Environmental Impacts of Human Activites

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

2020 update (First published 2014)

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).

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Annex I: Noise Mitigation Measures for Pile-Driving

1 Introduction

The aim of this inventory is to describe technical noise mitigation measures to be ap-plied during pile driving as well as alternative low-noise foundation concepts especially for offshore wind turbines and to analyse their effectiveness and feasibility. Thereby, the correlation between blow energy, sound pressure level and pile diameter (Betke & Matuschek 2010) is taken into account.

Monopiles are the most widely used foundation types in offshore wind farms and companies have by far the most extensive experience in their construction. Thus, they form the basis for comparative considerations with other less common foundation types. As the 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, the following chapters will additionally consider the operational readi-ness for increasingly large monopiles and turbines.

Reflecting the state of the art in the year 2020, the annotated list is a summary of ex-isting practices in the installation of offshore wind turbines and captures science as well as growing industry experience and expertise in developing and applying measures.

The noise mitigation systems are based on various principles. Two fundamentally dif-ferent noise reduction approaches are distinguished. Whereas primary noise mitiga-tion counteracts the generation of noise directly at the source, secondary noise mit-igation 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 radi-ates through the water column whereas another part radiates through the water satu-rated ground in a specific way and may again couple to the water column at some distance (Dahl & Reinhall 2013). This effect may limit secondary noise mitigation in their effectiveness if not explicitly addressed by the method.

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. It is possible to combine noise reduction approaches or methods. However, noise reduction of simultaneously applied methods cannot simply be summed up It is thus of paramount importance to monitor their effectiveness and where required the compliance with legal noise limits using standardised measuring approaches.

Some currently applied noise mitigation systems such as big bubble curtains, isolation casings or Hydro Sound Dampers can be considered as state of the art technology for certain water depths and pile diameters. A comprehensive analysis of data on noise emissions from pile driving and the application these systems during the construction of offshore wind farms from 2012 to 2019 in the German EEZ of the North Sea and the Baltic Sea has recently been published (Bellmann et al., 2020). Their advantages and disadvantages as well as restrictions and technical notes are also reflected in the report.

In addition to noise mitigation methods, several alternative low-noise foundation types exist or are under development. Recently, progress has been made to further develop these methods and experience has been gained in offshore pilot projects or commer-cial applications. Using these methods, wind turbines can be founded without impact pile driving and therefore less underwater noise generation is expected.

The diversity of primary and secondary noise mitigation approaches as well as alter-native 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. Alternative low-noise foundations provide a good alternative to impact pile driving. They do not require additional noise mitigation measures. However, replacing impulsive noise by continuous noise of varying source characteristics and intensities can also have an impact on the marine environment which has to be critically reviewed.

2 Big Bubble Curtains (BBC)

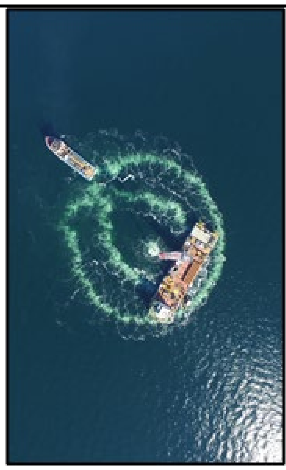
Type of Noise Reduction: Secondary

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)



2.1 Technical Description of the System

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 & 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 & Howell 2004; Stokes et al. 2010; Reinhall & Dahl 2011; Dahl & 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.

2.2 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 & Matuschek 2010; ITAP 2013) but not further developed for commercial use.

2.3 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. 1). Best results were achieved with a distance between pipes larger than the water depth (Nehls et al. 2016). Frequencies best attenuated by the BBC are those above ~1 kHz, however, differences between individual BBCs have been measured (Dähne et al. 2017) (Fig. 1). 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).

2.4 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.

2.5 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).

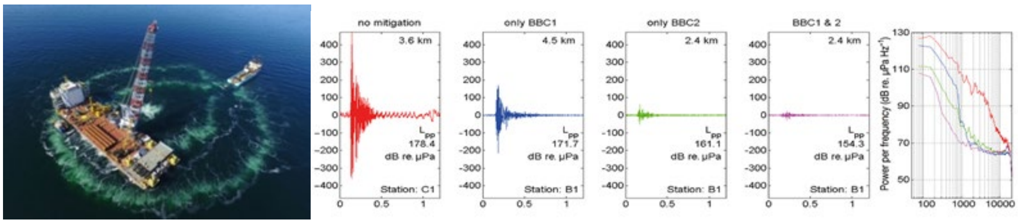


Fig. 1. Double BBC combined with HSD at OWF Veja Mate (left, © Hydrotechnik Lübeck GmbH), recordings of pile driving at OWF DanTysk using 0 to 2 BBCs at distances between 2.4 and 4.5 km and power spectral densities (Dähne et al. 2017). BBC1: System Weyres, air volume stream 0.11 m³/m min-1, BBC2: System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

3.1 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. 2) 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.

3.2 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 & Jung 2018).

3.3 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. 2). 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 & 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.

3.4 Development Status

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.

3.5 Suitability for XXL monopiles

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 & 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).

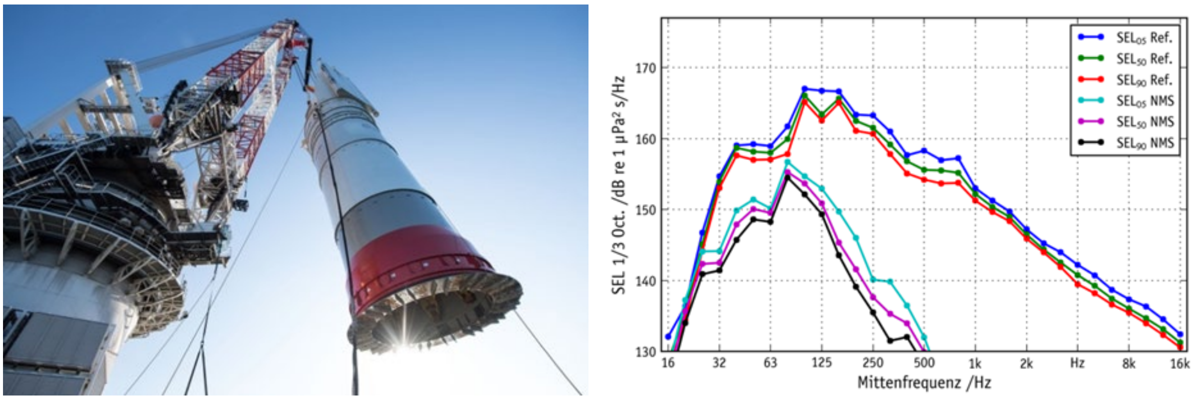


Fig. 2. Monopile installation at the OWF Borkum Riffgrund 1 using the Integrated Monopile Installer with NMS (left, © Ørsted). Frequency spectra (SEL third-octave band level) of ramming noise with and without NMS at OWF Borkum Riffgrund 1, measured 750 m from the pile given as percentiles (right, Gündert et al. 2015).

4 Hydro Sound Dampers

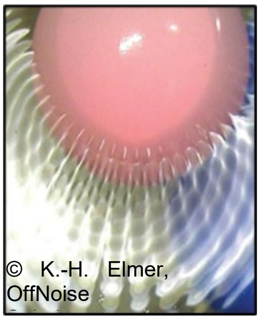
Type of Noise Reduction: Secondary

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)



4.1 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. 3). 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 & Dähne 2017).

4.2 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).

4.3 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. 3).

4.4 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.

4.5 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 (Fig. 3). 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).

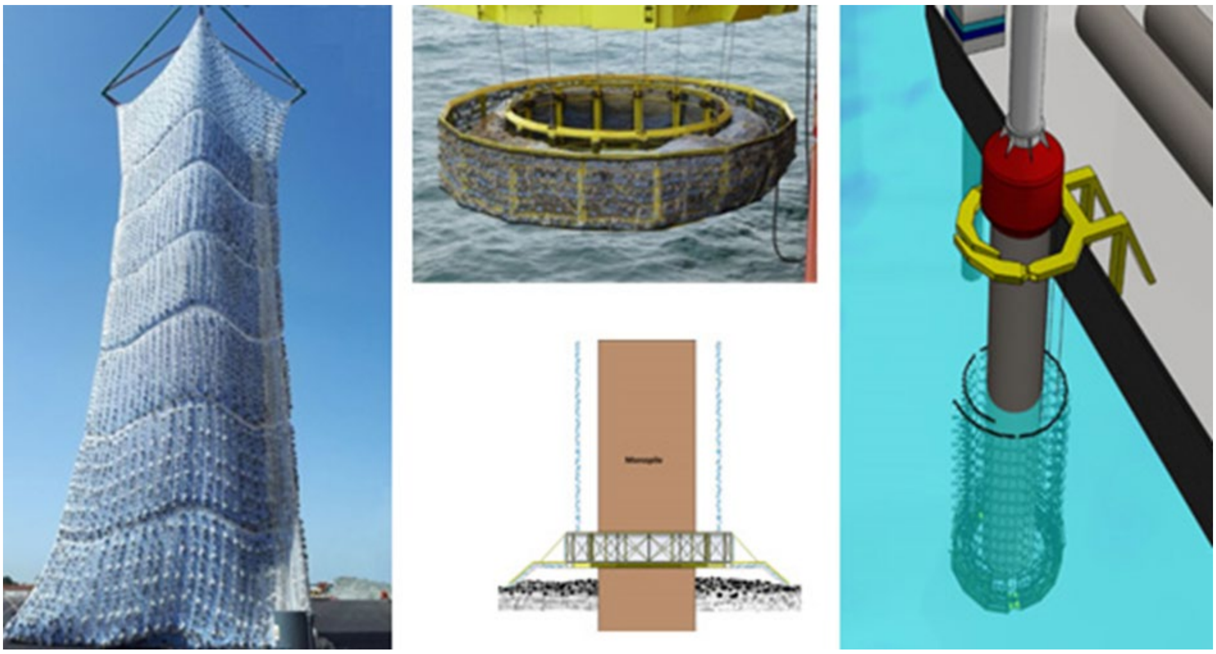


Fig. 3. HSD net for a water depth of 40 m with larger HSD elements on the bottom (due to compressibility with hydrostatic pressure (left). HSD basket below pile frame (center, top). Concept of a HSD basket covering the sea floor close to the pile in order to mitigate also ground coupling effects (center, 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

5.1 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. 5). 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. 4). In this particular case, piling occurred only above sea level (Frühling et al. 2011).

