



OSPAR inventory of measures to mitigate the emission and environmental impact of underwater noise (2016 update)



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OSPAR Convention

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

Convention OSPAR

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

Acknowledgement

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Photo acknowledgement:

Cover page: ©Jan Haelters

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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 continuous 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

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

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

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

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

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

2 Big Bubble Curtains (BBC)

2.1 Technical Description of the System

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

2.2 Experience with Big Bubble Curtains

Big bubble curtains have been applied as an effective noise mitigation technique in several practical and experimental setups, e.g. in several projects under offshore conditions in the German North Sea since 2008. BBCs have been applied single, double or triple. Noise measurements are available from the research platform *FINO 3* (pile Ø 4.7 m, water depth 23 m, BBC length 440 m, Grießmann 2009) and (in various configurations) the construction of the commercial OWF *Borkum West II*¹ (pile Ø 2.5 m, water depth 26-33 m, single BBC length 560 m, Pehlke *et al.* 2013) during which a pre-laid revolving² system was deployed for the first time. In 2011/12 various experimental setups of the BBC were applied during the construction of 40 tripods using the pre-piling procedure. Preparations, installation and adjustment took 5.5 h per pile (Pehlke *et al.* 2013). This did not result in any delays of the pile installation since it was done before the installation platform was moored at the site. BBCs have further been applied during the construction of a number of OWFs: *Nordsee Ost*, *Meerwind Südost* (double), *DanTysk* (double), *GlobalTech I* and *Baltic II* (double) and substations *Borkum West II*, *Meerwind*, *Nordsee Ost* and *Borkum Riffgrund*. During application of a BBC the entire oscillating structure has to be surrounded by air bubbles. Tidal currents require an elliptical nozzle pipe. Over 20 different configurations with respect to radius, air volume, hole diameter and distance, air feed-in, and pipe volume have been tested. Also pre- or post-laying (with respect to the positioning of the installation platform) have been used. In up to 25% of deployments technical problems occurred which often resulted in a lower noise reduction (Bellmann & Remmers 2013).

2.3 Noise Mitigation

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

¹ Renamed later to *Trianel Offshore Wind Farm Borkum*

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

(SEL) and 10-17 dB (peak) resulting in a reduction of the noise exposed area by 90% (Pehlke *et al.* 2013). The best noise reduction was achieved in frequency bands between 800 Hz and 5 kHz (Figure 1) whereas the maximum piling noise was radiated between 100 and 400 Hz. Noise reduction decreased by 4 dB when the air supply was reduced from 0.32 m³ to 0.15 m³ per min and m nozzle pipe (Pehlke *et al.* 2013) Additional tests were performed with a double BBC, which however could only be installed as two half-circles. The results revealed that a double bubble curtain can increase the reduction achieved by a single bubble curtain. When the distance between both pipes is large enough to allow for the formation of two separate bubble curtains a higher reduction can be achieved than with a smaller distance, when both bubble curtains unite. Best results of up to 18 dB (SEL) and over 20 dB (peak) were achieved when the distance between both nozzle pipes (80 m) was three times the water depth. The amount of sound energy that re-enters the water column via the seismic path (Nedwell & Howell 2004, Applied Physical Sciences 2010) is possibly also reduced due to the large diameter of the system. In cases where a higher noise reduction is required (e.g. for large monopiles) a double bubble curtain offers an even higher reduction potential.

2.4 Development Status

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

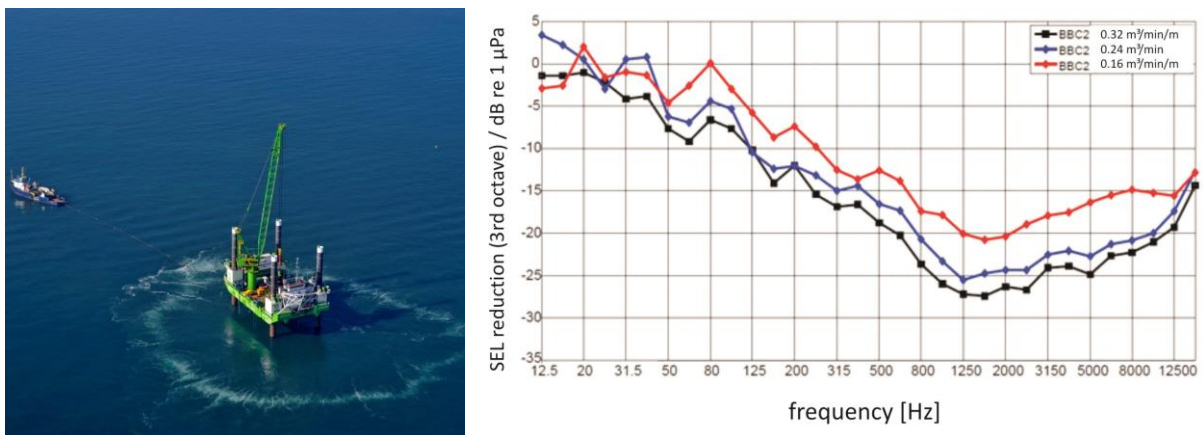


Figure 1: Left: Application of a BBC by Hydrotechnik Lübeck at the OWF Borkum West II (photo: Trianel GmbH/Lang). Right: Noise reduction achieved by a BBC at the OWF Borkum West II as a function of air supply (source: Bellmann 2012, modified)

