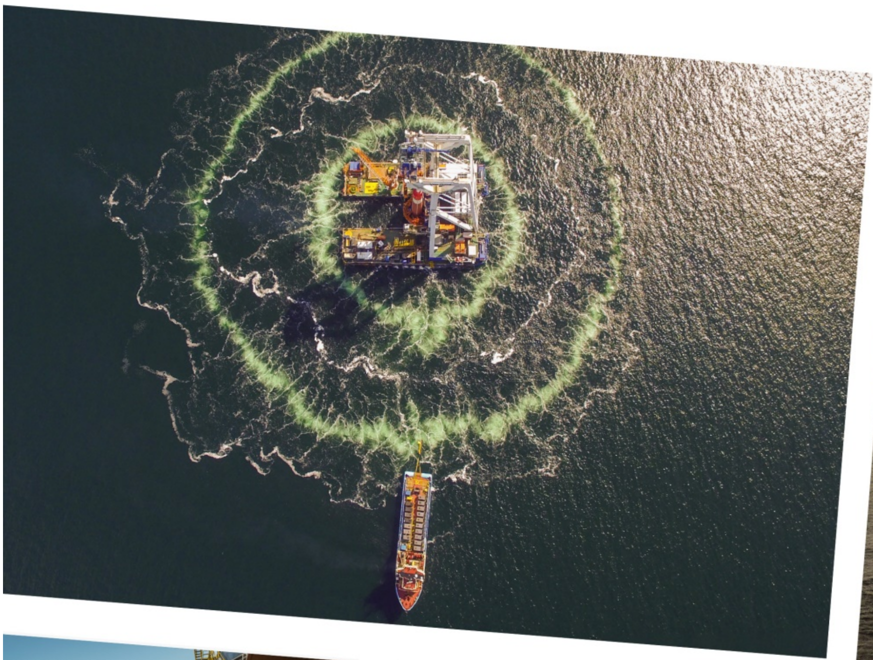
# Noise mitigation for the construction of increasingly large offshore wind turbines

## Technical options for complying with noise limits

**Sven Koschinski & Karin Lüdemann**




Federal Agency for Nature Conservation

Marine Nature Conservation Directorate

Report commissioned by the Federal Agency for Nature Conservation, Isle of Vilm, Germany

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Authors:

Dipl. Biol. Sven Koschinski
Meereszoologie
Kühlandweg 12
24326 Nehmten
sk@meereszoologie.de

Dipl. Biol. Karin Lüdemann
Wissenschaftsbüro Hamburg
Hudtwalckerstr. 31a
22299 Hamburg
luedemann@wissensbuero-hh.de



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# 1. Introduction

Offshore wind energy is expected to make an important contribution in the context of transition to carbon-free energy generation. In the past two decades offshore wind energy has reached its technical maturity and the number of offshore windfarms and power generated has grown exponentially. The power rating per offshore wind turbine has increased considerably, from 660 W (Offshore Wind Farm (OWF) Bockstigen, Sweden – built in 1998) to 6 to 8.4 MW in OWFs currently being built (4C-Offshore, 2019). At the same time the sizes of monopiles and available pile driving equipment has increased making it possible to use XXL monopiles for increasingly large turbine sizes and water depths. Recently built monopile foundations have a diameter of 7 to 8 m and the steel industry is about to provide monopiles of up to 12 m in diameter and 100 m in length for the upcoming generation of 12 to 14 MW wind turbines and for greater water depths. Offshore construction of such large piles will have implications for the noise radiated into the marine environment during impact pile driving (Bellmann et al., 2018). Fig. 1 demonstrates a general interrelation of pile diameter and measured peak and sound exposure levels. Major sound energy is emitted in the low frequency range of about 100-500 Hz (Bellmann et al., 2015).

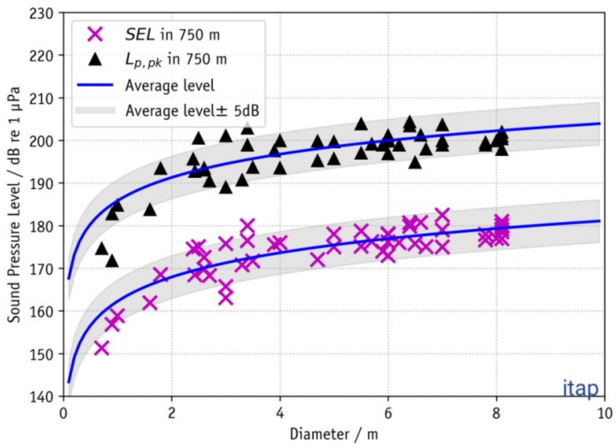



Fig. 1. Measured Peak Levels (LPeak) and broadband Sound Exposure Levels (SEL50) normalised to a distance of 750 m to the source during impact pile driving at various OWFs as a function of pile diameter (Bellmann et al. 2018).

Widespread adverse effects on marine organisms that are exposed to underwater noise have been shown to occur both on a short timescale (acute effects) and on a long timescale (chronic effects). **Fish and invertebrate species** depend on sound for vital functions. To date, around 100 fish and invertebrate species have been shown to be impacted by noise from human activities. These impacts include decreases in growth, body condition, feeding, productivity, abundance, immune competency and nutrition, and catch rates. Underwater noise has the potential to damage ears and other sensory organs (such as statocysts), cause developmental delays and malformations in their larvae, increased stress, and death. In particular, piling noise has an impact on abundance, growth, body condition, anti-predator defense, school coordination and cohesion, and cause masking, barotrauma injuries, stress and indirect trophic (predator/prey) effects (Thomsen et al., 2006; Mueller-Blenkle et al., 2010; Perrow et al., 2011; Casper et al., 2013; Bruintjes et al., 2016; Debusschere et al., 2016; Spiga et al., 2016; Casper et al., 2017; Halvorsen et al., 2017; Herbert-Read et al., 2017; Kastelein et al., 2017; Mahanty et al., 2017; Spiga et al., 2017). Impulsive noise, such as piling, as well as continuous noise have also been shown to impact ecological services provided by invertebrates such as water filtration, sediment mixing, and bio-irrigation which is key to nutrient cycling (Roberts et al., 2015; Solan et al., 2016). Management implications include the apparent inefficacy of ramp ups, intermittent sounds producing slower behavioral recovery, and drilling likely being less impactful than piling, especially if periods of rest between sessions are allowed (Neo et al., 2014; Neo et al., 2016). Impacts from particle motion, through the seabed or water, also need to be assessed (Weilgart, 2018).

With respect to underwater noise effects (at both, individual and population level) a particularly well investigated **marine mammal species** is the harbour porpoise. Impact pile driving has the potential to scare harbour porpoises away at distances > 20 km (Tougaard et al., 2009; Dähne et al., 2013). Research shows that noise mitigation measures can contribute much towards marine mammal conservation in windfarm construction areas. By the use of noise mitigation measures, the zone of responsiveness of harbour porpoises can be significantly decreased. At Dantysk wind farm (built in 2013 with bubble curtains employed as a noise mitigation technique) the range of deterrence was reduced to 12 km and responses lasted until 5 hours after cessation of piling. Elevated swimming speeds and increased feeding activity after cessation of pile driving indicate that porpoises were probably not able to feed during piling operations and the lost opportunities for feeding had to be compensated for (Dähne et al., 2018). Since harbour porpoises have very high food requirements, this makes them especially vulnerable to disturbance (Wisniewska et al., 2016). This predisposition can result in long term energetic consequences of disturbance, even when using noise mitigation.

Besides noise mitigation measures, acoustic deterrents (such as seal scarers) are being used prior to the start of piling in order to keep harbour porpoises out of the zone of hearing loss. However, the range of deterrence by these devices may also result in similar effects as mitigated piling noise. This has management implications with respect to specifications of scaring devices (Dähne et al., 2017; Dähne et al., 2018). To assess possible population consequences it is furthermore necessary also to take into account the observed behavioural reactions of porpoises to mitigated pile driving (using various mitigation measures) because the type of mitigation system is critical for the frequency content of the received noise.

Countries such as Germany, Belgium, the Netherlands, United Kingdom, Denmark, Japan, South Korea and Taiwan have introduced legal restrictions for underwater noise to protect marine wildlife and thus an increasing need to mitigate underwater noise arises. For example, in German waters a mandatory threshold of 160 dB (SEL) and 190 dB (peak-to-peak) at a distance of 750 m during pile driving has been established in 2008 for the protection of marine mammals. Today the implementation of technical noise mitigation systems is a standard requirement at offshore construction sites. A reliable compliance with the threshold is safeguarded by procedures including releases of tranches of 8-10 wind energy converters at a time and the obligation to deliver efficiency control reports based on in-situ measurements (Zeiler, 2018).

Several technical noise mitigation systems have the potential to reduce noise emissions during impact pile driving of offshore wind turbine foundations. Earlier reports have compiled information on such technical noise mitigation methods but also on alternative low-noise foundations (Koschinski and Lüdemann, 2011; 2013; OSPAR Commission, 2016). Due to the rapid and dynamic development of offshore wind and noise mitigation, an update is worthwile.

Several parameters influence the resulting noise levels such as pile diameter, water depth, soil structure and blow energy. The more energy is required to drive larger piles into the substrate, the less likely it is that existing mitigation methods alone will be suited to meet current noise standards in the future. For this reason the Geman Federal Agency for Nature Conservation organised an international conference on *Noise mitigation for the construction of increasingly large offshore wind turbines - Technical options for complying with noise limits* which took place in Berlin from November 22 to 23, 2018.

The aim of the conference and this report is to revisit the issue of underwater noise mitigation in the light of an anticipated further increase in turbine size. We describe and analyse the effectiveness of existing noise mitigation measures and readyness for use with increasingly large monopiles. Monopiles have by far the most extensive experience in the construction of offshore wind farms. Thus, they form the basis for comparative considerations. More experience is needed and explicitly desired with foundation types other than the monopile in order to make them a reliable, safe and economically viable alternative to the standard monopile and provide a benefit for the marine environment. This report gives a general view on the suitablity of existing noise mitigation methods for the piling of so-called "XXL monopiles" and alternative low-noise foundations for increasingly large turbines.

The noise mitigation systems are based on various principles. Here we distinguish between **primary and secondary noise mitigation**. Whereas primary noise mitigation counteracts the generation of noise directly at the source, secondary noise mitigation reduces the radiation of noise by placing noise barriers at some distance from the pile. During piling, about 1 % of the impact energy on the pile is transformed into unwanted underwater noise by oscillating circumferential expansion along the length of the pile caused by the hammer strike (Elmer et al., 2012). Some of this noise radiates through the water column whereas another part radiates through the water saturated ground in a specific way and may again couple to the water column at some distance (Dahl and Reinhall, 2013). This effect may limit secondary noise mitigation in their effectiveness if not explicitely addressed by the method.

Reliable and accurate prediction models to enable a prognosis of the noise levels prior to construction are available to assess the noise emission and configure possible mitigation measures. State of the art numerical prediction models have proven to be especially capable for this task, as they allow for a detailed consideration of the applied hammer technology, the pile geometry, possible noise mitigation measures as well as the specific propagation conditions in both water column and soil (Lippert, 2018).

In addition to noise mitigation methods, several alternative low-noise foundation types exist or are under development. Using these methods, wind turbines can be founded without impact pile driving and therefore less underwater noise generation is expected. Ideally, no additional noise mitigation will be required.