5.2 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. 4, 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. 4, 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.

5.3 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.

5.4 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. 4. 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. 5. 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

6.1 Technical Description

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).

6.2 Experience

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.

6.3 Noise Mitigation

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 & 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).

6.4 Development Status

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).

6.5 Suitability for XXL monopiles

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

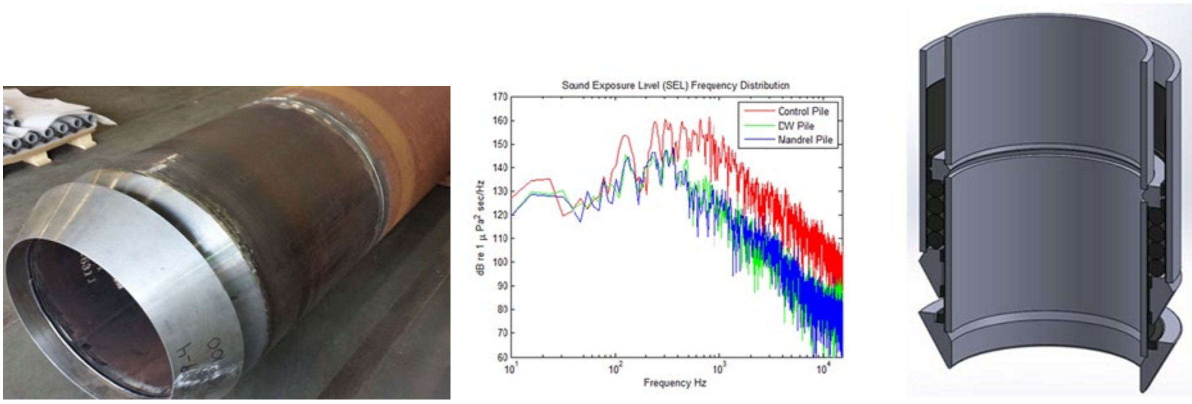


Fig. 6. Double pile stem with driving shoe (left), SEL frequency distribution (middle) during piling of control pile (red) and double pile configurations (green and blue), (Reinhall et al., 2015). Schematic of flexible coupling to connect outer and inner pile in the driving shoe (right, Reinhall et al., 2016).

7 Pulse prolongation by adaptation of hydraulic hammers

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

7.1 Technical Description

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 commercially available in 2022. 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 & 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. 7) (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. 7. 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 planned.

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8.1 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. 8). 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 & Dahl 2010; Dahl & 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.

8.2 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.

8.3 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. 8). 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}.

8.4 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).

8.5 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.

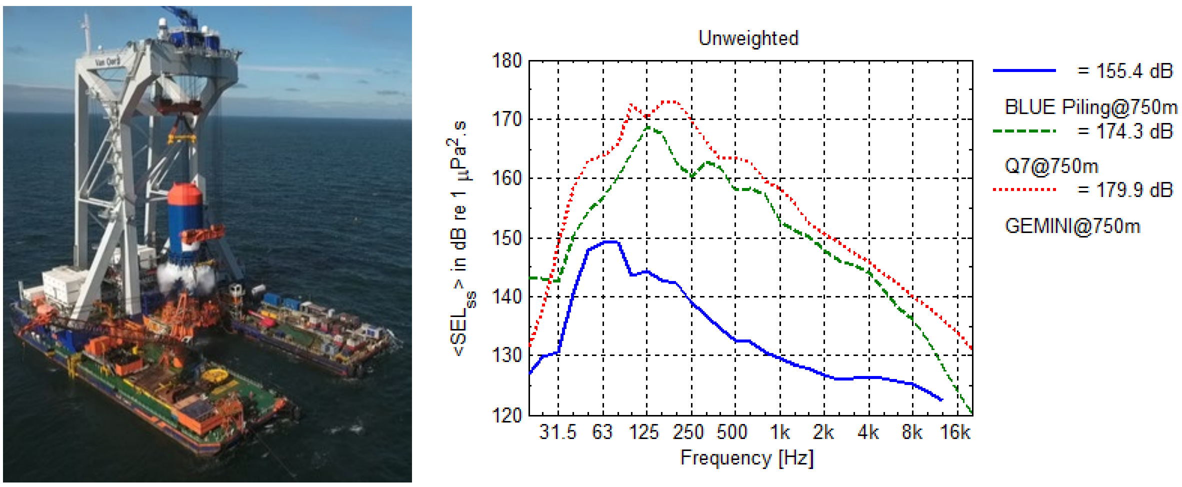


Fig. 8. Draining of seawater from BLUE 25M hammer upon completion of piling operation (left). Frequency spectrum of BLUE piling compared to impact piling at two reference piles (right, note different dimensions: BLUE Piling test: Ø6.5 m, water depth 22 m; reference Gemini OWF: Ø 6.6 m, water depth 30 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 succe

Image from:

9.1 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).

9.2 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 & 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).

9.3 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 &

Bellmann 2012) (Fig. 9). In other projects, noise emissions were in the same order. In all projects, noise emissions varied considerably (Elmer et al. 2007a; Betke & 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 & 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.

9.4 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).

9.5 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.).

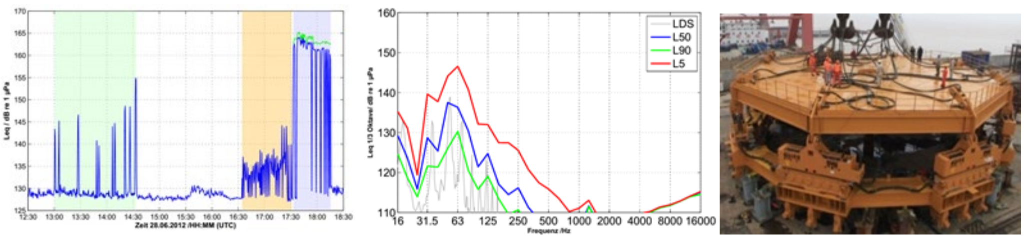


Fig. 9. Measured broadband noise levels (left, blue line: Leq 30s, green line: single strike SEL) at 750 m; OWF Riffgat Ø5.7m monopiles (green: four piles fully vibrated, orange: seal scarer, blue: impact pile driving with noise mitigation). Frequency spectrum measured over 98 min (middle, Leq given 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

© BAUER Spezialtiefbau

10.1 Technical Description

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 & 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.

10.2 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).

10.3 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 & 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.

10.4 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.

10.5 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).

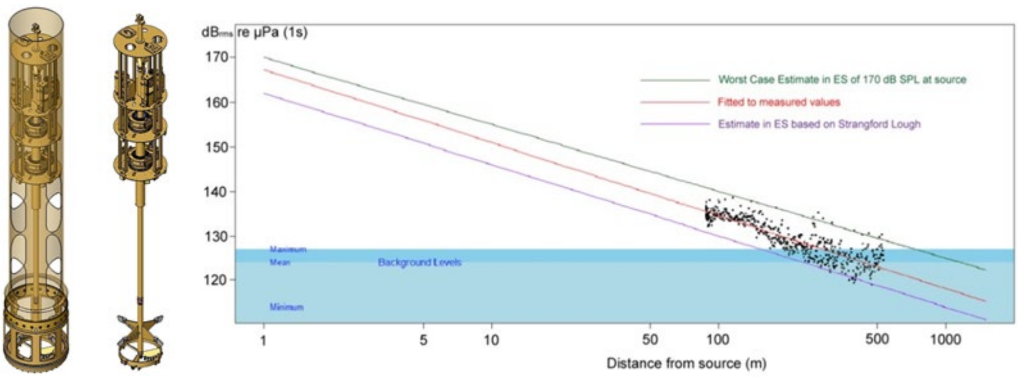
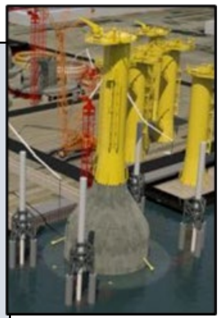


Fig. 10. MIDOS pile with drilling and mixing tool inside the structural pile (left, © BAUER Spezialtiefbau GmbH). Noise measurements of BSD 3000 drilling noise in rock (right, Scheller, 2018).

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.

11.1 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 & 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).

11.2 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.

11.3 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.

11.4 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.

11.5 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. 11. 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.

12.1 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. 12) 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).

12.2 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).

12.3 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 & 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.

12.4 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 & 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.

12.5 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. 12. 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.

13.1 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. 13) (Jacobsen 2018).

13.2 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.

13.3 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.

13.4 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) [1].

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

[1] Northland Power, the owner of the OWF Deutsche Bucht announced on 17 March 2020 to halt its plans to install two demonstration turbines on monobuckets due to technical issues: https://www.4coffshore.com/news/newsItem.aspx?nid=16990

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)

14.1 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.

14.2 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).

14.3 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).

14.4 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).

14.5 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).

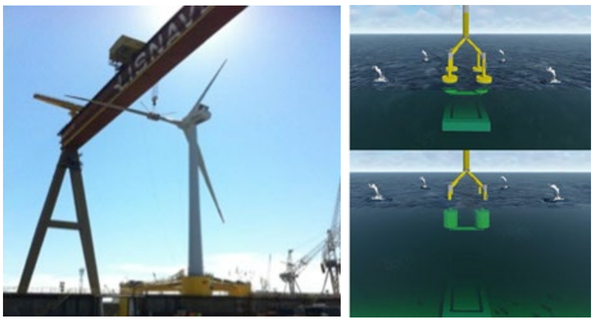


Fig. 14. Prefabrication of semisubmersible WindFloat (left, © Principle Power Inc.). TLP GICON-SOF installation concept with ballast anchor (right, © GICON).

