Overview of existing Noise Mitigation Systems for reducing Pile-Driving Noise

Michael A. Bellmann

itap – Institute for Technical and Applied Physics GmbH, Germany

ABSTRACT

Underwater noise caused by impulse pile-driving during the installation of offshore foundations is potentially harmful to marine life, especially marine mammals. In Germany the regulation authority (BSH) set following limit values: (i) Sound Exposure Level (SEL) = 160 dB (re 1 μ Pa^{2}s) and (ii) Peak Level (L_{Peak}) = 190 dB (re 1 μ Pa) which must be complied with at a distance of 750 m to the construction site. The experience over the last years shows that underwater sound during pile-driving mainly depends on pile diameter (currently up to 6.5 m) and the blow energy used. Measurements show values of up to 180 dB for the SEL and up to 205 dB for the L_{Peak}. Therefore, Noise Mitigation Systems (NMS) are necessary to minimize the underwater noise significantly. Since 2011 NMSs have to be applied during noisy construction work at all OWFs in Germany. The itap measured the underwater noise and evaluated the sound reduction due to the NMS used during nine OWF construction phases and several substations as well as transformer platform installations. Additionally, itap was involved in many funded research projects dealing with the evaluation and enhancement of existing NMS like OFF BW II. Overall, more than 700 piles were installed in the German North and Baltic Sea by using different NMS in different system configurations over the last years.

In this paper a general overview of existing and tested noise mitigation systems is given. The main results and general findings regarding the factors that influence noise reduction will be discussed. Finally, it will be discussed if a general State-of-the-Art exists regarding noise reduction and NMS from the acoustical point of view.

Keywords: Pile-Driving Noise, Noise Mitigation Measure, Hydro Sound, Noise Reduction Sound

1. INTRODUCTION

The installation of renewable energy sources offshore is growing fast in Germany, especially forced by the German energy turnaround after 2011. Currently, four offshore wind farms (OWF) are in operation and eight OWFs are under construction in Germany. The demand for renewable energies must go hand in hand with the awareness of sustainable issues, especially the conservation of nature and environment. Beside other ecological topics the hydro sound emissions move into the focus due to the fact that most foundations were and will be installed by using impulse pile-driving. This installation method leads to enormous acoustic emissions (hydro sound) which are potentially harmful to marine life, especially for the hearing of marine mammals like harbor porpoises and seals. For conservation of the marine fauna it is necessary to keep the noise input into the water as low as possible during noisy activities like pile-driving. Therefore, the German regulation authority BSH[1] set following limit values based on preliminary works of the Umweltbundesamt[2]: (i) Sound Exposure Level (SEL or L_E) = 160 dB (re 1 μ Pa^{2}s) and (ii) Peak Level (L_{Peak}) = 190 dB (re 1 μ Pa) which must be complied with at a distance of 750 m to the construction site.

Existing measurements over the last years show that hydro sound during pile-driving mainly depends on pile diameter (currently installations with a pile diameter up to 6.5 m are conducted) and the blow energy used. In Figure 1 measured data from itap for the acoustical parameters L_{Peak} and 50%

---

[1] BSH - Bundesamt für Seeschifffahrt und Hydrographie; Federal Maritime and Hydrographic Agency of Germany

[2] Federal Environmental Agency

percentile (mean value) of the Sound Exposure Level (SEL_{50}) over the last 10 years are shown as a function of the used pile diameter.

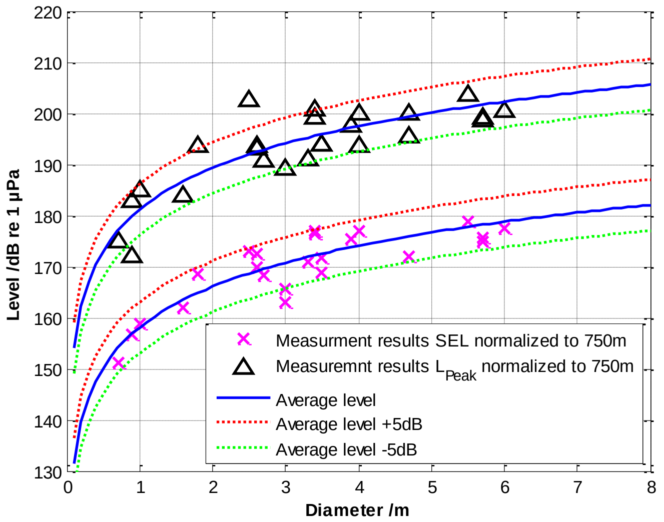

Figure 1: Measured Peak Levels (L_{Peak}) and broadband Sound Exposure Levels (SEL_{50}) during pile driving work without using noise mitigation systems (NMS) at diverse OWFs as a function of pile diameter measured by itap.

The measurements show values of up to 180 dB for the SEL_5[3] and up to 205 dB for the L_{Peak}. Therefore, Noise Mitigation Systems (NMS) are necessary and requested in Germany to minimize the hydro sound emissions significantly. The requested noise reduction mainly depends on the used pile diameter and can achieve values of up to 20 dB.

