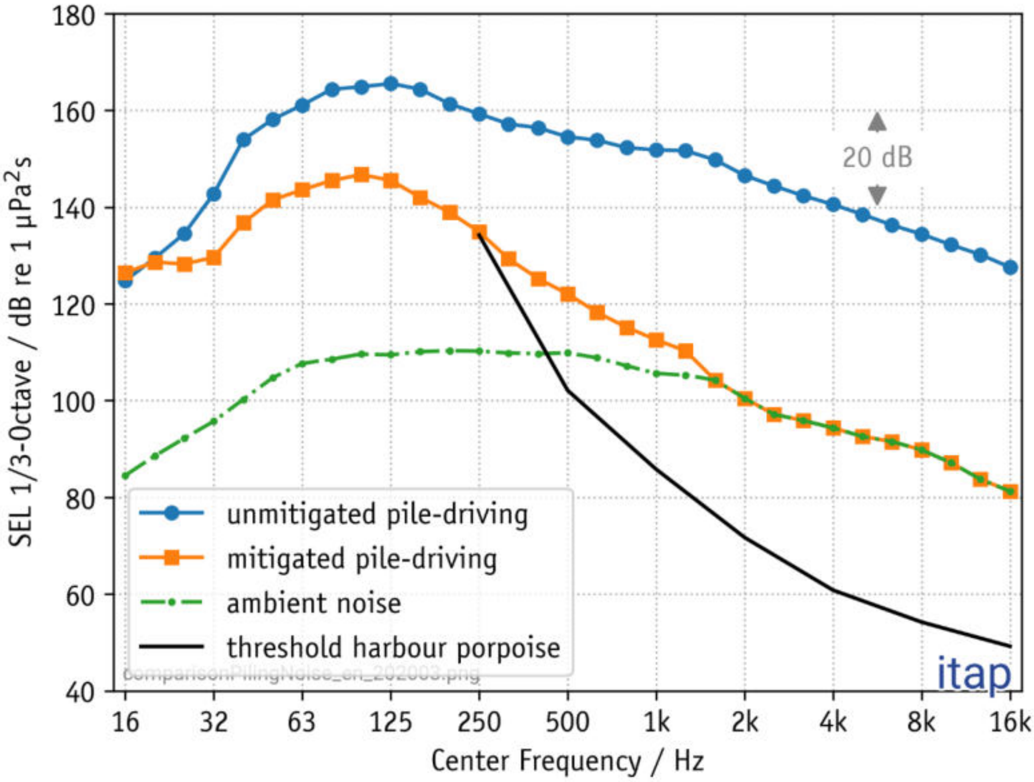

Figure 33: *Mitigated and unmitigated pile-driving noise, measured in a distance of 750 m to the foundation works at one large monopile. Moreover, the permanent background noise, measured between the pile-drivings with and without noise abatement measures, as well as the absolute threshold of hearing 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 singly 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 ≥ 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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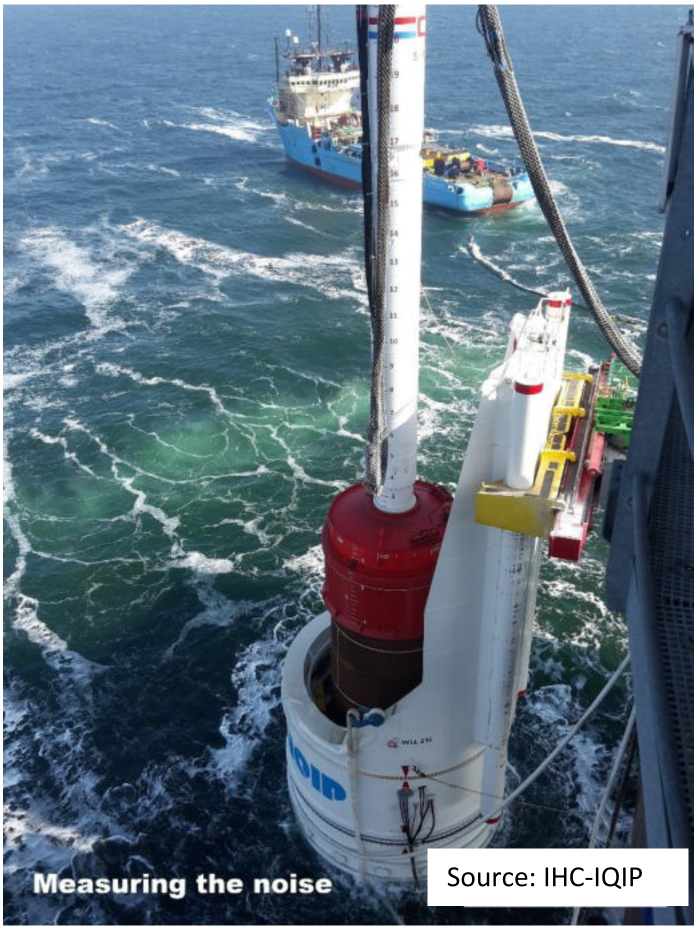
9. Appendix

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

<u>Advantages:</u>
- pile-sleeve integrated
- inclination measurement of the pile possible
- positioning tool integrated