3 Little Bubble Curtains (LBC)

3.1 Technical Description of the System

The principle of noise reduction in the little bubble (LBC) curtain is the same as in the big bubble curtain (chapter 0) In addition to scattering and absorption effects, the coupling of noise to the air/water mixture may be lower compared to water when the entire pile is in direct contact with the rising bubbles. The perforated pipes of little bubble curtains surround the pile in a close fit. The term “little” refers to the overall dimension and not the nozzle pipe length which could, depending on parameters like diameter, water depth and current velocity, even be longer compared to a BBC. Several variations of little bubble curtains have been tested: Layered ring systems, bubble curtains confined by steel, fabric or plastic guiding plates or casings (Caltrans 2009, Wilke *et al.* 2012) or a vertical arrangement of perforated tubes around the pile (*SBC: Small Bubble Curtain*) (ITAP 2013, Steinhagen & Mesecke-Rischmann 2013). The purpose of a confinement or the vertical arrangement of tubes (as in the *SBC*) is to prevent sound leakages otherwise created by drift of bubbles due to tidal currents at horizontal interspaces between the layers of the bubble curtain. In the *SBC* tidal currents and the complex upwelling characteristics of bubbles help surround the pile with a mixture of air and water (Steinhagen 2012).

3.2 Experience with Little Bubble Curtains

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

3.3 Noise Mitigation

The LBC has the potential to reduce noise in a broad range of frequencies. A precondition for effective noise mitigation is that the entire oscillating structure is surrounded by bubbles. Using the pre-piling procedure³ for frame constructions prevents structure-borne noise from being transmitted from cross beams when the bubble curtain forms an enclosure only around the pile. The seismic contribution to the propagation of the sound is not reduced by any of the variations of the LBC. The noise levels measured with a layered ring system as applied at the OWF *Baltic II* resulted in

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

a broadband noise reduction between 11 and 15 dB (SEL) measured at 750m (Schultz-von Glahn 2011, Zerbst & Rustemeier 2011). The noise reduction increased continuously from frequencies of approximately 25 Hz and was highest at frequencies of 1-10 kHz. It also revealed a good noise reduction even in the critical frequency range of 125-1,000 Hz, where the major energy of the pile driving signal is emitted. This result is similar to the noise reduction (12 dB (SEL), 14 dB (peak)) in the direction of tidal flow with only the lower unit of the layered LBC during the construction of the OWF *alpha ventus* (Betke & Matuschek 2010). During the test of a confined system the broadband noise level was reduced by 4-5 dB (SEL) (Wilke *et al.* 2012). However, the interpretation of this unexpectedly low noise reduction is difficult since the test pile was anchored firmly about 65 m deep in the seabed and was strongly encrusted. Thus, acoustic properties were different compared to a pile actively driven into the ground. In the SBC the resulting noise reduction in the first offshore test varied among configurations tested (regarding air volume, number of pipes, hydrophone position). The configurations with 3 or more compressors achieved noise reductions of 11-14 dB (SEL) and 14-19 dB (Peak) (Steinhagen & Mesecke-Rischmann 2013). The second offshore test confirmed these results by noise reductions of 9-13 dB (SEL) and up to 14 dB (Peak) (ITAP 2013) ([Figure 2](#)).