Since 2011 NMSs have to be applied during noisy construction work at all OWFs and converter platforms in Germany, especially during all pile-driving activities after the approval of the BSH. Germany was the first country to assess and to require the compliance of limiting values worldwide. The problem was that a lot of (theoretical) solutions or prototypes for noise mitigation measures existed in 2011 but most experiences were based on laboratory studies (summary in e. g. 7). Between 2000 and 2010 only few real tests with NMS under offshore conditions were performed (e. g. 9, 12 & 13). In 2011 the research project ESRa[4] performed a so-called round robin test under “real” and comparable offshore conditions with five different NMS concepts at one fixed test pile in the Baltic Sea. The result was that all tested NMS were not able to reduce the underwater noise by 10 dB in several hundred meter distances to the construction site (14). Additional, the OWF *Borkum West II* with the integrated research project OFF BW II[5] started at the same time. At this OWF a NMS system had to be used during all noise installation processes for the first time worldwide, especially during pile-driving. A “Big Bubble Curtain” (BBC) was used to reduce the pile-driving noise at 38 of 40 foundation installations (tripods with three piles per foundation; total 114 piles). During the installation work concepts for a robust and offshore practical NMS system were developed for the first time. Additionally, factors influencing noise reduction were investigated by using different system configurations of the BBC. Since 2012 each OWF was requested to apply a NMS during each pile-driving activity in Germany and the efficiency of the NMS had to be evaluated by underwater sound measurements in accordance with requirements of the BSH (chapter 3). Furthermore, a lot of research projects dealing with noise reduction were performed since no common State-of-the-Art regarding noise mitigation systems was available.

[3] SEL_5: 95% percentile value of the SEL that means 95% of all blows per installation has lower SEL values. The SEL_5 must be compared with the German limiting value 160 dB @750 m distance.
[4] ESRa – Evaluation von Systemen zur Rammschallminimierung an einem Offshore-Testpfahl. Founded project by BMU and PTJ, FKZ 0325307.
[5] OFF BW II – Entwicklung und Erprobung des Großen Blasenschleiers zur Minderung der Hydroschallemissionen bei Offshore-Rammarbeiten. Project funded by BMU and PTJ, FKZ 0325309A/B/C.

In this paper a general overview of existing and tested noise mitigation systems is given. The main results regarding noise reduction and general findings regarding factors that influence the noise reduction will be shown and discussed. Finally, it will be discussed if a general State-of-the-Art currently exists regarding noise reduction and NMS from the acoustical point of view.

2. EXISTING NOISE MITIGATION MEASURES

Currently (2014) many noise mitigation systems are available. Some of the systems were integrated into normal construction processes without any time delays and they were often used as a kind of "standard" noise mitigation system like the BBC system. Other NMS were only used once or twice in a prototype version during the installation of test piles within research projects. In Table 1 all NMS tested under real offshore conditions by itap are summarized. Additionally, the range of tested system configurations for each NMS is shown. A general overview of existing noise mitigation measures and concepts as well as other foundation installation procedures than pile driving are summarized in Koschinski & Lüdemann (2013). Therefore, all tested NMS are just described briefly in the following subsections.

Table 1 – List of tested and evaluated noise mitigation systems (NMS) under offshore conditions. Underwater sound measurements conducted by itap GmbH. Furthermore tested influencing factors and parameters of each NMS are summarized.

Noise mitigation system (provider)	**Tested configurations**	**Number of foundations (piles)**
Single Big Bubble Curtain – BBC (Hydrotechnik Lübeck GmbH & Weyres Offshore GmbH)	Supplied air volume ($\leq 0{,}5$ m^3/(min*m)), diameter and length of the nozzle hose (length: 400 m – 1.000 m), hole configuration of the nozzle hose, distance to construction site (40 m – 125 m), air feed-in (one- or double sided), ballast chain (inside/outside), pre-laying or post-laying, water depth (10 m to 43 m)	> 150 (300)
Double Big Bubble Curtain – DBBC (Hydrotechnik Lübeck GmbH & Weyres Offshore GmbH)	DBBC: distance between nozzle hoses (6 m – one water depth)	> 150 (300)
Small Bubble Curtain – SBC (Menck GmbH)	Supplied air volume, hole configuration of the nozzle hose	2 (2)
Hydro Sound Damper – HSD (OffNoise-Solutions GmbH)	Number and size of HSD elements	> 10 (> 10)
Noise Mitigation Screen - IHC-NMS (IHC Merwede)	Space between inner and outer tube, additional BBC inside	> 150 (150)
Cofferdam (Advanced Offshore Solutions ApS)	Space between pile and cofferdam	< 10 (< 15)

2.1 Single and Double "Big Bubble Curtain" (BBC and DBBC)

A "Big Bubble Curtain" functions as follows: air is pumped into a nozzle hose lying on the seabed and it escapes through holes that are provided for this purpose. Thus an air bubble curtain is generated within the water column due to buoyancy. Usually, the entire construction site (installation vessel and foundation structure) is enveloped by a bubble curtain system. Sound due to pile driving work must pass through those ascending air bubbles and is thus attenuated, Figure 2 (right). In case of a double BBC two nozzle hoses are deployed in a specified distance to each other on the seabed.

The sound attenuating effect of the noise mitigation system BBC or air bubbles in water is caused by: (i) sound scattering on air bubbles (resonance effect) and (ii) (specular) reflection at the transition between water layer with and without bubbles (air water mixture; impedance leap).

