OSPAR COMMISSION

OSPAR inventory of measures to mitigate the emission and environmental impact of underwater noise

Biodiversity Series

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OSPAR Convention

The Convention for the Protection of the Marine Environment of the North-East Atlantic (the "OSPAR Convention") was opened for signature at the Ministerial Meeting of the former Oslo and Paris Commissions in Paris on 22 September 1992. The Convention entered into force on 25 March 1998. It has been ratified by Belgium, Denmark, Finland, France, Germany, Iceland, Ireland, Luxembourg, Netherlands, Norway, Portugal, Sweden, Switzerland and the United Kingdom and approved by the European Community and Spain.

Convention OSPAR

La Convention pour la protection du milieu marin de l'Atlantique du Nord-Est, dite Convention OSPAR, a été ouverte à la signature à la réunion ministérielle des anciennes Commissions d'Oslo et de Paris, à Paris le 22 septembre 1992. La Convention est entrée en vigueur le 25 mars 1998.
La Convention a été ratifiée par l'Allemagne, la Belgique, le Danemark, la Finlande, la France, l'Irlande, l'Islande, le Luxembourg, la Norvège, les Pays-Bas, le Portugal, le Royaume-Uni de Grande Bretagne et d'Irlande du Nord, la Suède et la Suisse et approuvée par la Communauté européenne et l'Espagne.

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1. Purpose of the OSPAR Inventory

The 2009 JAMP Assessment on the environmental impact of underwater noise recommended amongst others that OSPAR Contracting Parties in a next step should develop guidance on measures to mitigate noise emissions and the environmental impacts of underwater noise on the marine environment (OSPAR 2009a). The Quality Status Report 2010 recommended that OSPAR should increase efforts to develop, review and apply mitigation measures to reduce the impacts of underwater noise and develop Guidelines on best environmental practices (BEP) and best available techniques (BAT) for mitigating noise emissions and their environmental impacts (OSPAR 2010).

The purpose of this inventory is to provide OSPAR Contracting Parties an overview of effectiveness and feasibility of mitigation options to avoid or reduce emissions and impacts of underwater noise, and to support OSPAR EU Member States in establishing programmes of measures in relation to underwater noise under the MSFD by 2015. The inventory is designed to help avoid and reduce the introduction of underwater noise and/or its impacts on the marine environment through a common understanding of best mitigation options and by aiding Contracting Parties in their choice of options in the management of underwater noise sources and ultimately by the application of best available techniques (BAT) and best environmental practice (BEP), as defined in Appendix 1 to the OSPAR Convention, for activities generating impulsive and/or continous noise underwater noise.

Developing and employing adequate mitigation measures would help OSPAR Contracting Parties and any other interested party in their efforts to reduce potentially negative effects of anthropogenic underwater noise on the marine environment and to reach Good Environmental Status (GES) according to the Marine Strategy Framework Directive (MSFD) in terms of underwater noise pollution for their national marine waters (Art. 9).

2. Introduction

A condensed overview of current knowledge on trends in pressures and impacts of the North-East Atlantic and its regions was provided by OSPAR with the Quality Status Report 2010 (QSR 2010). Underwater noise is recognised as one of the main pressures in the marine environment and the noise levels are thought to be increasing internationally. The OSPAR Region II and III seem to be most affected by noise-generating human activities and there are signs of effects on marine life (OSPAR 2010). Marine mammals, many fish species and even some invertebrates use sound to communicate, to find mates, to search for prey, to avoid predators and hazards and to navigate.

Many of the human activities like offshore construction, sand and gravel extraction, drilling, shipping, use of sonar, underwater explosions, seismic surveys, acoustic harassment or deterrent devices generate sound and contribute to the general background level of noise in the sea. Underwater sound from anthropogenic sources has the potential to mask biological communication and to cause behavioural reactions, physiological effects, injuries and mortality in marine animals. Possible impacts depend in particular on the nature of the sound and the acoustic sensitivity of the animal.

The quantification of the extent of the impacts is very difficult due to the great variability in sound characteristics, in animal sensitivities and in the scale of noise-generating activities (OSPAR 2010). The comprehensive part of the QSR 2010 dealing with underwater noise is based on an extensive overview of the impacts of anthropogenic underwater sound in the marine environment compiled by OSPAR in 2009 (OSPAR 2009a, 2009b). The JAMP-assessment includes indications on the acoustic characteristics and the level of any noise generating activity per region, on possible impacts in the marine environment as revealed from the overview document, information on regulations, site investigations and Environmental Impact Assessments (EIA) in all OSPAR Contracting Parties and recommendations on further work needed on assessment, reporting, mitigation and monitoring at an OSPAR level.

The "Marine Strategy Framework Directive" (2008/56/EC) requires a framework for community action in the field of marine environmental policy. Member States shall take the necessary measures to achieve or maintain good environmental status (GES) within the marine environment by the year 2020 (Article 1 (1) of the Directive). This objective entails the provision of "ecologically diverse and dynamic oceans and seas which are clean, healthy and productive within their intrinsic conditions" for which the impacts of substances and energy – specifically including noise – does not cause pollution effects (Article 3(5) of the Directive).The MSFD therefore complements the existing work of OSPAR on the protection of the North-East Atlantic.

However, not only in Europe underwater noise forms an important issue with respect to the effects of human activities in the marine environment. General questions concerning the impacts of underwater noise have been dealt with at various international scientific meetings such as for example the Third International Conference on the Effects of Noise on Aquatic Life held in Budapest 2013 (http://www.an2013.org/index.html) or have been examined and compiled in reports by international bodies (*e. g*. CBD 2012, NOAA 2013).

In recent years the need for actions to minimise the possible impacts of anthropogenic underwater noise to the marine environment came more and more into the focus again both of the scientific community and governmental as well as non-governmental organisations (e. g., BOEM 2013, ACCOBAMS 2013a). ACCOBAMS (2013b) gives an overview of decisions, resolutions and/or recommendations of a variety of international bodies (e. g. CBD, IWC, CMS, ASCOBANS, IUCN) that have been produced with the aim of regulating noise-generating human activities and abating the negative effects of acoustic pollution. In addition, a compilation of the use of mitigation measures by some (European) countries is given taking into account various sound sources.

This OSPAR inventory of underwater mitigation measures focus on certain human activities which are considered of prime concern. As mentioned above the inventory is designed to help CPs avoiding and reducing the introduction of underwater noise generated by certain human activities and its environmental impacts by applying appropriate mitigation measures. The mitigation measures are presented separately in annexes each covering one of the following human activities (Those in grey are yet to be completed and added in due course):

- Annex 1: pile driving;
- Annex 2: seismic surveys;
- Annex 3: explosions;
- Annex 4: high frequency impulsive sources (*e.g*. echosounders);
- Annex 5: dredging;
- Annex 6: sonar;
- Annex 7: shipping.

3. General considerations for mitigation of underwater noise in OSPAR-area

As stated in OSPAR 2009a there is a wide variety of noise-generating human activities in the marine environment. Emitted frequencies range from low frequency in the range of several Hz to very high frequency emissions of several hundred kHz. Source levels may also vary largely depending on the activity (OSPAR 2009a). Due to the variation in acoustic characteristics of the anthropogenic noise sources, the site specific sound propagation and the differences in acoustic sensitivity of marine biota (OSPAR 2009b), there is no generic set of mitigation measures that can be recommended. Mitigation measures for underwater noise should therefore be adjusted to match specific area- and project-related characteristics.

In general, the overriding objective of all mitigation approaches is to minimise or reduce to an acceptable level the negative impacts of underwater noise generated by human activities to marine life. Death, injury or other temporal and permanent physical damage/impairment as well as disturbance can be seen as examples of negative impacts. Such impacts only can occur if the respective activity takes place in an area where noise sensitive species are present at the same time. In that sense, to achieve the aim of mitigation beside pure technological measures a number of additional options exists that are more or less independent from the activity itself.

In principle, environmental effects of anthropogenic underwater noise may be reduced or avoided by reducing the source level and/or the propagation of noise or by restricting noise generating activities to areas and times not bearing sensitive species. The following list contains options that may be taken into account when considering noise mitigation measures independent of the sort of activity planned:

- if possible, refraining from applying activities generating harmful noise;
- general exclusion of noise generating activities for a certain time of the year (*e.g.*, prohibition of pile driving in the Dutch part of the North Sea within the first 6 month of a year to protect fish larvae from being killed [as food basis for protected seabirds], in particular);
- overall restriction of anthropogenic underwater noise to a certain level (*e.g.*, limitation of impulsive noise during offshore wind farm construction to 160 dB SEL in the German part of the North Sea to protect especially harbour porpoises from being injured);
- general exclusion of noise generating activities from certain areas (*e.g.*, by transferring of shipping lanes);
- spatio-temporal exclusion or limitation of noise causing activities (*e.g.*, BMU 2013 to protect harbour porpoises from disturbance at most sensitive time of their life cycle);
- using alternative techniques with lower sound emissions;
- modification of operational state of noise source, *e.g.*, reducing ship speed.

It may be helpful to design a site and activity specific noise mitigation concept prior to the deployment of any measures. For that purpose it seems to be appropriate to

- forecast possible underwater noise emissions of the planned activity;

- forecast the cumulative effects taking into account the noise introduction of other sources in the same area;
- evaluate the site-specific sound propagation by using appropriate models;
- analyse occurrence and seasonality of sensitive and/or protected marine species in that area in order to identify sound mitigation needs;
- conduct an EIA with respect to the activity planned.

At least in case marine mammals are the species of concern additional measures are available to prevent any death, injury or other physical damage rather than disturbance of individual specimen due to the activity:

- displacing animals from the area of harmful underwater noise with the aid of Acoustic Deterrent Devices (ADDs) and/or Acoustic Harassment Devices (AHDs) such as pingers or seal scarers;
- employing so called soft-start or ramp-up procedures if appropriate to allow animals to escape the area effected detrimentally by the noise;
- ensuring the absence of marine mammals from the impact zone by visual or acoustic monitoring (preferably real time) with the aid of marine mammal observer (MMO) and passive acoustic monitoring (PAM) respectively during the construction phase (*e.g.*, JNCC 2009, 2010).

References

ACCOBAMS, 2013a. Anthropogenic noise and marine mammals. Review of the effort in addressing the impact of anthropogenic underwater noise in the ACCOBAMS and ASCOBANS areas. - ACCOBAMS-MOP5/2013/Doc 22.

ACCOBAMS, 2013b. Methodological Guide: Guidance on underwater noise mitigation measures. - ACCOBAMS-MOP5/2013/Doc 24.

BMU, 2013. Concept for the Protection of Harbour Porpoises from Sound Exposures during the Construction of Offshore Wind Farms in the German North Sea (Sound Protection Concept). - German Federal Environment Ministry (BMU).

BOEM, 2013. Quieting Technologies for Reducing Noise during Seismic Surveying and Pile Driving. Workshop held at Silver Spring, USA, February 25-27, 2013.

CBD, 2012. Scientific synthesis on the impacts of underwater noise on marine and coastal biodiversity and habitats. - Montreal, Canada

DIRECTIVE 2008/56/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive)

JNCC, 2009. Annex B - Statutory nature conservation agency protocol for minimizing the risk of disturbance and injury to marine mammals from piling noise. - Joint Nature Conservation Committee (JNCC), Marine Advise, Aberdeen.

JNCC, 2010. JNCC guidelines for minimising the risk of injury to marine mammals from using explosives. - Joint Nature Conservation Committee (JNCC), Marine Advise, Aberdeen.

NOAA (2013). Draft Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammals. Acoustic Threshold Levels for Onset of Permanent and Temporary Threshold Shifts. Draft: 23 December 2013 – in public commenting.

OSPAR (2009a). Assessment of the environmental impact of underwater noise. - Biodiversity Series, OSPAR report 436. ISBN : 978-1-906840-76-1

OSPAR (2009b). Overview of the impacts of anthropogenic underwater sound in the marine environment. Biodiversity Series. - OSPAR report 441. ISBN : ISBN 978-1-906840-81-5

OSPAR Commission (2010). Quality Status Report. - ISBN 978-1-907390-38-8.

Annex I:

Noise Mitigation Measures for Pile-Driving

Introduction

The **aim of this inventory** is to describe technical noise mitigation measures to be applied during pile driving of offshore wind turbines as well as alternative low-noise foundation concepts and to analyse their effectiveness and feasibility. The annotated list is a summary of existing practices and captures science as well as industry experiences and expertise in developing and applying measures.

Several **noise mitigation systems** have the potential to reduce noise emissions during impact pile driving depending on parameters which influence the source level such as pile diameter, soil structure and blow energy. The noise mitigation systems are presented as separate principles in chapters 2-6. However, an exact classification into one or the other category is not always possible and sometimes the principles are mixed. In Germany, the effectiveness of noise mitigation measures and compliance with the legal noise limit must be verified using a standardised approach (BSH 2013).

Sound pressure level: Results of measurements during pile driving at various offshore locations show a positive correlation between blow energy, sound pressure level and pile diameter (Betke 2008, Betke & Matuschek 2010). Other parameters which influence the sound pressure level are the soil structure and the size of the hydraulic hammer. The key to effectively reducing underwater noise with respect to the broadband sound pressure level is to mitigate the low frequency range of about 100-400 Hz, as major energy is emitted in these frequency spectra (Wilke *et al*. 2012).

Propagation paths: The primary source of underwater sound from pile driving is associated with the compression of the pile by the hammer strike. This longitudinal compression produces a radial expansion which propagates down the pile at ultrasonic speed. This produces a cone shaped ‘Mach’ wave front in the surrounding medium with the apex of the cone travelling along with the bulge (Dahl & Reinhall 2013). Models of contribution of propagation pathways (air path, water path, seismic path) for underwater noise of pile driving have demonstrated that the direct water path dominates in nearly the whole frequency range (100 Hz to 1 kHz) over the indirect seismic (through the ground) or airborne pathways. Accordingly, noise mitigation techniques primarily have been designed to mitigate the radiation into the water. However, the seismic contribution is the limiting factor for the overall effectiveness of mitigating the water path in many cases (Applied Physical Sciences 2010) as it can re-enter the water column at some distance. The sound wave of the ‘Mach cone’ of the downward travelling bulge of the pile is projected downward into the sediment. But after reflection at the terminal end of the pile, the bulge travels up again and produces another conical wave front which radiates towards the sediment surface at a certain angle and finally penetrates into the water (Dahl & Reinhall 2013). This angle is determined by the different sound speeds in the pile and the surrounding medium (17.9^{o} in water or 18.7^{o} in sediment). At the transition it is deflected to an angle of 29^{o}. Thus, the seismic pathway should be considered in order to further improve noise mitigation systems.

In addition to noise mitigation methods, several **alternative foundation types** exist or are under development. With these, wind turbines can be founded without impact pile driving and therefore less underwater noise generation is expected (chapters 7-11). For most of these technologies, noise measurements during the offshore installation process are not yet available. During the installation, continuous rather than impulsive sound is emitted. However, the impact of continuous sound of a given level cannot be directly compared to the impact of impulsive sound of the same level. Finally, information on **additional noise mitigation concepts or alternative methods** under development is presented in chapters 12-13.