15. Push-In and Helical Piles

Type of Noise Reduction: Primary

Noise Reduction Principle: Alternative foundation type

Development Status: Concept

15.1 Technical Description

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. 15, 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. 15, 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 & Ottolini 2018).

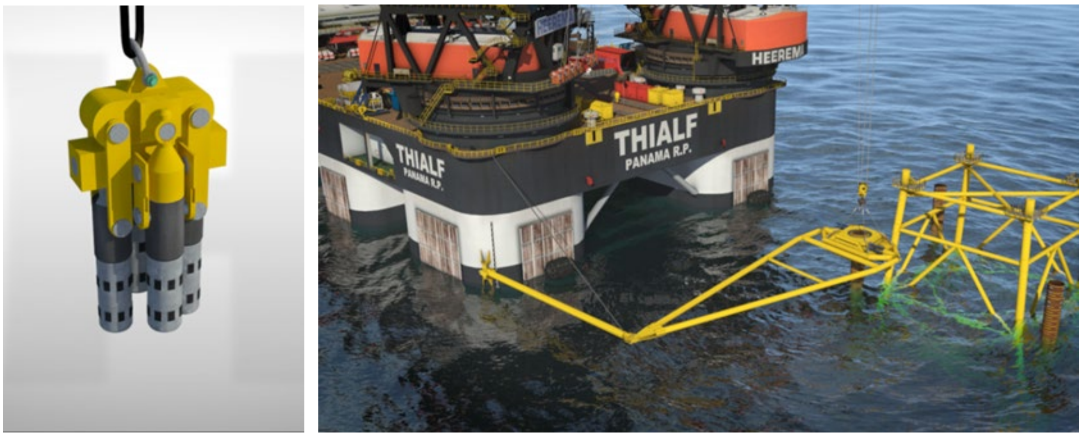


Fig. 15. Concept of push-in piles with specific tool (left). Helical piles as jacket pinpile with rotating tool (right), © Heerema Marine Contractors.

16. 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 noise 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.

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

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Annex II: Measures and Techniques to Mitigate the Impact of Seismic Surveys

This inventory has been adapted from Chapter 4 of the following report:

> Genesis (2015). Inventory of measures and techniques to mitigate the impact of seismic surveys. Report prepared for Department of Energy and Climate Change. Report number J73874A-Y-RT-24000/D01. 51pp.

1 Introduction

A review of available guidelines specifically relating to mitigation of the potential impacts of seismic surveys was undertaken for all OSPAR countries, recognising that the guidelines are typically part of a wider regulatory process and therefore do not provide complete information in relation to the assessment process implemented for a specific project. Guidelines were available for the UK, Greenland, Denmark Ireland, Spain and Norway. The Netherlands have also developed draft guidelines (*pers. com*., Ministry of Infrastructure and the Environment, 3rd November 2015), which are to be implemented in 2016. No guidelines were identified for Belgium, Finland, France, Germany, Iceland, Luxembourg, Portugal, Sweden or Switzerland.

In order to ensure a complete review of mitigation measures, worldwide guidance was also reviewed. Guidance was available for the USA, Canada, Brazil and a number of other South American countries, Australia and New Zealand. Many of these guidelines are based on the UK guidelines, which were originally produced by the UK Joint Nature Conservation Committee (JNCC) in conjunction with the Sea Mammal Research Unit (SMRU) in 1995, but which have subsequently been reviewed four times and the current guidelines date from 2017 (JNCC, 2017).

Although some countries have adopted the UK guidelines, in many cases they have recognised the need for additional mitigation measures. A summary of the different measures in use worldwide, is provided in Section 4.2. Further details on the mitigation measures are also provided in Sections 4.3 to 4.5, dividing them broadly into those required prior to seismic surveys (Section 4.3 Planning), those in place during the survey (Section 4.4 Mitigation during operations) and those enacted following a survey (Section 4.5 Post survey measures).

In addition, there has been significant research into developing alternatives to seismic airguns and this is discussed in Section 6.

2 Comparison of Guidelines Worldwide

A comparison of relevant guidance in use in the OSPAR countries and across the world (Table 1) has been carried out. The countries and the guidance included are:

United Kingdom (JNCC, 2017);

Ireland (Department of Arts, Heritage and the Gaeltacht. *Guidance to Manage the Risk to Marine Mammals from Man-made Sound Sources in Irish Waters.* January 2014);

Spain (MARM 2011 and MAGRAMA 2014);

Greenland (,EAMRA – Greenland Government (2015);

Denmark (Danish Energy Agency)

Norway (Fiskeri OG Kystdepartementet and Olje OG Energidepartementet, undated);

Netherlands (Draft guidelines provided in email dated 3rd November 2015);

USA (BOEM 2012);

Canada (Fisheries and Oceans Canada, 2007);

New Zealand (New Zealand Department of Conservation, 2013),

Australia (Department of the Environment, Water, Heritage and the Arts, 2008); and

Brazil (MaMaCoCoSEA, 2015).

The description of procedures and requirement etc. is to a large extent based on the available guidelines at the time of finishing of the report. New guidelines may have been made avaible since.

The Norwegian guidelines focus solely on mitigating the potential impacts of seismic surveys on the fishing industry and are therefore not comparable to the other guidelines which focus on mitigation of impacts to marine mammals. The Norwegian guidelines have therefore not been included in the table[2].

It should be recognised that industry-wide and individual company practices will often supplement national guidelines, such as IAGC Recommended Mitigation and Monitoring Measures (IAGC, 2015) and OGP Minimum Expectations for the Control of Specific Risk Areas, Section 2.10.10 Marine Life and Sound (IOGP, 2013).

[2] The Norwegian Institute for Marine Research and the Fisheries Directorate comments on hearings concerning seismic activity. When planning a survey the licensee will contact both the authorities and fishery organisations in order to coordinate their activities with other activities. No later than five weeks prior to the start-up of survey activities, the licensee shall submit details of the survey to relevant authorities. Based on the information submitted, the authorities will provide advisory feedback to incorporate the consideration of living resources, fishery activity and fish resources, such as spawning. The Norwegian Marine Research Institute and the Directorate of Fisheries are responsible for notification of sensitive areas with respect to fish, marine mammals and fisheries. Vessels carrying out seismic surveys must have a fisheries liaison officer (FLO) on board when it is necessary due to fishing operations in the area. The FLO shall actively contribute to enabling both petroleum activities and fisheries to coexist at sea, giving advice to the ship's management and aid communication between the seismic vessel and fishing vessels in the area. The FLO is encouraged to report sights and activities of marine mammals in the mandatory report.

Table 1: Comparison of Guidelines by Country

		Country									
	UK	Ireland	Greenland	Denmark	Spain	Netherlands	USA (Gulf of Mexico)	Canada	Australia	New Zealand	Brazil
Date guidelines last updated	2017	2014	2015 (see link in dmb4)	Terms and recomendations used by DEA	2011 (Mitigation guidelines) 2014 (MMO manual)	2016	2012	2007	2008	2013	2005 (could not access but reviewed in MaMaCoCoSEA, 2015)

		Country									
	UK	Ireland	Greenland	Denmark	Spain	Netherlands	USA (Gulf of Mexico)	Canada	Australia	New Zealand	Brazil
Type of surveys covered	Geophysical surveys including those using seismic airguns and sub-bottom profiling equipment (pingers, sparkers, boomers and CHRIP systems), United Kingdom Continental Shelf (UKCS).	*Seismic surveys (testing and full operation of airguns, water guns, sparkers, boomers, VSP, check-shot systems) in inshore and offshore systems. Multi-beam, single-beam, side-scan sonar, pinger and chirp system surveys in bays, inlets or estuaries, and within 1500m of the entrance of enclosed bays/inlets/estuaries'*	offshore seismic surveys	Seismic surveys and other activities where recommendations are appropriate	Seismic surveys in Spanish waters.	Seismic surveys.	Seismic surveys in Gulf of Mexico.	Surveys using air source arrays in Canadian marine waters.	Seismic surveys in Australian waters.	Seismic surveys in New Zealand continental waters. 3 levels defined based on power output, and VSP only included if it falls into one of the levels.	Seismic surveys

		Country									
	UK	Ireland	Greenland	Denmark	Spain	Netherlands	USA (Gulf of Mexico)	Canada	Australia	New Zealand	Brazil
Species covered	Marine mammals	Marine mammals	Marine mammals and fisheries	Marine mammals	Cetaceans (although MMO manual also mentions turtles).	Marine mammals.	Marine mammals and turtles.	Marine mammals and turtles. Species listed as endangered or threatened. Population effects on other marine species.	Whales (baleen and large toothed whales). Specifically excludes smaller dolphins and porpoises.	Primarily marine mammals but encouraged to adopt for other key species (turtles, penguins, seabirds).	Marine mammals and turtles

		Country									
	UK	Ireland	Greenland	Denmark	Spain	Netherlands	USA (Gulf of Mexico)	Canada	Australia	New Zealand	Brazil
Size of exclusion zone	500 m	1,000 m	500 m	500 m safety zone 200 m injury zone	Defined based on modelling of 180 dB re 1 µPa (likely range 300 m to 3,000 m). Independent verification of noise levels.	500 m	500 m	500 m	3 zones defined: 3 km observation zone 2 km (1 km for sources < 160 dB re 1µPa² s) low power zone 500 m shutdown zone	3 zones defined dependent on survey level and species sensitivity 1.5 km (1km for Level 2) for Species of Concern with calves 1 km (600 m for Level 2) for Species of Concern 200 m other marine mammals	500 m 1,000 m following delay of soft start

MMO qualifications and requirements	All MMOs must be ’trained’, defined as having undertaken a JNCC recognised training course and have some experiance of visually spotting marine mammals. In areas of importance[3], MMOs also required to be ’experianced’, defined as having a minimum of 20 weeks experiance implementing the guidelines in UK waters obtained over the previous ten years, preferabley in the previous five.	Qualified and experienced MMOs must be present. Number of MMOs not specified. JNCC recognised training course and minimum of 6 weeks survey experience over a 3 year period.	Four trained MMO including two certified PAM-operators	Not currently specified	No minimum number defined. Medical certificate/ eyesight test required. Previous professional experience. MMO manual gives details of responsibilities and equipment.	1 MMO or “ecological expert” No specific qualifications identified.	Minimum 2 observers. MMOs must have completed protected species observer programme.	Number of MMOs not specified. Trained MMO but qualifications not specified. .	Trained crew with proven experience in whale observation. Only require MMOs if likelihood of encountering whales increases. Need to be trained and experiences but qualifications not specified.	2 MMOs Qualified (recognised course, assessment and 12 weeks experience under supervision)	Minimum of 3 MMOs on board, 2 on duty, work shift 1.5 hrs, 0.5 hrs rest. Experience or specific training.