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

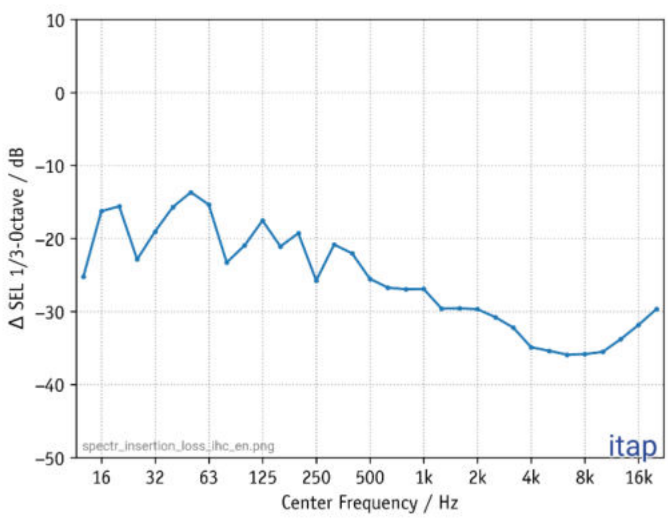
Offshore-suitable Noise Abatement System.

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*

- 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

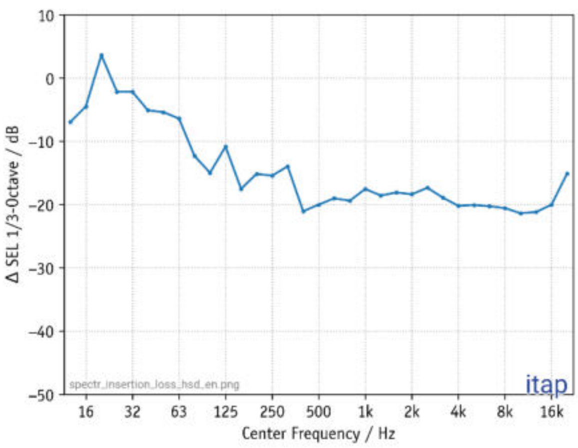
Offshore-suitable Noise Abatement System.

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

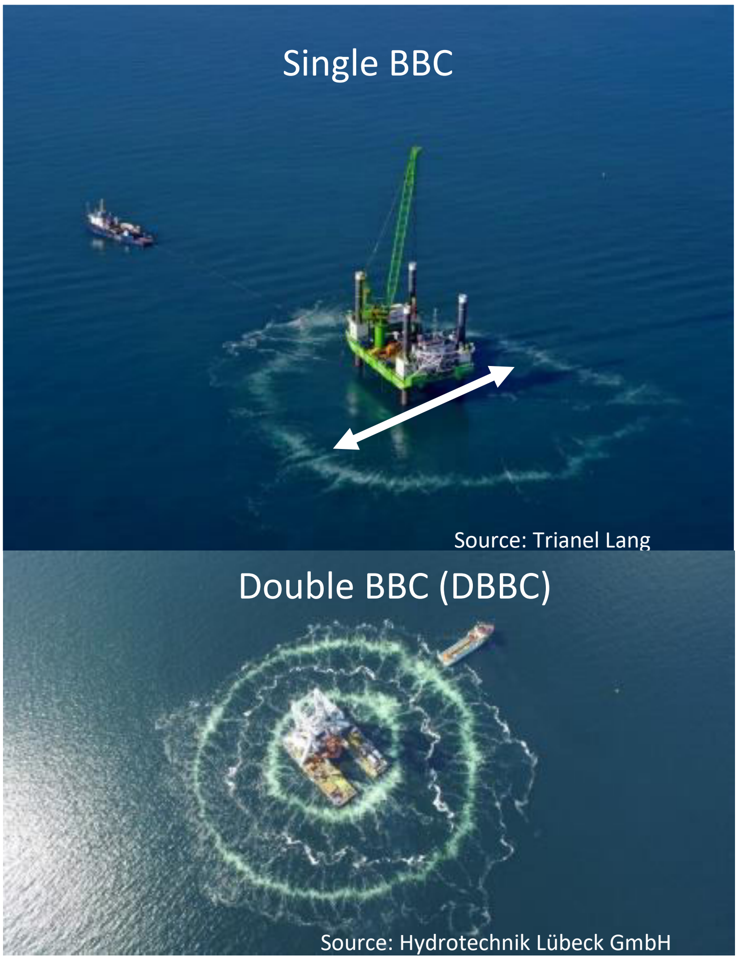
Broadband insertion loss ΔSEL [dB]

Minimal	Median	Maximal
10	11	12

spectral insertion loss



Single or double Big Bubble Curtain (BBC / DBBC)



- 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

<u>Advantages:</u>
- independent of foundation structure
- independent of the installation vessel

<u>Disadvantages:</u>
- 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

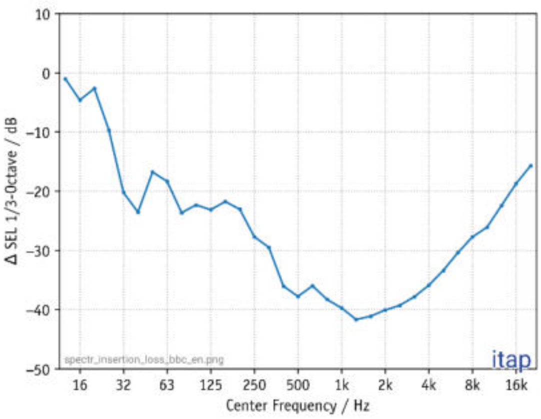
Offshore-suitable Noise Abatement System.

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