1 Big Bubble Curtains (BBC)

1.1 Technical Description of the System

A bubble curtain is formed by freely rising bubbles created by compressed air injected through perforated pipes encircling the pile. Due to the difference in density and sound velocity between water and air there is an impedance mismatch. As air in contrast to water is compressible, bubbles in water change the compressibility of the water and the propagation velocity of sound within the media. Acoustic stimulation of bubbles close to their resonance frequency effectively reduces the amplitude of the radiated sound wave by means of scattering and absorption effects. The interaction among the multitude of gas bubbles increases their noise reduction potential (Elmer *et al*. 2007a, Grießmann *et al*. 2009). A big bubble curtain (BBC) is a ring of perforated pipes positioned on the sea floor around any kind of pile driven deep foundations at large distance. Compressors located on the construction platform feed air into the pipe. The air passes into the water column by regularly arranged holes in the pipe. Freely rising bubbles form a large curtain around the entire structure, thus shielding the environment from the noise source.

1.2 Experience with Big Bubble Curtains

Big bubble curtains have been applied as an effective noise mitigation technique in several practical and experimental setups, e.g. in several projects under offshore conditions in the German North Sea since 2008. BBCs have been applied single, double or triple. Noise measurements are available from the research platform ***FINO 3*** (pile ∅ 4.7 m, water depth 23 m, BBC length 440 m, Grießmann 2009) and (in various configurations) the construction of the commercial **OWF *Borkum West II***[1] (pile ∅ 2.5 m, water depth 26-33 m, single BBC length 560 m, Pehlke *et al*. 2013) during which a pre-laid revolving[2] system was deployed for the first time. In 2011/12 various experimental setups of the BBC were applied during the construction of 40 tripods using the pre-piling procedure. Preparations, installation and adjustment took 5.5 h per pile (Pehlke *et al*. 2013). This did not result in any delays of the pile installation since it was done before the installation platform was moored at the site. BBCs have further been applied during the construction of a number of OWFs: *Nordsee Ost*, *Meerwind Südost* (double), *DanTysk* (double), *GlobalTech I* and *Baltic II* (double) and substations *Borkum West II*, *Meerwind*, *Nordsee Ost* and *Borkum Riffgrund*. During application of a BBC the entire oscillating structure has to be surrounded by air bubbles. Tidal currents require an elliptical nozzle pipe. Over 20 different configurations with respect to radius, air volume, hole diameter and distance, air feed-in, and pipe volume have been tested. Also pre- or post-laying (with respect to the positioning of the installation platform) have been used. In up to 25% of deployments technical problems occurred which often resulted in a lower noise reduction (Bellmann & Remmers 2013).

1.3 Noise Mitigation

During the construction of ***FINO 3*** a noise reduction by 12 dB (SEL) and approx. 14 dB (peak) was achieved with best results in the frequency range around 2 kHz (Grießmann 2009). At the OWF ***Borkum West II*** two different pipe configurations were tested which differed in hole diameter and distance between individual holes ("small distance": hole ∅ 1.5 mm and distance between holes 0.3 m; "large distance": hole ∅ 3.5 mm and distance between holes 1.5 m). The configuration "small distance" achieved ~3 dB better results. With maximum air supply the noise reduction was 9-13 dB (SEL) and 10-17 dB (peak) resulting in a reduction of the noise exposed area by 90% (Pehlke *et al*.

[1] Renamed later to *Trianel Offshore Wind Farm Borkum*

[2] The pipe-laying vessel positioned one nozzle pipe ring around the first location and the second ring around the next location but one. Repositioning occurs after the installation vessel is moved.

2013). The best noise reduction was achieved in frequency bands between 800 Hz and 5 kHz (Figure 1) whereas the maximum piling noise was radiated between 100 and 400 Hz. Noise reduction decreased by 4 dB when the air supply was reduced from 0.32 m³ to 0.15 m³ per min and m nozzle pipe (Pehlke *et al.* 2013) Additional tests were performed with a double BBC, which however could only be installed as two half-circles. The results revealed that a double bubble curtain can increase the reduction achieved by a single bubble curtain. When the distance between both pipes is large enough to allow for the formation of two separate bubble curtains a higher reduction can be achieved than with a smaller distance, when both bubble curtains unite. Best results of up to 18 dB (SEL) and over 20 dB (peak) were achieved when the distance between both nozzle pipes (80 m) was three times the water depth. The amount of sound energy that re-enters the water column via the seismic path (Nedwell & Howell 2004, Applied Physical Sciences 2010) is possibly also reduced due to the large diameter of the system. In cases where a higher noise reduction is required (e.g. for large monopiles) a double bubble curtain offers an even higher reduction potential.

1.4 Development Status

Many studies have revealed that air bubbles in water effectively reduce the propagation of underwater noise. Based on the results achieved in applications in Germany accompanied by research projects it can be argued that today the BBC is the best-tested and the most thoroughly proven noise mitigation technique for foundations of OWFs such as frame constructions (jackets, tripods) and smaller monopiles. Double or even triple BBCs offer options for larger monopiles. Today's BBC systems are robust and the entire handling of the BBC can be done independently of the jack-up rig. The deployment of the bubble curtain hampers neither the construction works nor the progress of the construction process as the mitigation system is installed prior to shifting the installation rig (Pehlke *et al*. 2013). A driven winch fitted with hydraulic or pneumatic brakes aids the circular laying of the pipe. The pipe-laying vessel has two complete redundant bubble curtain systems on board which can be installed revolvingly (Cay Grunau, Hydrotechnik Lübeck GmbH, pers. comm.; Bernhard Weyres, Weyres Offshore, pers. comm.). The systems are suitable for the prevailing depths and current velocities in the German EEZ. Applying the bubble curtain before or after positioning the installation vessel and by connecting the compressors before or after the installation of the mitigation system grants flexibility with regard to various construction schedules. All of the currently available big bubble curtain systems are reusable. Major costs are generated by the supply of bubble curtains with compressed air.

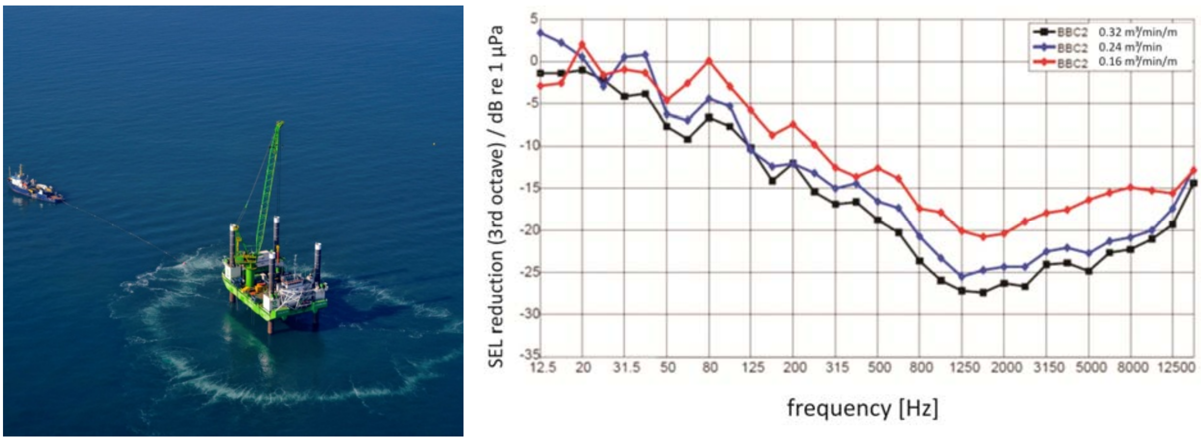

***Figure 1**: Left: Application of a BBC by Hydrotechnik Lübeck at the OWF Borkum West II (photo: Trianel GmbH/Lang). Right: Noise reduction achieved by a BBC at the OWF Borkum West II as a function of air supply (source: Bellmann 2012, modified)*

2 Little Bubble Curtains (LBC)

2.1 Technical Description of the System

The principle of noise reduction in the little bubble (LBC) curtain is the same as in the big bubble curtain (chapter 1) In addition to scattering and absorption effects, the coupling of noise to the air/water mixture may be lower compared to water when the entire pile is in direct contact with the rising bubbles. The perforated pipes of little bubble curtains surround the pile in a close fit. The term "little" refers to the overall dimension and not the nozzle pipe length which could, depending on parameters like diameter, water depth and current velocity, even be longer compared to a BBC. Several variations of little bubble curtains have been tested: **Layered ring systems**, **bubble curtains confined** by steel, fabric or plastic guiding plates or casings (Caltrans 2009, Wilke *et al*. 2012) or a vertical arrangement of perforated tubes around the pile (***SBC: Small Bubble Curtain***) (ITAP 2013, Steinhagen & Mesecke-Rischmann 2013). The purpose of a confinement or the vertical arrangement of tubes (as in the *SBC*) is to prevent sound leakages otherwise created by drift of bubbles due to tidal currents at horizontal interspaces between the layers of the bubble curtain. In the *SBC* tidal currents and the complex upwelling characteristics of bubbles help surround the pile with a mixture of air and water (Steinhagen 2012).

2.2 Experience with Little Bubble Curtains

During bridge construction works in California pile driving noise could be reduced effectively using a **confined or layered bubble curtain**. However, the experiments were conducted at conditions different from those found at many OWF sites (water depth 4-15 m, ∅ 2.4-2.7 m) (Caltrans 2009). Noise measurements conducted close to the pile (10-100 m) are not comparable to those made in the North Sea (250-1,500 m) because seismic sound waves coupled to the water at some distance may have reduced the effectiveness of the noise mitigation system. This effect may have been overlooked in near-source measurements. A pre-installed lower unit of a **layered bubble curtain** was tested during the construction of the German OWF *alpha ventus* (water depth 30 m, ∅ 2.6 m, tripod) (Grießmann *et al*. 2010, Betke & Matuschek 2010). The tidal current caused a large unwanted sound leakage. Another test was successfully performed with the upper unit at a two test piles at the OWF *Baltic II* (water depth 27.5 m, ∅ 1.5 m, IHC S-1200 hammer). Pilot tests of a **confined bubble curtain** (octagonal base ∅ 5.25m) were conducted at a test pile in the Baltic Sea in 2011 (water depth 8.5 m, ∅ 2.2 m, hammer: *MENCK MHU 270T*) (*ESRa* project, Wilke *et al*. 2012). The ***SBC*** was tested during two offshore tests at the OWF *BARD Offshore 1* (water depth 39.5 m, ∅ 3.35 m, tripiles, hammer: *MENCK MHU 1900S*) in 2011/12. The design used in the second test was applied in combination with the installation vessel's guiding frame. It used flexible tubes instead of rigid pipes (total length 1,200 m) which were uncoiled from winches on the top of the pile (Figure 2) (ITAP 2013, Steinhagen & Mesecke-Rischmann 2013).

2.3 Noise Mitigation

The LBC has the potential to reduce noise in a broad range of frequencies. A precondition for effective noise mitigation is that the entire oscillating structure is surrounded by bubbles. Using the pre-piling procedure[3] for frame constructions prevents structure-borne noise from being transmitted from cross beams when the bubble curtain forms an enclosure only around the pile. The seismic contribution to the propagation of the sound is not reduced by any of the variations of the LBC. The noise levels measured with a **layered ring system** as applied at the OWF *Baltic II* resulted in a broadband noise reduction between 11 and 15 dB (SEL) measured at 750m (Schultz-von Glahn 2011,

[3] With this procedure, the piles are driven through a template prior to attaching the jacket or tripod.

Zerbst & Rustemeier 2011). The noise reduction increased continuously from frequencies of approximately 25 Hz and was highest at frequencies of 1-10 kHz. It also revealed a good noise reduction even in the critical frequency range of 125-1,000 Hz, where the major energy of the pile driving signal is emitted. This result is similar to the noise reduction (12 dB (SEL), 14 dB (peak)) in the direction of tidal flow with only the lower unit of the layered LBC during the construction of the OWF *alpha ventus* (Betke & Matuschek 2010). During the test of a **confined system** the broadband noise level was reduced by 4-5 dB (SEL) (Wilke *et al*. 2012). However, the interpretation of this unexpectedly low noise reduction is difficult since the test pile was anchored firmly about 65 m deep in the seabed and was strongly encrusted. Thus, acoustic properties were different compared to a pile actively driven into the ground. In the **SBC** the resulting noise reduction in the first offshore test varied among configurations tested (regarding air volume, number of pipes, hydrophone position). The configurations with 3 or more compressors achieved noise reductions of 11-14 dB (SEL) and 14-19 dB (Peak) (Steinhagen & Mesecke-Rischmann 2013). The second offshore test confirmed these results by noise reductions of 9-13 dB (SEL) and up to 14 dB (Peak) (ITAP 2013) (Figure 2).

2.4 Development Status

As bubble curtains have been successfully applied in many experiments and practical setups, their suitability for reducing sound emissions is fully recognised. The different variations of little bubble curtains currently available are reusable, robust and flexible in their application. To quickly and easily attach LBC systems to the piling frame or gripper, some further development work with respect to handling and operation has to be done. So far, the most advanced system, the ***SBC***, is specifically designed to meet the demands of *BARD* tripile foundations. The improved system of the second offshore test is characterised by the use of standard components and easy handling. For the SBC, a full-scale test under offshore conditions has been successfully completed. For the complete **layered ring system** and the **confined bubble curtain** a proof or their effectiveness under offshore conditions is not available yet. Little bubble curtains have the potential to be applied in commercial OWFs shortly. They can be easily combined with BBC's.