3.4 Development Status

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

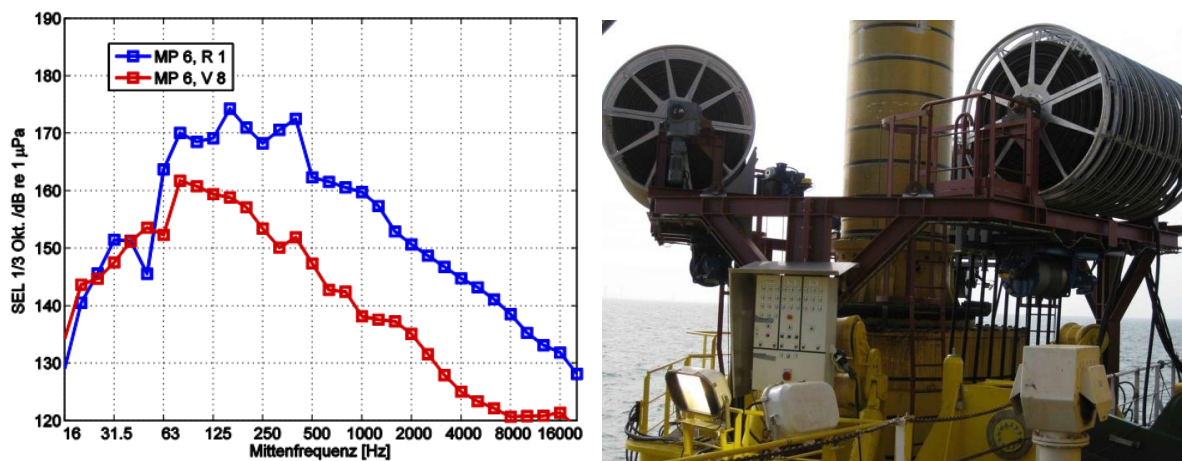


Figure 2: Third octave band spectrum (*left*, measured at OWF *BARD* Offshore 1, distance 750m) of piling noise (blue: reference without mitigation, red: with *SBC* (air volume: 160m³/min). Improved *SBC* design with flexible tubes which can be uncoiled from winches on the top (*right*) (sources: ITAP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

4 Isolation Casings

4.1 Technical Description of the System

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

4.2 Experience with Isolation Casings

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

4.3 Noise Mitigation

By combining several principles of noise reduction in various layers, isolation casings have a high noise reduction potential comparable to or exceeding that of a bubble curtain (Elmer *et al.* 2007a, Caltrans 2009). Important features are acoustic decoupling and inclusion of air into layers. Frequency-dependent noise reduction varies depending on the specific design. With smaller piles (\varnothing 1.2 m) in shallow water (6 m), the *IHC NMS* reduced noise mainly in frequency bands between 150 Hz and 8 kHz (Bob Jung, *IHC Hydrohammer*, Kinderdijk, NL, pers. comm.). At two met masts, measured overall noise reduction (\varnothing 3.35 m, water depth 25 m, hammer: *IHC S800*) was between 9 dB (OWF *Nordsee Ost*) and 11 dB (Ijmuiden) (Wilke *et al.* 2012). At the OWF *Riffgat*, an improved version of the *IHC NMS* achieved an overall noise reduction in the order of 17 dB compared to the prediction of 180 dB (SEL) made beforehand. It must be taken into account that the prediction was

given with an uncertainty of 5 dB and consequently the same uncertainty has to be applied to the noise reduction value. Unfortunately, no measurements of pile driving noise without mitigation system were performed. Reliable comparative measurements are still lacking. For a 5.7 m pile in sandy soil at 750 m distance single event sound pressure levels varied between 162 and 166 dB (SEL) (Figure 3). The average level was 163 dB (SEL) / 187 dB (peak) (Gerke & Bellmann 2012). For 6.5 m piles driven at sites with cohesive soils (clay) measurements are not available. However, due to soil differences a large variation can be expected. In a pilot test the measured overall broadband noise reduction by the *BEKA* shell was only 6-8 dB (SEL). However, the interpretation of this unexpectedly low noise reduction is difficult since the test pile was anchored firmly about 65 m deep in the seabed and was strongly encrusted. Thus, acoustic properties were different compared to a pile actively driven into the ground. An offshore field test is still lacking.

4.4 Development Status

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

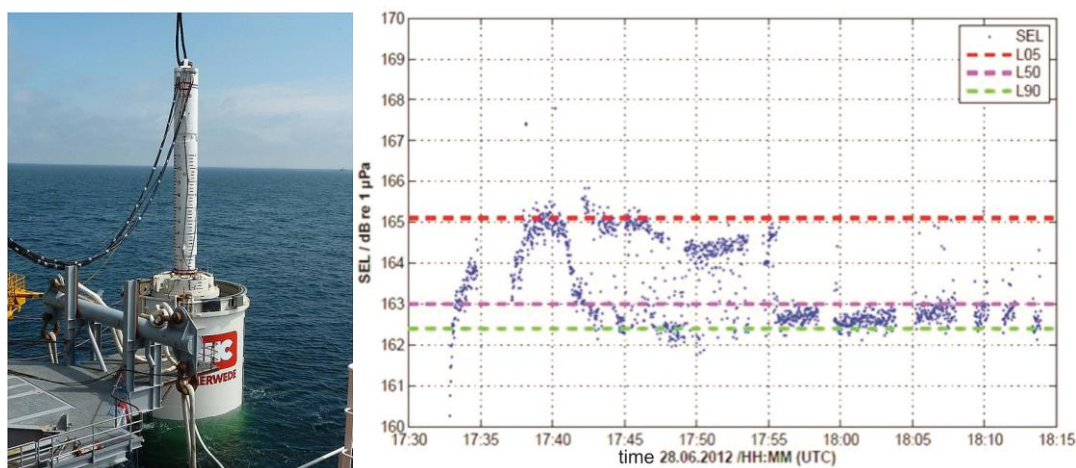


Figure 3: Left: Application of the *IHC* Noise Mitigation Screen NMS at the OWF *Riffgat* (source: *Riffgat* 2013, modified). Right: Broadband noise sum level during piling at the OWF *Riffgat* (measured at 750 m; blue points: SEL of each of the 1,403 piling strikes; red, magenta and green dotted lines: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