		Country									
	UK	Ireland	Greenland	Denmark	Spain	Netherlands	USA (Gulf of Mexico)	Canada	Australia	New Zealand	Brazil
Pre survey observation period	30 minutes. 60 minutes in waters > 200 m deep.	30 minutes. 60 minutes in waters > 200 m deep.	30 minutes 60 minutes in waters > 200 m deep.	30 minutes 60 minutes in waters > 200 m deep.	30 minutes. 60 minutes in waters > 200 m deep.	30 minutes.	30 minutes	30 minutes.	30 minutes	30 minutes by Passive Acoustic Monitoring (PAM) and MMO (Level 1) 30 minutes by MMO (Level 2)	30 minutes

[3] Includes designated Marine Protected Areas (MPA) in UK waters and waters >200m deep west of Shetland.

		Country									
	UK	Ireland	Greenland	Denmark	Spain	Netherlands	USA (Gulf of Mexico)	Canada	Australia	New Zealand	Brazil
Soft start procedure	Airguns >180 cubic inch: From start of soft-start until full operational power: minimum of 20 minutes; from the start of soft-start until start of the survey line: maximum of 40 minutes. Aiguns <180 cubic inch: From start of soft-start until full operational power: minimum of 15 minutes; from start of soft-start until start of the survey line: maximum of 25 minutes. Electromagnetic sources: where practical, ramp up in a uniform	*ramp up over a minimum of 20 minutes and maximum 40 minutes depending on survey type*	Ramp up over minimum 20 minutes.. Increase recommende at 6 dB/minute	Ramp up over minimum 20 minutes.	Increase by 6dB per 5 minutes and never faster than 6 dB/min.	Ramp up over 20 minutes.	Ramp up over minimum 20 minutes and maximum 40 minutes.	Ramp up over 20 minutes.	Ramp up over 30 minutes.	Ramp up in period 20 to 40 minutes.	Ramp up in period 20 to 40 minutes.

		Country									
	UK	Ireland	Greenland	Denmark	Spain	Netherlands	USA (Gulf of Mexico)	Canada	Australia	New Zealand	Brazil
Visual observation during operations	Not mandatory.	*MMOs must concentrate their efforts on the measures to be taken in advance of and during commencement, breaks in and resumption of the sound-producing activity. The guidance presented in this document does not imply that MMOs must monitor the area of operations during all daylight hours. However, MMOs may be required to work for extended periods within the hours of daylight as*	Two MMOs shall be posted when shooting	Not specified directly	Watch to be maintained throughout operations.	Not specified.	2 observers at all times during daylight hours.	Regular watch of the safety zone if power above certain defined thresholds.	During daylight hours, continuous observation required.	Minimum 1 MMO on watch during daylight hours	2 MMOs on watch throughout daylight hours (even if not firing)

		Country									
	UK	Ireland	Greenland	Denmark	Spain	Netherlands	USA (Gulf of Mexico)	Canada	Australia	New Zealand	Brazil
Shut down procedures	Delay soft start if marine mammal in mitigation zone. No shut down requirement during operations if marine mammal enters exclusion zone.	Delay soft start if marine mammal in exclusion zone. No shut down requirement during operations if marine mammal enters exclusion zone.	If marine mammals are detected with exclosure zone, firing shall be reduced ti mitigation gun	Reduce output to mitigation gun if mammal in 200 m injury zone.	Delay soft start if cetacean in exclusion zone. Immediate shut down if cetacean in exclusion zone.	Shut down if marine mammal within 500 m exclusion zone.	Delay soft start if cetacean in exclusion zone. Immediate shut down if marine mammal/turtle in exclusion zone.	Delay soft start if cetacean in exclusion zone. Immediate shut down if marine species enters exclusion zone.	Delay soft start if whale is in shut down zone. Immediate shut down if whale enters or is about to enter shut down zone. Power down to lowest setting if whale in low power zone. Require additional trained crew member or MMO if whale in observation zone.	Delay soft start or shut down source during operations if there is a species of concern with calves within 1.5 km, species of concern within 1 km or any other marine mammal within 200 m.	Delay soft start if marine mammal in exclusion zone. Immediate shut down if marine mammal enters exclusion zone.

		Country									
	UK	Ireland	Greenland	Denmark	Spain	Netherlands	USA (Gulf of Mexico)	Canada	Australia	New Zealand	Brazil
Night time or low visibility requirement s	Soft start to commence in daylight hours if possible. PAM should be used during periods when visual mititgation not possible e.g. darkness, low visibilty.	No soft start allowed.	It is recommended to initiate surveys when visibility is good	Not specified but PAM and orther requirements can be set as a condition for certain surveys	Use of PAM. Recommend use of night vision binoculars. Seismic surveys at night only in areas where no sensitive species or avoiding sensitive times of year.	Require use of PAM.	No soft start unless PAM is used.	PAM must be used if full extent of exclusion zone not visible and if area identified as a critical habitat for endangered or threatened species.	Soft start can be undertaken if less than 3 whales in power down or shut down zones in preceding 24 hours. If sightings are frequent or higher than expected may need to contact Regulator.	Start up if PAM available. If no PAM Level 2 survey can start if <3 marine mammal instigated shutdowns/delay ed starts in last 24 hrs.	Not allowed to start airguns at night/weather conditions too poor, unless a small airgun is kept active.
PAM	PAM may be recommended for certain areas e.g areas of importance.	No requirement to use PAM.	Requirede when visibility is low and seastate above 3	Not specified but can be set as a condition for certain surveys	PAM must be used in conjunction with visual observations. PAM must be used at night/poor visibility.	PAM must be used before the soft start and before the use of an Acoustic Deterrent Device (ADD).	PAM must be used at night/poor visibility.	PAM must be used in low visibility conditions.	Not required. Listed as possible additional mitigation measure.	2 PAMS for Level 1	Not required.

		Country									
	UK	Ireland	Greenland	Denmark	Spain	Netherlands	USA (Gulf of Mexico)	Canada	Australia	New Zealand	Brazil
Other requirements	Specific guidelines for high resolution surveys (e.g. sub-bottom profiling).		Systematic sampling of seabird and marine mammal data. Modelling inpact areas of the noise before survey. If othere seismic takes place a joint model shall be prepared. Measurements of actual noise generated shall be conducted	Requirement for fisheries liaison officer, and requirements for coordination. Recommendations also covers line change and breaks.	Specific measures listed for multi beam and side scan surveys.	ADD to deter harbour porpoises must be used for 30 minutes prior to the start of the survey.		Additional measures may be required for species of concern.	Closed areas for southern right whales and fur seals.	Specific guidelines for VSP.	Seasonal closed areas for specific species during breeding. No surveys in waters < 12 m.

		Country									
	UK	Ireland	Greenland	Denmark	Spain	Netherlands	USA (Gulf of Mexico)	Canada	Australia	New Zealand	Brazil
Post survey requirement s	MMO report sent to Regulator and copied to JNCC after completion of survey. Time scale usually specified in consent (e.g. 28 days).	Report submitted to Regulator within 30 days.	MMO report, MMO data and noise measurements to be delivered at end of survey year	Not specified but can be set as a condition for certain surveys	Final report to Regulator within 20 days.	None specified though does state that permit holder shall carry out monitoring and evaluation.	Survey and sighting reports on 1st and 15th of each month. Sighting resulting in a shut down – report within 24 hrs of shut down. Final report.	None specified.	Report to be submitted within 2 months to Regulator.	Report to be submitted within 60 days to Regulator. Format specified in guidelines. Raw data within 14 days.	Report to be submitted to Regulator within 5 days.

3 Planning

3.1 Collection of Baseline Data

Effective mitigation measures rely on establishing good baseline data on the marine species likely to be present within the area where the seismic survey will take place. Baseline data is based on existing literature and survey data. In areas where data is limited additional environmental surveys may need to be undertaken prior to the seismic survey (JNCC, 2010b and MARM, 2011).

A roadmap for planning, executing, evaluating and improving the design of seismic surveys was put together by Nowacek *et al*. (2013). The roadmap highlights the need for ongoing monitoring to help evaluate the effectiveness of mitigation measures and to feed into future design of mitigation measures.

Some regulatory authorities facilitate access to information and maintain a database of references relating to the distribution and abundance of marine species.

3.2 Avoidance of Sensitive areas

The avoidance of areas of ecological importance, based on the presence of endangered or sensitive species and/or high cetacean or marine diversity, is an effective mitigation measure, but it relies on up-to-date designation of sensitive areas. Different countries have taken different approaches to spatial restriction of seismic activity:

- Currently in the UK, JNCC define areas of importance as discrete areas of important habitat for marine mammal species. These have the potential to be delineated and managed for conservation and ultimately such areas could be designated as marine protected areas (MPAs). Currently, these areas include Special Areas of Conservation, Marine Conservation Zones, Nature Conservation MPAs and waters greater than 200m deep west of sheltand. Additional mitigation requirements may be recommended for operations in these areas e.g. combined use of MMO and PAM during daylight hours. ;
- The Spanish guidelines (MARM, 2011) require spatial restrictions to be put in place in sensitive areas and around protected areas. Sensitive areas and protected areas are defined for each region within the guidelines. In addition, they recommend a 20 km buffer zone around protected areas for cetaceans and that this distance should be increased if there is limited data on protected species;
- The Greenland guidelines (EAMRA 2015) are aimed for use in Greenland waters and have specified protection zones for narwhals, belugas, bowhead whales and walruses. The guidelines contain maps showing the extent of the different protection zones and associated seasonal restrictions;
- Brazil (MaMaCoCoSEA, 2015) and Australia (Department of the Environment, Water, Heritage and the Arts, 2008) have defined exclusion zones and time periods for specific species (Brazil: breeding humpback and right whales, Franciscana dolphin, turtle nesting season and manatee areas, Australia: southern right whales and fur seals).