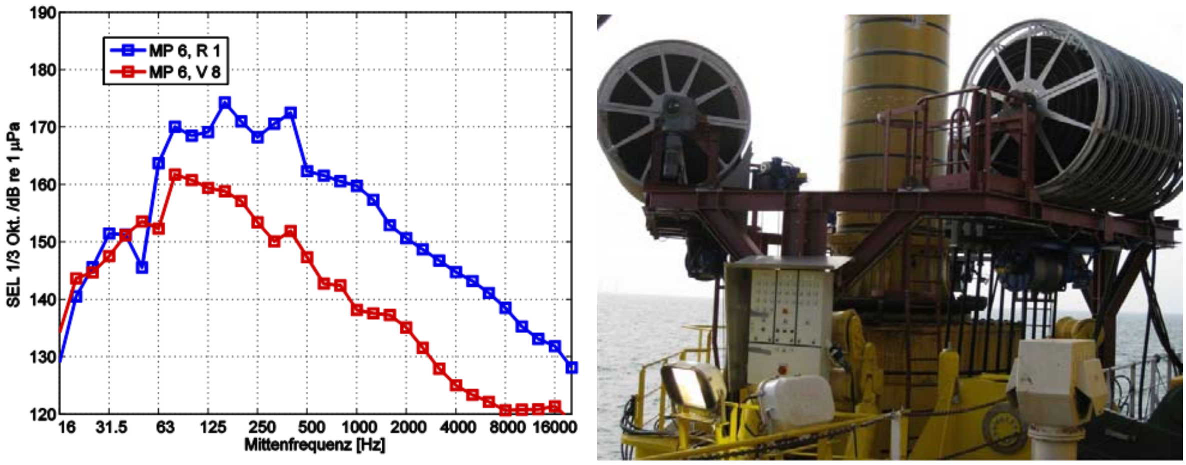

Figure 2: *Third octave band spectrum (left, measured at OWF BARD Offshore 1, distance 750m) of piling noise (blue: reference without mitigation, red: with SBC (air volume: 160m³/min). Improved SBC design with flexible tubes which can be uncoiled from winches on the top (right) (sources: ITAP 2013, Steinhagen 2012)*

3 Isolation Casings

3.1 Technical Description of the System

The principle of an isolation casing is a shielding effect of a casing around a noise radiating pile. A simple steel pipe would reflect a part of the noise back inside. More complex systems make use of absorption, scattering and dissipation effects of additional layers containing air, foam, composites or rising bubbles. Impedance mismatch causes reflections at phase transitions water-steel-air. Additional absorption of the air- and foam layers improves the noise reduction (Elmer *et al*. 2007a, Nehls *et al*. 2007). Acoustically decoupled pile guidings centralize the pile. Available commercial systems are the *IHC* Noise Mitigation Screen and *BEKA* Shells which come in custom-made sizes. The ***IHC* Noise Mitigation Screen (NMS)** (Figure 3) by *IHC Offshore Systems* is put over the pile or in an improved system the pile is inserted from the top. Its features are an acoustically decoupled double-wall with an air filled interspace and a multi-level and a multi-size bubble injection system creating an additional noise barrier around the pile (van Vessem 2012). The ***BEKA* Shells** developed by *Weyres Offshore* consist of two hydraulically movable multi-layered half-shells which are closed around the erected pile and then lowered to the seabed. Its features are two concentric double-walled steel layers filled with a sound absorbing composite material, two multi-level and multi-size bubble injectors and decoupling by means of special vibration dampers (Weyres 2012).

3.2 Experience with Isolation Casings

During **bridge construction works in California** pile driving noise could be reduced considerably using a steel casing with a bubble curtain inside. However, the experiments were conducted at conditions different from those found at many OWF sites (water depth 4-15 m, ∅ 2.4 m; max. impact energy 570 kJ) (Caltrans 2009). Noise measurements were conducted close to the pile (10-100 m) and are not comparable to those made in the North Sea (375-750 m) because seismic sound waves coupled to the water at some distance may have been missed in some of these measurements. During a **comparative research project**, the effectiveness of various isolation casings (steel, rubber, foam) was tested under laboratory and shallow water (8.5 m) conditions (Schultz-von Glahn *et al*. 2006, Elmer *et al*. 2007a). A double-walled plastic tube, filled with polyurethane foam, achieved the best results in laboratory experiments. Pilot tests of the **NMS** were performed in a river and the North Sea with pile diameters from 0.9 m to 3.5 m (van Vessem 2012). The first commercial application was in 2012 at the German OWF *Riffgat* in the North Sea (water depth 18-23 m, embedment depth 29-41 m, monopile ∅ 5.7 m resp. 6.5 m, hammer: *IHC S1800*). The dimensions of the *IHC NMS* were: 30 m x ∅ 10 m, 360 t. Pilot tests of the ***BEKA* Shells** were conducted in the Baltic Sea in 2011 (water depth 8.5 m, ∅ 2.2 m, hammer: *MENCK MHU 270T*). Their dimensions were: 9 m x 4 m x 4 m, 40 t (Wilke *et al*. 2012).

3.3 Noise Mitigation

By combining several principles of noise reduction in various layers, isolation casings have a high noise reduction potential comparable to or exceeding that of a bubble curtain (Elmer *et al*. 2007a, Caltrans 2009). Important features are acoustic decoupling and inclusion of air into layers. Frequency-dependent noise reduction varies depending on the specific design. With smaller piles (∅ 1.2 m) in shallow water (6 m), the ***IHC* NMS** reduced noise mainly in frequency bands between 150 Hz and 8 kHz (Bob Jung, *IHC Hydrohammer*, Kinderdijk, NL, pers. comm.). At two met masts, measured overall noise reduction (∅ 3.35 m, water depth 25 m, hammer: *IHC S800*) was between 9 dB (OWF *Nordsee Ost*) and 11 dB (Ijmuiden) (Wilke *et al*. 2012). At the OWF *Riffgat*, an improved version of the *IHC* NMS achieved an overall noise reduction in the order of 17 dB compared to the prediction of 180 dB (SEL) made beforehand. It must be taken into account that the prediction was given with an uncertainty of 5 dB and consequently the same uncertainty has to be applied to the noise reduction value. Unfortunately, no measurements of pile driving noise without mitigation system were performed. Reliable comparative measurements are still lacking. For a 5.7 m pile in sandy soil at 750 m distance single event sound pressure levels varied between 162 and 166 dB (SEL) (Figure 3). The average level was 163 dB (SEL) / 187 dB (peak) (Gerke & Bellmann 2012). For 6.5 m piles driven at sites with cohesive soils (clay) measurements are not available. However, due to soil differences a large variation can be expected. In a pilot test the measured overall broadband noise reduction by the ***BEKA* shell** was only 6-8 dB (SEL). However, the interpretation of this unexpectedly low noise reduction is difficult since the test pile was anchored firmly about 65 m deep in the seabed and was strongly encrusted. Thus, acoustic properties were different compared to a pile actively driven into the ground. An offshore field test is still lacking.

3.4 Development Status

Isolation casings are reusable and thus cost-effective. However, isolation casings are attached directly to the piling frame and influence the construction time and costs. Several full-scale pilot tests accompanied by noise measurements have been successfully completed with the ***IHC* NMS** for various pile diameters at different water depths. At the OWF *Riffgat* a full-scale test was performed under commercial conditions. The results achieved are of special interest as the NMS and the monopile applied were the largest measured so far and the NMS was further optimised compared to the first tests. By optimising some acoustic properties of the system (e.g. distance between pile and isolation casing or dimensions of the air-filled interspace) and acoustic decoupling (Gerke & Bellmann 2012), the noise reduction was improved (Gerke & Bellmann 2012). It can be concluded that the system is suitable to achieve a considerable noise reduction during pile driving of large monopiles. By the successful application of the *IHC* NMS, its robustness and suitability for offshore applications, manageability, flexibility in construction logistics and safety has been demonstrated. Overall *IHC* NMS can be considered proven technology for pile diameters and water depths prevailing at the OWF *Riffgat.* Further commercial applications of further improved NMS are planned for 2014 in the OWFs *Borkum Riffgrund I* (water depth 30 m, monopile ∅ 6.0 m) and *Butendiek* (water depth 23 m, monopile ∅ 6.5 m). An application with pre-piled jackets or tripods is under development. The development of the ***BEKA Shells*** is still at the pilot stage awaiting full-scale testing in a commercial OWF.

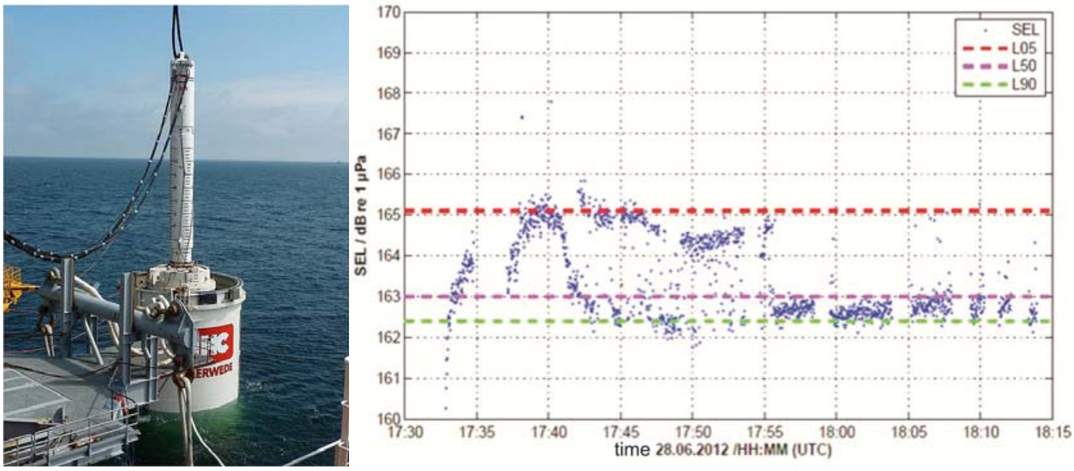

Figure 3: *Left: Application of the IHC Noise Mitigation Screen NMS at the OWF Riffgat (source: Riffgat 2013, modified). Right: Broadband noise sum level during piling at the OWF Riffgat (measured at 750 m; blue points: SEL of each of the 1,403 piling strikes; red, magenta and green dotted lines: percentile values of 5%, 50% and 90% of measurements) (source: Gerke & Bellmann 2012, modified)*

4 Dewatered Cofferdams

4.1 Technical Description of the System

A cofferdam is a large rigid steel tube surrounding the pile from seabed to surface. The interspace is dewatered hence pile driving takes place in air and the propagation of sound is decoupled from the body of water. This system reduces the sound energy transfer to the sea water by separating the direct contact between the pile and the sea water (McKenzie Maxon 2012). Dewatering can be done by pump heads at the bottom (Thomsen 2012) or using overpressure (Frühling 2011, Heerema 2013). A **Cofferdam** developed by *Lo-Noise Aps* (Figure 4, left) is placed on the seabed into which the pile is inserted and centred with a pile guidance system placed on the top and bottom of the cofferdam. The annular gap between the pile and the cofferdam is sealed at the lower end by a tight rubber seal preventing water to flow in during the dewatering process (Thomsen 2012). Another concept is based on the principle of **Pile-in-Pipe Piling** (Frühling *et al*. 2011). In this case, the noise mitigation is applied directly as part of the base frame foundation in which pile sleeves act as protective pipes (Figure 4, right). As in separate cofferdams the complete dewatering of the pile sleeves is critical for the effectiveness in reducing piling driving noise. The pile sleeves (or extensions of them) reach beyond sea level hence piling occurs only above sea level (Frühling *et al*. 2011).

4.2 Experience with Cofferdams

In the US, **Cofferdams** have been applied in various commercial projects, e.g. in the form of sheet pile walls in shallow water under near shore conditions (Caltrans 2009). In deeper water, a pilot test with a dewatered cofferdam by *Lo-Noise* Aps with an inner diameter of 2.5 m (pile length 36 m, pile ∅ 2.13 m, hammer *MENCK MHU 800*, water depth 15 m) was performed in Aarhus Bight in December 2011 to demonstrate the system's efficiency to the client *Siemens* (Figure 4, middle) (Thomsen 2012). A second offshore test was performed at the OWF *Anholt* located in the Kattegat (pile ∅ 5.9 m, cofferdam ∅ 6.3 m, water depth 19 m) was not successful because the pile was not designed for the use with a cofferdam. It had protrusions (trunnions) at the side and thus required a large annular gap. Pile positioning off the centre finally resulted in the failure of the seal (Thomsen 2012). This incident demonstrated that the engineering phases of pile and cofferdam must be addressed during the whole design phase in order to avoid complications. In commercial projects, a tripod cofferdam has been deployed in the North Sea during the construction of the converter platform *HelWi*n *alpha* in June 2013 (pile Ø 3.2 m, water depth 23 m) (Lo-Noise 2013, SeaRenergy 2013) (Figure 4, left). Furthermore, *Lo-Noise* has also applied its dewatering system principle on the jacket of the *BorWin beta* converter platform at a depth of 40 m and *HelWin CAT*. The principle of **Pile-in-Pipe Piling** was used during the construction of the converter platform *DolWin alpha* in 2013. A pile-in-pipe noise reduction system developed by *ABB's* Corporate Research Centre (Wijk 2013) was applied at the six legs of the jacket foundation (Figure 4, right).

4.3 Noise Mitigation

A good noise mitigation of a **Cofferdam** can be expected based on the large impedance mismatch between air and steel (Applied Physical Sciences 2010). In a practical application an average broadband noise reduction of 23 dB (SEL)/17 dB (peak) was achieved at the Aarhus Bight test, measured at 750 m for 100% pile driving power. Best results were achieved at frequencies of 100-500 Hz (Figure 4, middle) (McKenzie Maxon 2012) where highest noise levels are emitted during pile driving. These results are in line with expectations from models (about 20 dB; Applied Physical Sciences 2010). In addition the measurements at Aarhus Bight confirmed that direct contact between the pile and the cofferdam decreases the effectiveness in reducing piling driving noise as noise reduction was only 13 dB (SEL)/13 dB (peak) (McKenzie Maxon 2012). Based on finite element models the theoretical noise reduction achieved by **Pile-in-Pile Piling** was calculated as 43 dB at maximum when there was no contact between pile and cofferdam (Frühling *et al*. 2012). However, the model also demonstrated that the guiding pieces lead to considerable sound leakages. This effect could be minimised by the application of rubber inserts for acoustic decoupling, resulting in a noise reduction for the dewatered case with decoupled guiding pieces of up to 27 dB under ideal conditions (Frühling *et al* 2011). The *ABB* system applied at the *Dolwin alpha* jacket platform reduced the noise during piling to levels below 160 dB (SEL) at 750 m distance (Wijk 2013, Heerema 2013).

4.4 Development Status

Sheet pile walls have been applied as **Cofferdams** in various commercial projects (mainly bridges) in the U.S. and thus can be considered proven technology in shallow water. A full-scale test has been completed with a dewatered isolation casing, which corresponds to a cofferdam, at the *Benicia-Martinez Bridge*, California at water depths of 5-7 m (Caltrans 2009). A first test with a small monopile (∅ 2.13 m) in European waters at 15 m water depths at Aarhus Bight was successfully completed with regard to noise mitigation and handling. Commercial projects of *Lo-Noise* cofferdams have been conducted at two converter platforms, *BorWin beta* and *HelWin alpha* (Lo-Noise 2013, SeaRenergy 2013). It is an advantage of the free-standing cofferdam with regard to economic efficiency that material is saved as compared to the version that is part of the foundation because the system is reusable. A dewatered gap along the whole water column can be best provided with monopiles and pre-piled foundations whereas post-piled base frame constructions require further adaptations of the cofferdam. A successful commercial application of *ABB*'s **Pile-in-Pipe Piling** system was at the converter platform *DolWin alpha* (Wijk 2013, Heerema 2013). Dewatering took place by using compressed air. The installation of a foundation with pile-in-pipe piling is similar to the installation of a conventional jacket foundation. A difference is that the pile sleeves have to extend above the water and have to be dewatered to act as protective pipes. For wind turbine applications design work has been performed for a jacket foundation with four corner piles. The result of a scientific concept study was that such a piled steel construction can be safely anchored in the North Sea at water depths of 30 m and a high noise reduction is to be expected (Frühling *et al*. 2011). For the pile-in-pipe system additional material is required according to the construction, resulting in a higher weight (Frühling *et al*. 2011).