5 Dewatered Cofferdams

5.1 Technical Description of the System

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

5.2 Experience with Cofferdams

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

5.3 Noise Mitigation

A good noise mitigation of a Cofferdam can be expected based on the large impedance mismatch between air and steel (Applied Physical Sciences 2010). In a practical application an average broadband noise reduction of 23 dB (SEL)/17 dB (peak) was achieved at the Aarhus Bight test, measured at 750 m for 100% pile driving power. Best results were achieved at frequencies of 100-500 Hz (Figure 4, middle) (McKenzie Maxon 2012) where highest noise levels are emitted during pile driving. These results are in line with expectations from models (about 20 dB; Applied Physical Sciences 2010). In addition the measurements at Aarhus Bight confirmed that direct contact between the pile and the cofferdam decreases the effectiveness in reducing piling driving noise as noise reduction was only 13 dB (SEL)/13 dB (peak) (McKenzie Maxon 2012). Based on finite element

models the theoretical noise reduction achieved by Pile-in-Pile Piling was calculated as 43 dB at maximum when there was no contact between pile and cofferdam (Frühling *et al.* 2012). However, the model also demonstrated that the guiding pieces lead to considerable sound leakages. This effect could be minimised by the application of rubber inserts for acoustic decoupling, resulting in a noise reduction for the dewatered case with decoupled guiding pieces of up to 27 dB under ideal conditions (Frühling *et al.* 2011). The *ABB* system applied at the *Dolwin alpha* jacket platform reduced the noise during piling to levels below 160 dB (SEL) at 750 m distance (Wijk 2013, Heerema 2013).

5.4 Development Status

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

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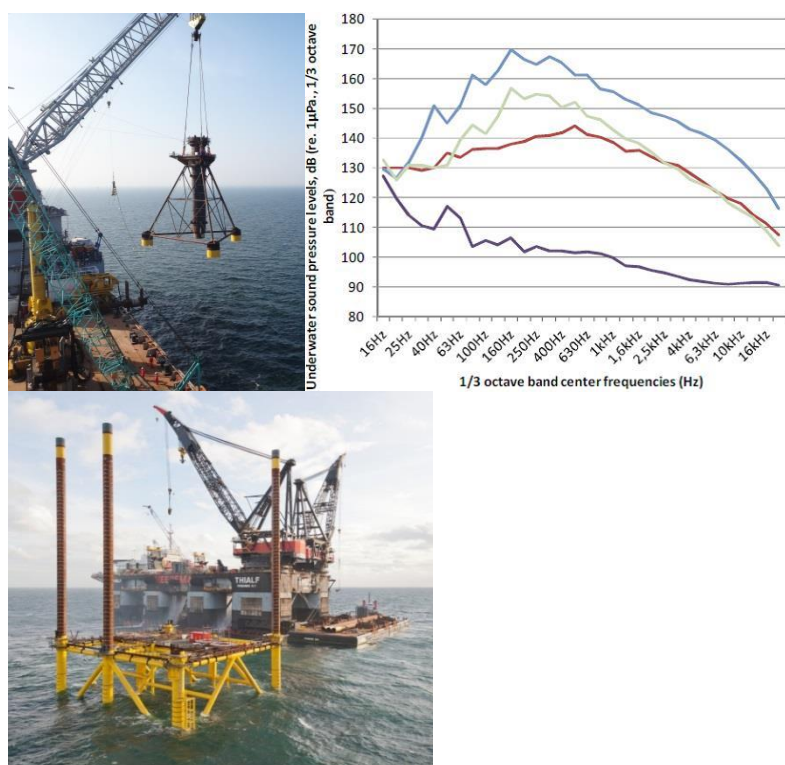


Figure 4: Cofferdam application at Helwin alpha (left, source: Lo-Noise Aps) and 3rd octave spectra measured at Lo-Noise Aarhus Bight test with 100% pile driving power (violet: background noise, red: av. with cofferdam, light green: av. with cofferdam pile contact, blue: av. without cofferdam) (middle,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

6 Hydro Sound Dampers (HSD) / “Encapsulated Bubbles”

6.1 Technical Description of the System

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

6.2 Experience with Hydro Sound Dampers (HSD) / “Encapsulated Bubbles”

Primary tests with *HSD* were conducted in the large wave flume of the Coastal Research Centre (FZK). These *HSD* elements were designed to reduce noise at frequencies around 100-300 Hz. In the *ESRa* project various types of *HSD* balloons and robust *HSD* foam elements were attached to three

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

6.3 Noise Mitigation

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

6.4 Development Status

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

As all systems attached close to the pile or foundation structure the deployment time has to be considered in order to guarantee a smooth and organised course of construction without delays. At the OWF *London Array* the installation of the noise mitigation system took only about 3-4 hours