3.3 Seasonal Restrictions

Seasonal restrictions for certain categories of survey, to avoid sensitive time periods such as migration, reproduction and calving, can also provide effective mitigation.

The UK guidance (JNCC, 2017) require seasonal considerations to be taken into account at the planning stages. , although it is acknowledged that, for most species in UK waters, any seasonal patterns may vary considerably between years. Where information on seasonality is lacking, or where long-term records do not support the existence of a consistent pattern of seasonality, it should therefore be assumed that animals could be present in the area at any time of the year. It should also be noted that there are additional seasonal restrictions relating to the spawning periods and areas for commercially exploited fish species, but these are separately assessed and not included in the guidelines.

In The Netherlands, sensitive time periods also have to be taken into consideration at the application stage, and whenever possible surveys must be undertaken during the less sensitive periods.

There are potential difficulties associated with enforcing seasonal restrictions. The Spanish guidelines, for example, specify that feeding, breeding and calving times should be avoided and that the 20 km buffer zone around protected areas for cetaceans should be applied. However, they also acknowledge that there is insufficient data to accurately define these periods for most marine areas adjacent to Spain.

As noted in Section 4.3.2 there are seasonal restrictions in place for Greenland waters (DCE, 2011), in Brazilian waters (MaMaCoCoSEA, 2015) and in Australian waters (Department of the Environment, Water, Heritage and the Arts, 2008).

In Norway time limits have been introduced for seismic activity in areas with important spawning grounds and in areas where there are concentrated spawning migrations. Based on information submitted from the licensee, the authorities will provide advisory feedback to incorporate the consideration of living resources, fishery activity and fish resources, such as spawning. A "soft start" with weaker sound impulses is recommended in sensitive areas.

3.4 Potential simultaneous and Cumulative impacts

Operators could also consider the potential cumulative impacts, not only in relation to potential cumulative sound impacts, for example two seismic surveys taking place simultaneously, or a seismic survey taking place adjacent to another activity resulting in impulsive sound (e.g. windfarm piling), or consecutive seismic surveys taking place in the same area; but also in relation to a combination with other impacts, for example potential physiological / physical impacts of sound on cetaceans may be increased if there are impacts related to other environmental pressures, e.g. chemical contamination (MARM, 2011).

Any overlap between planned seismic surveys or with other impulsive sound sources such as pile driving, could be considered as a potential impacts over a range of tens of kilometres in relation to small cetaceans and potentially over a range of hundreds of kilometres for large cetaceans. This could be taken into consideration through individual Contracting Parties' licensing and consenting arrangements.

In Greenland, a joint noise model has to be prepared, in case several seismic surveys are planned in the same area.

3.5 Impact Assessment

Most guidance requires a full review of which cetaceans are likely to be in the area, including seasonal variations in sensitivity and distribution, together with an environmental assessment identifying possible impacts on cetaceans and the proposed mitigation measures to be implemented to limit those impacts.

National consenting and licensing procedures will additionally require a detailed impact assessment to support the applications, in most cases including a noise propagation assessment relevant to the depth of water and the nature of the seabed, and the conditions included in the approvals will be tailored to reflect the potential impacts and proposed mitigation. Where appropriate, specific requirements taken from the national guidelines will also be included as legally-binding conditions.

The Greenland guidelines require an Environmental Impact Assessment (EIA) to be including noise propagation modelling. The noise models need to be confirmed by acoustic measurements in the field. The EIA needs to describe the methods chosen to reduce or baffle unnecessary high frequency noise, taking account of the noise spectrum before and after the addition of the mitigation measures. Cumulative effects from multiple temporally overlapping or consecutive surveys need to be considered. If the environmental impacts are low (based on a scope), the EIA can be replaced by an Environmental Mitigation Assessment (which is a reduced EIA).

The Dutch and UK permitting systems also requires a detailed impact assessment to support the applications that clearly specifies the potential impacts.

3.6 Determining the Size of the Exclusion Zone

The exclusion zone (also referred to in some countries as the safety or mitigation zone) is a defined area around the sound source where it is believed there is the potential for physical injury to marine mammals. The potential for hearing damage, auditory masking, and behavioural impacts including disturbance may, however, extend beyond this zone.

Exclusion zones form a key mitigation tool within guidelines both in OSPAR Contracting Parties and worldwide. However, there are significant differences in the extent of the exclusion zone and how it is defined:

- In the UK, the US and Canada the exclusion zone is generally taken as a 500 m radius from the sound source (JNCC, 2017, Fisheries and Oceans Canada, 2007 and BOEM 2012). This is based on the distance at which cetaceans may reliably be observed and may not therefore necessarily fully protect the animals.
- The US marine fisheries service (NMFS) additionally requires the application of propagation loss models in order to identify where the 180 decibel root mean squared (dB rms) isopleth occurs, as this has been cited as the level at which auditory damage and other physical injury is likely to occur in cetaceans (Compton *et al.*, 2008). This approach appears to have been adopted for California but not in the Gulf of Mexico (BOEM, 2012);
- Within the OSPAR region, a similar approach has been adopted in Spain (MARM, 2011) where the exclusion zone is defined by the position of the 180 dB root mean square (rms) isopleth. The Spanish guidance recognises that the calculated radius may exceed the distance over which cetaceans can be reliably observed, and the guidance therefore requires additional MMOs to be used, potentially using additional boats, to cover the full exclusion zone. The Spanish guidelines also require ground truthing of the propagation modelling once the survey is underway (i.e. to verify the model results against actual measurements).
- Australia and New Zealand have defined a range of zone sizes (up to 3,000 m) based on the energy of the sound sources and the sensitivity of the environment.

For operational simplicity, the exclusion zone should normally be based on the most sensitive species known to occur in the waters covered by the guidelines.

3.7 Minimising Airgun Sound Propagation

Guidelines advise operators to use airgun arrays of the lowest practicable volume. The geometry of seismic source arrays is typically designed to maximise downward energy and therefore reduce horizontal sound propagation, and to minimise high frequencies (JNCC 2017, MARM 2011). There is limited research into other methods for minimising airgun sound propagation. Where available the information is presented below.

A number of methods to reduce the high frequency component of the airgun signatures are in development. One example is the eSource airgun which has been developed by Bolt Technology. It is a flexible bandwidth airgun, where the bandwidth is controlled by the way the air is released. This may reduce the unwanted frequencies and the environmental impact (Bolt Technology, 2014).

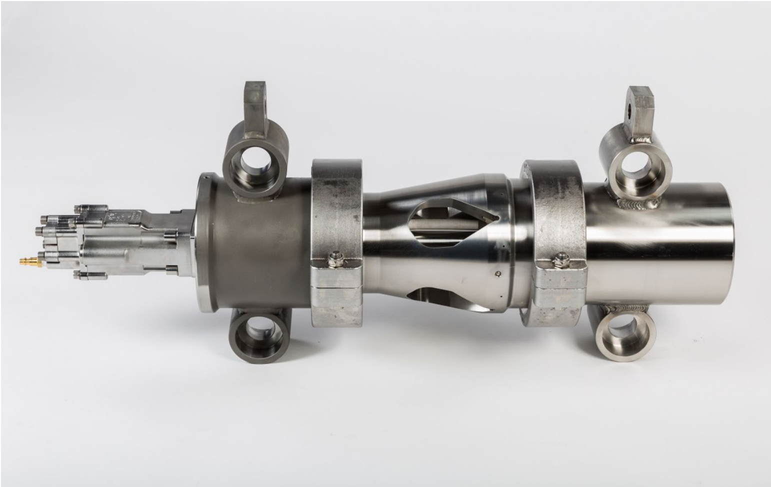

Figure 1: Bolt Technology eSource airgun design

Airgun silencers have also been investigated (Weilgart (ed.), 2010). These are acoustically absorptive shells which surround the airgun, but they are currently not robust or reliable enough to provide the level of repeated use required for commercial seismic survey operations (CSA Ocean Sciences Inc., 2014).

The use of higher sensitivity hydrophones to allow the use of lower source levels and narrower sound beams has been proposed and should be encouraged (Castellote, 2007). One such technology is fibre-optic receivers placed on the seafloor, which are stationary and have a greater sensitivity and signal to noise ratio than towed streamer hydrophones, thus allowing smaller volume airguns to be used (CSA Ocean Sciences Inc., 2014). Another example of seafloor receivers is ocean bottom node technology which uses the same principle as fibre-optic receivers reducing the distance the received signal has to travel, but the sound source levels are usually similar to conventional arrays to ensure that sufficient energy is reflected back from the sub-surface geology. There are now several companies offering this technology (e.g. Sonardyne, 2011), and it is widely used for 4D reservoir surveys.

Parabolic reflectors are designed to be towed over the airgun array to reflect the energy downwards, to reduce the required energy of the airgun array. They are difficult to use in certain weather conditions and also not suitable for shallow water due to the greater reflections (CSA Ocean Sciences Inc., 2014).

Abma and Ross (2013) have investigated the use of “popcorn shooting”. This involves varying the activation time of the air guns during the survey rather than activating them all simultaneously. Notches in the spectra of airguns can be reconstructed using traces of other airguns, this allows the overall peak amplitude of the airguns to be reduced. The advantage of popcorn shooting over other alternative methods is that it uses existing equipment with only minor modifications.

4 Mitigation during Operations

4.1 Pre-shoot Watch

The UK guidelines, Greenland guidelines, Spanish guidelines, Danish guidelines and Irish guidelines all recommend that the pre-shooting search should be conducted over a minimum period of 30 minutes before commencing the use of any airguns. The MMO should make a visual assessment to determine whether any marine mammals are within 500 -1000 m of the centre of the airgun array (dependingon the guidelines being used) during the pre-shooting search period.