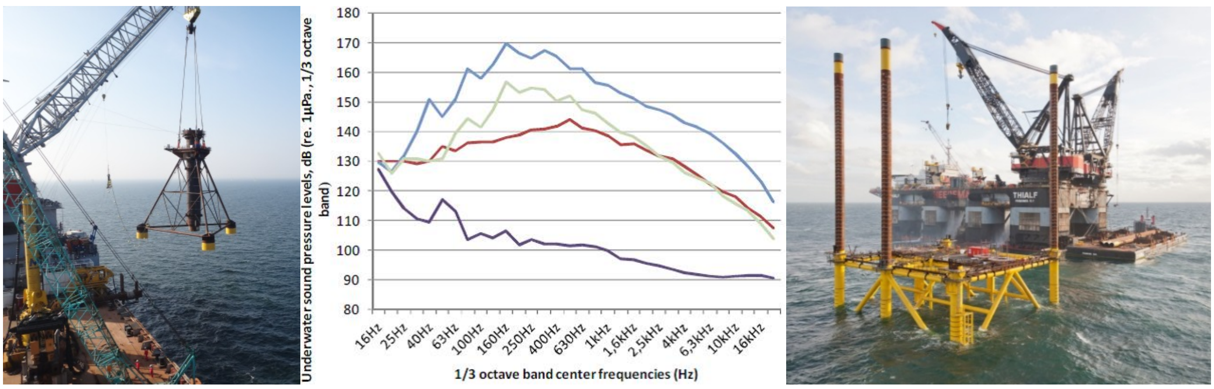

Figure 4: ***Cofferdam*** *application at Helwin alpha (left, source: Lo-Noise Aps) and 3rd octave spectra measured at Lo-Noise Aarhus Bight test with 100% pile driving power (violet: background noise, red: av. with cofferdam, light green: av. with cofferdam pile contact, blue: av. without cofferdam) (middle, source: McKenzie Maxon 2012).* ***Pile-in-Pipe-Piling*** *during the installation of Dolwin alpha (right, source: TenneT/ABB).*

5 Hydro Sound Dampers (HSD) / "Encapsulated Bubbles"

5.1 Technical Description of the System

Hydro Sound Dampers (***HSD***) are a patented system by the company *OffNoise Solutions GmbH.* Small air filled elastic balloons and robust PE-foam elements are fixed to nets or frames which are placed around the pile. The frequencies at which the maximum noise reduction is provided are adjustable by variations in the size of elements. The main principle is based on the excitation with the resonant frequencies causing scattering and absorption as well as reflection at the transition from water to air (Lee *et al*. 2011, Elmer *et al*. 2012). High energy absorption is reached by means of material damping. PE foam elements act like tuned impact absorbers (Elmer *et al*. 2012). The *HSD* system is variable with respect to assembly design and has a light weight. A system using the identical principle of ***Encapsulated Bubbles*** is currently under development in the US (Lee *et al*. 2010, 2011, 2012). The idea is to achieve a reduction of the low frequency components of pile driving noise where maximum energy is emitted. Balloons of diameters ranging from 6-12 cm have a predicted resonant frequency in the range 175-500 Hz (Lee *et al*. 2012).

5.2 Experience with Hydro Sound Dampers (HSD) / "Encapsulated Bubbles"

Primary tests with ***HSD*** were conducted in the large wave flume of the **Coastal Research Centre (FZK)**. These *HSD* elements were designed to reduce noise at frequencies around 100-300 Hz. In the ***ESRa*** project various types of *HSD* balloons and robust *HSD* foam elements were attached to three layers of nets arranged as concentric rings around a test pile (Wilke *et al*. 2012). All *HSD* elements were tuned to a resonant frequency of 120 Hz in order to mitigate the noise of 100-500 Hz. Further, *HSD* were tested during the installation of the British OWF ***London Array*** (monopiles Ø 5.7 m, max. impact energy 1,400 kJ) (Figure 5). PE foam elements of different sizes were tuned at frequencies of 63 Hz, 125 Hz, 250 Hz and 500 Hz (Remmers & Bellmann 2013). These tests aimed at demonstrating the system's offshore applicability and functionality (Bruns & Kuhn 2013). A proof-of-concept experiment of the ***Encapsulated Bubbles*** was performed in a freshwater lake in Texas, US with a mechanically-vibrated **barge as a noise source**. A screen of encapsulated bubbles shielded the sound source from the hydrophone. The size of encapsulated bubbles was chosen so that the screen provided the most noise reduction at the peak frequencies emitted by the barge (about 70 Hz) (Lee *et al*. 2012). In a second experiment, an encapsulated bubble curtain of about 900 polyurethane balls spaced 125 cm by 27 cm was used to partially shield a receiving area in direct line from **underwater pile driving** noise (8 steel piles Ø 1.2 m) at a distance of 2.5 km (Lee *et al*. 2012).

5.3 Noise Mitigation

In the **FKZ laboratory experiments** using a sound source of gradually changing frequencies ("sweeps") a broadband reduction by 20-22 dB (SEL) and 19 dB (peak) was achieved by the *HSD* (Elmer 2010, 2011). In the ***ESRa***-project a broadband noise reduction by 4-14 dB (SEL) was measured at distances of 375 m and 750 m (Wilke *et al*. 2012). However, the interpretation of this unexpectedly low noise reduction is difficult since the test pile was anchored firmly about 65 m deep in the seabed and was strongly encrusted. Thus, acoustic properties were different compared to a pile actively driven into the ground. At the OWF ***London Array*** reductions of singular third octave bands of 5-17 dB in the frequency range of 100 Hz to 2 kHz were achieved, corresponding to a broadband reduction of 9 dB (SEL) / 10 dB (peak) (Figure 5) (ITAP 2013). The American tests also demonstrate that ***Encapsulated Bubbles*** effectively reduce underwater noise. The test with a mechanically-vibrated **barge as a noise source** revealed a noise reduction of up to 18 dB near the bubble resonance frequency and thus a higher noise reduction could be achieved compared to a bubble curtain measured in comparison (Lee *et al*. 2012). The curtain of tethered encapsulated bubbles provided a spectral pile driving noise reduction up to 14 dB in the 100-300 Hz frequency band coincident with the peak frequencies generated by the pile driving event (Lee *et al*. 2012).

5.4 Development Status

An important advantage of the *HSD* / *Encapsulated Bubbles* compared to bubble curtains is that no compressors are needed to provide the noise reduction making the system more cost-efficient (Lee *et al*. 2011). Experience gained with ***HSD* elements** under offshore conditions is available from the *ESRa* project and from the OWF *London Array*. After analysing the pilot test in the Baltic Sea (water depth: 8.5 m) and the first full-scale test under offshore conditions in the North Sea (water depths 11-27, current velocities 1-1.5m/s, wave heights of 1-1.5 m) (Bruns & Kuhn 2013), the system has demonstrated its robustness and manageability for various water depths. A considerable noise reduction was achieved with best efficiency in the frequency range where highest emissions occur during pile driving. An optimised *HSD* system will be applied in cooperation with *Menck* at the OWF *Amrumbank West* in February 2014. Sophisticated nets consisting of three layers equipped with a total of 11 different elements (robust bladders and foam elements of different sizes) will be used. Beside the frequency range of 50-200 Hz the improved system also aims specifically at the frequency range above 800 Hz (Karl-Heinz Elmer, *OffNoise Soultions*, pers. Comm.).

As all systems attached close to the pile or foundation structure the deployment time has to be considered in order to guarantee a smooth and organised course of construction without delays. At the OWF *London Array* the installation of the noise mitigation system took only about 3-4 hours longer than piling without noise mitigation (Kuhn *et al*. 2013). The system requires little space on the construction vessel. Due to the low weight and the flow-through there is no need for complex and costly adaptations in construction design. The weight of only 17 t (in the OWF *London Array*) makes minor adaptations on the installation platform necessary. The experience collected so far can result in a further development of the concept, e.g. an alternative attachment of the *HSD* system directly at the pile hammer (Kuhn *et al*. 2013). In addition the combination of the HSD system close to the pile with a big bubble curtain at greater distance offers good potential to reduce the noise level further. Future adaptions will apply more HSD elements per area thereby keeping the cost advantage achieved by doing without the use of compressors.

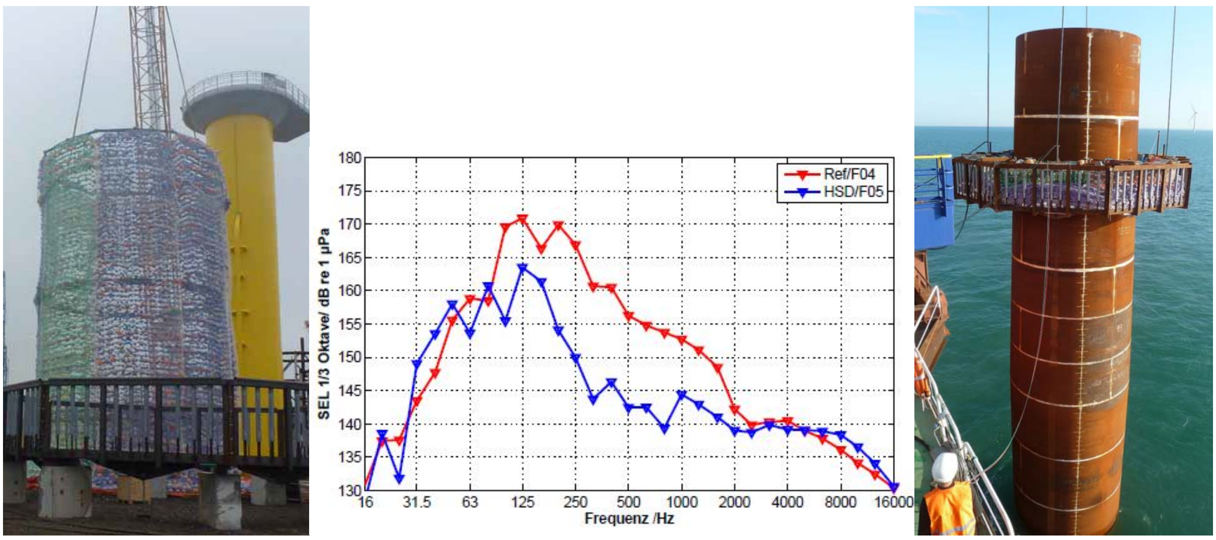

Figure 5: *<u>Left</u>: HSD net in a test set-up. <u>Middle</u>: 3rd octave spectra of piling without (red) and with HSD (blue) at London Array. <u>Right</u>: HSD in a practical application at London Array (sources: Bruns & Kuhn 2013, Elmer et al. 2012, ISD 2013, modified)*

6 Vibratory Pile Driving (Vibropiling)

6.1 Technical Description of the System

Vibropiling is a technique used to make the pile oscillate at a low frequency of about 20 Hz. Counteracting rotating eccentric weights induce vertical vibrating movements of the pile and enable penetration into the seabed (Saleem 2011). For large piles a number of vibratory hammers can be linked. The broadband level of the radiated noise emissions is reduced as sound at frequencies below a so-called lower cut-off frequency does not propagate in shallow waters like those prevailing in the North Sea. However, harmonics at higher frequencies are also emitted (Figure 6) which determine the noise level in water throughout the operation (Betke & Matuschek 2012). Even a combination of vibropiling and impact pile driving contributes to the overall noise reduction as fewer strikes are needed for impact piling. This can reduce the adverse effect of impulsive sound because with increased number of blows, the energy accumulates over time in the ears of the marine animals (NMFS 2007, Southall *et al*. 2007).

6.2 Experience with Vibropiling

Piles of various materials, shapes and sizes have been driven using vibratory hammers. During the construction of an artificial island in Hong Kong, 130 piles (Ø 22 m) have been vibrated to their target depth of 25 m successfully (Ziadie 2013). In European OWFs various piles have been anchored by a combination of vibratory and impact piling. For three piles of a demonstration turbine by ***BARD Engineering*** *GmbH* at Hooksiel (river Jade, water depth 5 m, ∅ 3.35m, tripiles), half of the penetration depth of 44 m was achieved by vibropiling. At the **OWF Anholt** one monopile was vibrated to target depth of 18 m another one met refusal 1m before target depth (water depth 17-18 m, full penetration depth 19-20.2 m, ∅ 5.3 m) (LeBlanc Thilsted 2013). At the OFW ***alpha ventus*** vibropiling was combined with impact piling at six turbines (water depth 30 m, ∅ 2.6 m, tripods). The first 9 m of the target depth of 30 m could be driven with a vibratory hammer. During the construction of the **OWF *Riffgat*** (water depth 18-23 m, ∅ 5.9 and 6.5 m) part of the target depth was also reached by vibropiling (Gerke & Bellmann 2012). In sand it was possible to vibrate the first 13-21 m of the target depth of ca. 30 m. At sites with more cohesive soils (silt/clay) the piles could be vibrated into the seabed up to 18-24 m of the final depth of ca. 40 m. Measured soil parameters (lateral stiffness, resistance to driving) at vibrated piles in the **OWF Anholt** were at least equal compared to impact driven piles and showed no indication of sand loosening. In an onshore test (six piles, penetration depth 20 m, ∅ 4.3 m) at Cuxhaven (Germany), the equivalence of lateral bearing capacity of piles driven with either vibropiling or impact piling is to be analysed (Herwig *et al*. 2013).

6.3 Noise Mitigation

In various projects, noise levels (L_{eq}) emitted during vibropiling were about 15-20 dB lower than those of impact piling (Elmer *et al*. 2007a, Betke & Matuschek 2010, ITAP 2012, Kringelum 2013). The main energy is radiated at lower frequencies compared to impact piling. The underwater noise levels at the OFW ***alpha ventus*** varied considerably during vibropiling. The broadband level of about 142 dB (SEL) (157 dB in the loudest period) at 750 m distance was substantially lower than the sound levels during impact piling of about 167 dB (SEL)). However, a high frequency tonal component up to about 10 kHz went with the regular operational noise and was audible especially at the end of the piling process as a high buzzing sound (Betke & Matuschek 2010). At the OWF ***Anholt***, in hard soils and during refusal the noise was significantly higher than during smoothly operated vibropiling. At 750 m distance vibropiling noise was 150 dB (SEL) under normal operation, with up to166 dB (SEL) during refusal, compared to 171-175 dB from impact piling (Kringelum 2013). During vibropiling at the OFW ***Riffgat*** the median broadband L_{eq} measured at a distance of 750 m was 145 dB compared to

> 160 dB during impact piling. The fundamental frequency of the vibratory hammer was 17-18 Hz. Figure 6 shows noise emissions in this frequency and its harmonics. In cohesive soil such as compact clay layers vibration cannot achieve further advance of the pile. In that case sound levels increase and the frequency range shifts towards higher frequencies (main energy in normal mode <1,000 Hz, when the pile is stuck 300-2,500 Hz) (Elmer *et al*. 2007a, Betke & Matuschek 2010). Contrary to impact piling, vibropiling emits continuous sound. The overall impact of impulsive sound on marine organisms cannot be directly compared to that of continuous sound. The adverse impact of continuous sound might also accumulate over time.