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

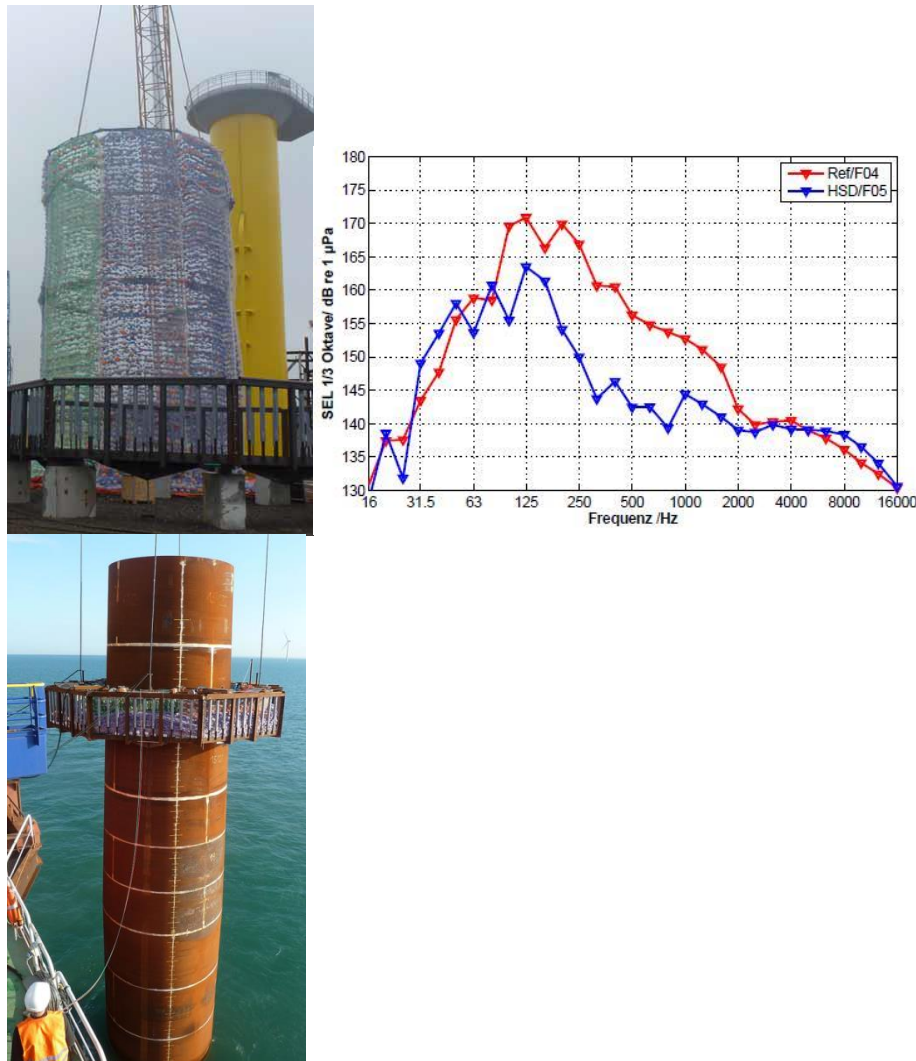


Figure 5: Left: HSD net in a test set-up. Middle: 3rd octave spectra of piling without (red) and with HSD (blue) at London Array. Right: HSD in a practical application at London Array (sources: Bruns & Kuhn 2013, Elmer *et al.* 2012, ISD 2013, modified)

7 Vibratory Pile Driving (Vibropiling)

7.1 Technical Description of the System

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

7.2 Experience with Vibropiling

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

7.3 Noise Mitigation

In various projects, noise levels (L_{eq}) emitted during vibropiling were about 15-20 dB lower than those of impact piling (Elmer *et al.* 2007a, Betke & Matuschek 2010, ITAP 2012, Kringelum 2013). The main energy is radiated at lower frequencies compared to impact piling. The underwater noise levels at the OFW *alpha ventus* varied considerably during vibropiling. The broadband level of about 142 dB (SEL) (157 dB in the loudest period) at 750 m distance was substantially lower than the sound levels during impact piling of about 167 dB (SEL)). However, a high frequency tonal component up to about 10 kHz went with the regular operational noise and was audible especially at the end of the piling process as a high buzzing sound (Betke & Matuschek 2010). At the OWF *Anholt*, in hard soils and during refusal the noise was significantly higher than during smoothly operated vibropiling. At 750 m distance vibropiling noise was 150 dB (SEL) under normal operation, with up to 166 dB (SEL) during refusal, compared to 171-175 dB from impact piling (Kringelum 2013). During vibropiling at the OFW *Riffgat* the median broadband L_{eq} measured at a distance of 750 m was 145 dB compared