During the installation, continuous rather than impulsive sound is emitted at varying levels and including various frequencies. Due to major differences in acoustic properties the impact of continuous sound of a given level cannot be directly compared to the impact of impulsive sound of the same level. Thus, possible effects, especially with respect to disturbance must be addressed in future scientific studies and the regulatory framework.

In each of the chapters on noise mitigation measures, a technical description and a brief description of the underlying noise mitigation principle is given. Further, the experience from tests or projects and the noise reduction are being described. The development status and the suitability for XXL monopiles is also given. In the chapters on low-noise foundations, the scalability for increasingly large wind turbines is briefly analysed on the basis of information presented at the conference.

The noise reduction achieved is given as the ΔSEL, i. e., the difference between sound exposure level normalised to a distance of 750 m of piling with and without noise mitigation. Depending on the mitigation method, it may not be possible to measure these at the same pile and thus, in some cases it is given in comparison to a similar reference pile. The difference in peak sound pressure level is usually larger than the ΔSEL, but it is a very sensitive metric with a (large uncertainty). If a number of noise mitigation systems are used in combination, the combined ΔSEL is smaller than the sum of each separate noise mitigation measures. Decibel values for noise reduction are project and site specific and thus cannot be guaranteed.

The compilation of secondary noise mitigation methods starts with three methods which already can be considered state of the art under conditions typically found in the North Sea: big bubble curtains, isolation casings and Hydro Sound Dampers. The remainders are not arranged according to their relevance or state of development. Secondary noise mitigation methods are followed by primary noise mitigation methods and alternative low noise foundations or noise-free foundations. The boundary between the two latter is not sharp as the biological significance of sounds generated during their deployment has not been well studied yet.

## 2. Big Bubble Curtain (BBC)

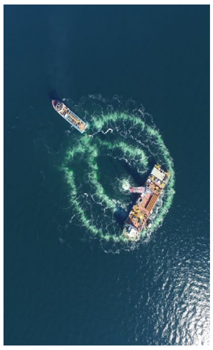
**Type of Noise Reduction:** Secondary

**Noise Reduction Principle:** Reflection, scattering and absorption (frequency dependent)

**Combination with:** E.g., single, double, triple application, isolation casing, HydroSound Dampers, reduced blow energy, prolonging pulse duration

**Noise Reduction:** Single: up to 15 $dB_{SEL}$ (depth: 25m), double: up to 18 $dB_{SEL}$ (40 m)

**Development Status:** State of the art (up to ~40 m water depth, ~8 m pile diameter)





Technical Description

A BBC is formed by bubbles freely rising from a weighted nozzle pipe on the sea floor at larger distance to a monopile, tripod or jacket foundation. Its design must ensure that the BBC is fully closed around the entire structure to avoid noise leakage. In order to ensure a uniform pressure distribution, the diameter of the nozzle opening increases from the feed points. A pipe-laying vessel with a driven winch fitted with hydraulic or pneumatic brakes aids the circular or eliptic pipe installation. Compressors located on the vessel are used to feed air into the nozzle pipe. Operational depth is limited. The optimum pressure difference between pressure inside the hose and hydrostatic pressure is 3 to 4 bar (Nehls et al., 2016). Further, sufficient air volume stream must be provided. At greater depth an increased air volume stream (and thus more compressors) is needed due to compressibility of air bubbles. During rising their volume increases and bubbles split. Bubble drift by currents requires the use of an elliptical nozzle pipe. Principal mechanisms responsible for the noise reduction depend on the frequency content of the radiated sound. A broad range of frequencies is attenuated by the impedance mismatch between water and the bubbly layer (water + air). This causes wave reflections and scattering at the interface between the two media. At higher frequencies, acoustic stimulation of bubbles close to their resonance frequency additionally reduces the noise by means of absorption (Tsouvalas and Metrikine, 2016). In contrast to noise mitigation systems close to the pile, seismic waves such as bottom-generated Mach waves re-entering the water column (Nedwell and Howell, 2004; Stokes et al., 2010; Reinhall and Dahl, 2011; Dahl and Reinhall, 2013) can also be mitigated by large diameters of the BBC. This increases its overall noise reduction potential which otherwise would be limited due to recoupling of seismic waves.

Experience

**Big bubble curtains** have been applied as an effective noise mitigation technique at >700 piles in the North and Baltic Seas in single or double applicaton (Bellmann et al. 2018). The installation process can be adapted to construction activities. Two complete redundant bubble curtain systems on the pipe-laying vessel can be installed revolvingly. Installation can be done before or after the installation vessel is in position and thus time delays can be kept low. Tractive forces causing material fatigue can deform the nozzles requiring redrilling to keep noise reduction constant between locations (Nehls et al., 2016).
**Little Bubble Curtains** (with bubbly water close to the pile) have been applied experimentally in the German test field *alpha ventus* and the OWF *BARD Offshore 1* (Betke and Matuschek, 2010; ITAP, 2013) but not further developed for commercial use.

Noise Mitigation

Over 2,000 measured data sets at distances between 50 m and 5,000 m to piles are available, inside and outside the BBC, as well as pressure and air flow measurements inside the nozzle pipe. As a single application with an air volume stream of 0.3 $m^3$/min*m, the noise reduction (ΔSEL) was in the range of 11-15 dB at 25 m water depth, decreasing with depth (8-14 dB at ~30 m and 7-11 dB at ~ 40 m). A **double BBC** increased the noise reduction by an additional ~3 dB. With a larger air volume stream (> 0.5 $m^3$/min*m) required for deeper water, a maximum ΔSEL of 18 dB was measured at ~ 40 m and a mean ΔSEL of 15-16 dB at >40 m. However, this value is based on few measurements only. Decreased noise reduction has been found in cases of strong currents or sub-optimal configuration (Bellmann et al. 2018). This observation demonstrates that project specific configurations are necessary. In double applications the distance between nozzle pipes must be large enough to allow for the formation of separate bubble curtains (Fig. 2). Best results were achieved with a distance between pipes larger than the water depth (Nehls et al., 2016). Frequencies best attenuated are those above ~1 kHz, however, differences between individual BBCs have been measured (Dähne et al., 2017) (Fig. 2). These product-specific mitigation properties can be particularly important with respect to harbour porpoise disturbance which is strongest at >1 kHz (Dyndo et al., 2015).

Development Status

The BBC is the best-tested and proven noise mitigation technique for OWF foundations such as jackets, tripods or monopiles. Today's BBC systems are robust and the entire handling of the BBC can be done independently of the jack-up rig. All of the currently available big bubble curtain systems are reusable. Major costs are generated by the supply of bubble curtains with compressed air. Up to a water depth of ~30 m the BBC can be considered state of the art because, with an optimised system, a ΔSEL of 15 dB (single) to 18 dB (double) can be reliably achieved. Due to decreasing effectiveness in deeper waters, a ΔSEL of 15 dB can be challenging and a project specific adaptation/optimization is required (Bellmann et al., 2018). BBCs will have to be customised for each project.

Suitability for XXL monopiles

Larger wind turbines may not only be installed using larger monopiles but also at increasing water depths, which both can be challenging. Double or even triple BBCs offer options for larger monopiles. The BBC can further be combined with other noise mitigation measures to meet legal standards at larger water depths or with larger pile diameters which may emit higher noise levels (Bellmann et al., 2018). To increase the noise reduction, BBCs have so far been combined with additional noise mitigation by isolation casings (Ch. 3), HSD (Ch. 4) or reduced blow energy (Ch. 16).

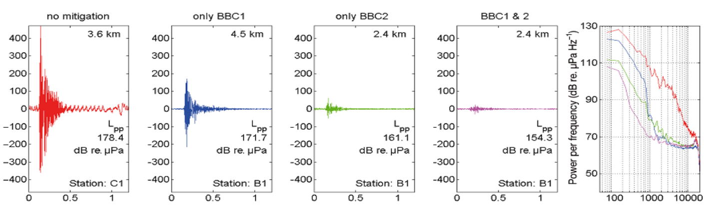



Fig. 2. Double BBC combined with HSD at OWF Veja Mate (left, © Hydrotechnik Lübeck GmbH), recordings of pile driving at OWF DanTysk using 0 to 2 BBCs at distances between 2.4 and 4.5 km and power spectral densities (Dähne et al., 2017). BBC1: System Weyres, air volume stream 0.11 m³/m min-1, BBC2: System Hydrotechnik Lübeck, air volume stream 0.43-0.52 m³/m min-1.

## 3. Isolation Casings

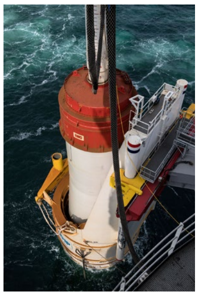
**Type of Noise Reduction:** Secondary

**Noise Reduction Principle:** Shielding, reflection

**Combination with:** Additional built-in features, (double) BBC, reduced blow energy, prolonging pulse duration

**Noise Reduction:** 13-16 $dB_{SEL}$ (depth: <40 m)

**Development Status:** State of the art (up to ~40 m water depth, ~8 m pile diameter)



© Ørsted

Technical Description

An isolation casing is a shell-in-shell system around the pile in which a shielding effect of the casing reduces the radiated noise. The IHC Integrated Monopile Installer including the Noise Mitigation Screen (NMS) (Fig. 3) has a number of additional built in features which aid in decoupling radiated noise from the water column close to pile. Its features are an acoustically decoupled doublewall with an air-filled interspace and a bubble curtain inside the casing which reduces coupling of sound pressure waves to the steel shells by absorption, scattering and dissipation effects (Gündert et al., 2015). Impedance mismatch further causes reflections at phase transitions between water, air and steel. The pile is inserted into the Integrated Monopile Installer from the top. It provides accurate pile positioning and pile inclination measurement. An acoustically decoupled pile guiding system centralizes the pile. The Integrated Monopile Installer is available for various water depths and for pile diameters ranging from 0.6 m to 8.8 m (currently used up to 8.0 m) using sizeable shells.

Experience

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 Ø 5.7 m resp. 6.5 m, hammer: IHC S1800). The dimensions of the IHC NMS were: 30 m x Ø10 m, 360 t. Until now, the Integrated Monopile Installer with NMS has been successfully applied in over 450 pile installations for pile diameters of up to 8 m with a very low rate of malefunctions (<1%). It can be completely integrated into the installation process keeping installation time short. Compared to piling without noise mitigation, there are no additional weather restrictions due to the deployment. So far, the system has been applied at water depths up to 45 m. Jacking up the installation vessel can compensate for water depth differences between locations within a wind farm (van Vessem and Jung, 2018).

Noise Mitigation

By combining several principles of noise reduction in various layers around the pile, isolation casings such as the NMS are capable of a high noise reduction comparable to or exceeding that of a bubble curtain (Ch. 2), (Elmer et al., 2007a; CALTRANS, 2009). The noise reduction by the NMS measured in various commercial OWF projects was in the range of 13 to 16 $dB_{SEL}$ even at a water depth of up to 40 m. At higher frequencies (≥ 500 Hz) the NMS achieves noise reductions of 40 dB and more in individual third octave bands (Gündert et al., 2015), (Fig. 3). Noise mitigation is also insensitive to currents (Bellmann et al., 2018). Due to their principle of inhibiting noise radiation at close range, seismic sound waves can couple to the water at some distance which would limit the overall noise reduction (Dahl and Reinhall, 2013; Chmelnizkij et al., 2016) which is, for compliance purposes, usually measured at a standardised distance of 750 m. In combination with a double BBC, a ΔSEL between 18 and 20 dB has been achieved at a water depth of ~40 m. Up to 25 m depth a slightly higher ΔSEL could be achieved.