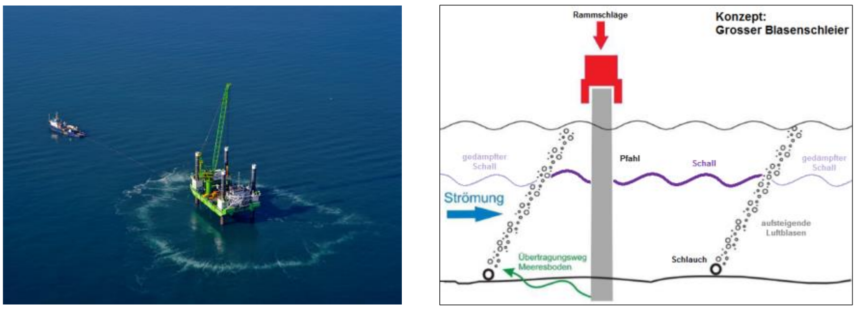

Figure 2: Left: Photo of an operating BBC (7); right: Principles of a “BBC” (7)

2.2 Small Bubble Curtain (SBC)

Instead of locating one or two nozzle hose(s) on the seabed several nozzle hoses are fixed in short distances (< 0.5 m) to the pile in vertical direction; that means from the sea surface to the seabed. The feed-in (supplied) air of the used compressors will flow under high pressure directly towards the pile so that the whole pile can be installed in a water-air composite. Therefore, the sound radiation of the pile into the water will be affected significantly by reducing the sound velocity and by generating an impedance gap.

2.3 Hydro Sound Damper (HSD)

The HSD system consists of a fisher net where HSD elements with different sizes and distances from each other were mounted. With ballast ring on the seabed and a floating system on the sea surface the fisher net including the HSD elements can be located in a short distance (< 1 m) around the pile. The HSD elements can be foam plastic elements or gas-filled balloons. The radiated noise from the pile must cross the HSD elements and will be reduced due to reflection and absorption. In principal the HSD elements act like air bubbles in the water with the advantage that they cannot be drifted by current and their size and, therefore, the resonance frequency is adjustable.

2.4 Noise Mitigation Screen (IHC-NMS)

The IHC-NMS system consists of a double-wall steel screen (tube). The pile will be inserted into this system. The space between the two screens is filled with air; additionally, air bubbles can be feed-in between pile and NMS system (water-air-composite). The radiated sound crosses the internal bubble curtain as well as the air-filled double-wall steel screen and will be reduced due to reflection (impedance gap).

2.5 Cofferdam

The cofferdam system consists of a single-wall steel tube. The pile will be inserted into this system. Near the seabed a gasket (seal ring) is installed so that the space between pile and cofferdam can be evacuated from water by pumps. In principal the pile can be installed “in air” and not in water so the pile radiates the sound into air and will cross the steel tube thereafter. Due to the different impedances the pile-driving noise will be reduced by reflection.

2.6 Other noise mitigation systems

There are many other noise mitigation systems or concepts available than summarized in Table 1, like the BeKa-shell or the “Little Bubble Curtain”. But most of them are not tested under real offshore conditions or just exist in a preliminary version (prototype).

2.7 Combination of Noise Mitigation Systems

For the installations of monopiles with a diameter of > 5.0 m several combinations of the NMS listed above were used to enhance the resulting noise reduction during the last two years. In principal a combination of one NMS acting close to the pile with a BBC (acting far away from the pile) is possible. The following combinations were evaluated with underwater noise measurements:

- Two different bubble curtain systems (e. g. DBBC + BBC system; result: a “triple” BBC)
- IHC-NMS + single BBC
- HSD + single BBC or double BBC

3. HYDRO SOUND CONCEPTS and MEASUREMENTS

In the course of the approval procedure a construction monitoring according to the measurement instruction “Standard, Investigation of the Impacts of Offshore Wind Turbines on the Marine Environment (5)“ must be conducted in Germany. Therefore, the underwater sound pollutions due to noisy construction work like pile-driving are measured at a distance of 750 m and 1,500 m from the foundation according to the specifications of underwater noise measurements by the BSH (4). Additionally, underwater sound pollutions are measured simultaneously at a fixed measuring location outside the construction sites at a distance of about 10 km and more in or in the direction of the next Natura 2000 area. Usually, one hydrophone will be used per measurement location in a height of 2 m to 5 m above the seabed (lower one-third of the water column) to describe and to evaluate the pile driving noise by the acoustical parameters Peak Level (L_{Peak}) and Sound Exposure Level ($SEL_{5, 50, 90}$) (BSH, 2011).

The BSH also sets requirements for the evaluation of noise mitigation systems (6). In general pile-driving activities must be conducted once with and once without the presence of the noise mitigation system under comparable boundary conditions. However, the number of measurement positions at distances between 750 m and 1,500 m should be increased to minimum four to investigate the influencing factors like the bathymetry or the current.

In addition to the standard measuring program (5) further measurements were conducted at a distance of 20 m to 5,000 m from the construction site in several research projects. The maximum number of hydrophones used per pile installation was 52 hydrophones at 13 different distances and up to 16 different hydrophone heights per location (2).