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

7.4 Development Status

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

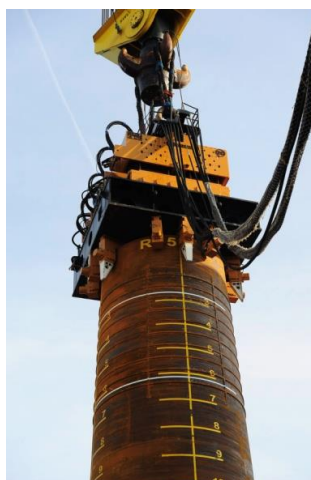
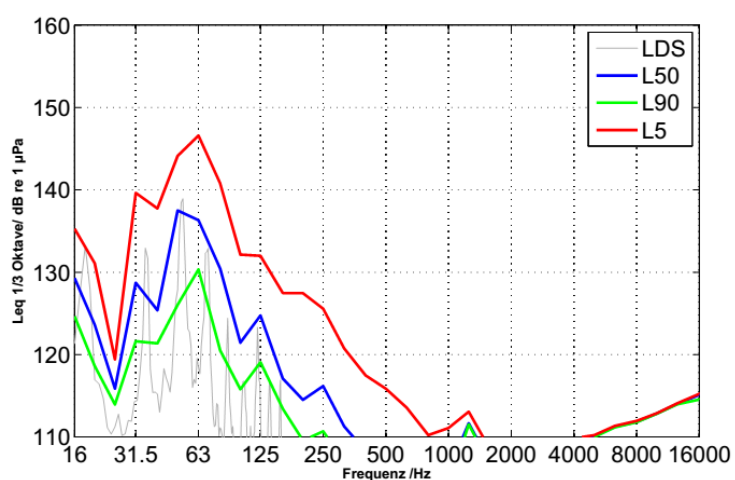


Figure 6: Left: frequency spectrum of a vibratory hammer in the OWF Riffgat at pile R14, measured at 750m distance over 98 min (Leq as 5, 50 and 90 % percentiles in 30s intervals and resolution of third octaves 'L5, L50, L90' and with a resolution of 1 Hz 'LDS'). Right: multiple linked hydraulic vibratory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

8 Drilled Foundations

8.1 Technical Description of the System

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

8.2 Experience with Drilled Foundation

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

8.3 Noise Mitigation

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

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than predicted as very low frequencies are not transmitted at shallow water. Drilling generates continuous noise whose impact on the marine environment is not directly comparable to that of impulsive noise (Southall *et al.* 2007).

8.4 Development Status

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

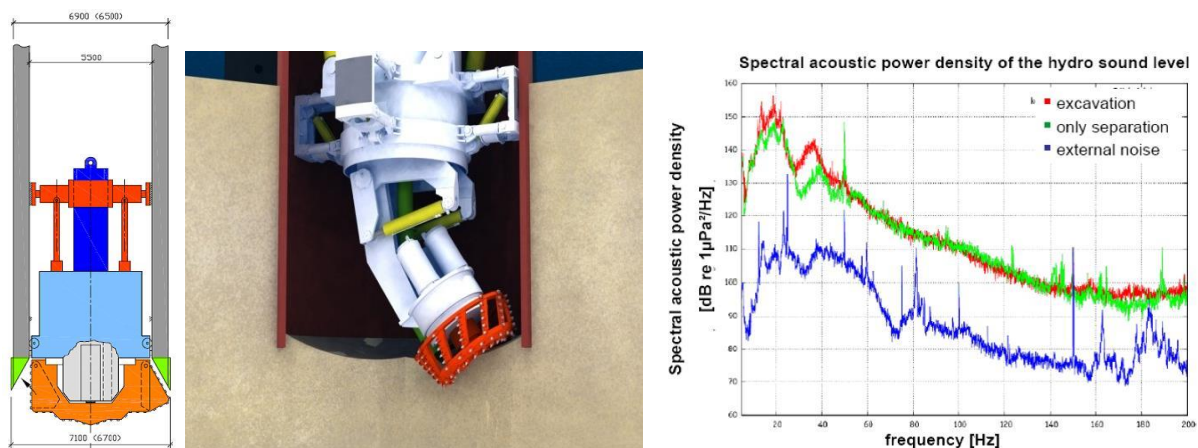


Figure 7: Left: *Ballast Nedam's* concept (source: Van de Brug 2011). Middle: OFD concept (source: *Hochtief Solutions AG*, Essen). Right: Hydrosound measurement during the operation of a *Herrenknecht VSM* (source: Ahrens & Wiegand 2009)