An additional feature which allows for further reducing the noise is the reduction of blow energy (“HiLo piling”). In this piling method, the blow rate is increased and the energy per strike reduced. A reduction in blow energy by 50 % would achieve further 2.5 dB in ΔSEL (Bellmann et al., 2018). A disadvantage is that the number of strikes is increased, and probably also the duration per monopile installation.

<u>Development Status</u>

The Integrated Monopile Installer with NMS is a proven technology which has shown its ability to substantially reduce piling noise. In over 450 successful applications of the NMS, its suitability for offshore applications, manageability, flexibility in construction logistics and safety has been demonstrated. It is state of the art up to a water depth of about 40 m and a pile diameter up to about 8 m. It has been proven a robust and reliable system which has no impact on installation times. It is reusable and cost-effective.

<u>Suitability for XXL monopiles</u>

In contrast to a BBC, noise mitigation by an NMS is largely independent of water depth (Bellmann et al. 2018). To increase the noise reduction, NMS have so far been combined with additional noise mitigation by (double) BBCs (Ch. 2), or reduced blow energy (Ch. 16). Prolonging the pulse duration is another possibility to further reduce the noise level (Ch. 7). Early experiments using this principle reached a ΔSEL of up to 7 dB, but struggled with the durability of pile cushion material such as steelwire, wood, nylon and Micarta (Laughlin, 2006; Elmer et al., 2007a). The company IHC IQIP currently develops a method using water as a pile cushion called “PULSE”. This has been successful with an S-90 hammer and a test pile (Ø 1m) and resulted in a ΔSEL of 6 – 9 dB and also less material fatigue compared to a reference pile. Upscaling for XXL monopiles would require an additional weight of 108 t and height of the hammer of 3.2 m (van Vessem and Jung, 2018). With increasing pile lengths the crane may reach its limit and the installation process may need some adaptations: depending on the availability of installation methods the NMS may have to be put over the pile (such as already done in the OWF Riffgat) instead of inserting piles into the NMS from the top (current method).

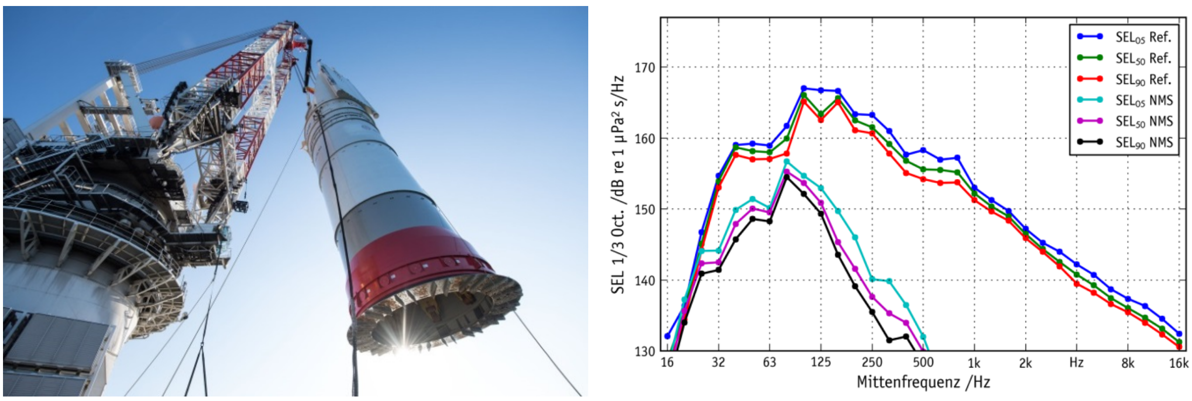



Fig. 3. Monipile installation at the OWF Borkum Riffgrund 1 using the Integrated Monopile Installer with NMS (left, © Ørsted). Frequency spectra (SEL third-octave band level) of ramming noise with and without NMS at OWF Borkum Riffgrund 1, measured 750 m from the pile given as percentiles (right, Gündert et al. 2015).

## 4. Hydro Sound Dampers

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**Type of Noise Reduction:** Secondary

**Noise Reduction Principle:** Scattering and absorption by resonators, reflection, dissipation and material damping (frequency tuning possible)

**Combination with:** BBC, reduced blow energy, prolonging pulse duration

**Noise Reduction:** 10-13 $dB_{SEL}$ (depth: <45 m)

**Development Status:** State of the art (up to 40 m water depth, ~8 m pile diameter)

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Technical Description

Hydro Sound Dampers (HSD) are sizeable gas filled elastic balloons and robust PE foam elements fixed to a ballasted net. The net is in a basket under the pile frame which is lowered to the sea floor by means of winches (Fig. 4). The pile is inserted from the top. The HSD system has a relatively low weight of 16 to 60 t. The main principle is based on absorption, scattering by excitation of elements at their resonant frequencies and material damping. In addition, reflection occurs at the transition from water to air (Elmer et al., 2012). HSD foam elements additionally act as impact absorbers by means of material damping. The frequency of maximum noise mitigation is adjustable by the use of various sizes of elements. The resonance frequency decreases with element size. Elastic balloons must be sized according to increasing water depths due to compressibility by hydrostatic pressure. This customisable design enables mitigating noise at specific frequencies adjusted to conservation requirements, e. g. reduction at low frequencies representing maximum piling energy, or at higher frequencies to reduce harbour porpoise disturbance (Dähne et al., 2017; Tougaard and Dähne, 2017).

Experience

HSD have been successfully applied with >340 piles in various commercial offshore windfarms at water depths up to 45m and pile diameters up to 8 m with a very low rate of malefunctions (<1%). Each application requires a project specific design (Bellmann et al., 2018).

Noise Mitigation

Noise reduction by HSD is largely independent of water depth and currents. The overall noise reduction (ΔSEL) at 750 m measured in offshore windfarm projects is in the range of 10 to 13 dB even at great depth (Elmer 2018). Depending on the size of HSD elements, noise can also be reduced at very low frequencies (< 100 Hz) where piling energy is at a maximum (Bellmann et al. 2018). At the OWF Amrumbank, the noise reduction at specific frequencies between 100 and 800 Hz reached a ΔSEL of >20 dB (Bruns et al., 2014). In combination with a double BBC (Ch. 2) a ΔSEL of 18-24 dB has been achieved with a pile diameter of 7.8 m at a water depth of 40 m (Elmer, 2018). HSD can be adjusted to unwanted ground coupling effects (concept in Fig. 4).

Development Status

Hydro Sound Dampers have often been used and tested in piling applications. HSD are available on the market and are considered state of the art noise mitigation with pile diameters of up to 8 m and a water depth of <45 m. The system is lightweight, cost-efficient (no compressors needed) and the handling of the system does not lead to larger delays of the piling operations. Current HSD-Systems are applicable for monopiles up to 10 m. Due to the lightweight structure using openable net baskets, there is practically no size limit. For larger depths practicability and efficiency still remain to be proven.

Other than in BBC (Ch. 2), no depth dependence of efficiency has been found (Bellmann et al., 2018). HSD systems will have to be customised for each project. The number of HSD elements per area must be weighed against desirable noise reduction and buoyancy.

Suitability for XXL monopiles

Currently available HSD net baskets can be used with monopile diameters up to 10 m. For larger diameters, specific adaptations are needed. There are already concepts for HSD nets to be used with larger monopile diameters at increasing water depth. Larger HSD elements for depths up to 50 m have already been developed. Increasing the water depth from 40 to 50 m would result in up to 35 % more volume of HSD nets and 35 % more weight of HSD baskets. Current crane capacity would not allow for inserting very long monopiles from the top. An openable HSD basket already allows inserting monopiles of unlimited length from the side. In 2017, two monopiles (Ø 7.5 m) per day have been installed in the OWP Arkona in the German Baltic Sea using the openable HSD-System for XXL monopiles (Elmer, 2018). To increase the noise reduction, HSD can be combined with a BBC (Ch. 2), prolonging pulse duration (Ch. 7) or a reduced impact energy (Ch. 16).

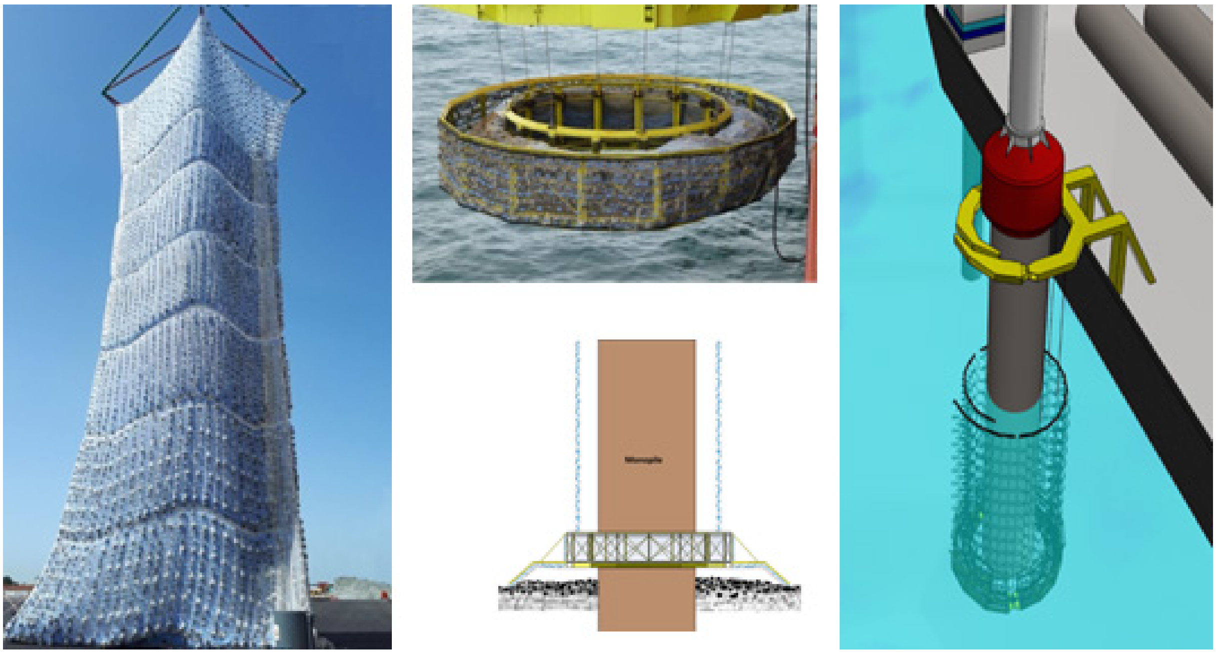

Fig. 4. HSD net for a water depth of 40 m with larger HSD elements on the bottom (due to compressibility with hydrostatic pressure (left). HSD basket below pile frame (center, top). Concept of a HSD basket covering the sea floor close to the pile in order to mitigate also ground coupling effects (center, bottom). Concept of an openable HSD basket for very long monopiles to be inserted sideways (right). © K.-H. Elmer, OffNoise Solutions.