6.4 Development Status

The offshore application of vibropiling in combination with impact piling is proven technology. The equipment is market-available. There are long-standing experiences from various projects, e.g. bridge construction. Vibropiling has been successfully applied during the installation of offshore wind turbines. The installation of monopiles using vibratory hammers has a number of advantages (Saleem 2011, Ziadie 2013): Vibropiling is cost effective as it is 3-4 times faster than impact piling. Vibratory hammers are directly clamped to the pile. Resulting easier handling further speeds up installation. The linking of vibratory hammers can increase the centrifugal force. As a consequence there is no limit for the pile diameter which enables the installation of large monopiles. This is cost efficient compared to frame constructions for which more steel and a longer construction time is needed. Further, the driving process needs less energy compared to impact piling resulting in lower costs. In addition, vibratory hammers allow for pile extraction and adjustment if obstacles are discovered during installation. Another advantage is that concrete piles which are less resonant than steel can also be vibrated into the ground which could further reduce the noise. However, based on recent experiences, vibropiling is mostly applied in combination with impact pile driving as exclusive application of vibropiling does not allow for verification of load bearing capacity using standard procedures such as relating blow count and penetration depth. Also accurate prediction methods for driveability are needed. Further comparative studies on the applicability of standard design procedures in fully driven piles as well as on pile-soil interactions of vibrated vs. driven piles are underway (LeBlanc Thilsted 2013).

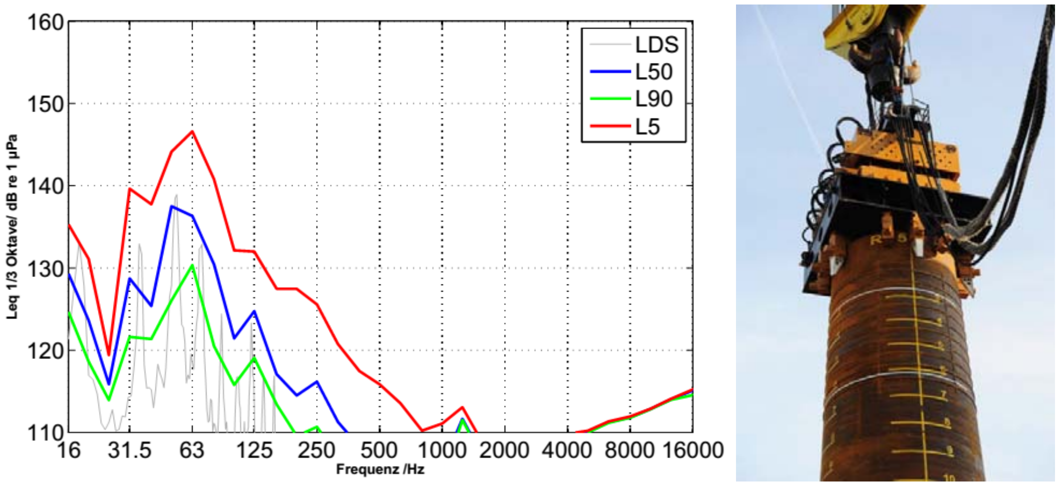

Figure 6: *Left: frequency spectrum of a vibratory hammer in the OWF Riffgat at pile R14, measured at 750m distance over 98 min (Leq as 5, 50 and 90 % percentiles in 30s intervals and resolution of third octaves 'L5, L50, L90' and with a resolution of 1 Hz 'LDS'). Right: multiple linked hydraulic vibratory hammer system with four hammers 'Super Quad Kong' used in the OWF Riffgat with pile diameters of up to 6.5 m (sources: ITAP 2012, www.riffgat.de*)

7 Drilled Foundations

7.1 Technical Description of the System

Monopiles may be embedded using different drilling technologies. Several providers have developed concepts for offshore foundation drilling based on their experience from onshore vertical drilling technologies. Lower noise emissions can be expected compared to impact pile driving. Other advantages relate to the independence of the local geology. The Dutch company ***Ballast Nedam*** in co-operation with *MT Piling* has developed a vertical shaft drilling concept for pre-stressed concrete monopiles (Ø 6-7 m). The pile is transported afloat to the offshore location where it is upended and positioned in the guiding frame. The drilling machine is inserted into the pile and locked hydraulically. By excavating material from the inside (Figure 7) the pile penetrates deeper into the ground (Van de Brug 2011). A steel cutting shoe fitted to the bottom end of the pile creates an overcut and allows the pile to sink deeper into the seabed. The stability of the monopile is reached by a self-hardening drill fluid in the resulting annular gap (Van de Brug 2009, 2011). The material of the pile is of minor importance for the drilling technology but concrete monopiles are heavier then steel monopiles and need larger cranes and jack-up rigs. The **Offshore Foundation Drilling (OFD)** process as developed by the German companies *Herrenknecht* and *Hochtief* is technologically based on the Vertical Shaft Sinking Machine (*VSM)* (Rosenberger *et al*. 2011). A hydraulically controlled telescopic boom with rotary grinder drills inside and underneath the monopile (Ø up to 10 m) (Figure 7). The excavated material is removed through pipes. As a partial-face excavating machine the VSM is flexible with respect to shaft diameter of the pile. The *VSM* creates a slight overcut in which a specific mortar is added. The cohesion of this mortar is broken up when the pile sinks into the sea bottom due to shear force. The British company **Fugro Seacore** applies hydraulic *top drive* methods where propulsion is generated above the pile head and the axial force is transmitted to the bottom end of the pile by a drill pipe. The cut spoil is flushed out with sea water. *Fugro Seacore* drills with exactly the outer diameter of the pile. Depending on seabed conditions the pile can be lubricated with a thin film of a rapidly degrading material to allow for better penetration (Seacore 2013). Very hard strata can be destroyed using a down-the-hole hammer which shatters the rock.

7.2 Experience with Drilled Foundation

Vertical drilling is already being used in offshore areas as seabeds like bedrock, bolder, clay or soil interspersed with large stones are not driveable by impact pile driving. Initial knowledge was gathered during the installation of the OWF *Bockstigen* (Gotland, Sweden), which was founded in limestone. In the UK a number of wind farms have been founded on seabeds with mixed layers of sand, boulder clay and sand stone using *Drive Drill Drive*, e.g., the OWFs *North Hoyle* (monopile Ø 4 m, length 25 m), *Gunfleet Sands* (Ø 4.7 m, length 46 m) und *Teeside* (Ø 4.7 m, length up to 51 m).

7.3 Noise Mitigation

Sound measurements were conducted during **seabed drilling** works of *Fugro Seacore* to create rock sockets (Ø 1.15 m) of a tidal generator in bedrock sediment. Back-calculated source levels were 162 dB (SEL) at 1m. The operation of a **down-the-hole hammer** (in which a piston hammers on the drill bit) at a pier at a water depth of < 6 m at Becher's Bay, California resulted in sound levels of 136-182 dB (rms) at 1 m (Dazey *et al*. 2012). During drilling works of the ***Herrenknecht VSM*** in of a vertical shaft in the underground system in Naples (Ø 5 m, depth 39 m, 25 m below groundwater level) the structure- and water-borne sound was measured. Based on these data the potential noise emissions in an offshore application were predicted as approximately 160 dB (Leq) at 1m or 117 dB at 750 m (Ahrens & Wiegand 2009, Herrenknecht AG 2009, Rustemeier *et al*. 2012). Measurements under offshore conditions are not yet available but the sound level at some distance could be lower than predicted as very low frequencies are not transmitted at shallow water. Drilling generates continuous noise whose impact on the marine environment is not directly comparable to that of impulsive noise (Southall *et al*. 2007).

7.4 Development Status

Drilling is proven technology in bedrock, sandstone or limestone. It is available on the market. There are limitations with respect to certain kinds of seabeds though. For exclusively drilled monopiles in e.g. sandy soil without filling of the annular gap, no stability investigations have been made yet. A cost advantage would result from the use of concrete rather than steel monopoles or expensive frame constructions like jackets, tripods and tripiles. For this reason *Ballast Nedam's* method relies on concrete monopiles whereas the other suppliers of drilling technology initially prefer steel monopiles, but keep concrete monopiles as an option for the future (Rosenberger *et al*. 2011, Van de Brug 2011). ***Ballast Nedam*****:** Concrete drilled monopiles are currently in the concept stage but the installation by vertical drilling is considered technically feasible (Van de Brug 2009). An offshore demonstration project would be the next step. ***Offshore Foundation Drilling*** is currently in the pilot stage. Comprehensive studies on the technical and economic feasibility and various model tests have been performed (Herrenknecht 2010) and a special mortar for the annular gap has been developed (Gipperich 2012). Numeric analyses have shown that a monopile founded by means of *VSM* technology has the same bedding behaviour as a driven pile of the same size (Ahrens & Wiegand 2009). This has also been confirmed by a large-scale onshore experiment at two drilled monopile prototypes (scale 1:8) in the autumn of 2012 (Christoph Budach, *Hochtief Solutions AG*, pers. comm.). As a next step a nearshore test (scale 1:1) is planned with the original OFD drilling technology. The use of a ***Fugro Seacore*** *leader leg* pile handling system makes vertical drilling interesting for the much heavier concrete monopiles without the use of floating cranes. The system consists of two vertical leader legs with a gripping unit between them which lifts the pile presented as a floating object by use of hydraulic rams. So far, the system has been used for steel monopilesof up to 300 t. For concrete monopiles the system needs to be further developed (Peter Clutterbuck, *Fugro Seacore Ltd.*, pers. comm.).

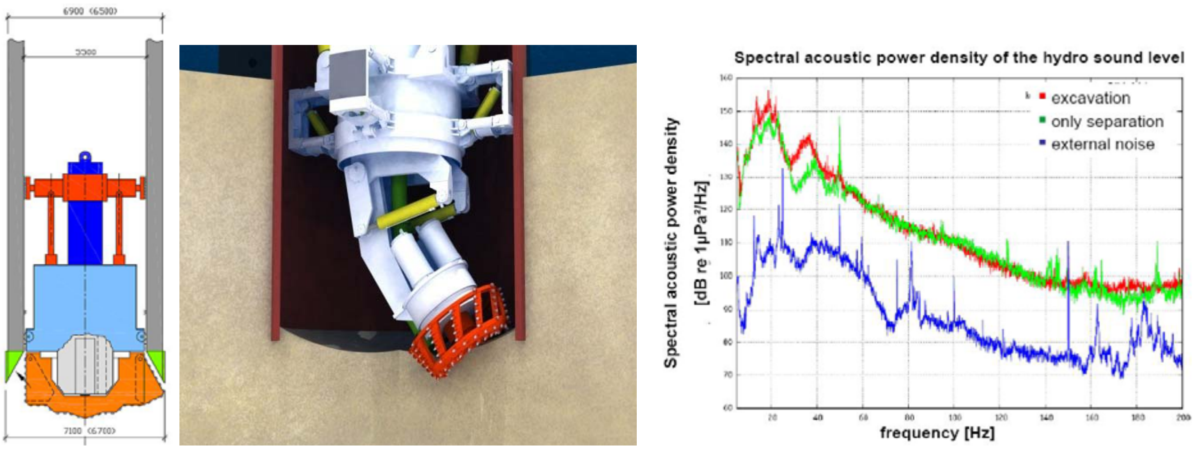

Figure 7: *Left: Ballast Nedam's concept (source: Van de Brug 2011). Middle: OFD concept (source: Hochtief Solutions AG, Essen). Right: Hydrosound measurement during the operation of a Herrenknecht VSM (source: Ahrens & Wiegand 2009)*

8 Gravity Base Foundations

8.1 Technical Description of the System

Gravity base foundations are large box girders whose stability is achieved by the self-weight of the structure, supplemented by additional ballast. The available models differ in shape and production details (overview in Koschinski & Lüdemann 2013). Production takes place onshore and the foundation is shipped to the offshore location where it is settled out. There the wind turbine is installed on the foundation and grouted afterwards.

8.2 Experience with Gravity Base Foundations

Gravity base foundations have been installed in several OWFs, predominantly in the Baltic Sea at water depths of up to 20 m, e.g. at *Vindeby, Tunø Knob, Nysted, Sprogø, Rødsand* and *Middelgrunden* in Denmark, *Lillgrund* in Sweden (Figure 8, above right) and in the North Sea at *Thornton Bank* in Belgium (Figure 8, above left). The foundations mostly consist of a ground plate with open cave chambers and a shaft reaching beyond the water surface. At their offshore location, most models are ballasted by sand or gravel. Soil preparation is mostly required to ensure the upright positioning of the structure. The sea floor is excavated until a load-bearing layer or the final embedment depth is reached and eventually filled with additional layers. On sandy grounds scour protection has to be installed to prevent erosion. A gravity base foundation developed by ***STRABAG Offshore Wind GmbH*** is planned for water depths of up to 55 m. It is made of a triangular box of pre-stressed concrete opening to the top (weight about 7,000 t). The concrete shaft ends about 20 m above sea level. Stones or sand-filled bags serve as scour protection (Wahrmund 2012). The **CraneFree Gravity Foundation** by ***Seatower AS*** is a self-installing floatable gravity base foundation, also suitable for larger water depths (Figure 8, below). The lower part consists of concrete, the upper part of steel. The foundation is towed to the site where three tugs hold it in place. When the final position is reached, a hydraulic valve is opened and sea water flows into the foundation, thereby slowly lowering the structure to the sea bed. Flowing concrete is injected under the foundation filling up the void underneath. This procedure achieves the full contact between seabed and foundation without dredging and levelling the seabed before installation. The foundation has steel skirts at the bottom which penetrate into the sediment. Comparable to a bucket foundation they provide additional stability to the structure. The weight of the structure is less than in a conventional gravity base foundation. Sand is filled into the hollow chamber of the foundation as additional ballast. Decommissioning can be done by reversing the installation process.

8.3 Noise Mitigation

No specific sound measurements of the construction of gravity base foundations are available. As impact pile driving is not necessary no impulsive sound is emitted. Apart from ship noise, additional continuous noise is to be expected from soil preparation by suction hopper dredger (except for the *Seatower CraneFree*-concept). Noise emissions will also be produced by the dynamic positioning systems of the working ships (Wahrmund 2012). It may be assumed that the total noise emissions will be lower than for impact pile driving. Hydroacoustic measurements during dredging of a suction hopper dredger showed maximum sound levels of 150 dB (rms) at 750 m (ISD 2010, cited in Wahrmund 2012). A direct comparison of the impact of continuous sound on marine organisms to that of impulsive sound is not possible solely based on the sound level. The frequency distribution of the signal is also important, specifically with regard to disturbance. Furthermore, the background noise has to be considered, as habituation to continuous sound is another possible effect. In case the foundation protrudes beyond sea level, it possibly reduces the operational noise of the turbine as the steel mast is acoustically decoupled from the water.