9 Gravity Base Foundations

9.1 Technical Description of the System

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

9.2 Experience with Gravity Base Foundations

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

9.3 Noise Mitigation

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

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9.4 Development Status

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

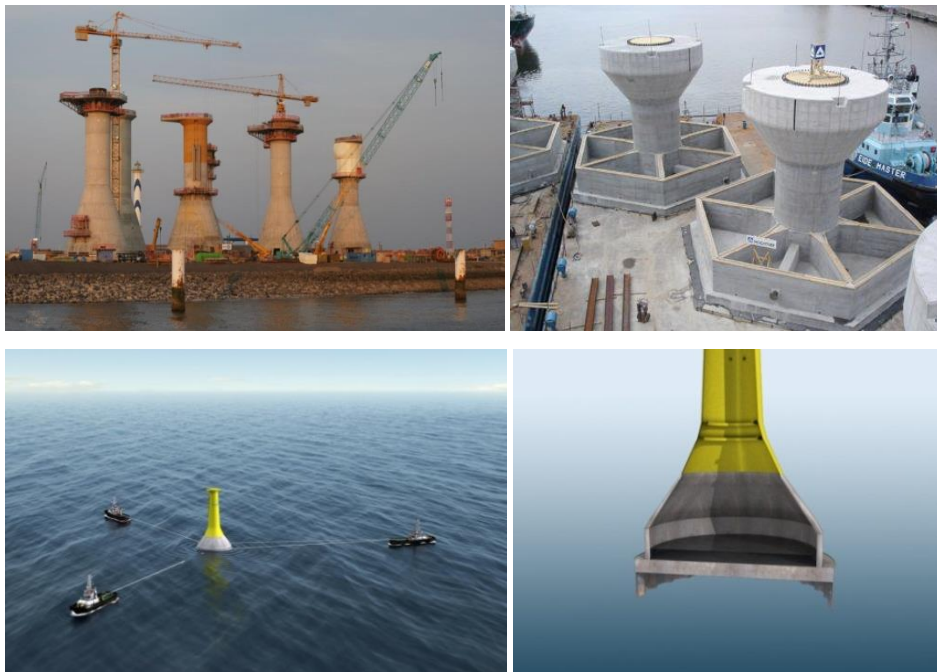


Figure 8: Above: Gravity base foundations of the OWFs Thornton Bank (left, source: Wikimedia Commons) and Lillgrund (right, source: Freisen 2010). Below: Seatower CraneFree gravity base foundation. The bottle shaped foundation is towed to the site and positioned (left). Steel skirts at the bottom (right)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

10 Floating Wind Turbines

10.1 Technical Description of the System

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

10.2 Experience with Floating Wind Turbines

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

10.3 Noise Mitigation

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

10.4 Development Status

The number of different floating concepts reflects the importance for the offshore wind sector. Some concepts are based on proven technologies such as wind turbines or floats whereas other concepts are completely new developments. Platforms are market available. Technical challenges

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such as dynamic loads in shallow waters, pitch and roll of turbines, safe moorings and economic challenges such as cost competitiveness still have to be tackled. Thus, further development and full scale demonstrations are needed. One advantage of floating foundations resulting in cost advantages is that the installation and repair can be carried out in a dockyard. To date, the project *HYWIND* is pre-commercial. The projects *GICON-SOF*, *INFLOW* and *WINDSEA* are in the experimental stage. The pilot stage has been reached by *WindFloat* with a full-scale and *Poseidon 37*, *Sway*, and *Blue H*, with downsized offshore prototypes, and *WINFLO* with a prototype under construction.

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

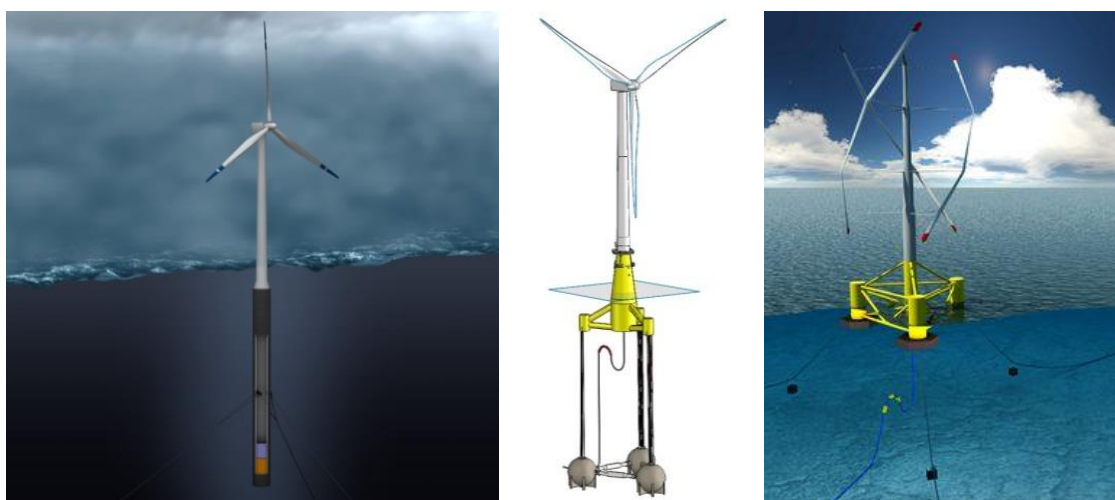


Figure 9: SPAR buoy in the *HYWIND* project (left, source: Siemens 2009, \varnothing yvind Hagen/ Statoil), *Blue H* concept with submergible gravity based anchors (middle, source: Nico C. F. Bolleman, *Blue H Engineering BV*, NL), *INFLOW* concept of a semi-submersible platform (right: source: Inflow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