## 5. Dewatered Cofferdams

**Type of Noise Reduction:** Secondary

**Noise Reduction Principle:** Decoupling noise from the water column

**Combination with:** BBC, HSD, reduced blow energy, prolonging pulse duration

**Noise Reduction:** Up to 23 $dB_{SEL}$ (depth: 15 m)

**Development Status:** Monopile full scale prototype tested offshore in 2011, state of the art in substations

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Technical Description

A cofferdam is a steel tube surrounding the pile from seabed to surface decoupling pile vibrations from water by means of a dewatered annular gap and thus effectively reducing sound energy transfer (Fig. 6). The air fully separates the pile surface from sea water. The pile is centred with a guidance system (McKenzie Maxon, 2012; Thomsen, 2012). The cofferdam needs to be sealed effectively at the bottom and dewatered by pumps (Thomsen, 2012) or overpressure (Frühling et al., 2011; Heerema Marine Contractors, 2013). A cofferdam which has been used for offshore platforms is based on the principle of Pile-in-Pipe Piling. The noise mitigation system is integrated into the base frame foundation as protective pile sleeves reaching beyond sea level (Fig. 5). In this particular case, piling occurred only above sea level (Frühling et al. 2011).

Experience

Offshore wind farm applications of cofferdams have been used for jacket installations of platforms (BorWin beta and DolWin alpha converter platforms at a depths ≤40 m and HelWin alpha cable access tower and piles with a Ø up to 3.2 m) (Wijk, 2013). For DolWin alpha platform the jacket leg itself was dewatered using air inlets on the top and outlets and seals at the bottom of the jacket leg (Fig. 5, top). Due to special underwater jacket configuration for BorWin beta platform an external cofferdam was used as an extension on top of the pile sleeve which did not extend above the water (Fig. 5, bottom).

In 2011 and 2012, full scale prototype monopiles have been installed using cofferdams in Aarhus Bight (pile length 36 m, pile Ø 2.13 m, cofferdam Ø 2.5 m, water depth 15 m,) and at the OWF Anholt (pile Ø 5.9 m, cofferdam Ø 6.3 m, water depth 19 m) (McKenzie Maxon, 2012; Thomsen, 2012). However, the Anholt pilot test was not successful because protrusions of the pile which were not designed for use with a cofferdam resulted in an inappropriate cofferdam design with large seals at the bottom. As a consequence of pile positioning off the center, the seal failed and the annular gap was not completely dewatered.

Noise Mitigation

The measurements at the Aarhus Bight test pile confirmed a high noise reduction potential of cofferdams (ΔSEL = 23 dB) which however is compromised in the case of direct contact between the pile and the cofferdam (ΔSEL = 13 dB) (McKenzie Maxon, 2012). It seems that the failure of the seal, which could have been prevented by adaptation of the pile design to the cofferdam, disrupted the industry's confidence in this noise mitigation system. To the knowledge of the authors there are currently no cofferdam applications in offshore windfarm construction.

Suitability for XXL monopiles

Foundations using cofferdams for noise mitigation are scalable. However, water pressure acts against the seal from the bottom and thus their size and the hydrostatic pressure are limiting factors.

If used with larger monopiles it is of particular importance that the engineering of the piles and their corresponding cofferdam must be matched closely. Jacket foundations provide another option for large wind turbines to avoid technical challenges with large monopiles. A concept study for a jackets foundation for water depths up to 30 m with pile sleeves extending above the water to be used as cofferdams similar to proven platform technology (pile-in-pipe-piling) is available (Frühling et al., 2011).


Fig. 5. Schematic drawing (top left) and application of jacket legs extending above the water surface and thus acting as cofferdams at Dolwin alpha (top middle); air hoses for dewatering the pile sleeve (top right) at DolWin alpha; Installation of a cofferdam extension on top of the pile sleeve (bottom left) and piling through the complete cofferdam at BorWin beta (bottom right) © TenneT

Fig. 6. Cofferdam application with monopile (left: Aarhus Bight, right: OWF Anholt) ©K.E. Thomsen

## 6. Double Piles/Mandrel Piles

**Type of Noise Reduction:** Secondary

**Noise Reduction Principle:** Decoupling of noise radiation in water and sediment

**Combination with:** E.g., BBC, HSD, reduced blow energy, prolonging pulse duration

**Noise Reduction:** 16 $dB_{SEL}$ (depth: 10 m)

**Development Status:** Two full-scale tests successfully performed nearshore


© J. Laughlin, WSDOT

<u>Technical Description</u>

The double pile consists of two concentric steel piles flexibly connected by a special driving shoe, assuring that there would be no pile-to-pile contact during driving. This allows for an air gap between the two tubes. The inner pile is equipped with a reinforced toe that serves as a sealing to prevent water intrusion. A hydraulic impact hammer strikes the inner pile only which pulls the tethered outer pile along into the sediment. The noise mitigation principle is the decoupling of sound from the water and also the substrate. Depending on the pile design, the inner tube (mandrel) can be removed after the pile has reached its final penetration depth. The mandrel can be re-used repeatedly (Reinhall et al., 2015).

<u>Experience</u>

Two full-scale tests of various configurations of double-walled piles with an outer diameter of 0.8 m were performed at different locations in Puget Sound, Washington at 10 m and 8 m water depth. The inner pile was driven using a single acting impact hammer with a maximum energy of 154 kJ, resp. 275 kJ. The first test was performed in soft sediment whereas the substrate at the second test site consisted of dense glacial deposits.

<u>Noise Mitigation</u>

The primary source of underwater noise from pile driving is associated with circumferential expansion along the length of the pile caused by the hammer strike. The air gap and the flexible coupling of the double pile prevent the radial expansion wave from interacting with the water and the sediment. Other than the cofferdam (Ch. 5), the double pile also addresses the propagation of Mach sound waves directly from the sediment (Reinhall and Dahl, 2011). These could otherwise bypass other secondary noise mitigation systems deployed close to the pile which shield the noise radiation in the water column only. In the first full-scale field test, the ΔSEL (measured at 500 m distance) was 16 dB (Reinhall et al., 2015). A second field test reveiled a lower noise reduction due to unexpected steel-to-steel contact between double pile and a template making the interpretation difficult (Reinhall et al., 2016).

<u>Development Status</u>

After finite element simulation and prototype testing, in 2014 and 2015 two full-scale test piles were successfully driven at two sites with different soil types in nearshore environments. In the second test it was shown that the pile capacity of the novel piles was comparable to that of a control pile with the same outer diameter (Reinhall et al., 2015; Reinhall et al., 2016).

<u>Suitability for XXL monopiles</u>

So far, only piles with small diameters (0.8 m) were built. The scalability remains to be shown in further applications.

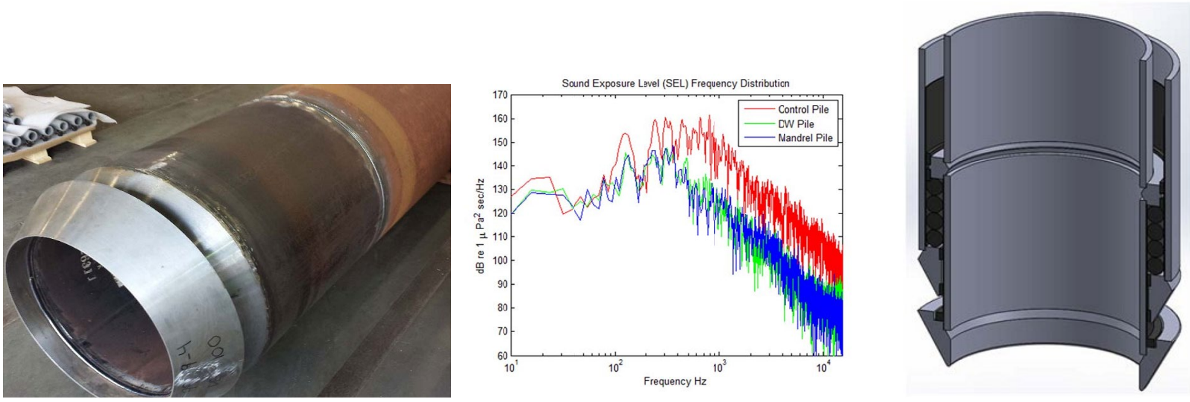


Fig. 7. Double pile stem with driving shoe (left), SEL frequency distribution (middle) during piling of control pile (red) and double pile configurations (green and blue), ( Reinhall et al., 2015). Schematic of flexible coupling to connect outer and inner pile in the driving shoe (right, Reinhall et al., 2016).

## 7. Pulse prolongation by adaptation of hydraulic hammers

| | |
|---|---|
| **Type of Noise Reduction:** Primary<br>**Noise Reduction Principle:** Prolongation of the pulse duration<br>**Combination with:** All secondary noise mitigation methods<br>**Noise Reduction:** ~9 $dB_{SEL}$ (as suggested by numerical prediction model)<br>**Development Status:** Concept, under development | |

Early experiments making use of pulse prolongation were made with small piles using pile cushions of a steel wire, plywood, nylon and Micarta between piston and pile. The principle of this method consists of reducing the driving force while acting on the pile over a longer period. Application of pile cushions reached ΔSELs between 7 dB for steel wire and 26 dB for wood. However, these experiments struggled with the durability of pile cushion material and safety issues (Laughlin, 2006; Elmer et al., 2007b).

The company IHC IQIP currently develops an adjustable cushioning method using a liquid between pistons to reduce the generation of noise. This addon for a standard hammer (called PULSE, Piling Under Limited Stress Equivalent) requires 4 % more energy. Installed in an IHC S90 hammer (PULSE weight 1 t, height 1 m) an additional noise reduction (ΔSEL) of 6-9 dB has been measured. A 10 % efficiency improvement in pile driving time and reduced material fatigue could be achieved. It is currently upscaled for use with the largest hammer (S4000 hammer) expected to be ready by the end of the year 2019. The expected noise reduction (ΔSEL) is 4-6 dB. Dimensions of the PULSE system for this hammer are an additional 108 t in weight and 3.2 m in length (van Vessem and Jung, 2018).

The company MENCK is developing a noise reduction unit (MNRU) using a number of metal blocks placed between the ram weight which is accelerated by the hydraulic fluid and the anvil which transfers the impact energy to the pile (Fig. 8) (Steinhagen, 2019). Damping the contact force between anvil and pile using this method also reduces material fatigue of the pile. The MNRU can simply be added to existing standard hydraulic hammers. By the use of the MNRU, the efficiency of the hammer is slightly reduced (in a model from 97 to 84 %). By the use of a sufficient hammer size, it can be safeguarded that the pile is still driveable. For a 6.5 m monopile and a 3500 kJ hammer a numerical model predicted a ΔSEL of 9 dB and a Δpeak of 11 dB. The duration of the energy transfer into the pile during a pile strike is almost doubled by the MNRU and noise emissions are shifted to lower frequencies (Steinhagen, 2019).


Fig. 8. View of a standard hydraulic impact hammer and a modified hammer (right) with a MENCK Noise Reduction Unit (MNRU) added between ram weight and anvil (left, © MENCK) and IHC S-90 hammer with added PULSE system in black housing (middle) and cross-sectional view (right, © IHC IQIP).