8.4 Development Status

Gravity base foundations have been used for offshore wind turbines in many cases and are therefore a proven technology, at least in shallow water of up to about 20 m (OWF *Thornton Bank*). For greater water depths there is no experience with this foundation type and the development has to be considered in the pilot stage. The application of gravity base foundations is planned for offshore wind farms at water depths of up to 45 m. In the German Bight it is intended to test wind turbines on gravity base foundations at appropriate locations. Experiments were performed in the small as well as in the large wave channel by *Strabag Offshore Wind GmbH* and according to the company the next step would be a full-scale test in an offshore test field. Furthermore, a test foundation was built at *Strabag*`s factory premises in Cuxhaven in a 7 m deep excavation pit based in ground water. The soil properties correspond to those of the future wind farm locations. Experiments were performed to investigate the stability under cyclical loads (Strabag 2012, Holger Wahrmund, *Strabag Offshore Wind GmbH*, pers. comm.). Other companies such as *Gravitas Offshore Ltd*, a consortium of *Hochtief*, *Costain* and *Arup*, also offer gravity base foundations for offshore wind turbines. In August 2012, the consortium secured funding from British public authorities, which is meant to support further development of *Gravitas* foundations (Gravitas 2012). According to the company ***Seatower*** considerable cost advantages can be achieved with their *CraneFree*-foundations. The concept is cost-optimized by effective serial production, eliminating the need for specialized installation vessels and soil preparation at the site as well as saving material due to the use of a bucket-like steel skirt. A similar installation procedure is normally used for gravity base foundations in the offshore oil and gas business in which the company has long-standing experience. The design is fully developed and has been tested on a model.

Figure 8: *Above: Gravity base foundations of the OWFs Thornton Bank (left, source: Wikimedia Commons) and Lillgrund (right, source: Freisen 2010). Below: Seatower CraneFree gravity base foundation. The bottle shaped foundation is towed to the site and positioned (left). Steel skirts at the bottom (right) provide additional stability (source: Seatower 2013*)

9 Floating Wind Turbines

9.1 Technical Description of the System

There are various concepts for floating wind turbines on platform types using different stabilisation mechanisms. A **ballast-stabilised** deep water application is a SPAR buoy, a ballasted hollow steel cylinder. Due to its vertical position the draft is very deep and this type of foundation is suited for areas with deep waters (120-700 m) such as the Norwegian or Iberian coasts. A **mooring-line stabilised** platform is the tension leg platform (TLP) which is vertically moored by tethers held constantly tensioned and thereby semi-submerged (which also reduces the wave attack area). It is suited for waters > 20 m. Tethers can be connected to suction anchors, driven piles or counterweights. The platform is held stable by the buoyancy force which is always greater than wind and wave forces. A **buoyancy-stabilised** concept is that of wind turbines mounted on semi-submersible platforms. Another difference between floating wind turbine concepts is the type and arrangement of turbines. Vertical axis wind turbines may be advantageous in semi submersibles due to their low centre of gravity (*INFLOW*) (Figure 9, right). Downwind turbine operation may be needed if the floater acts as a wind vane (*Sway, WINDSEA*). Some of the concepts are designed for a number of turbines on a single platform (*WINDSEA*) or are combined with wave energy absorbers (*Floating Power Plant)*.

9.2 Experience with Floating Wind Turbines

The floating wind turbine ***HYWIND*** was installed in 2009 off the Norwegian coast at 220 m depth (Figure 9, left). It is a SPAR buoy (Ø 6 m, draft 100 m) with a three-point mooring spread and a 2.3 MW wind turbine (rotor Ø 82 m, hub height 65 m) on top. In 2011 it already generated 10 GWh of electricity. Between 2007 and 2009 a 75% size ***Blue H*** prototype based on the TLP was installed off the Italian coast (water depth 113 m, draft 15 m, 80 kW wind turbine) tensioned with a 1,000 t counterweight (Blue H 2013, Lessner 2010) (Figure 9, middle). ***Sway***, another TLP prototype scaled 1:6 was installed in 2011 off the Norwegian coast. Its tower is stiffened by vertical steel cables kept under high tension. It is moored with a single suction anchor. ***WindFloat***, a full-scale prototype of a 2 MW wind turbine on a **semi-submersible** platform (draft 20 m, weight 6,000 t) was installed in 2011 off the coast of Portugal (depth 42-53 m). It is stabilised by water tanks and water entrapment plates at the three corner columns. It has already withstood waves of up to 15 m in its first winter. For flexible horizontal trimming, ballast water is pumped between the tanks. The foundation is moored by four drag embedded anchors (Principle Power Inc. 2013). The 1:3 scaled prototype ***Floating Power Plant Poseidon 37*** is a wind and wave energy hybrid system (Poseidon 2013). The platform contains ten 50 kW wave energy absorbers and is the basis for three 11 kW wind turbines. The first prototype has been installed for four test periods off the Danish island of Lolland in the Baltic Sea.

9.3 Noise Mitigation

Since floating concepts allow for a high level of pre-fabrication onshore, the underwater noise during installation is limited to transport and the anchoring process. Noise emissions of the anchoring process with suction anchors are comparable to those arising from the installation of bucket foundations. Another future option presented by *GICON* is to use drilled micropiles.

9.4 Development Status

The number of different floating concepts reflects the importance for the offshore wind sector. Some concepts are based on proven technologies such as wind turbines or floats whereas other concepts are completely new developments. Platforms are market available. Technical challenges such as dynamic loads in shallow waters, pitch and roll of turbines, safe moorings and economic challenges such as cost competiveness still have to be tackled. Thus, further development and full scale demonstrations are needed. One advantage of floating foundations resulting in cost advantages is that the installation and repair can be carried out in a dockyard. To date, the project *HYWIND* is pre-commercial. The projects *GICON-SOF, INFLOW* and *WINDSEA* are in the experimental stage. The pilot stage has been reached by *WindFloat* with a full-scale and *Poseidon 37*, *Sway,* and *Blue H,* with downsized offshore prototypes, and *WINFLO* with a prototype under construction.

The pilot phase of ***HYWIND*** with a two-year research programme has been successfully completed. The next milestone will be to increase cost competiveness. Small pilot wind farms of up to five wind turbines are currently projected. The ***WindFloat*** prototype is tested since 2011. There are plans for the installation of further turbines at the same site by 2016. A functional full-scale demonstrator of the ***GICON-SOF*** *is* projected for a site off the German Baltic Sea coast (water depth < 20m) for 2014. It will likely be realized with a wind turbine of a rated power of 2-4 MW (Burkhard Schuldt, *GICON*, pers. comm.). ***Blue H Engineering*** is planning a 5 MW floating system with a commercially available turbine for 2016. ***Sway*** announced a full-scale prototype already approved by the government for 2013. ***Floating Power Plant*** is in the fourth test phase of its down-scaled prototype *Poseidon 37* (width 37 m) including wave energy absorbers. Larger prototypes (width 80 m and 110 m) are projected for 2014/15 and 2016/17 (Anders Køhler, *Floating Power Plant AS*, pers. comm.). The French project ***INFLOW*** includes a novel design of a 2 MW gearless vertical axis wind turbine resulting in a low-lying centre of gravity. This is beneficial for the dimensioning and cost of the semi-submersible. A prototype was projected for 2013 (Inflow 2013). The French ***WINFLO*** concept, a semi-submersible construction with a two-blade wind turbine projected a 1 MW demonstration project off the coast of Brittany for 2013 (Nass & Wind 2013). The Norwegian concept ***WINDSEA*** consists of a semi-submersible offering a cost effective solution by using three wind turbines on top of each of the corner columns (Windsea 2011). Two turbines operate upwind while one has a downwind drive. Successful tests of a 1:40 model in a wind tunnel and wave basin resulted in plans for a full-scale prototype with three wind turbines of a rated power of 3.6 MW (turbine height 71-90 m above sea level, draft 23 m, rotor Ø 104 m) for which the company is currently seeking investors.

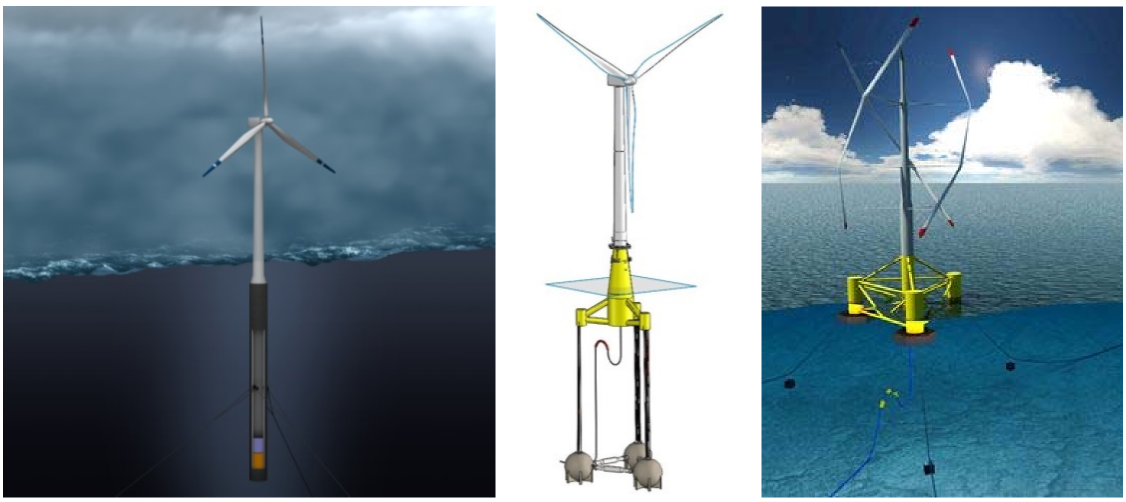

Figure 9: *SPAR buoy in the HYWIND project (left, source: Siemens 2009, Øyvind Hagen/ Statoil), Blue H concept with submergible gravity based anchors (middle, source: Nico C. F. Bolleman, Blue H Engineering BV, NL), INFLOW concept of a semi-submersible platform (right: source: Inflow 2013)*

10 Bucket Foundations (suction bucket /- caisson / -can)

10.1 Technical Description of the System

A bucket foundation is a large downward directed steel caisson which is founded in the seabed by suction pumps. The resulting vacuum in combination with the force of the hydrostatic pressure and the weight of the structure makes it penetrate into the seabed. Repositioning is possible by reversing the installation process if full penetration cannot be achieved in the first step or at the time of decommissioning. Bucket foundations are commonly used in the offshore oil and gas industry, i.a. suction anchors for deep water tension leg platforms. Various foundation concepts for wind turbines based on buckets exist, e.g. monopods or multiple bucket concepts. The installation needs no pile driving, therefore noise emissions are low compared to conventional concepts. On the other hand an innovative technology requires higher effort on development and certification (Barkhoff *et al*. 2013).

10.2 Experience with Bucket Foundations

Platform concepts: Several platforms have been mounted on bucket foundations in water depths of 50-70 m off Western Africa or Malaysia and in the North Sea (e.g. in the Trent gas field) (Overdick 2013a). The platform can either be carried by a super barge or wet-towed to the offshore site as MOAB (*Mobile Application Barge*). In the German EEZ the first substation of a commercial OWF has been installed by bucket foundations at ***Global Tech I*** in 2013 (water depth 40 m). The substation (weight about 9,000 t) is based on the MOAB principle with bucket foundations at each of the four legs. The swimming platform was wet towed to the offshore location. Once installation was completed, the buckets (Ø 11 m, height 9.5 m, wall thickness 50 mm, weight 834 t each) penetrated 9 m into the sandy sediment (Figure 10) (Barkhoff *et al*. 2013). **Monopod concepts:** Prototypes of monopiles mounted on single suction buckets have been successfully installed. In 2002, a 3.0 MW wind turbine (height 89 m) on a bucket foundation (Ø 12 m, height 6 m, weight 135 t) was successfully installed in marine sediments in a polder near **Frederikshavn** (Ibsen *et al*. 2005). In 2009, a mobile met mast (height 38 m) was installed at the OWF ***Horns Rev 2*** on a bucket foundation (Ø 12 m, height 6 m, weight 165 t) (LeBlanc *et al*. 2009). Two meteorological met masts on monopods designed by the Danish company *Universal Foundation* have been installed at the location of the projected OWF ***Dogger Bank*** in 2013 (Figure 10). The installation took 7 h from lifting until complete installation (Ibsen 2013). A failure of a bucket installation occurred in April 2005, when *ENERCON* planned to install a 4.5 MW E-112 wind turbine on a bucket foundation nearshore at **Hooksiel** (Ø 16 m, height 15 m, wall thickness 25 mm, water depth 4 m) (LeBlanc 2009). However, during the installation the caisson deformed and the operation was suspended. According to Ibsen (2013) the heavy load pontoon *Giant 4* collided with the skirt at a penetration depth of 3 m. The steel was dented inside by 8-16 cm and the caisson distorted during suction at a penetration depth of 6.8 m.

10.3 Noise Mitigation

For the installation process electric underwater suction pumps are needed. From the underwater noise perspective, the noise emissions of the suction pumps are of basic interest. However, no sound measurements are known so far. During installation of the *Horns Rev 2* monopod reportedly emissions were low and mainly derived from the Diesel generator on the deck of the installation vessel (Christian LeBlanc Thilsted, *DONG Energy Wind Power*, pers. comm.).

10.4 Development Status

Bucket foundations cannot be used at all soil types but generally soil profiles that are suitable for driven monopiles (sand, silt or clay) can also be assumed suitable for bucket foundations (Ibsen 2013). Scour protection can be integrated in the system using perforated steel partitions (Ekkehard Overdick, *Overdick GmbH & Co. KG*, pers. comm.) or welded cut plates (Ibsen 2013) on top of the buckets. **Platform concepts:** Bucket foundations are proven technology for platforms in the oil and gas sector. A prototype for a substation of an OWF has successfully installed at *Global Tech I*. **Monopod concepts:** The bucket foundation has to penetrate evenly into the seabed in order to guarantee an upright position of the supporting structure. Large lateral loads (such as from wind turbines) are more difficult to absorb with a small embedment depth in buckets compared to standard deep foundations (Abdel-Rahman & Achmus 2005). A successful example is the monopod in Frederikshavn. The collapsing of the *Enercon* bucket near Hooksiel illustrates that buckling of the thin shell structure is a critical issue during installation. Post buckling analysis led to the development of a multi-shell system (Figure 10) with additional longitudinal stiffeners with significantly larger buckling load (Ibsen 2013). The installation of the monopod met masts at *Horns Rev 2* and *Dogger Bank* used traditional cylinders. **Multiple bucket concepts:** Concepts with three-legged jackets with bucket foundations have been developed by the companies *Overdick GmbH & Co. KG* and *SPT Offshore*. *SPT Offshore's* concept of fully prefabricated turbines with a wider base compared to standard jackets (*SIWT, Suction Installed Wind Turbine,* Figure 10) offers advantages in manufacturing and installation (Riemers 2013). The SIWT is intended for use at water depths of 15-60 m and suited for 3 – 10 MW wind turbines. However, the effects of high vibration loads in jackets with multiple buckets are yet to be investigated. *SPT Offshore* has been selected as one of the four final candidates to be demonstrated at full-scale for the UK Round 3 OWF (Carbon Trust 2012). The installation of a full scale prototype of an SIWT is planned by *DONG Energy* at one of the companies' German projects in 2014 (Figure 10). This foundation type is intended to proof a cost-efficient and low-noise alternative to traditional foundation methods, especially for the next generation of offshore wind turbines (5-8 MW) at water depths of 25-60 m (DONG Energy 2013). Currently it is unclear how the mechanical resistance and stability of bucket foundations is impacted by the influence of cyclical loads. In contrast to monopod foundations in which an extreme point load can result in the collapse or detachment of the bucket, the foundation on jackets with multiple buckets is more promising from a technological perspective. The use of multiple buckets leads to smaller sized buckets compared to monopods. The structure can be levelled during installation by changing the suction pressure in the individual suction buckets (DONG Energy 2013).