The measuring systems applied for recording hydro sound are stand-alone measuring systems that were developed and built by itap.

4. RESULTS

4.1 General

Overall more than 700 piles were installed and measured by itap in the North and Baltic Sea by using different NMS during normal construction phases of nine offshore wind farms, several offshore supply stations and test piles. The water depth varied between 8 m and 45 m. Influencing parameters of the used NMS like supplied air volume of a BBC system used on the resultant noise reduction were investigated as well as other influencing factors like water current on the noise reduction .

The following results are based on measured data at a distance of 750 m to the construction site (acoustical far-field). A statistical approach for the evaluation of the noise reduction potential of a NMS was developed in the research project OFF BW II (7) due to the fact that some thousand blows per pile installation are usually needed and the resulting noise reduction varies during the whole pile-driving activity. That means that the mean value as well as a kind of minimum and maximum of the resulting noise reduction is calculated.

Insertion loss or (sound) transmission loss is generally considered for characterization of the effectiveness of a noise mitigation system (noise reduction). Transmission loss can be depicted broadband that means as a single value, or frequency resolved, as 1/3 Octave spectrum for instance.

For broadband depiction the broadband Sound Exposure Level (single SEL value) or the Peak Level (L_{Peak}) when using a noise mitigation system is subtracted from the broadband SEL of the reference condition (without noise mitigation system), meaning the difference (ΔSEL or ΔL_{Peak}) is calculated. The greater the difference the higher is the insertion loss and the better is the noise mitigation system. Advantage of this parameter is the possibility to record and describe the noise reducing effect of a noise mitigation system by a single value. In case of a frequency resolved transmission loss the values for each used frequency band will be used (Figure 3).

4.2 Noise Mitigation System (single and double) „Big Bubble Curtain“ (BBC)

Measurements as well as theoretical assessments and studies about the functioning of bubble curtains or air bubbles in water are known from literature (e. g. summarized in 7, 8, 10 & 11). But those data predominantly refer to theoretical calculations, laboratory studies or applications during construction work in harbor basins. The first offshore applications of the noise mitigation system “Big Bubble Curtain” were conducted during the construction of the research platform FINO 3 (9) and at one test foundation of the OWF *alpha ventus* (13). The application of the BBC in series was developed and tested during the installation of an entire wind farm (OWF *Borkum West II*) for the first time in the course of the research project OFF BW II (7).

Over the last 3 years the most often used NMS system during normal construction processes was the (single or double) BBC system from different manufacturers and in different system configurations (Table 1). Overall more than 20 different system configurations of (single and double) BBC systems were tested at minimum 600 foundation installations in nine different OWFs, converter platform and test pile installations.

In Figure 3 an example of the measured 1/3 octave spectra of the Sound Exposure Level (SEL_{50}) with and without the “Big Bubble Curtain” at a distance of 750 m is shown. The BBC was operated with different supplied feed-in air volumes.

The maximum levels of the pile-driving noise measured at a distance of 750 m are around 100 Hz and 400 Hz depending on the hammer type used and the pile diameter (in this case pile diameter ~2.4 m; 800 kJ hammer). Towards higher and lower frequencies the levels decrease significantly. A difference in noise levels between the 1/3 Octave spectra without and with NMS are measured from 80 Hz towards higher frequencies by using the BBC system (Figure 3). The difference spectra (spectral insertion loss or transmission loss) of presented BBC configurations are also shown in Figure 3. Negative values mean that the NMS used reduces the pile-driving noise; zero or positive values mean that the NMS does not affect the pile-driving noise.

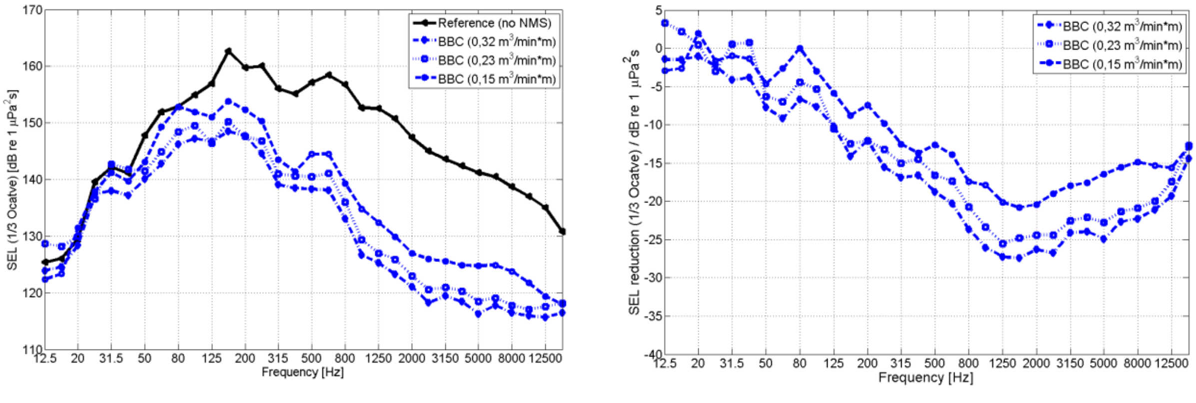

Figure 3: Left: An example of the 1/3 octave spectra of the averaged Sound Exposure Level (SEL_{50}) with and without the Big Bubble Curtain in different system configuration (used supplied air volume) measured at a distance of 750 m to the pile. Right: Difference spectra (spectral insertion loss).