## 8. BLUE Piling

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**Type of Noise Reduction:** Primary

**Noise Reduction Principle:** Prolongation of the pulse duration

**Combination with:** All secondary noise mitigation methods

**Noise Reduction:** 19-24 $dB_{SEL}$ (depth: 22.4 m)

**Development Status:** Full scale prototype successfully tested under offshore conditions, improvements on technology currently studied and implementation

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© Fistuca BV

Technical Description

Another method using the principle of pulse prolongation (Ch. 7) is BLUE piling. The innovative *BLUE 25M* hammer uses a large water column to generate the driving force. Sea water inside a steel tube closed at the bottom is pushed upwards and allowed to fall on the pile. The resulting pulse drives the pile in the ground. This cycle is repeated until the pile reaches its desired depth. The acceleration is much lower compared to a hydraulic impact hammer (Winkes, 2018). During the piling process seawater is added, thereby gradually increasing the blow energy as needed. The principle of primary noise reduction is the prolongation of the pulse duration. In BLUE piling, the pulse duration is increased by a factor of up to 20 compared to a hydraulic hammer. When the impact energy is distributed over a longer period, the maximum impact force and thus the amplitude of the lateral extension of the pile is reduced. At the same time the spectrum emitted is shifted to lower frequencies because the oscillation period of compression waves in the pile is prolonged (Fig. 9). The reduced propagation velocity of the lateral extension directly decreases the sound emission (Elmer et al., 2007a; Elmer et al., 2007b). Lower pile vibrations also reduce the pressure amplitude in the seismic component of radiated noise (Reinhall and Dahl, 2010; Dahl and Reinhall, 2013). The gradual increase in force also reduces material fatigue by lowering the tension stress on the pile. No stiffeners are needed on the internal platform and the piles can be driven fully assembled with all appendages.

Experience

BLUE piling uses a completely different method for pulse prolongation than the other techniques of pulse prolongation described in Ch. 7. A number of nearshore and offshore tests with various hammer sizes were conducted. In the most recent test in summer 2018 the function of the BLUE 25M hammer prototype could be proven. The blows were about 100 ms long (compared to about 8 ms of a hydraulic hammer). Additional work is still needed to increase the capacity and reliability. Further testing is being planned.

Noise Mitigation

Direct comparisons between conventional and BLUE piling methods are difficult as this would require switching the equipment at the same pile. An offhore test with a pile (Ø 6.5 m), reveiled the best noise reduction in third octave level bands between 100 Hz and 4 kHz compared to a reference pile driven conventionally in the same waters (Fig. 9). The SEL in these third octave band levels were up to 24 dB lower. With respect to broadband values (10 Hz-20 kHz) ΔSEL was 19-24 dB. In >95 % of all blows, the noise level measured at a distance of 750 m was below 160 $dB_{SEL}$.

Development Status

In summer 2018, a full scale prototype of the BLUE 25M has been tested under offshore conditions. Before it is ready for the market, improvements and additional tests are needed (Winkes, 2018).

Suitability for XXL monopiles

According to the manufacturer, the BLUE 25M hammer is already capable of driving the largest piles as they deliver over six times more energy than the largest available hydraulic hammers. Its rated maximum energy is 25 MJ. It still remains to be shown whether the legal noise standards can be met without additional external noise mitigation methods and how noise reduction changes with increasing depth. However, since BLUE piling is a primary noise mitigation method, it would be promising to be combined with secondary noise mitigation methods such as the BBC (Ch. 2) , HSD (Ch. 4) or isolation casings (Ch. 3) to reach very high ΔSELs in future applications.

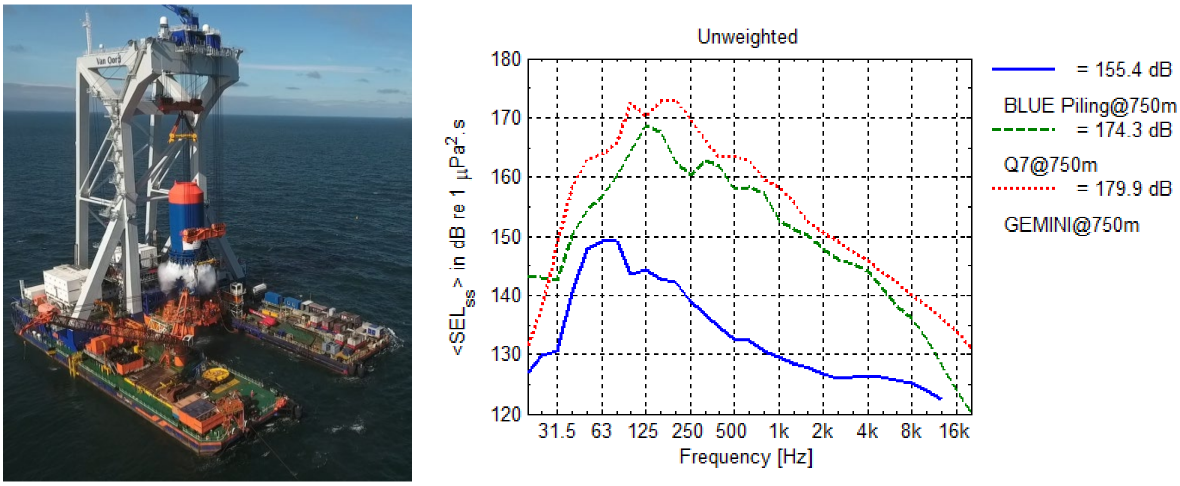



Fig. 9. Draining of seawater from BLUE 25M hammer upon completion of piling operation (left). Frequency spectrum of BLUE piling compared to impact piling at two reference piles (right, note different dimensions: BLUE Piling test: Ø6.5 m, water depth 22 m; reference Gemini OWF: Ø 6.6 m, water depth 30 m; reference Q7 OWF: Ø 4 m, water depth 19-24 m), © Fistuca BV.

## 9. Vibropiling

**Type of Noise Reduction:** Primary

**Noise Reduction Principle:** Alternative piling method using low frequency oscillations

**Noise Reduction:** 10-20 $dB_{Leq,\ 30s}$ (depth: <25 m)

**Development Status:** Proven technology in combination with impact piling. Exclusive vibopiling: Offshore pilot wind turbine with monopile successfully installed in Dutch waters. Ø 7.5 m monopiles in pilot OWF projected for early 2021

Image from: Elmer et al. 2007a

Technical Description

Vibropiling is a technique using flexural oscillations which reduce cohesion in the pile-soil boundary and enable penetration into a sandy seabed by means of rotating eccentric weights operating at low frequencies (<20 – 40 Hz). The main energy is radiated at lower frequencies compared to impact piling. Noise emissions are limited to operating frequencies and their harmonics (Elmer et al., 2007a). Sound waves below a lower cut-off frequency do not propagate in shallow waters. As a result, high peak levels can be avoided and continuous sound levels can be kept low. If obstacles are discovered during installation the procedure can be reversed and the pile retrieved. To increase the centrifugal force, multiple vibratory hammers can be linked to one unit (Saleem, 2011).

Experience

There are long-standing experiences of vibropiling from various offshore projects. In various OWFs, the technique has been applied in combination with impact piling. Exclusive vibropiling does not allow for standard verification of load bearing capacity using the relation of blow count and penetration depth. In a number of OWFs, piles of various sizes have been partly driven by vibropiling: e. g., three piles nearshore at Hooksiel demonstrator (Ø 3.35m), two monopiles at the OWF Anholt (Ø 5.3 m, one pile met refusal just before before target depth) (LeBlanc Thilsted, 2013), 18 tripod pinpiles at the OFW alpha ventus (Ø 2.6 m,), and 30 monopiles at the OWF Riffgat (Ø 5.7 m) (Gerke and Bellmann, 2012). Soil parameters (lateral stiffness, resistance to driving) at vibrated piles in the OWF Anholt were at least equal to those of impact driven piles and showed no indication of sand loosening. In 2014, six piles (Ø 4.3 m) were installed onshore within soil conditions comparable to average North Sea soil conditions with saturated, glacial sands in a sandpit near Cuxhaven using vibropiling down to full penetration depth of 18.5 m. Lateral load testing revealed results comparable to impact driven piles. Vibropiling can be significantly faster and noise levels are reduced compared to impact piling. Material fatigue in vibrated piles is significantly below that of impact driven piles. In 2014, all 196 pinpiles of the 49 jacket foundations (Ø 2.4 m, water depth 22-25 m) in the OWF Nordsee Ost have successfully been vibropiled to app. 1/3 of final depth. Afterwards the piles have been hammered to final depth. A condition monitoring system has been installed at 5 of the jackets which measures the foundations' load reactions also enabling to derive the structural response of the foundations (Meyer, 2018).

Noise Impact

At the OFW Riffgat the median broadband equivalent continuous sound levels (Leq, 30s) measured at a distance of 750 m was 145 dB re 1µPa. The frequency spectrum shows strongest noise emissions in the operation frequency of 17 to 18 Hz and its harmonics. Noise emissions from vibropiling are in the order of 10 to 20 dB (Leq,30s) below mitigated impact pile driving at identical monopiles (Gerke and Bellmann, 2012) (Fig. 10). In other projects, noise emissions were in the same order. In all projects, noise emissions varied considerably (Elmer et al., 2007a; Betke and Matuschek, 2010; Kringelum, 2013). Some noise peaks resulting from a rattling sound created by loose connections of the vibrohead have been reported (Meyer, 2018). When the penetration of the pile slows down towards the end of vibropiling or in cohesive soils, harmonics at higher frequencies up to ~10 kHz or increasing sound levels (<16 dB at the OWF Anholt) have been reported (Elmer et al., 2007a; Betke and Matuschek, 2010; Kringelum, 2013). Vibropiling produces continuous noise. A direct comparison of noise levels to those from impulsive noise of impact piling is not possible and does not allow assessing consequences for the marine environment. Thus, the impact of vibropiling on the environment needs to be investigated. Depending on conservation objectives, a combination of vibropiling and impact piling may (at higher costs) contribute to overall reductions in the noise budget as the installation is quicker and fewer strikes are needed for subsequent impact piling. This can reduce the risk of injury because with increased blow numbers, the energy accumulates in mammals' ears (Southall et al., 2007). Concrete piles which are less resonant than steel piles can also be vibrated into the ground and thus noise can be further reduced.

Development Status

Combined with impact piling, vibropiling can be considered proven technology for OWF foundations. The equipment is market-available. Due to easier and more reliable handling, shorter installation times, lower energy demands and material savings, OWF foundation piles exclusively driven with vibro hammers can be a more cost-effective method which generates lower noise levels compared to impact piling. No full-scale OWF has been installed yet by exclusive vibropiling. Further comparative studies on the applicability of standard design procedures in fully vibropiled piles as well as on pile-soil interactions of vibrated vs. driven piles are underway. Successful onshore and offshore tests with monopiles and jacket pinpiles have been conducted. For early 2021 the first OWF (Kaskasi II) with fully vibropiled monopiles (Ø up to 7.5 m) is projected at a water depth of 18 to 25 m (Meyer, 2018).

Suitability for XXL monopiles

Depending on soil conditions, there is practically no limit to pile diameter as the force can be increased in a multiple application (Saleem, 2011). During airport construction off Hainan, China, XXL piles (Ø 30 m, 34 m long) have been vibrated to target depth successfully (Ziadie, APE, pers. comm.).