In deep waters (>200 m) the pre-shooting search can be extended to 60 minutes, as deep diving species (e.g. sperm whale and beaked whale) are known to dive for longer than 30 minutes. A longer search time in such areas is therefore likely to lead to a greater detection and tracking of deep diving marine mammals (JNCC, 2017). CSAS (2015) recommend that the observation period should be based on the maximum duration of species specific deep dive cycles, rather than using estimates of 30 minutes and 60 minutes.

Guidelines also set out the recommended time delays to be implemented if a cetacean is observed within the mitigation zone during the pre-shooting search (20 minutes from the last cetacean observation in the mitigation zone in the UK guidelines, and 30 minutes in some of the other guidelines, e.g. Australia, Gulf of Mexico, Brazil, Canada, New Zealand and Spain).

Whale density, particularly mysticetes whale density, can show significant short-term and small-scale inter-annual variation related to dynamic oceanographic processes, e.g. ice edges. Areas of temporarily sporadic high densities may therefore occur within the zone of influence of certain seismic surveys. If a survey is planned in an area that includes such habitats, it may therefore be appropriate to determine the concentrations of animals in the survey area by undertaking pre-surveys (e.g. boat or helicopter surveys) a maximum of one week in advance of the proposed seismic survey. If significant marine mammal aggregations are detected, the seismic survey should be delayed until repeat surveys confirm that non-critical densities are found in the area.

4.2 Use of Acoustic Deterrent Devices

Acoustic Deterrent Devices (ADDs) have traditionally been used to deter marine mammals from fishery activities and have also been used around wind farm developments. However, the effectiveness of the devices has been debated. They also introduce sound, and it has been suggested that this could result in adverse effects, including injury at close range.

The draft Dutch guidelines recommend the use an ADD prior to the start of the survey to deter harbour porpoises, and specifically mention use of the SEAMARCO Acoustic Porpoise Deterrent and banana pingers.

No other guidelines recommend the use of ADDs. The UK JNCC guidelines for minimising the risk of disturbance and injury to marine mammals whilst using explosives (JNCC, 2010a) mention the possible use of ADDs to exclude animals from the exclusion zone, but stress that ADDs should only be used in conjunction with visual and/or acoustic monitoring, and for as short a period as necessary to minimise the introduction of additional noise. JNCC also stress that the evidence for the efficacy of ADDs is limited.

Compton *et al* (2008), quoting studies by Pierson *et al.* (in Proceedings of the seismic and marine mammals workshop, 1998) and Mate *et al.* (in Acoustical deterrents in marine mammal conflicts with fisheries, 1987), note that seals have been shown to alter behaviour in response to ADDs, and that harbour porpoises have been demonstrated to habituate to ADDs within two weeks. There is therefore the potential risk that habituation could lead to long-term exposure to sound levels that could lead to chronic auditory damage.

4.3 Soft Start

The soft start is undertaken during the period between when the airguns commence shooting and the time when full operational power is achieved. Soft starts involve gradually increasing the sound released from the seismic source. This is usually achieved by initially firing a single airgun, generally the smallest airgun, with subsequent activation of additional sources in ascending size order, usually over a period of 20 to 40 minutes, in order to allow animals to move away. Where possible, it is recommended that this build-up of power occurs in uniform stages to provide a consistent increase in output. Some guidelines specify a rate of sound increase, for example the Spanish guidelines specify a rate of increase of 6 dB per 5 minutes (MARM, 2011).

During the soft start if airgun firing stops for more than 10 minutes then the UK guidelines recommend that a further pre-shooting search and 20 minute soft start needs to be carried out.

Ideally there should be a soft start every time the airguns are turned on, although the UK and the Greenland guidelines allow exceptions for certain types of airgun testing, and for the use of a 'mini-airgun' (single gun volume less than 10 cubic inches (cu. in.)). The UK and Spanish guidelines recommend that, where possible, soft starts should be planned so that they commence within daylight hours and when visibility is adequate, whereas other guidelines (e.g. Ireland) do not allow soft starts to commence or re-commence surveys at night or during periods of low visibility.

Once the soft-start has been performed and the airguns are at full power, the UK and Greenland guidelines recommend that the survey line should start immediately, and that operators should avoid unnecessary firing at full power before commencement of the line.

The effectiveness of the soft starts has been questioned as there is the possibility that the procedure could lead to habituation, or even that the initially weak sound could attract animals (Compton *et al*., 2008). However other findings support the effectiveness of the soft start procedure (Wensveen et al. 2015). Given ongoing research into the effectiveness of the soft start procedure, a detailed revision of the requirements may eventually be required.

4.4 Line Changes

Airgun use during line changes is discouraged in most guidelines, but the exact requirements depend on the size of the airgun and the time taken for the line change. As a minimum, most guidelines recommend a reduction in airgun use with only small guns allowed to continue firing during line changes.

The UK guidance relating to line changes depends on the duration of the line turn (JNCC, 2017). For line turns that will take longer than 40 minutes, the equipment should be turned off and a pre-shooting search and soft-start undertaken prior to the start of the next line. If the line turn can be completed in less than 40 minutes, firing can continue if certain conditions are met, e.g. reduction in power and increase in shot point interval. Typically, only surveys using small air guns or some ocean bottom cable surveys can turn within 40 minutes (Stone, 2015b). .

4.5 Marine Mammal Observers

The use of MMOs for visual monitoring is recommended in all guidelines worldwide, and is the most commonly used method of mitigation. However, there are significant variations in the numbers of MMOs used, the training requirements, the equipment requirements and the exact nature of the MMOs' role and authority.

The most consistently recommended elements of guidelines relating to MMOs are:

- MMOs should be certified (attendance at a recognised course) and have previous experience (up to 12 weeks under supervision), including experience with species specific to the area of operation. In the UK, MMOs need to have attended a JNCC recognised training course;
- Recent medical certificate, including testing of vision (MARM, 2011);
- MMOs should normally be independent of the operator of the seismic survey and should report back directly to the regulator, however, this is not explicitly stated in many guidelines;
- More than one MMO may be required depending on the size of the exclusion zone, the duration of the survey, the sensitivity of the area, the duration of daylight hours and whether the species specific to area of operation are difficult to spot from the surface;
- MMO (and, if relevant, PAM operative) work and rest hour periods should be agreed with the survey operator prior to the commencement of offshore operators. For example, Castellote (2007) recommends a maximum watch of 4 hours, with a 30 minute break for a 1.5 hour watch (implemented in Brazil guidelines), and Wright and Cosentino (2015) recommend a maximum watch of 2 hours;
- There should be clear lines of communication between MMOs and both onboard and onshore survey management and key personnel, including the officers and crew of the survey vessel;
- The MMO should have the authority to delay/stop seismic work, if required to comply with the legal conditions attached to the approval;
- Equipment for the MMO should include binoculars, night vision binoculars, method of measuring range (e.g. range finder stick, reticle binoculars), a communications radio, copies of relevant protocols and appropriate reporting templates; and
- There should be a specified time period for submitting the MMO report to the regulator, for example in MARM 2011 this is 20 days from completion of the survey. The UK guidelines do not specify a time period, although the deadline for submitting the reports to the regulator and JNCC is specified in the UK survey consent.
- In Greenland, MMO's are requested to collect systematic data on seabirds and marine mammals besides their MMO duties.

Additional useful information can be found in the IACG Guidance for Marine Life Visual Observers, December 2001 or the Marine Mammal Observer & Passive Acoustic Monitoring Handbook, 2015.

Visual Monitoring Procedures

Visual monitoring can never be 100% reliable, but observations should be undertaken from a suitable location on the vessel (normally the highest point) where the MMOs have a 360^o view of the sea area.

Wright and Cosentino (2015) recommend that surveys should not be started during periods of restricted visibility, because visual observation is limited during rough weather, poor visibility (e.g.

fog) and at night. However, many guidelines recognise these difficulties and recommend the use of PAM as an alternative to visual observation during these periods.

The UK guidelines state PAM should be used during periods of restricted visibility, whilst at the same time recognising its limitations (see Section 1.2), but the guidelines do not define limits for restricted visibility. The UK guidelines also recommend that "where possible", soft starts should be planned so that they commence within daylight hours, but they do not specifically reject the possibility of soft starts during periods of restricted visibility.

MMOs need to estimate the range of the animal. This can be done by a variety of methods. In the UK, the most commonly used method is to use a rangefinder stick (Stone, 2015b), but some observers use reticle binoculars. The Spanish MMO Manual (MAGRAMA, 2014) requires the use of reticle binoculars and states that a rangefinder stick should only be used in the event that reticle binoculars cannot be used. However, it is not made clear under what conditions a rangefinder stick could be used. Wright and Cosentino (2015) recommend that rangefinder sticks should not be used as this method is inaccurate, but it is questionable whether the level of inaccuracy is significant.

4.6 Restrictions on Airgun Use during Operations

The UK guidelines and the Irish guidelines do not contain any requirement to stop using the airguns if cetaceans are spotted within the mitigation zone during operations. All of the other guidelines reviewed (see Table 1) require deactivation of the source if cetaceans are observed wtihin a defined zone.

4.7 Passive Acoustic Monitoring

Passive Acoustic Monitoring (PAM) systems are underwater hydrophones (either towed arrays or static moored systems), processing units and software that detect and process underwater sound. Specialised PAM systems can detect the vocalisations of whales, dolphins, porpoises and other marine mammals. PAM operatives are required to set up and deploy the equipment and to interpret the detected sound.

For mobile surveys such as seismic surveys, towed PAM arrays can be used in conjunction with, or instead of, visual observation, particularly during periods of poor visibility and at night (when some guidelines require the use of PAM). PAM has a number of limitations: it can only detect cetaceans if they are vocalising / echolocating, it cannot always reliably detect the range (distance from source) of the species and it cannot reliably identify all species.

Generally, the efficiency of PAM is limited, as the method only record vocalizing whales. It was for example recently showed that bowhead whales stopped vocalising when approached by a seismic vessel and therefore were undetected by PAM (Blackwell et al 2015).