Figure 10: *Left: Suction Installed Wind Turbine (SIWT) of SPT Offshore (source: SPT Offshore, Woerden NL). Middle: Multi-shell concept of Universal Foundation (2013). Right: Suction buckets for the substation at Global Tech 1 (Source: Global Tech 1 2013).*

11 Additional noise mitigation concepts

11.1 High Frequency – Low Energy Piling

A modification of impact piling can further reduce the noise level. High Frequency – Low Energy Piling (*HiLo Piling*) is a method adapted by the Dutch company *IHC*. It makes use of a lower impact energy with an increased blow rate (90 blows/min. compared to 40 blows/min. in standard operation). A reduction in impact energy by 50% reduces the noise level by 3 dB (Wilke *et al*. 2012). This also reduces stress on pile and equipment.

11.2 Mandrel Piles

A concept to also mitigate the seismic component of piling noise at the source is a double-walled pile of which the outer pile shields the noise against the sediment and at the same time is the structural element, *i.e*. the monopile. The inside pile would be driven by an impact hammer acting as a mandrel which pulls the tethered outer pile along into the sediment. A driving shoe at the bottom would help displace the sediment for the outer pile. The two piles would need an annular air gap between and connected in a way that would inhibit noise transmission between both walls. Within the air gap the compression wave generated by the impact which causes circumferential expansion along the length of the pile cannot couple to water or sediment. A prototype (∅ 15.2 cm) has been field tested and was found to provide more than 20 dB attenuation at a distance of 5 m. Further development is needed (BOEM in press). A full scale test of the mandrel pile is planned for July 2014 in Puget Sound outside Seattle (Per G. Reinhall, University of Washington, pers. comm.)

11.3 Slit Piles

Another theoretical approach is cutting vertical slits into a pile. The slits would absorb or interfere with the radial expansion of the pile which would propagate along the pile after impact. This would eliminate the resulting supersonic greatly decreasing the amount of energy entering the sediment and the water column (BOEM in press). Possible problems associated with this concept could be maintaining an identical bearing capability and corrosion.

12 Additional Low-Noise Foundation Concepts

12.1 Silent pile driving

Numerical investigations revealed that prolonging the pulse duration[4] reduces the corresponding sound emission (Elmer *et al*. 2007a, b). As the impact energy is distributed over a longer time period, the maximum impact force and thus the amplitude of the lateral extension is reduced. At the same time the frequency spectrum emitted is shifted to lower frequencies because the oscillation period is prolonged. Hence, the reduced propagation velocity of the lateral extension directly decreases the sound emission. This would not only have a positive effect on sound in the water but also on the seismic component of radiated noise. The prolongation of pulse duration is a theoretical noise mitigation method, however, no practical and effective solutions for large piles have been presented yet (Koschinski & Lüdemann 2013). Piling cushions between hammer and pile are not suited for large monopiles and a coiled steel cable which revealed a prolongation of the pulse duration by a factor

[4] The typical pulse duration of a pile strike is about 4 ms (Elmer et al. 2007a, b).

greater than 2 and a noise reduction by up to 7 dB was effective only for a few strikes (Elmer *et al*. 2007b).

A novel technology making use of this effect without using conventional hydraulic pile driving hammers is *BLUE Piling* by the Dutch company *FISTUCA BV* (Winkes & Genuit 2013). It uses a large water column to generate the driving force. *BLUE Piling* increases the pulse duration by a factor of 20. Sea water inside a steel tube closed at the bottom is pushed upwards by igniting a gas mixture in a combustion chamber at the bottom (Figure 11, left). The flue gasses are kept from freely expanding by the mass inertia of the water column. The pressure increase generates a downward force and lifts the water column at the same time. A second downward force pulse is produced when the water falls down again (Figure 11, middle). This cycle is repeated until the pile reaches its desired depth. Advantages are a lower noise emission of 25 dB or more (without external mitigation methods), a gradual force build-up, a low tension stress and also cost-effectiveness. The reduced propagation velocity of the lateral extension of the pile should not only decrease the underwater noise emission but also the seismic component of radiated noise which is often limiting external noise mitigation systems. The pile driving properties have been investigated in a successful near-shore test with a prototype (∅ 2.2 m, 35 t + 80 t of water) and a closed ended pile of ∅ 0.66 meter and an open ended pile of ∅ 2.25 meter (Figure 11, right). The blow duration was 80 ms for the primary and over 100 ms for the secondary blow. The maximum SEL for the 0.66 m pile was 152 dB re 1µPa²s, the maximum peak level was 179 dB re 1µPa at measuring distance of 70 m. A larger hammer (about 600 kJ) is to be built and tested near shore in 2014 before scaling up the technology for full-scale monopiles (projected for 2015) (J. Winkes, FISTUCA BV, Eindhoven, NL pers. comm.).

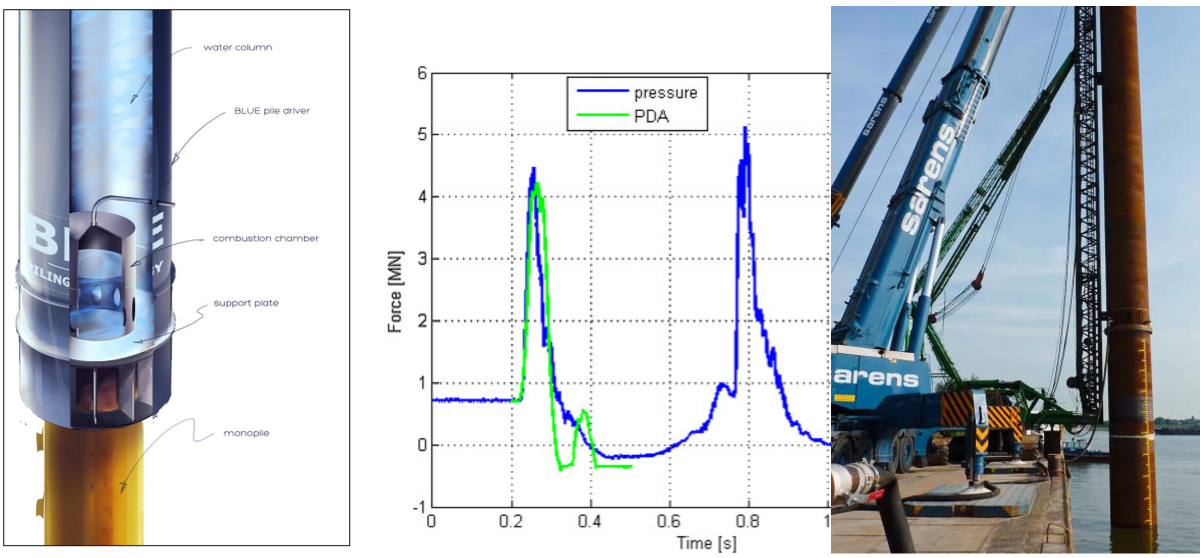

Figure 11: *Left: schematic overview of the BLUE pile driver (left), middle: blow characteristics of primary and secondary pulses measured in the water column (blue) and with strain sensors in the pile (green), right: photograph from the nearshore test (Source (modified): Winkes & Genuit 2013).*

13 References

Ahrens, C. & Wiegand, J. (2009): Foundation of Offshore Wind Power Plants - an introduction of the Vertical Shaft Machine as an economic and ecologic alternative. http://search.informit.com.au/documentSummary;dn=848024769051558;res=IELENG (15.12.2013)

Applied Physical Sciences (2010): Mitigation of Underwater Pile Driving Noise During Offshore Construction. Final Report. Report Nr. M09PC00019-8. http://www.bsee.gov/uploadedFiles/BSEE/Research_and_Training/Technology_Assessment_and_Research/M09PC00019-8PileDrivingFinalRpt.pdf

Bellmann, M. (2012): Die technische Entwicklung von Schallminderungstechnologien: Stand der Forschung (?). Presentation „Minimierung von Unterwas-serschall bei der Gründung von Offshore-Windenergieanlagen: Anforderungen und Möglichkeiten", IHK Rostock, 28 March 2012. http://www.offshore-stiftung.com/60005/Uploaded/Offshore_Stiftung|2012_03_28_HRO_SOW_Schallschutz_2_Bellmann.pdf (15.12.2013)

Bellmann, M. & Remmers, P. (2013). Noise Mitigation Systems (NMS) for reducing Pile Driving Noise – Experiences with different NMS especially "Big Bubble Curtain". Presentation 166th Meeting of the Acoustical Society of America, 2-6 December 2013, San Francisco, USA

Betke, K. (2008): Minderung von Unterwassergeräuschen beim Bau von Offshore WEA - Schallschutzhüllen und andere Verfahren. Presentation Workshop „Forschungsergebnisse der Begleitforschung zur Rammungsschallemission bei der Installation der Forschungsplattform FINO3" FOWEUM, BSH Hamburg 8. Oktober 2008.

Betke, K. & Matuschek, R. (2010): Messungen von Unterwasserschall beim Bau der Windenergieanlagen im Offshore-Testfeld „alpha ventus". Abschlussbericht des ITAP zum Monitoring nach StUK 3 in der Bauphase an die Stiftung Offshore-Windenergie, Varel. http://www.bsh.de/de/Meeresnutzung/Wirtschaft/Windparks/StUK3/Fachgutachten_Bauphase_av/Schallbericht_Bauphase_2009.pdf (15.12.2013)

Betke, K. & Matuschek, R. (2012): Hydroschallimmissionen einer Vibrationsramme. In: Rustemeier *et al.*, Abschlussbericht zum Forschungsvorhaben „Konzeption, Erprobung, Realisierung und Überprüfung von lärmarmen Bauverfahren und Lärmminderungsmaßnahmen bei der Gründung von Offshore-WEA („Schall3")", p. 101-104.

Blue H (2013): www.bluehgroup.com

BOEM (in press). Report of the BOEM workshop Quieting Technologies for Reducing Noise during Seismic Surveying and Pile Driving, 25-27 February 2013, Silver Spring, Maryland USA.

Bruns, B. & Kuhn, C. (2013): Technischer Einsatz der Hydroschalldämpfer (HSD) beim OWP 'London Array'. Presentation held at the HSD Project meeting on 18.08.2013. 37 pp. http://www.hydrosounddamper.de/hsd/index.php/news/hsd-projekttreffen-2013.html?file=files/blue_business/Literatur/TOP%2003%202013.08.22%20Projekttreffen%20HSD%20BWII%20-%20technischer%20Einsatz%20HSD%40LA.pdf (15.12.2013)

BSH (2013): Offshore-Windparks, Messvorschrift für die quantitative Bestimmung der Wirksamkeit von Schalldämmmaßnahmen, Bericht Nr. M100004/05, Bundesamt für Seeschifffahrt und Hydrographie, Hamburg, Germany, 25 pp.

Caltrans - California Department of Transportation (2009): Technical Guidance for Assessment and Mitigation of the Hydroacoustic Effects of Pile Driving on Fish (Final). Prepared by ICF Jones & Stokes and Illingworth & Rodkin, Inc. http://www.dot.ca.gov/hq/env/bio/files/Guidance_Manual_2_09.pdf (15.12.2013)

Carbon Trust (2012): Foundations. Accessed in Dec. 2013 at http://www.carbontrust.com/media/105314/foundation_innovators_29may2012.pdf

Dahl, P.H. & Reinhall P.G. (2013): Beam Forming of the Underwater Sound Field from Impact Pile Driving, Journal of the Acoustical Society America 134(1): EL1-6. doi: 10.1121/1.4807430

Dazey, E., McIntosh, B., Brown, S. & Dudzinski, K. M. (2012): Assessment of underwater anthropogenic noise associated with construction activities in Bechers Bay, Santa Rosa Island, California. J. Env. Prot. 3: 1286-1294.

DONG Energy (2013): Jacket on suction bucket. Full scale test in the German North Sea. 8 pp. Doc. no. 1636880. Dec. 2013. Unpublished.

Elmer, K.-H., Betke, K. & Neumann, T. (2007a): Standardverfahren zur Ermittlung und Bewertung der Belastung der Meeresumwelt durch die Schallimmission von Offshore-Windenergieanlagen: SCHALL2. - Project 0329947 final report. The German Federal Environment Ministry.

Elmer, K.-H., Betke, K. & Neumann, T. (2007b): Standardverfahren zur Ermittlung und Bewertung der Belastung der Meeresumwelt durch die Schallimmission von Offshore-Windenergieanlagen: Untersuchung von Schallminderungsmaßnahmen an FINO 2. - Project 0329947 A final report. The German Federal Environment Ministry.

Elmer, K.H., Gattermann, J., Kuhn, C. , Bruns, B. (2012): Hydroschalldämpfer (*HSD*) zur Schallminderung bei Offshore Rammarbeiten, Presentation DUH Conference „Herausforderung Schallschutz beim Bau von Offshore Windparks“, 25./26 September 2012, Berlin.

Freisen, M. (2010): Schwerlastfundamente für den Offshore Windpark Lillgrund. Presentation at “Husum Wind” 2010.

Frühling, I., Neuber, M., Overdick, E., Rolfs, M. Schmugler, J., Schönherr, J. & Tsakonakis, A. (2011): Abschlussbericht zum Forschungsvorhaben “Konzeptstudie zur Entwicklung einer neuartigen Gründungstechnologie unter Einbeziehung von Errichtungslogistik (Teilprojekt 1) und Schallschutz (Teilprojekt2)”. FKZ 0325142. 71 pp.

Gerke, P. & Bellmann, M. (2012): Offshore Windpark „Riffgat“. Messung der Bauschallimmissionen. Itap Projekt Nr.: 1924-12-e-pg, 40 S, commissioned by Offshore-Windpark Riffgat GmbH & Co KG

Gipperich, C. (2012). Offshore Foundation Drilling, Presentation DUH Conference „Herausforderung Schallschutz beim Bau von Offshore Windparks“, 25./26 September 2012, Berlin.