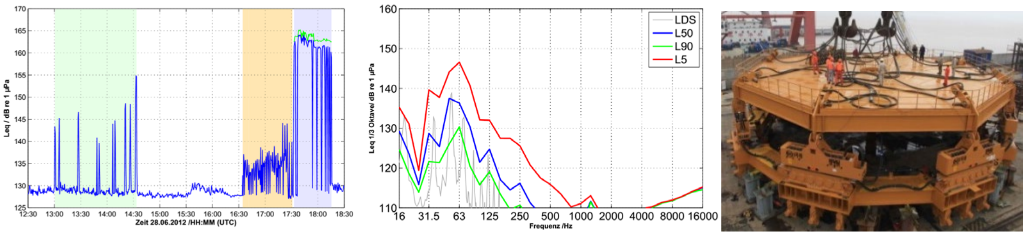


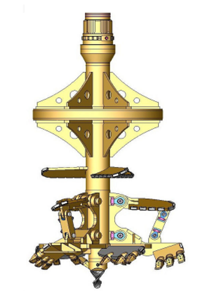

Fig. 10. Measured broadband noise levels (left, blue line: Leq 30s, green line: single strike SEL) at 750 m; OWF Riffgat Ø5.7m monopiles (green: four piles fully vibrated, orange: seal scarer, blue: impact pile driving with noise mitigation). Frequency spectrum measured over 98 min (middle, Leq given as 5, 50 and 90 % percentiles in third-octave levels and with 1 Hz resolution (LDS), 30 s intervals (ITAP 2012). Eight vibratory hammers in a multiple application for XXL monopiles with Ø 22 m (right, ©American Pile Driving Equipment Inc., Bill Ziadie).

## 10. Drilled Foundations

**Type of Noise Reduction:** Primary

**Noise Reduction Principle:** Alternative low-noise foundation

**Development Status:** State of the art e. g., for open hole drilling in hard substrate and drive-drill-drive (relief drilling inside impact driven piles). Successful full-scale onshore test of drilling/mixing technology for grouting jacket pinpiles in sandy sediments. Vertical Shaft sinking Machine Drilling has been tested onshore.



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Various equipment are currently in use in diverse offshore drilling applications such as drilling in hard substrates (bedrock, sandstone, limestone or mixed layers), relief drilling inside a pile when resistance is met and impact piling ceases, or even drilling and installing piles in sandy sediments. **Hard substrates** cannot be penetrated by impact piling. Several drilling methods are available. Fugro Seacore uses a drilling tool extension (underreamer) underneath the pile which creates an overcut and allows drilling exactly the pile diameter. Additional vertical thrust can be exerted on the pile using hydraulic forces to allow for better penetration (Koschinski and Lüdemann, 2013). An underwater drill rig *Bauer BSD 3000* for water depths > 60 m and for drilling Ø 2 m jacket pinpiles into rocky subsoils withstands strong currents. A recoverable conductor casing in a template ensures stability during drilling and grouting the pile into the borehole which has a slightly larger diameter than the pile (Scheller, 2018). The **Drive-Drill-Drive** method combines impact piling or vibropiling with drilling. When resistance is met, the material inside the pile is drilled out. The *Dive Drill* is suitable for **various soil conditions**. A temporary casing is installed by means of a casing oscillator which enables penetration of the casing into the borehole which is drilled using an underreamer. After drilling, the pile is inserted, grouted and the temporary casing recovered. Due to limited diameters of drills they are applicable for e.g., pre-piled jackets. In **sandy sediments**, it is required that the bearing capacity is increased by mixing the loosened soil with cement slurry which is then pushed out into the anulus and grouts the pile in place. This is enabled by a specific drilling method, the *MIDOS* (*Mixed Drilled Offshore Steel*) pile system: An extendable drilling and mixing tool is inserted in a structural casing used as e. g., a pinpile for prepiled jackets. This method is usually applied with 30 to 45 m long and Ø 2 m to 2.5 m piles with a ~0.4 m larger tip to create an anulus.

Experience

Vertical offshore drilling is frequently being used in seabeds not driveable by impact piling. Due to low noise and vibration, drilling is increasingly used for environmental reasons. Commissioned in 1998, the Swedish OWF Bockstigen was the first project with drilled monopiles in limestone. Its five 550 kW turbines have been repowered in 2018 and the towers maintained (www.4Coffshore.com). Since then, experience has been gained in various projects using diverse types of drilling equipment. Relief drilling (Drive-Drill-Drive) has been applied at the OWFs Beatrice, North Hoyle, Gunfleet Sands and Teeside installed on seabeds with mixed layers of sand, boulder clay and sand stone with pile diameters up to 4.7 m. *BSD 3000* has been successfully used for the first time for the foundation of a tidal turbine off the Scottish coast in bedrock at a depth of 37 m in 2011 (Scheller, 2018). In a field test in the Persian Gulf, the capacity of the MIDOS Pile was seen to perform well (GDG, 2019).

Noise Impact

Underwater drilling noise emissions depend, i.a. on the type of equipment and soil. Noise emissions are from drill head, crusher box, casing oscillator, machines, air lift or pumps. Sound pressure levels of underwater bedrock drilling with the BSD 3000 measured at 100 to 500 m distance were between 120 and 140 dB (Leq). Back-calculations reveiled a best fit source level of 167.8 dB (1 s integration). A similar level was calculated based on measurements of structure- and water-borne sound during drilling of a Herrenknecht Vertical shaft Sinking Machine (VSM) in the underground of Naples (Ø 5 m, 25 m below groundwater level). Based on these data the potential noise emissions in an offshore application were predicted as 160 dB (Leq) at 1 m or 117 dB at 750 m (Koschinski and Lüdemann, 2013). Drilling generates continuous noise whose impact on the marine environment is not directly comparable to that of impulsive noise (Southall et al., 2007) and thus needs to be investigated.

Development Status

There are two technologies currently available for the installation of drilled and grouted piles: (1) Dive Drill with casing oscillator in which the borehole is always supported by a temporary casing, and (2) Top Drill with sacrificial casing in loose material on top of the rock or open hole drilling in rock. Relief drilling can be done inside Ø 7 m monopiles. The MIDOS Pile designed for embedding Ø 2.5 m jacket pinpiles in sand was successfully tested in a full-scale test onshore. Herrenknecht Offshore Foundation Drilling with VSM, a hydraulically controlled telescopic boom with rotary grinder drilling inside and underneath a monopile, has been tested in a large-scale onshore experiment (two drilled monopiles at scale 1:8) in 2012 (OSPAR Commission, 2016). The design is fully developed and awaits the next step to a full-scale pilot project (B. Jung, Herrenknecht, pers. comm.). Van Oord's (formerly Ballast Nedam's) concrete drilled monopiles (OSPAR Commission, 2016) are at concept stage.

Suitability for XXL wind turbines

Market available drilling technologies for application in sand which is the prevailing condition in the North Sea (e.g., MIDOS Pile) are currently only suited for jacket pinpiles. Jackets are scalable for larger turbines. Offshore Foundation Drilling with VSM is currently a concept for Ø 10 m monopiles and is scalable for even larger monopiles. Scalability and noise reduction potential may in future outweigh the disadvantage of likely longer installation times. The Fugro Seacore leader leg pile handling system enables vertical drilling for large monopiles without the use of cranes. The system consists of two vertical leader legs with a gripping and hydraulic lifting unit (OSPAR Commission, 2016).

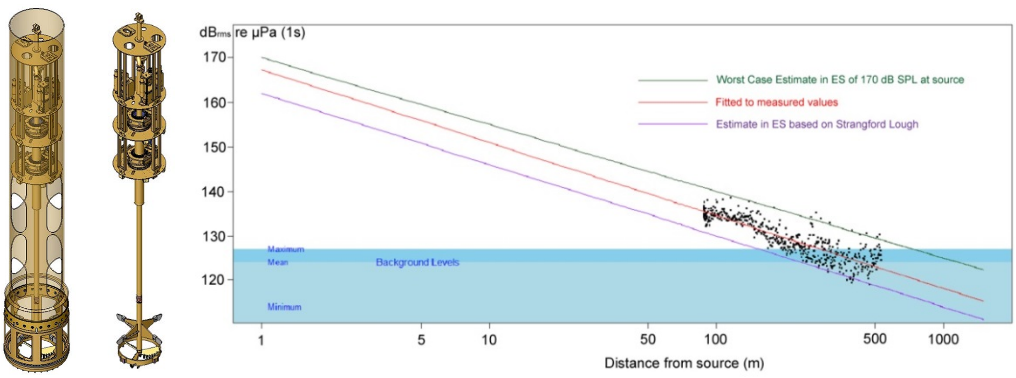



Fig. 11. MIDOS pile with drilling and mixing tool inside the structural pile (left, © BAUER Spezialtiefbau GmbH). Noise measurements of BSD 3000 drilling noise in rock (right, Scheller, 2018).

## 11. Gravity Base Foundations

**Type of Noise Reduction:** Primary

**Noise Reduction Principle:** Alternative foundation type

**Development Status:** Proven technology at water depths of up to ~40 m. Full scale prototype of Cranefree gravity base successfully installed, viable commercial design for water depths up to ~ 70 m.



Technical Description

Gravity base foundations are large reinforced concrete or steel/concrete hybrid structures whose stability is achieved by the submerged weight of the structure, supplemented by additional ballast (e. g., sand). Available models differ in shape and production details (Koschinski and Lüdemann, 2013). Production takes place onshore and the foundations are shipped to the offshore location where they are deployed on the seabed. The tower and the wind turbine are either pre-installed onshore or installed on the foundation after deployment. As an example, the bottle-shaped self-installing floatable Seatower Cranefree gravity base foundation is towed to the OWF site. It is lowered onto a pre-installed gravel filter layer by letting seawater fill the hollow foundation. It is thereafter fixed to the seabed by ballasting it with sand through a pipe. A steel skirt penetrating into the sediment provides additional stability to the structure. By reversing the process, the foundation can be quickly decommissioned after its lifespan of ~50 years (Halldén, 2018).

Experience

Gravity base foundations have been installed in several OWFs, predominantly in the Baltic Sea at water depths of up to 40 m, e. g. at Vindeby, Tunø Knob, Nysted, Sprogø, Rødsand and Middelgrunden in Denmark, Lillgrund in Sweden, and in the North Sea at Thornton Bank in Belgium and Blyth in the UK. The foundations mostly consist of a ground plate with open cave chambers and a shaft reaching beyond the water surface. A Cranefree gravity base foundation weighing approx. 1,500 tons has been installed with a meteorological mast at Fécamp OWF site in the British Cannel at a water depth of 30 m (Halldén, 2018; 4C-Offshore, 2019). Depending on the conservation objectives, the footprint of foundations may be an issue. E. g., in areas with a sensitive seabed fauna, this may be a disadvantage. Its dimension depends on the design of the foundation itself and the scour protection which may also be needed. However, footprints of gravity base foundations are not necessarily much bigger than those of monopiles. Prevention of noise and full and easy decommissioning are among the advantages of gravity base foundations.

Noise Impact

No specific sound measurements during the course of construction of gravity base foundations are available. No impulsive sound is emitted. Apart from ship noise, additional continuous noise is to be expected from soil preparation and creation of the filter layer. Noise emissions may also be produced by dynamic positioning systems of working ships, or if dredgers are used for soil preparation. But this may apply to a number of foundation variants and is not specific for gravity base foundations. A simple comparison of absolute noise levels to those from impulsive noise of impact piling does not allow assessing consequences for disturbance of marine animals.