4.8 Active Acoustic Monitoring

Active acoustic monitoring (sonar) comprises the emission of a sound signal that reflects off submerged objects and back to a signal receiver, to produce a 2D or 3D image of the water column. Active acoustic monitoring allows detection of non-vocalising mammals and allows more accurate determination of range and bearing (Castellote, 2007). However, there are concerns that it has a limited detection range and beam (detection) width, it is unable to differentiate between many marine mammal species and it could be harmful to marine mammals. Further research, development, validation and field trials are needed before this technology could be considered as useful mitigation for seismic surveys. Work is already being undertaken under the IOGP JIP and by BP Canada, to investigate both the applicability of the technique and potential harmful effects.

4.9 Aerial Surveys

Aerial surveys can be undertaken before and after seismic surveys to allow collection of additional baseline data. They are not generally used during surveys to inform real-time mitigation as planes need to fly above 300 m altitude to avoid causing direct disturbance, and this can limit observational accuracy (Compton, 2008). However, digital cameras now allow survey planes to fly above 600 m and they have been widely used for offshore windfarm surveys, and they could therefore be potentially used during seismic surveys.

The Australian guidelines recommend the use of spotter vessels or aircraft where the likelihood of encountering whales is high and that, where they are used, an experienced MMO should be employed on board the spotter vessel / aircraft.

4.10 Sound Baffling

The use of screens of air bubbles to surround the seismic array at a prescribed distance has been suggested and tested (Castellote, 2007). The air bubbles create a dynamic barrier which reflects the sound waves from the array.

The majority of the previous literature available for bubble curtains relates to piling noise reduction (Lucke *et al.*, 2012; Würsig *et al.*, 2000), but towed systems are also being developed to reduce airgun noise. However a reliable mobile system has yet to be successfully designed and tested. Systems tested to date have been fragile and difficult to deploy and maintain.

Bubble curtains attenuate sounds in two ways, they create an impedance contrast to the acoustic waves and the bubbles have a resonant frequency which absorbs sound (Ross *et al*., 2005). The resonant frequency of the bubbles is dependent on their size and radii, with larger bubbles having lower natural resonant frequency (JASCO, 2008). Modelling of the sound reduction carried out by JASCO (2008) found that bubble curtains could potentially reduce the sound level by 10 dB for most frequencies. However, the bubble curtain modelled was located on either side of the airgun array and it has been noted that this only reduces sound in those directions, and the effectiveness of the technology for deeper waters was also questioned. The concept is shown in Figure 2 (NCE, 2007).

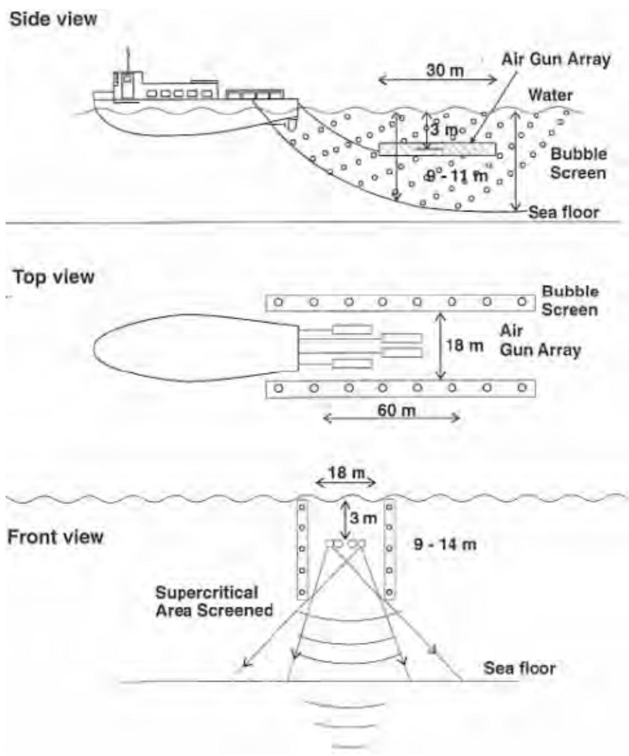

Figure 2: Example of bubble curtain used during a seismic survey 1996

Helmholtz Resonators have also been proposed to reduce the sound propagation associated with the use of airguns, as the technology is often used for sound suppression (AdBm Technologies, 2014). The resonators, which can be made of metal, are placed on or around the individual airguns (Figure 3), and calculations indicate that the system should amplify the signal downwards to the seafloor (AdBm Technologies, 2014). This technology is, however, still in development, and the information available is limited.

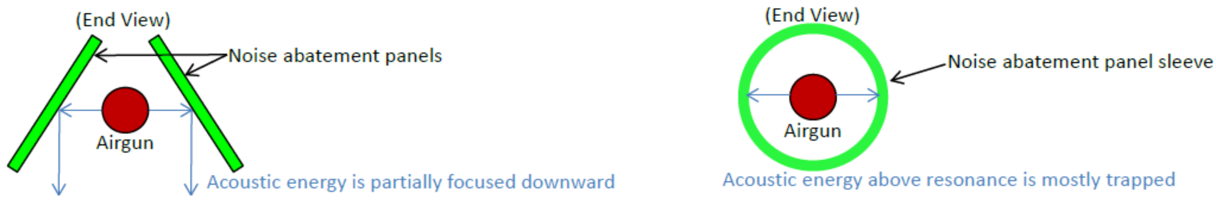

Figure 3: Helmholtz resonator technolgy for airgun sound suppression

4.11 Mitigation for Other Species

The mitigation measures reviewed focus almost exclusively on marine mammals. Castellote (2007) noted that other species (turtles, fish and sedentary species) should also be taken into consideration.

Auditory studies suggest that sea turtles, specifically loggerhead and green turtles, are able to hear and respond to low frequency sound, but their hearing threshold appears to be high (DFO (Department Fisheries and Oceans), 2004). Based on studies that have been conducted to date, it is considered unlikely that sea turtles would be more sensitive to seismic operations than cetaceans or some fish. Mitigation measures designed to reduce the risk or severity of exposure of cetaceans to seismic sounds should therefore also reduce the risk or severity of exposure of sea turtles. However, sea turtles are harder to detect, both visually and acoustically, than many species of cetaceans, so mitigation strategies based on sightings or acoustic detection are expected to be less effective for turtles than for cetaceans (DFO, 2004).

There is also anecdotal evidence that turtles can become entrapped in certain types of tail buoys used during seismic surveys. Debris guards are typically fitted to the underside of tail buoys to ensure that any marine debris is deflected away from the undercarriage, and they can also prevent sea turtles from becoming fatally entrapped in gaps at the front of the tail buoy undercarriage (Ketos Ecology, 2009).

The Norwegian guidelines (Fiskeri-OG Kystdepartementet Olje - OG Energidepartementet, undated) deal exclusively with interactions with fishing vessels. They require extensive planning prior to the survey to ensure liaison with stakeholders and consideration of spawning areas, as well as the presence on board of a fishery expert. Seasonal restrictions have also been introduced in important spawning ground areas (these are shown on the licences for specific blocks). The UK imposes similar requirements in relation to fisheries liaison officers and seasonal restrictions to protect spawning, where requested by the relevant fisheries authorities (DECC (Department of Energy and Climate Change), 2014). Greenland has not currently placed any restrictions in relation to fish spawning but require a fisheries liaison officer to be on board when appropriate. They also note that if the currently depleted stocks of Atlantic cod around Greenland were to increase in the future, measures to protect any identified spawning grounds may need to be considered.

5 Post Survey Measures

5.1 MMO reports and Sharing of Data

In the UK, MMOs are required to submit a report on completion of the seismic survey. Marine mammal recording forms are available for this purpose (JNCC, 2012) and MMO data from all UK seismic surveys are returned to JNCC where, after appropriate quality checks, they are included in a database. The data from these forms are analysed by the JNCC. The most recent report to be produced based on MMO data covers the period 1994 to 2010 (Stone, 2015a).

The Spanish guidelines specify that MMOs must submit a report within 20 days of completion of the seismic survey directly to MAGRAMA.

The Greenland guidelines specify that MMOs must submit a report and the results of systematic observatins of seabirds and marine mammals by end of December of the survey year.

Norwegian seismic data are released after a set number of years (2 to 10 years, depending on the type of data) by the Norwegian Petroleum Directorate. This could reduce the need for repeated seismic surveying of the same area. The UK has a similar system, with some data released after a period of time and other, more extensive, data available for purchase.

5.1 Post Survey Monitoring

The Spanish guidelines identify the need for additional surveys to be undertaken in areas where baseline data is poor and all information needs to be submitted to the Regulator for use by future surveys.

MARM 2011 also require an evaluation of the efficiency of the mitigation measures to allow these to be revised if necessary prior to the next survey.

5.2 Impulsive Noise Monitoring

The MSFD requires the monitoring of impulsive anthropogenic noise, so that inputs can be managed to ensure that they do not adversely affect the marine environment. The UK’s option for monitoring impulsive noise is the UK Marine Noise Registry (MNR). Information on activities which generate impulsive sounds between 10 Hertz (Hz) – 10 kHz is required to be submitted to MNR. The information will be analysed annually, and the number of days of seismic activity over a set period of time (month, season and year) will be mapped for the UK oil and gas licensing blocks, beginning in 2015. The aim of the MNR is to quantify the pressure on the environment, which will in turn, aid in the definition of a baseline level for impulsive noise in UK waters. The Netherlands and Ireland are also maintaining a similar noise registry, and there are developments in the EU and OSPAR to require Member States and Contracting Parties to maintain and report comparable data, e.g. regional noise registry in support of OSPAR and HELCOM.

6 Potential alternatives to seismic air gun surveys

6.1 Marine Vibroseis

Seismic vibroseis has been used on land, and new technology is now being developed to use it in the marine environment for oil and gas exploration. Marine vibroseis, also called marine vibrators, use electrical vibrators to produce a frequency sweep across a 5 to 90 Hz range. The duration of a typical sweep is between 5 to 12 seconds. Due to the length of the sweep and the interval between sweeps, marine vibroseis is considered to be a continuous sound source and is not considered to be impulsive. As marine mammals are generally considered to be less vulnerable to continuous noise than pulsed noise (Southall *et al*., 2007) this is thought to reduce the potential impact on marine life. Virtually any signal can be produced e.g. swept sine, pseudo-random noise (NCE, 2007), and the technology is claimed to be well suited to shallow water although more complicated arrays may be required for deeper water. Frequencies above 100 Hz, which are not required for oil and gas exploration, are significantly reduced in comparison to seismic and the overall sound energy produced is lower than airguns (NCE, 2007).