Figure 3 (right picture) shows that the noise reduction of the BBC increases with increasing frequency from 80 Hz to 1.6 kHz. At higher frequencies the difference decreases slightly probably due to the low noise levels in this frequency range.

Furthermore, the supplied air volume has a positive effect on the resulting noise reduction in the whole presented frequency range. This effect was validated with measured data in different OWFs and different BBC system configurations during the last years (1).

The configurations of the nozzle hose (hole diameter and distances between two holes) of the BBC system was also varied to investigate the influence of the size and the number of bubbles in the water column (water –air composite). In Figure 4 the spectral insertion losses of the two extremes of the tested nozzle hose configurations are presented (7). Both BBC configurations were tested with the same supplied air volume and under comparable boundary conditions.

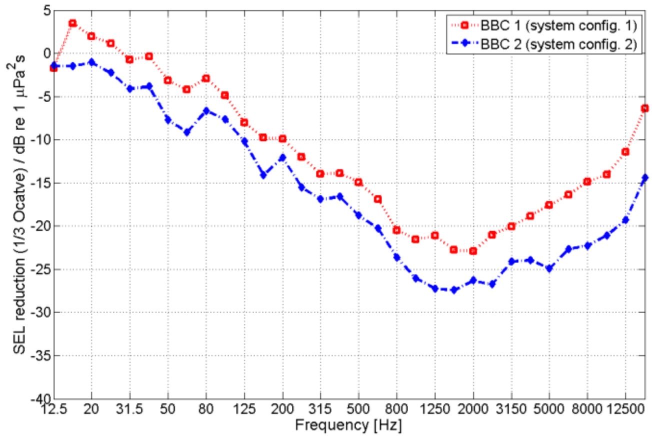

Figure 4: Difference spectra (spectral insertion loss) of a BBC system with different configurations of the nozzle hose used but the same supplied air volume (config. 1: big holes and large distances between the holes; config. 2: small holes with short distances between the holes.)

Figure 4 shows that smaller and more air bubbles reduce the pile-driving noise better than only few big sized bubbles produced by a BBC if the water-air composite ratio is comparable. It can be assumed that the influence of reflection due to impedance differences between water and the water-air composite is higher than the effect of any resonance interactions between the bubbles and the pile-driving noise.

4.3 General Overview

Table 2 summarizes existing and evaluated noise mitigation systems including the (broadband) insertion loss (ΔSEL) of the best available system configuration of each NMS. Usually the resulting noise reduction for the L_{Peak} is a little higher than for the SEL.

Table 1: Summary of the existing and evaluated noise mitigation systems including the (broadband) insertion loss of the best available system configuration for each NMS.

Nr.	Noise Mitigation System	Influencing factors	ΔSEL [dB]
1	Single “Big Bubble Curtain” (BBC)	Supplied air volume, diameter and length of the nozzle hose, hole configuration of the nozzle hose, air feed-in (one- or double sided), ballast chain (inside/outside), pre-laying or post-laying, DBBC: distance between nozzle hoses (6 m – one water depth)	$10 \leq 13 \leq 15$
2	Double “Big Bubble Curtain” (DBBC)		$14 \leq 17 \leq 18$
3	“Small Bubble Curtain” (SBC)	Supplied air volume, hole configuration of the nozzle hose	~ 14
4	Hydro-Sound-Damper (HSD)	Number and size of HSD elements	$8 \leq 10 \leq 13$
5	Noise Mitigation Screen (IHC-NMS)	Space between inner and outer tube, additional BBC inside	$10 \leq 12 \leq 14$
6	Cofferdam	Space between pile and cofferdam	With problems < 10 dB Without problems > 20 dB[6]
7	IHC-NMS + BBC		$17 \leq 19 \leq 23$

[6] With problems: sealing gasket damaged; without problems: results only reported by the manufacturer

In Figure 5 an overview of the (spectral) insertion loss of different noise mitigation systems is given by presenting the difference 1/3 octave spectra.

The general shape of all shown curves in Figure 5 is that with increasing frequency the noise reduction (ΔSEL) increases up to a frequency of about 1 kHz to 2 kHz. In this frequency range the pile-driving noise can be reduced by up to 40 dB with several NMS. At higher frequencies the noise reduction decreases significantly; probably due to the low levels in this frequency range. But the absolute noise reduction between different NMS or different system configurations of the same NMS (e. g. BBC) differs significantly over the whole frequency range. The frequency range between 80 Hz and 400 Hz dominates the overall broadband (single) value for the insertion loss due to the acoustic energy distribution of the pile-driving activities (Figure 3). The highest noise reduction was measured by using the combination of the IHC-NMS and a BBC.