Global Tech 1 (2013): http://www.globaltechone.de/presse/mediathek/

Gravitas (2012): Press Release. DECC / Demonstrator. August 2012. http://www.gravitasoffshore.com/press/Gravitas%20Press%20Release%20-%2020.08.12.pdf (15.12.2013)

Grießmann, T. (2009): Forschungsplattform FINO 3 - Einsatz des großen Blasenschleiers. Presentation at BSH “Meeresumweltsymposium” 2009. http://www.bsh.de/de/Das_BSH/Veranstaltungen/MUS/2009/Dokumente/Griessmann_P.pdf (15.12.2013)

Grießmann, T., Rustemeier, J., Betke, K., Gabriel, J., Neumann, T., Nehls, G., Brandt, M., Diederichs, A. & Bachmann, J. (2009): Erforschung und Anwendung von Schallminimierungsmaßnahmen beim Rammen des FINO3 - Monopiles. FKZ 0325077-A, 0325077-B, 1-130. 2009. Berlin, Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit. Final Report of BMU funded project „Schall bei FINO3".

Grießmann, T. Rustemeier, J. & Rolfes, R. (2010): Research on mitigation measures at alpha ventus. 24. Conference of the European Cetacean Society. Pile driving in offshore windfarms. Stralsund, 21 March 2010.

Heerema Marine Contractors (2013): Incorporating the Pile-Driving Noise Mitigation Method in Jacket Design. Poster, presented at the StUK-Plus Conference in Berlin, Oct. 2013. http://stukplusconference.com/wp-content/uploads/2013/12/Poster_Heerema%20Marine%20Contractors_Incorporating%20the%20pile-driving%20noise%20mitigation%20method%20in%20jacket%20design.pdf (15.12.2013)

Herrenknecht AG (2009): Machbarkeitsstudie zum Einsatz der Vertical Shaft Sinking Machine (VSM) im Bereich der Errichtung von Offshore-WEA. FKZ 0325064. Finale Report according to 8.2 NKBF 98. 20 pp.

Herrenknecht AG (2010): Machbarkeitsstudie zum Einsatz der Vertical Shaft Machine (VSM) im Bereich der Errichtung von Offshore-WEA. Finale Report according to 8.2. NKBF 98 (FKZ 0325064). 20 pp.

Herwig, V., Zacharioudaki-Apelidou, F., Heitmann, K., Lippert, S. & von Estorff, O. 2013. “Vibrated Pile Validation” Project for Offshore Monopiles. Poster presented at StUKplus Conference, 30-31 October 2013, Berlin.

Ibsen, L.B.; Liingaard, S. & Nielsen, S.A. (2005): Bucket Foundation, a status. Proceedings of the Copenhagen Offshore Wind 2005. http://wind.nrel.gov/public/SeaCon/Proceedings/Copenhagen.Offshore.Wind.2005/documents/papers/Future_innovative_solutions/L.B.Ibsen_Bucket_Foundation_a_status.pdf (15.12.2013)

Ibsen, L.B. (2013): Debunking Myths About Suction Bucket Foundations - To evaluate their suitability at a variety of sites. Presentation, held at the conference “Future Offshore Foundations 2013”, 23-25 October 2013, Bremen, Germany

Inflow (2013): www.inflow-fp7.eu

ITAP (2013). Offshore Messkampagne 1 (OMK 1) für das Projekt BORA im Windpark BARD Offshore 1. Projekt Nr.: 1924-12-mb. Institut für Technische und Angewandte Physik GmbH, Oldenburg. 139 S.

Koschinski, S. & Lüdemann, K. (2013). Development of Noise Mitigation Measures in Offshore Wind Farm Construction 2013. Report commissioned by the Federal Agency for Nature Conservation, Vilm, Germany. 97 pp.

Kringelum, J. (2013). Industrial Approach to Underwater Noise Mitigation. Presentation: EWEA Offshore 2013, 19-21 November 2013, Frankfurt, Germany

Kuhn, C., Bruns, B., Gattermann, J. & Elmer, K.H. (2013): Einsatz der Hydro-Schall-Dämpfer (HSD) beim Windpark London Array - lessons learned. Presentation held at the HSD Project meeting on 18.08.2013. http://www.hydrosounddamper.de/hsd/index.php/news/hsd-projekttreffen-2013.html?file=files/blue_business/Literatur/TOP%2005%202013.08.22%20Projekttreffen%20HSD%20BWII%20-%20Ausblick%20HSD%20System.pdf (15.12.2013)

LeBlanc, C. (2009): The Monopod Bucket Foundation: Recent Experience and Challenges Ahead. Presentation Hamburg Offshore Wind, 12. May 2009. http://www.gl-group.com/pdf/No12_Bakmar.pdf (15.12.2013)

LeBlanc, C., Ahle, K., Nielsen, S.A. & Ibsen, L.B. (2009): The Monopod Bucket Foundation - Recent experiences and challenges ahead. Poster session presented at The European Offshore Wind Conference & Exhibition, Stockholm, Sweden. http://vbn.aau.dk/files/19025671/The_Monopod_Bucket_Foundation.ppt (15.12.2013)

LeBlanc Thilsted, C. (2013). Vibro-driving of monopiles – experiences from Anholt Offshore Wind Farm. Presentation: EWEA Offshore 2013, 19-21 November 2013, Frankfurt, Germany

Lee, K.M., Hinojosa, K.T., Wochner, M.S., Argo IV, T.F., Wilson, P.S. & Mercier, R.S. (2010): Attenuation of low-frequency underwater sound using bubble resonance phenomena and acoustic impedance mismatching. Proceedings of Meetings on Acoustics, Volume 11, 1-17. http://acousticalsociety.org/ (15.12.2013)

Lee, K.M., Hinojosa, K.T., Wochner, M.S., Argo IV, T.F., Wilson, P.S. & Mercier, R.S. (2011): Sound propagation in water containing large tethered spherical encapsulated gas bubbles with resonance frequencies in the 50 Hz to 100 Hz range. J. Acoust. Soc. Am. 130 (5), 3325-3332.

Lee, K., Wochner, M.S. & Wilson, P.S. (2012): Mitigation of low-frequency underwater anthropogenic noise using stationary encapsulated gas bubbles. Proceedings of the 11th European Conference on Underwater Acoustics, 8 pp.

Lessner, A. (2010): Wie ein Korken im Wasser. erneuerbare energien 2/2010: 18-21

Nass & Wind (2013): www.nassetwind.com (15.12.2013)

Nedwell, J. & Howell, D. (2004): A review of offshore windfarm related underwater noise sources. - Cowrie Report No. 544 R 0308.

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.

Overdick (2013a): http://www.overdick.com/what-we-do/offshore-oil-gas

Overdick (2013b): http://www.overdick.com/projects/offshore-wind/moab-veja-mate

Pehlke, H., Nehls, G., Bellmann, M., Gerke, P. & Grunau, C. (2012): Project: HYDROSCHALL OFF BW II. Entwicklung und Erprobung des „Großen Blasenschleiers“ zur Minderung der

Hydroschallemissionen bei Offshore-Rammarbeiten. Förderkennzeichen 0325309A/B/C. Akustische Messungen bei den Rammungen in Forschungsphase 1 im Offshore-Windpark Borkum West II. 23. April 2012. http://www.hydroschall.de/wp-content/uploads/2012/05/Kurzbericht-Schallminderung20120425.pdf (15.12.2013)

Pehlke, H., Nehls, G., Bellmann, M., Gerke, P., Diederichs, A., Oldeland, J., Grunau, C., Witte, S. & Rose, A. (2013). Entwicklung und Erprobung des Großen Blasenschleiers zur Minderung der Hydroschallemissionen bei Offshore-Rammarbeiten Projektkurztitel: HYDROSCHALL-OFF BW II. FKZ 0325309A/B/C. ITAP, Hydrotechnik Lübeck and BioConsult SH, Husum (Germany). 240 pp.

Poseideon (2013): www.floatingpowerplant.com (15.12.2013)

Principle Power Inc. (2013): http://principlepowerinc.com/products/windfloat.html (15.12.2013)

Remmers, P. & Bellmann, M.B. (2013): Untersuchung und Erprobung von Hydroschalldämpfern (HSD) zur Minderung von Unterwasserschall bei Rammarbeiten für Gründungen von Offshore-Windenergieanlagen - Auswertung der Hydroschallmessungen im OWP London Array. Report by itap GmbH, commissioned by TU Braunschweig, 55 pp. Accessed in Dec. 2013 at http://www.hydrosounddamper.de/hsd/files/blue_business/Literatur/Messbericht_London_Array_v3.pdf

Riemers, M. (2013): Evaluating Suction Pile Founded Tripod Jackets For Fast, Noise-Free And (Partial) Integrated Installation, presentation at Future Offshore Foundations, 23 October 2013 Bremen, Germany

Riffgat (2013): http://www.riffgat.de (15.12.2013)

Rosenberger, F., Zedler, T. & Wiegand, J. (2011): Ein Bohrer sticht in See. Erneuerbare Energien 05/2011: 54-59

Rustemeier, J., Neubert, M., Grießmann, T., Ewaldt, A., Uhl, A., Schultz-von Glahn, M., Betke, K., Matuschek, R. & Lübben, A. (2012): Konzeption, Erprobung, Realisierung und Überprüfung von lärmarmen Bauverfahren und Lärmminderungsmaßnahmen bei der Gründung von Offshore-Windenergieanlagen ("Schall 3"). FKZ 0327645. Institut für Statik und Dynamik an der Gottfried Wilhelm Leibniz Universität Hannover, Hannover. 236 S.

Saleem, Z. (2011): Alternatives and modifications of monopile foundation or its installation technique for noise mitigation. Report commissioned by the North Sea Foundation, 66 pp. www.vliz.be/imisdocs/publications/223688.pdf (15.12.2013)

Schultz-von Glahn, M., Betke, K. & Nehls, G. (2006): Minderung des Unterwasserschalls bei Rammarbeiten für Offshore-WEA - Praktische Erprobung verschiedener Verfahren unter Offshore-Bedingungen. UFOPLAN 205 53 113. Umweltbundesamt. Dessau. 59 pp.

Schultz-von Glahn, M. (2011): Messung der Hydroschall-Immissionen bei Probe-Rammarbeiten am Offshore-Windpark EnBW Baltic 2 sowie Messung und Beurteilung der Wirksamkeit von Schallminderungsmaßnahmen. Report, Project Nr. 1653-10-svg, 9 June 2011, 33 pp.

Seacore (2013): Shah Deniz, Baku http://www.seacore.com/projects/shah-deniz-baku (15.12.2013)

Seatower (2013): http://www.seatower.com

Siemens (2009): Hywind: Siemens und StatoilHydro installieren erste schwimmende Windenergieanlage. Press Release 10 June 2009.

http://www.siemens.com/press/de/pressemitteilungen/?press=/de/pressemitteilungen/2009/renewable_energy/ere200906064.htm (15.12.2013)

Southall, B.L., Bowles, A.E., Ellison, W.T., Finneran, T.E., Gentry, R.L., Greene Jr., C.R., Kastak, D., Ketten, D., Miller, J.H., Nachtigall, P.E., Richardson, W.J., Thomas, J.A. & Tyack, P.L. (2007): Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations. - Aquatic Mammals 33(4): 411-521.

Steinhagen, U. (2012): Kleiner Blasenschleier, Presentation Conference of „Deutschen Umwelthilfe e. V." "Herausforderung Schallschutz beim Bau von Offshore-Windparks", 25.-26. September, Berlin

Steinhagen, U. & Mesecke-Rischmann, S. (2013): Abschlussbericht zum BMU-Verbundforschungsvorhaben: Untersuchung und Erprobung eines 'Kleinen Blasenschleiers' zur Min-derung von Unterwasserschall bei Rammarbeiten für Gründungen von OWEA ("Hydroschall-OFF BO1"), Teilprojekt G. Förderkennzeichen: 0325334G. Report of Menck GmbH, 48 pp. unpublished.

Strabag (2013): http://www.strabag-offshore.com/projekte/schwerkraft-testfundament.html (15.12.2013)

Thomsen, K.E. (2012): Cofferdam-State of the art noise mitigation, Presentation Conference of "Deutsche Umwelthilfe e. V." "Herausforderung Schallschutz beim Bau von Offshore-Windparks", 25.-26 September 2012, Berlin.

van de Brug, E. (2009): Drilled Concrete Monopile. http://www.bsh.de/en/The_BSH/Events/Cetacean_Society/index.jsp (15.12.2013)

van de Brug, E. (2011): Drilled Concrete Monopile -Kriegers Flak R&D Project - Executive Summary. In: von Nordheim, H., Krause, J.C. & Maschner, K. (Eds.): Progress in Marine Conservation in Europe 2009. 2nd International Conference on Progress in Marine Conservation in Europe. BfN-Skripten 287, 151-158.

van Vessem, H. (2012): IHC Offshore Systems. Presentation, held at the "Symposium Sound Solutions", North Sea Foundation, February 02 2012. http://www.noordzee.nl/wp-content/uploads/2011/11/ihc-noise-mitigation-screen.pdf (15.12.2013)

Wahrmund, H. (2012): Offshore Wind Schwerkraftfundamente, Presentation Conference of "Deutsche Umwelthilfe e. V." "Herausforderung Schallschutz beim Bau von Offshore-Windparks", 25.-26 September 2012, Berlin.

Weyres, B. (2012): Die BEKA Schale als Schallminderung für Impulsrammung, Presentation Conference of "Deutsche Umwelthilfe e. V." "Herausforderung Schallschutz beim Bau von Offshore-Windparks", 25.-26 September 2012, Berlin.

Wijk, U. (2013): Dolwin 1 – Further achievements In HVDC Offshore Connections. Abstract. http://proceedings.ewea.org/offshore2013/conference/mobile/speakerdetails.php?id=91&day=4 (15.12.2013)

Wilke, F., Kloske, K. & Bellmann, M. (2012): ESRa-Evaluierung von Systemen zur Ramsmchallminderung an einem Offshore-Testpfahl. Förderkennzeichen 0325307. Technical Report Mai 2012. http://www.offshore-stiftung.com/60005/Uploaded/Offshore_Stiftung|ESRa_TechnischerAbschlussbericht.pdf (15.11.2012)

Windsea (2013): http://windsea.com/sfiles/07/1/file/windsea.pdf (15.12.2013)

Winkes, J. S. & Genuit, B.A.G. (2013). The future of offshore pile driving: bigger, deeper , more silent? Presentation EWEA Offshore 2013 conference, 19-21 November 2013, Frankfurt, Germany

Zerbst, S. & Rustemeier, J. (2011): Bericht über Messungen des Hydroschalls im Rahmen der Proberammungen für den zukünftigen Offshore-Windpark Baltic II. ISD-A-04/2011, March 2011, 18 pp.

Ziadie, W. (2013). Driving Off Shore Wind Piles Quietly. Presentation BOEM Workshop “Quieting Technologies for Reducing Noise During Seismic Surveying and Pile Driving”, 25-27 February 2013, Silver Spring, Maryland USA

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