The technology is still developing, and future units may be electromechanical or hydraulic, but there are already several systems that are commercially available (CSA Ocean Sciences Inc., 2014). An example system developed by PGS is shown in Figure 4 (taken from NCE, 2007). The technology still requires development to determine the optimum frequency range of the sweep and duty cycle, but the technology has been identified as one of the most promising alternatives to seismic airguns by various workshops on alternative technologies (CSA Ocean Sciences Inc., 2014; NCE, 2007; Weilgart (ed.), 2010). A Joint Industry Programme report assessed the environmental impact due to marine vibroseis (LGL and MAI, 2011). In most environmental habitats the impact of marine vibroseis was expected to be less than airguns. However, masking was noted to potentially be more of a problem and the need for extra research was highlighted as there have been virtually no detailed studies of the impacts to marine life.

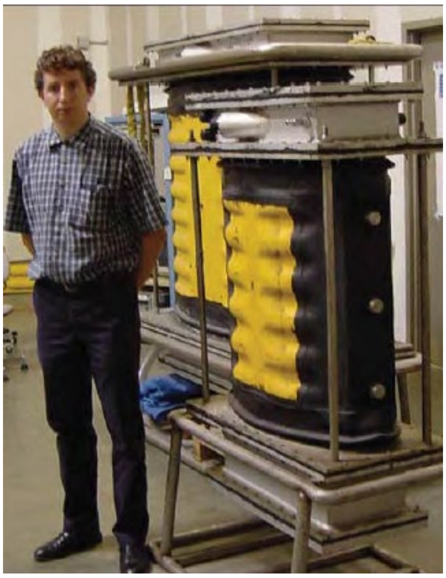

Figure 4: PGS Marine vibrator.

6.2 "Teles" – a Marine Siren

"Teles" is an advanced seismic source being developed by Cambridge Applied Physics Ltd (Figure 5). The system contains a tube through which water flows at a fluctuating rate controlled by a rotor / stator valve, creating frequency sweeps which contain low frequencies, with an acoustic power which has a thousand times lower peak than airguns (Cambridge Applied Physics Ltd., 2015). The system has been tested on a 1:10 scale model for the last three years, and the next stage of the development will be to test a 1:2 scale model as an oceangoing prototype. Due to the lower acoustic power and the focussed low frequency output, 10 – 80 Hz, the impacts to marine life are anticipated to be significantly lower than seismic airguns (Cambridge Applied Physics Ltd., 2015).

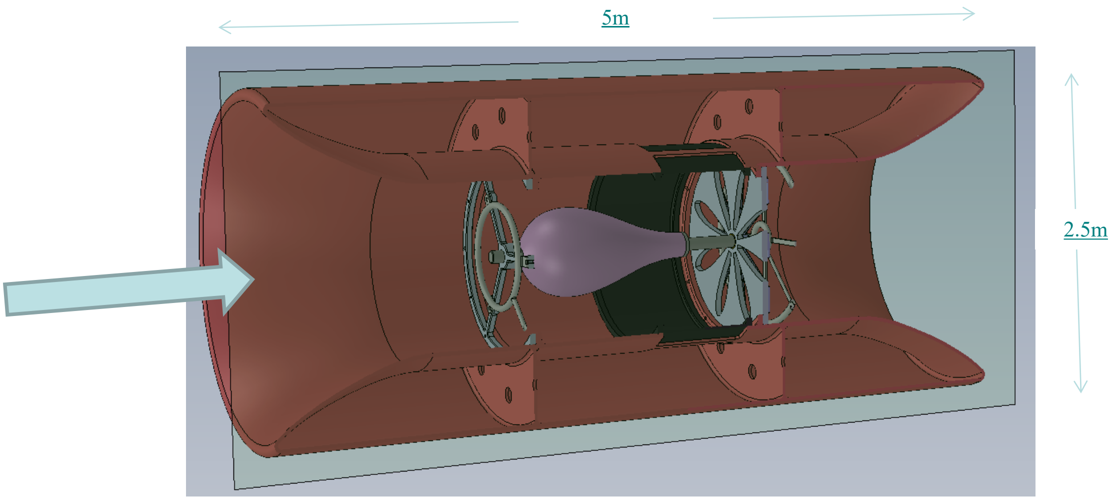

Figure 5: Design of the "Teles" marine siren (Cambridge Applied Physics Ltd., 2015)

6.3 Low-frequency Acoustic Sources

Originally designed as a ship sound simulator to study the potential impact of vessel noise, the low-frequency acoustic source (LACS) uses internal combustion (NCE, 2007). An acoustic pulse is created when two pistons push tow lids in opposite directions, and there are no bubbles created as in airguns. Two acoustic waves are created one of which is reflected off the sea surface, the signal is electrically generated and is lower in pressure than airguns. However, the project has been put on hold and no more information is available (CSA Ocean Sciences Inc., 2014).

6.4 Deep-towed Acoustic / Geophysical System

The US Naval Research Laboratory's deep-towed acoustics / geophysics system (DTAGS) operates at higher frequencies than airguns using a sweep signal. The resolution is higher but the reduced depth of penetration is a function of using higher frequencies. The sound level produced by the system is significantly lower than that produced by airguns, up to 200 dB re 1 µPa at 1 m. However, it is not stated if this is zero-peak or rms pressure (Weilgart (ed.), 2010). The system is towed at deeper depths than an airgun array and therefore the towing speed is slower.

The source is composed of a series of five concentric rings each composed of pie-shaped piezo-ceramic material. The natural resonance of the ceramic transducers provides the high frequencies and the size and shape of the barrel-shaped resonator cavity boosts the low frequencies. This combination yields a broadband signal (over two octaves) with a relatively flat spectrum (CSA Ocean Sciences Inc., 2014). There was only one system available in 2014 and it is not suitable as a replacement for a deep imaging airgun array (CSA Ocean Sciences Inc., 2014).

6.5 Low Impact Seismic Array

The low impact seismic array (LISA) uses a large array of small but powerful electromagnetic projectors to create a signal, and was described in a workshop report (Weilgart (ed.), 2010). It was found that a source level of about 142 dB re 1 µPa per volt at 1 m was achieved, at a peak frequency of 25 Hz, but the operating frequency could be reduced to less than 10 Hz with reasonable modifications, allowing use of an array for seismic exploration. The results indicate that it would be possible to achieve an array source level of about 223 dB re 1 µPa at 1 m, which is adequate for seismic surveying. The workshop, organised by CSA Ocean Sciences Inc. (2014), noted that, during a literature review, there was no further information available in relation to this technology and the stage of the development is not known.

6.6 Underwater Tuneable Organ-pipe

A pipe of a variable length is driven by an electromechanical piston source. The length of the pipe and other parameters varies the produced frequency, and the signal is a sine sweep with a sweep time as short as 5 seconds (NCE, 2007). The workshop organised by CSA Ocean Sciences Inc. (2014) noted that there was no further information available for this technology.

6.7 Electromagnetic Surveys

Electromagnetic surveys are not a replacement technology for seismic but they are seen as a complementary technology (CSA Ocean Sciences Inc., 2014). Active electromagnetic surveys use a dipole source, and a carefully designed, low-frequency electromagnetic signal is transmitted into the subsurface. Electromagnetic energy is rapidly attenuated in conductive sediments, but it is attenuated less and propagates faster in more resistive layers such as hydrocarbon-filled reservoirs. Grids of receivers on the seabed measure the energy that has propagated through the sea and the seabed (NCE, 2007).

The sources can be both stationary and towed, depending on the information required. The towed surveys use a continuous AC signal at one frequency, and the emitted signal is not in the audible range. The stationary source uses pulsed coded broadband signals, and the information received is of higher resolution than that obtained from a towed source (NCE, 2007). The information gained from the surveys can provide a lot of detail about the viability of the reservoir, but does not provide resolution of the geologic structure to inform decisions such as the best places to drill.

Some marine life is known to be electromagnetically sensitive and there could be other impacts on sensory systems (Kirschvink, 1997). More research is therefore needed to understand the potential impacts.

Passive magnetic surveys, also known as magnetotelluric surveys, measure the earth's natural electromagnetic field and are used to map subsurface resistivity (CSA Ocean Sciences Inc., 2014). Ocean bottom sensors are placed on the seabed and can be left to record data for up to months at a time. The main problem with the technology is that the sensors also record other ocean noises. This unwanted noise therefore needs to be removed before analysis, resulting in additional data processing. An initial test of the technology was carried out in the North Sea in April 2007 (Weilgart (ed.), 2010)). As a consequence of the long acquisition time to obtain useful data, this technique is not considered appropriate for exploration but could be useful for life of field studies (NCE, 2007).

6.8 Gravity and Gravity Gradiometry

Gravity surveys measure the variations in the earth's naturally occurring gravity field and are passive. Gravity gradiometry measures the gradient of the change in gravity. The gradiometry equipment is newer and more expensive than the gravity sensors alone, but a greater resolution is achieved and the data is on a similar scale to seismic data. This technique is not applicable to all geological settings, but used in combination with seismic it can reduce the extent of the seismic survey (Weilgart (ed.), 2010).

6.9 Shear Wave Generators

Shear wave generators directly excite the seafloor with a shear wave, an example system is shown in Figure 6. Shear waves are used in seismic surveys and so the principle is similar to standard airgun seismic surveys, but it is considered that the generators may be more useful for specific survey types, e.g. ocean bottom receiver surveys. It is thought that the generator will produce some audible sound when creating the shear wave and so it will not be silent. It has also been noted that the received shear wave data is very hard to interpret and so it is not known how useful the information would be (NCE, 2007), or what would be the environmental implications.

Figure 6: Example of a Shear wave generator

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