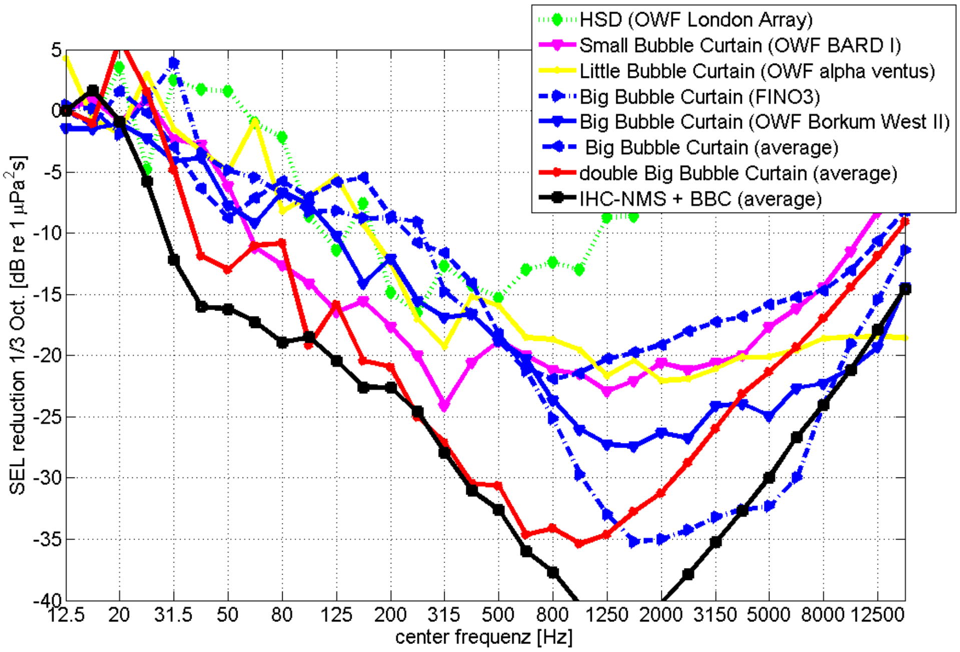

Figure 5: Overview of the spectral insertion loss (difference spectra) of different noise mitigation systems (including different system configurations of NMS).

4.4 Noise Mitigation by Reducing Pile-Driving Energy

The input of sound into water can also be reduced to a certain extent by decreasing the pile-driving (blow) energy.

A physically reasonable assumption is that the sound energy emitted is proportional to the mechanical energy (blow energy) applied. By doubling the blow energy the sound level would increase by max. 3 dB or generally by

$$L = 10 \log (E2/E1) \quad \text{dB} \tag{1}$$

if blow energy is increased from E1 to E2. Existing measurements from the OWF *Horns Rev II* (3) show that sound intensity increases with blow energy, as expected, but a proportionality, meaning an increase of the level with 10 log E is just roughly given. Measurements during the research project ESRa (14) and measurements in wind farms from 2011 until 2013 by itap (not published measuring data from current construction projects) showed that by doubling blow energy in the (energy) range in which a motion feed of the pile to be driven is provided, sound emission increases by 2 dB to 3 dB per doubling of driving energy. With minor driving energies (e. g. soft-start) that only produce either no or very low feed, higher increases in sound may result depending on blow energy.

Therefore, it can be assumed that reducing driving energy by 50% results in a reduction of sound of 2 dB to 3 dB.

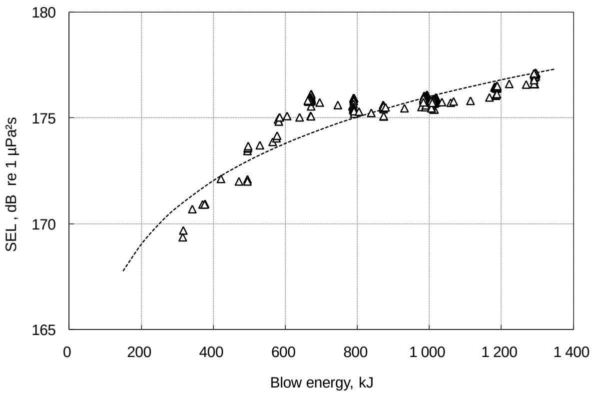

Figure: Measured Sound Exposure level in several hundred meter distance to the construction site depending on the blow energy used (3). The dotted line shows a simple log fit.

5. Discussion

The representative insertion loss of any noise mitigation system should be evaluated on the basis on measurements at a distance of several hundred meters (around 750 m). In the close vicinity of the pile (< 250 m) the measurement are conducted within the so-called acoustic near-field and are not really be compared to measurements in the acoustic far-field due to phase shifts between pressure and sound velocity (14). Additionally, potential effects of ground coupling are not be regarded in the NMS evaluation by using near field measurements. Ground coupling effect means that the sound from pile-driving activity is transmitted from the pile into the sediment and then it is emitted from the seabed into the water in the immediate vicinity of the pile. This is especially important for all NMS which act very close to the pile like the IHC-NMS or HSD system.

However, the resulting noise reduction significantly depends on the spectral distribution of the emitted pile-driving noise without noise mitigation since the insertion loss of all NMS tested significantly depends on frequency. The lower the frequency of the maximum noise levels from pile-driving is the lower is the expected noise reduction for the same NMS used.