Development Status

Gravity base foundations have been used for offshore wind turbines in many cases and are therefore a proven technology in water of up to about 40 m (Blyth Offshore Demonstrator Project Array 2). In the offshore oil and gas business, similar gravity base foundations are state of the art even in deep water. The Cranefree gravity base foundation is a commercially viable design engineered for various sizes and water depths (Halldén, 2018). Its design allows for absorption of static and dynamic loads. Effective serial production, eliminating the need for specialized installation vessels and saving material due to the use of a steel skirt are elements of the cost optimised concept. Several demonstration projects have proven the gravity base technology, including with 8.3 MW turbines.

Suitability for XXL wind turbines

As an example for gravity base foundation, the Seatower Cranefree foundation has been engineered for turbine sizes of 6 to 15 MW and higher and for water depths ranging from ~20 m to ~ 70 m. Its design allows for scaling it up for larger turbines (Halldén, 2018). In contrast to impact pile driven monopiles, noise emissions during construction are low and not expected to increase with size and depth.

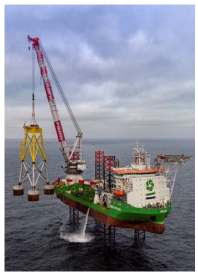
Fig. 12. Cranefree gravity base foundations: concept for an OWF using gravity base foundations (left). Construction of a foundation with a metmast in Fécamp, France (middle). Towing the metmast and its foundation to sea (right). © Seatower A/S.

## 12. Suction Bucket Jacket (SBJ)

**Type of Noise Reduction:** Primary

**Noise Reduction Principle:** Alternative low-noise foundation

**Development Status:** Proven technology with 32 turbines successfully installed since 2014. Further development may be needed due to currently limited experience.





Technical Description

Suction installed foundations, commonly referred to as suction buckets, suction caissons, suction piles or suction anchors, have been widely used in the offshore industry since the 1980's for a range of applications. Whilst the name used to describe these foundations may vary, they all share a common installation procedure whereby the principle of suction, generated by a pressure difference between the inside of an upside-down positioned bucket and the hydrostatic pressure at the seabed, leads to the structure being installed without any use of mechanical force. A key difference between suction installed and other foundation types is that the installation design and the installation process have a direct influence on the dimensions of the foundation. The installation process is highly dependent on soil type and soil strength and installation specific risks, such as the presence of hard inclusions (e. g., boulders), must be considered. For windfarm applications in shallow waters (water depths < 100 m), suction installed foundations generally have a larger footprint (to increase the installation driving force) and a lower length to diameter ratio compared to their use in the oil and gas industry. As a consequence, there are some limitations for the use of suction buckets compared to monopiles. In addition to the installation design requirements, lateral loads acting on the wind turbine generator result in axial forces on the buckets (via a push-pull mechanism, see Fig. 13) which can only be compensated for by spreading the forces over a larger area, which may further increase the overall jacket footprint (maximum plan area of the jacket, approximately 30m in diameter for the Borkum Riffgrund 1 SBJ). It follows that the installation process is potentially riskier due to the larger volume of soil in contact with the structure (as there is a higher risk of ground variability, of hitting a boulder or encountering a 'hard inclusion'). Furthermore, suction bucket jackets (SBJs) may not be suited for locations with large sand waves or high seabed mobility (due to their shallow embedment). They also require more scour protection than other foundation types. Due to the low hydrostatic pressure available there are installation challenges in very shallow water (water depths < 20m). Whilst these limitations need to be considered, reversing the installation process could allow repositioning and reinstalling of an SBJ if significant installation challenges are encountered, although this is not well proven (Ørsted, 2019). Similarly, reversing the suction process allows for full decommissioning of suction installed structures (OSPAR Commission, 2016).

Experience

Depending on site-specific conditions and country specific requirements, the SBJ is one of a range of alternative foundation solutions to the commonly used monopile foundation for locations where monopiles are not appropriate. Ørsted installed the world's first SBJ for an offshore wind turbine generator at the Borkum Riffgrund 1 OWF in Germany in 2014. Since then, SBJs with three suction buckets supporting a jacket structure have been deployed successfully at Borkum Riffgrund 2 (2018; 20 positions) and Aberdeen Bay (2018; 11 positions) OWFs. Thus, there is still limited industry experience relating to the design, fabrication and installation of SBJs in the offshore wind sector. This is especially true when compared to monopiles for which the complexity of installing has become well understood and manageable in practice. In contrast, the installation process for SBJ structures is yet to become standard practice and is thus considerably more complicated in practice than the installation process of monopiles (Ørsted, 2019).

Noise Impact

For the installation, underwater suction pumps are needed. In noise measurements at the OWF Borkum Riffgrund 2 the average sound pressure level ($L_{eq}$50) at a distance of 750 m did not differ from the background noise (137 dB). Noise of suction pumps could not be measured >500 m from the source. A slight increase of the 95 % percentile of the sound pressure level ($L_{eq}$95) was likely related to other sources on the installation vessel (Shonberg and Beeken, 2018). It must however be taken into account that the measured background noise at the site does not represent virgin conditions but was influenced by construction activities. Overall, suction bucket foundations are low-noise foundations.

Development Status

Suction buckets are suited to certain soil conditions such as sand, silt or clay. Their size and design is directly linked to water depth and soil conditions. Suction bucket jackets have demonstrated the potential for low-noise and quick installation times. Significant steps have been taken in the design aiming at increased competitiveness. For example, the SBJ used at Borkum Riffgrund 2 OWF was optimised with respect to weight and material use compared to the first full scale prototype (Shonberg and Beeken, 2018). The SBJ is proven technology in deepwater oil and gas application and for OWF substation platforms. The technology has successfully been transferred to offshore wind turbine jackets in shallower waters (Aberdeen Bay: depth range 23-29 m, Borkum Riffgrund 1 and 2: depth range 23-29 m). As is the case for most alternative foundation types, there is still limited installation experience.

Suitability for XXL wind turbines

The SBJ can be viewed as one of a range of foundation solutions to be used for locations where monopiles are not appropriate for various reasons, including compliance with noise protection standards. The SBJ is currently used with turbines of a capacity of up to 8.8 MW (4C-Offshore, 2019) and can be scaled for the use of larger turbines. With growing wind turbine generator size, the SBJ is an alternative to monopile foundations.

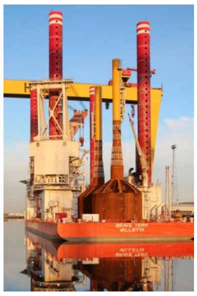
Fig. 13. Installation of a suction bucket jacket (left, OWF Borkum Riffgrund 2, © Ørsted). Idealised SBJ loading (right, OWF Borkum Riffgrund 1, Ørsted (2019)).

## 13. Mono Bucket Foundation

**Type of Noise Reduction:** Primary

**Noise Reduction Principle:** Alternative low-noise foundation

**Development Status:** Full scale prototype successfully installed nearshore in 2002, three foundations for met mast installed in the period from 2009 to 2017 before full and successful decommissioning, a significant number of offshore trial installations, two offshore pilot wind turbines scheduled for 2019.



© Universal Foundation

Technical Description

A Mono Bucket foundation is a steel caisson which is installed in the seabed by suction pumps. The resulting pressure difference between the inside and the outside of the caisson, and the self-weight of the structure, enables penetration into the seabed. Reversing the installation process allows repositioning in the case of unacceptable inclination or incomplete penetration, and full and easy decommissioning after operational lifetime. Bucket foundations (also called suction anchors, suction caissons, suction buckets) are commonly used in the offshore oil and gas industry for fixed and floating platforms. For wind turbines, currently two types of bucket foundations exist: the Mono Bucket and the three-or-four-legged suction bucket jacket (SBJ) using multiple buckets (Ch. 12). The Mono Bucket foundation can be levelled during installation by software-controlled pumps that secure verticality. Scour protection is an integral feature of the foundation by use of web structure on the top of the Mono Bucket (Fig. 14) (Jacobsen, 2018).

Experience

The Danish company Universal Foundation has successfully installed various prototypes of Mono Bucket foundations. Some of them have also successfully been decommissioned. Some of these Mono Buckets carried meteorological towers (met masts). In 2002, a 3.0 MW wind turbine (hub height 89 m) on a Mono Bucket foundation (Ø 12 m, height 6 m, weight 135 t) has been successfully installed in marine sediments in a polder near Frederikshavn (Ibsen et al., 2005) and is still in operation (Jacobsen, 2018). This demonstrates the developed design procedure for load handling, as well as that the use of Mono Buckets is also possible in very shallow water. The Carbon Trust recently published *Suction Installed Caisson Foundation Design Guidelines* (Cathie et al., 2019) to inform about the use of bucket foundations.

Noise Impact

The installation of a suction bucket does not require impact driving. The sound emissions from the electric suction pumps are generally lower than the measurable background noise at an offshore wind construction site, and hence noise emissions during Mono Bucket installation are very low compared to conventional concepts (e.g. monopiles). The pumps produce continuous noise which, in terms of threshold values, is not directly comparable to that of impulsive noise and thus needs further investigations.

Development Status

More than 2,000 bucket foundations have been installed in oil and gas activities worldwide. Suction buckets have demonstrated the potential for low-noise and quick installation in particular ground conditions such as sand, silt or clay. The application of Mono Buckets has the potential to lower the installation costs significantly, as no additional noise mitigation is needed. Since the first full-scale Mono Bucket installation in 2002, wind turbine sizes have increased and the technology has proven to be scalable to resist the corresponding increasing design loads. A full scale pilot of two 8.4 MW MHI Vestas V164 turbines is fully certified and financed and projected for installation in 2019 in the OWF Deutsche Bucht at 40 m water depth (Jacobsen, 2018).

Suitability for XXL wind turbines

The Mono Bucket is an alternative to a monopile foundation. The Mono Bucket is currently scaled for the use of 8.4 MW turbines. Designs for future challenges such as increasing turbine size, deeper waters and new regional challenges as earthquake and typhoon conditions are currently underway (Jacobsen, 2018).

Fig. 14. Installation of a Mono Bucket after full decommissioning (left). Design of a Mono Bucket carrying a wind turbine (right) , ©Universal Foundation.

## 14. Floating Wind Turbines

**Type of Noise Reduction:** Primary

**Noise Reduction Principle:** Alternative foundation type

**Development Status:**
Semi-submersible platform: WindFloat: successful 5-year full life cycle demonstation of full-scale prototype completed
Tension leg platform: experimental stage with downscaled models (TLP)
SPAR buoy: first commercial deep water OWF fully commissioned in 2017 (HYWIND)



Technical Description

There are various platform types for floating wind turbines using different stabilisation mechanisms. A **SPAR buoy** is a **ballast-stabilised** deep water application consisting of a ballasted hollow steel cylinder. Due to its vertical position the draft is very deep and thus it is suited for deep waters only (100 to >700 m). The **tension leg platform (TLP)** is a **mooring stabilised** platform which is vertically moored by multiple tethers held under tension. The balance of forces between buoyancy force and tensioning force makes the overall system very stable against wind and wave forces. This semi-submerged platform is suited for water depths > 20 m. Tethers can be connected to suction anchors, small drilled or impact driven piles or counterweights. A **buoyancy-stabilised** concept is that of wind turbines mounted on **semi-submersible platforms**. In some platforms, trimming tanks keep the inclination small and prevent swaying. There have been diverse concepts for type and arrangement of turbines such as vertical axis turbines (TWINFLOAT), downwind turbines (Fukushima FORWARD), multiple turbines (TWINFLOAT, WINDSEA) or conventional off-the-shelf wind turbines.