Both the NMS systems IHC-NMS and BBC were used several hundred times during the last two years. Within research projects and finished OWF construction works in Germany these two systems were enhanced regarding noise reduction and the offshore reliability during normal construction processes. The best system configuration of both systems (IHC-NMS and BBC) obtained noise reductions of more than 10 dB in series and they are reliable, offshore suitable and robust noise mitigation measures. The resulting noise reduction potential significantly depends on some important influencing system factors like the air volume supplied for the BBC or the size of the IHC-NMS. Most of the knowledge about these influencing parameters was gained for the “Big Bubble Curtain” since this NMS was the most used mitigation measure and the effectiveness was investigated and enhanced in two funded research projects (OFF BW II and GT Forschung[7]).

The sound mitigation obtained due to the BBC essentially depends on following parameters, as seen in the research project OFF BW II and other applications in current construction projects: (i) supplied air volume used (more air volume means more noise reduction; best practice ≥ 0.3 m^3/(min*m)), (ii) size and distance of holes (nozzle hose configuration; generating a constant water air composite along the nozzle hose), (iii) no turbulence generating obstacles in the nozzle hose (like ballast chain inside the hose) as well as (iv) the distance of both the nozzle hoses laid on the seabed when using a double bubble curtain (best practice ≥ one water depth).

At least two different noise mitigation systems from different manufacturers are available on the market and have shown reliable and constant noise reduction of ≥ 10 dB in their best system configuration. Additionally, some other NMS like the HSD-system are currently used during normal

[7] GT Forschung – Weiterentwicklung und Erprobung des Großen Blasenschleiers zur Minderung der Hydroschallimmissionen bei Offshore-Rammarbeiten. Founded project by BMU and PTJ, FKZ 41V6314, currently running

construction processes with comparable results and enhancements related to the reliability and offshore-practicality. From this point of view a minimum reduction of 10 dB for one single NMS could be set as State-of-the-Art.

The experience has shown that the resulting noise reduction can be enhanced by using combinations of independent NMS like two different BBC systems or IHC-NMS with a BBC. The OWF *Butendiek* has demonstrated that the German limiting values of 190 dB_{Peak} and 160 dB_{SEL} at a distance of 750 m can be fulfilled during the installation of monopiles with a pile diameter of maximum 6.5 m, if a combination of two separate MNS systems including a significant reduction of blow energy is used. The resulting noise reduction of two separate NMS significantly depends on frequency. Usually the resultant noise reduction of two NMS at the same time is lower than the sum of the insertion loss of each system. Reduction of blow energy by a factor of 1/2 to 1/4 of the predicted maximum blow energy leads to noise reduction of about 2 dB to 5 dB.

6. CONCLUSIONS

- ✓ An overview of existing and evaluated noise mitigation systems (NMS) to reduce the sound emission during pile-driving activities was given.
- ✓ The resulting noise reduction (insertion loss) of each evaluated NMS significantly depends on some system relevant factors of the used NMS like the air volume supplied for the Big Bubble Curtain (BBC). This means that for each application the best system configuration depending on several boundary conditions should be used.
- ✓ The evaluation of the insertion loss of a noise mitigation system must base on measurements at a distance of several hundred meters to the construction site to avoid acoustical near-field problems by conducting underwater noise measurements and to take into account possible ground coupling effects.
- ✓ The Big Bubble Curtain (BBC) system is the most investigated and used NMS (< 600 pile installations). The most influencing factors of this mitigation measure are known well: (i) supplied air volume used (more air volume means more noise reduction; best practice ≥ 0.3 $m^3/(min*m)$), (ii) size and distance of holes (nozzle hose configuration; generating a constant water air composite along the nozzle hose), (iii) no turbulence generating obstacles in the nozzle hose (like ballast chain inside the hose) as well as (iv) the distance of both the nozzle hoses laid on the seabed when using a double bubble curtain (best practice ≥ one water depth).
- ✓ The IHC-NMS system and the BBC system are offshore-suitable and produce noise reductions of < 10 dB in series. Some other mitigation systems are available and produce comparable results but they are not often used yet or they are not used in real construction processes in series.
- ✓ The combination of two separate noise mitigation systems increases the resulting noise reduction up to < 20 dB for the Sound Exposure Level and > 20 dB for the Peak Level (IHC-NMS + BBC).
- ✓ Reduction of blow energy can also be used as a noise mitigation measure. The bisection of the blow energy reduces the pile-driving noise by up to 3 dB.
- ✓ The State-of-the-Art regarding noise reduction is minimum 10 dB by using one noise mitigation system.

ACKNOWLEDGEMENTS

Many thanks to all companies involved during the performed offshore tests within several funded research projects and normal construction phases, especially to all OWF owners who allowed us to conduct a lot of underwater noise measurements within their construction processes.

Great thanks go to all manufacturers of noise mitigation systems for their courage to develop and build different concepts for reduction pile-driving noise. Additionally, thank you very much for the very constructive discussion during the improving and enhancing processes onshore and offshore; I enjoyed the very pleasant atmosphere.

Additionally, I thank all my colleagues, especially Patrick Remmers, Michael Müller, Siegfried

Gündert and Hauke Holst, for the very harmonic cooperation and productive discussions as well as for their excellent job by performing and analyzing measurements under partly very hard offshore conditions.

REFERENCES

1. Bellmann MA, Gündert S & Remmers P (2014) Offshore Messkampagne 2 (OMK 2) für das Projekt BORA im Offshore-Windpark Global Tech I BORA: Entwicklung eines Berechnungsmodells zur Vorhersage des Unterwasserschalls bei Rammarbeiten zur Gründung von OWEA. Project report No 2162-13-bel for the founded research project BORA (0325421A/B/C)
2. Bellmann MA (2013) Darstellung und Beurteilung der Erfahrungen mit den Schallminderungssystemen „Großer Blasenschleier“ und „Doppelter Großer Blasenschleier“ aus der praktischen Anwendung - Erfahrungsbericht aus den Bauphasen der Offshore Windparks Nordsee Ost, Global Tech I, Meerwind Süd/Ost und DanTysk, Projektbericht im Auftrag der zukünftigen OWP Betreiber.
3. Brandt MJ, Diederichs A, Betke K, Nehls G (2011): Responses of harbour porpoises (Phocoena phocoena) to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea. Mar Ecol Prog Ser 421: 205–216
4. BSH (2013a) Standard - Investigation of the Impacts of Offshore Wind Turbines on Marine Environment (StUK4)
5. BSH (2011) Offshore-Windparks - Messvorschrift für Unterwasserschallmessungen. Report by Müller & Zerbst on behalf of BSH (http://www.bsh.de/de/Produkte/Buecher/Standard/Messvorschrift.pdf)
6. BSH (2013b) Offshore-Windparks - Messvorschrift für die quantitative Bestimmung der Wirksamkeit von Schalldämmmaßen. report M100004/05 by Müller & Zerbst on behalf of BSH http://www.bsh.de/de/Produkte/Buecher/Standard/Messvorschrift_Schalldaemmmassnahmen.pdf
7. Diederichs A, Pehlke H, Nehls G, Bellmann MA, Gerke P, Oldeland J, Grunau C & Witte S (2014) Entwicklung und Erprobung des „Großen Blasenschleiers zur Minderung der Hydroschallemissionen bei Offshore-Rammarbeiten (HYDROSCHALL OFF BW II), technischer Abschlussbericht, Förderkennzeichen 0325309 A/B/C Grießmann T, Rustemeier J, Betke K, Gabriel J, Neumann T, Nehls G, Brandt M, Diederichs A, Bachmann J (2010): Erforschung und Anwendung von Schallminimierungsmaßnahmen beim Rammen des FINO3 – Monopiles. Hannover, Abschlussbericht zum BMU-Vorhaben „Schall bei FINO3“, FKZ 0325077.
8. Grießmann, T., Rustemeier, J., Betke, K., Gabriel, J., Neumann, T., Nehls, G., Brandt, M., Diederichs, A. & Bachmann, J. (2010): Erforschung und Anwendung von Schallminimierungs-maßnahmen beim Rammen des FINO3-Monopiles. Abschlussbericht zum BMU-Vorhaben "Erforschung und Anwendung von Schallminimierungsmaßnahmen beim Rammen des FINO3-Monopiles - Schall FINO3", Förderkennzeichen 0325023A und 0325077
9. Koschinski S, Lüdemann K (2013): Stand der Entwicklung schallminimierender Maßnahmen beim Bau von Offshore-Windenergieanlagen. Gutachten im Auftrag des Bundesamt für Naturschutz.
10. Nehls, G. & Betke, K. (2011) Darstellung und Bewertung der Auswirkungen von Schallemissionen durch Offshore-Rammarbeiten auf Meeressäugetiere. Im Auftrag des Offshore Forum Windenergie, Dez 2011
11. Nehls, G., Betke, K., Eckelmann, S. & Ros, M. (2007): Assessment and costs of potential engineering solutions for the mitigation of the impacts of underwater noise arising from the construction of offshore windfarms. - BioConsult SH report, Husum, Germany. On behalf of COWRIE Ltd. http://www.offshorewindfarms.co.uk/Assets/COWRIE-ENGFinal270907.pdf
12. Schultz-von Glahn M, Betke K, Nehls G (2006): Underwater noise reduction of pile driving for offshore wind turbines – Evaluation of several techniques under offshore conditions. UFOPLAN Ref. No. 205 53 113, final report. The Federal Environment Agency (Umweltbundesamt), Berlin, http://www.itap.de/uba-20553113.pdfWilke, F., Kloske, K. & M. Bellmann (2012) ESRa – Evaluation von Systemen zur Rammschallminderung an einem Offshore-Testpfahl. Technischer Abschlussbericht. Projektträger: PTJ, Forschungszentrum Jülich GmbH Förderkennzeichen 0325307.
13. Rustemeier J., Grießmann T., Betke, K., Gabriel, J., Thomas Neumann, T. & Küchenmeister, M. (2012) Erforschung der Schallminderungsmaßnahme Gestufter Blasenschleier (Little Bubble Curtain) im Testfeld alpha ventus. Abschlussbericht zum BMU-Vorhaben "Schall alpha ventus", FKZ 0325122 A und 0325122 B, gefördert vom Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit
14. Wilke F, Kloske K & Bellmann M (2012) Evaluation von Systemen zur Rammschallminderung an einem Offshore-Testpfahl. Technischer Abschlussbericht für das geförderte Projekt ESRa, Fördernummer 0325307