Experience

Of the various floater concepts, semi-submersibles and SPAR buoys have been most thoroughly tested. The **semi-submersible** 2 MW prototype WindFloat has produced 17 GWh in up to 12 m high waves and withstood fatigue of up to 17 m high waves and wind speeds up to 60 knots. The turbine and the floating platform moored by four drag embedded anchors and its trimming system performed well. During its deployment off the Portuguese coast (water depth 43 m) from 2011 to 2016 has demonstrated a full life cycle from installation to decommission (Martins, 2018). Other full-scale demonstrators have been commissioned in Japan (1 x 2 MW downwind turbine, Fukushima FORWARD, 2013; 1x 7 MW, Fukushima FORWARD, 2015 and removed in 2018; 1 x 3 MW Kitakyushu Demonstrator under construction (4C-Offshore, 2019). After successful tests of a 1:3 scaled prototype for a hybrid wind-wave power generator in Denmark since 2013, *Floating Power Plant* projects two full-scale prototypes *P80* at Dyfed and Katanes (UK) consisting of 2 to 3.6 MW wave energy converters on a semi-submersible platform supporting a 5 to 8 MW wind turbine (Floating Power Plant, 2019). The **SPAR buoy** based full-size prototype HYWIND with a three-point mooring spread and a 2.3 MW wind turbine has been tested off the Norwegian coast at 220 m depth since 2009. It produced > 40 GWh and withstood a maximum wave height of 19 m. In the world's first full-scale commercial floating OWF (HYWIND Scotland), five 6 MW turbines were installed at a depth <120 m in October 2017 (Equinor, 2019). Other full-scale demonstrators have been commissioned in Japan (1 x 5 MW downwind turbine, Fukushima FORWARD, 2016; 1 x 2 MW Sakiyama Floating Wind Turbine, 2012, relocated in 2015 for commercial operation) (4C-Offshore, 2019). On **TLP's** so far only downscaled prototypes (Blue H, Sway) have been tested. A number of projects await full-scale testing, such as GICON-SOF or PelaStar (Walia, 2018; Glosten, 2019).

Noise Impact

Due to a high level of pre-fabrication, the underwater noise during installation is limited to towing and anchoring. Noise emissions of the anchoring process depend on the type of mooring for which solutions such as drag or suction anchors, ballasted weights or small drilled or impact driven piles. Drilled or driven piles are comparable to those of solid foundations in terms of noise emission (Martins, 2018; Walia, 2018).

Development Status

A high level of prefabrication limiting offshore works to a minimum has the potential to make floating wind turbines cost competetive. Technical challenges such as dynamic loads in shallow waters, pitch and roll of turbines, and safe moorings have been extensively tested in various demonstration projects. The WindFloat full-scale prototype demonstrated the full life cycle of a semi-submersible from installation to decommissioning (Martins, 2018). Floating wind turbines are ready for the market, indicated by the first commercial OWF HYWIND Scotland commissioned in 2017. A number of **OWFs with semi-submersibles** are currently planned for the near future: WindFloat Atlantic (3 x 8.4 MW, under construction, depth <100 m), Kincardine (re-installation of the WindFloat demonstrator completed, 5 x 9.5 MW under construction, depth < 80 m), Groix et Belle-Île (approved, 4 x 6 MW, depth < 71 m), Golfe du Lion [Windfloat] (approved, 4 x 6 MW, depth < 80 m), EolMed [concrete platform] (approved, 4 x 6.2 MW, depth < 74 m), New England Aqua ventus (2 x 6 MW). Among current **TLP** demonstration projects are Provence Grand Large (approved, 3 x 8 MW, depth < 104 m), TLPWIND UK (concept, 1 x 5 MW, depth 81 m), GICON SOF (concept, 6-8 MW, 2 test sites).

Suitability for XXL wind turbines

The current state of the development aims at demonstrating the viability of future commercial scale OWFs and verifying new designs up-scaled from the first demonstrators. Based on experiences with full-scale demonstration projects and much larger platforms in the oil and gas industry, floating turbines are scalable (e. g., Glosten, 2019). Scaling WindFloat to 8 MW or 12 MW turbines does not require a change in design (Martins, 2018).

Fig. 15. Prefabrication of semisubmersible WindFloat (left, © Principle Power Inc.). TLP GICON-SOF installation concept with ballast anchor (right, © GICON).

## 15. Push-In and Helical Piles

**Type of Noise Reduction:** Primary

**Noise Reduction Principle:** Alternative foundation type

**Development Status:** Concept

© Heerema Marine Contractors

In a project by Heerema with the aim to reduce or completely eliminate piling noise, two different foundation concepts were developed for seabeds containing sand, clay or combinations thereof. **Push-in pile foundations** (Fig. 16, left) use a static force to drive piles into the seabed. They consist of a cluster of four individual small diameter piles which by use of hydraulic levers are pressed into the sediment. The static force of two piles is used to press one pile in, in an alternating manner. The pushing force can be as high as 3,000 t. The procedure includes a static load test and thus re-strikes are not needed (Ch. 9). The **helical pile foundation** (Fig. 16, right) uses a rotating motion to drive piles fitted with several helical blades into the soil. Due to a high axial capacity, shorter piles can be used compared to conventional piling. An interface with the installation vessel is needed to provide sufficient torque. Both concepts are compatible with current designs, but will require specific tools.

Both foundation types are at concept stage. In the first step it is the aim is to develop the **push-in foundation** for platforms in deeper water, such as in the oil and gas business and offshore substations in the wind industry. For dynamic loads typical for wind turbine foundations, more tests are required once the suitability of the technology can be shown. The installation process of the helical pile, the helical connection and the in-place capacity is to be tested in 2019 in geocentrifuge trials under laboratory conditions, planned at Delft University of Technology and the University of Dundee. Both foundation concepts aim at serving as future alternatives for jacket pinpiles for substations as well as deep water and floating wind turbine foundations of various sizes. The suitability for XXL wind turbines will depend on the jacket foundation design (Huisman and Ottolini, 2018).

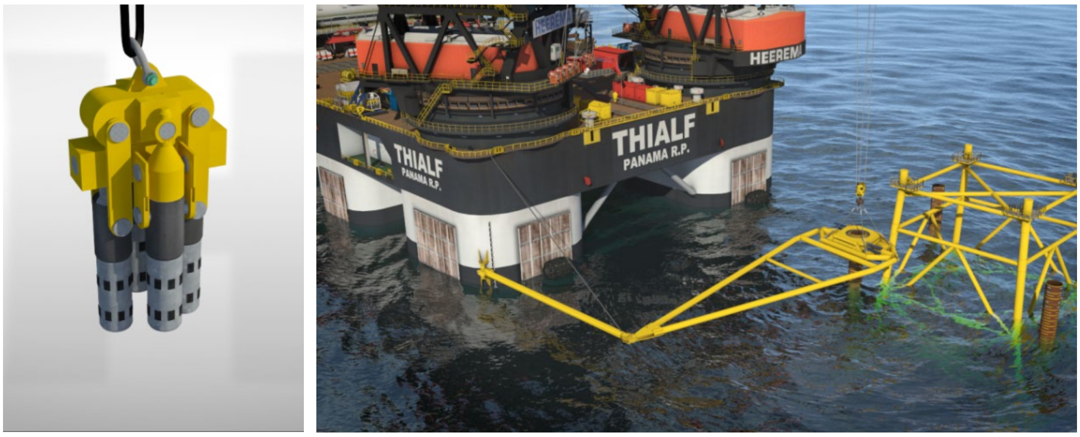



Fig. 16. Concept of push-in piles with specific tool (left). Helical piles as jacket pinpile with rotating tool (right), © Heerema Marine Contractors.

## 16. Further noise mitigation measures and alternative foundation variants

This report concentrates on the methods which were presented at the 2018 conference on *Noise mitigation for the construction of increasingly large offshore wind turbines*. As a consequence, not all noise mitigation measures or concepts could be described in detail.

Reduced blow energy is another primary noise mitigation measure as the radiated noise is a function of blow energy. The blow energy must be high enough to enable pile penetration to the desired depth. It is usually increased during the piling process. In some cases, the use of a higher blow rate enables lower blow energy (e. g., IHC HiLo piling).

Further mitigation methods the authors became aware of during their research of noise mitigation methods and alternative foundations are given in Tab. 1. A number of floating wind turbine projects not mentioned in this report are in their testing phase.

Tab. 1. Further mitigation methods and alternative foundations not mentioned in previous chapters

| **Mitigation system** | **Noise mitigation type** | **More information** |
|---|---|---|
| BeKa Shell | *Secondary* | http://www.weyres-offshore.de/cms/website.php?id=/de/leistungen/entwicklung/eigenentwicklungen.htm |
| HydroNAS, W3G Marine Ltd | *Secondary* | http://www.w3gmarine.com/hydronas.html |
| AdBm-NAS, AdBm Technology | *Secondary* | http://adbmtech.com/technology/<br>https://www.vanoord.com/news/2019-another-innovation-construction-offshore-wind-farms |
| Gravity tripod | *Alternative foundation* | https://www.4coffshore.com/news/newsItem.aspx?nid=13644 |

## 17. Conclusions

Some currently applied noise mitigation systems such as big bubble curtains, isolation casings or Hydro Sound Dampers can be considered state of the art technology for certain water depths and pile diameters. The potential for their improvement when used with growing pile diameters and lengths is given. But there are future challenges to be addressed now. Other systems are still in earlier developmental stages. The diversity of primary and secondary noise mitigation approaches as well as alternative low-noise foundations provide a toolbox to the offshore wind industry to keep the noise impact on marine ecosystems low even with growing turbine sizes. The diversity of offshore conditions at different locations requires individual solutions for different applications. It remains to be seen whether and to what extent existing noise mitigation measures can be further developed to meet legal noise standards and other thresholds when XXL turbines are used. Combinations of multiple noise mitigation measures are already being used with 8 m monopiles. In the future, additional noise mitigation and optimisation of current systems will increasingly become necessary. Combining primary with secondary noise mitigation systems is most promising. Alternative low-noise foundations provide a good alternative to impact pile driving. They do not require additional moise mitigation measures.

However, there are still open questions. Replacing impulsive noise by continuous noise of varying source characteristics and intensities (e. g. in vibropiling (Ch. 9), drilled foundations (Ch. 10), or soil preparation for certain gravity base foundations) also has an impact on the marine environment which has to be critically reviewed. This research area seems to have been rather neglected in recent years. Also, the effect of stretching the sound energy of pile strikes over a longer period (prolonging the impulse duration, Ch. 7 and Ch. 8) needs attention of research and nature conservation management. The role of noise radiation through the seabed which limits the noise reduction of some mitigation systems needs to be further addressed in research projects and modelling approaches. In addition, the impacts of particle motion still need to be better understood.

Other aspects of offshore wind energy foundations to be considered are the size of the footprint of foundations including scour protection (if necessary) and the overall $CO_2$ emission. For wind farm operators and investors, cost-efficiency and safety aspects may be ranked highest.

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