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

11.1 Technical Description of the System

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

11.2 Experience with Bucket Foundations

Platform concepts: Several platforms have been mounted on bucket foundations in water depths of 50-70 m off Western Africa or Malaysia and in the North Sea (e.g. in the Trent gas field) (Overdick 2013a). The platform can either be carried by a super barge or wet-towed to the offshore site as MOAB (*Mobile Application Barge*). In the German EEZ the first substation of a commercial OWF has been installed by bucket foundations at *Global Tech 1* in 2013 (water depth 40 m). The substation (weight about 9,000 t) is based on the MOAB principle with bucket foundations at each of the four legs. The swimming platform was wet towed to the offshore location. Once installation was completed, the buckets (\varnothing 11 m, height 9.5 m, wall thickness 50 mm, weight 834 t each) penetrated 9 m into the sandy sediment (*Figure 10*) (Barkhoff *et al.* 2013). Monopod concepts: Prototypes of monopiles mounted on single suction buckets have been successfully installed. In 2002, a 3.0 MW wind turbine (height 89 m) on a bucket foundation (\varnothing 12 m, height 6 m, weight 135 t) was successfully installed in marine sediments in a polder near Frederikshavn (Ibsen *et al.* 2005). In 2009, a mobile met mast (height 38 m) was installed at the OWF *Horns Rev 2* on a bucket foundation (\varnothing 12 m, height 6 m, weight 165 t) (LeBlanc *et al.* 2009). Two meteorological met masts on monopods designed by the Danish company *Universal Foundation* have been installed at the location of the projected OWF *Dogger Bank* in 2013 (*Figure 10*). The installation took 7 h from lifting until complete installation (Ibsen 2013). A failure of a bucket installation occurred in April 2005, when *ENERCON* planned to install a 4.5 MW E-112 wind turbine on a bucket foundation nearshore at Hooksiel (\varnothing 16 m, height 15 m, wall thickness 25 mm, water depth 4 m) (LeBlanc 2009). However, during the installation the caisson deformed and the operation was suspended. According to Ibsen (2013) the heavy load pontoon *Giant 4* collided with the skirt at a penetration depth of 3 m. The steel was dented inside by 8-16 cm and the caisson distorted during suction at a penetration depth of 6.8 m.

11.3 Noise Mitigation

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

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11.4 Development Status

Bucket foundations cannot be used at all soil types but generally soil profiles that are suitable for driven monopiles (sand, silt or clay) can also be assumed suitable for bucket foundations (Ibsen 2013). Scour protection can be integrated in the system using perforated steel partitions (Ekkehard Overdick, *Overdick GmbH & Co. KG*, pers. comm.) or welded cut plates (Ibsen 2013) on top of the buckets. Platform concepts: Bucket foundations are proven technology for platforms in the oil and gas sector. A prototype for a substation of an OWF has successfully installed at *Global Tech 1*. Monopod concepts: The bucket foundation has to penetrate evenly into the seabed in order to guarantee an upright position of the supporting structure. Large lateral loads (such as from wind turbines) are more difficult to absorb with a small embedment depth in buckets compared to standard deep foundations (Abdel-Rahman & Achmus 2005). A successful example is the monopod in Frederikshavn. The collapsing of the *Enercon* bucket near Hooksiel illustrates that buckling of the thin shell structure is a critical issue during installation. Post buckling analysis led to the development of a multi-shell system (Figure 10) with additional longitudinal stiffeners with significantly larger buckling load (Ibsen 2013). The installation of the monopod met masts at *Horns Rev 2* and *Dogger Bank* used traditional cylinders. Multiple bucket concepts: Concepts with three-legged jackets with bucket foundations have been developed by the companies *Overdick GmbH & Co. KG* and *SPT Offshore*. *SPT Offshore's* concept of fully prefabricated turbines with a wider base compared to standard jackets (*SIWT, Suction Installed Wind Turbine, Figure 10*) offers advantages in manufacturing and installation (Riemers 2013). The *SIWT* is intended for use at water depths of 15-60 m and suited for 3 – 10 MW wind turbines. However, the effects of high vibration loads in jackets with multiple buckets are yet to be investigated. *SPT Offshore* has been selected as one of the four final candidates to be demonstrated at full-scale for the UK Round 3 OWF (Carbon Trust 2012). The installation of a full scale prototype of an *SIWT* is planned by *DONG Energy* at one of the companies' German projects in 2014 (Figure 10). This foundation type is intended to prove a cost-efficient and low-noise alternative to traditional foundation methods, especially for the next generation of offshore wind turbines (5-8 MW) at water depths of 25-60 m (DONG Energy 2013). Currently it is unclear how the mechanical resistance and stability of bucket foundations is impacted by the influence of cyclical loads. In contrast to monopod foundations in which an extreme point load can result in the collapse or detachment of the bucket, the foundation on jackets with multiple buckets is more promising from a technological perspective. The use of multiple buckets leads to smaller sized buckets compared to monopods. The structure can be levelled during installation by changing the suction pressure in the individual suction buckets (DONG Energy 2013).



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

12 Additional noise mitigation concepts

12.1 High Frequency – Low Energy Piling

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

12.2 Mandrel Piles

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

12.3 Slit Piles

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

13 Additional Low-Noise Foundation Concepts

13.1 Silent pile driving

Numerical investigations revealed that prolonging the pulse duration⁴ reduces the corresponding sound emission (Elmer *et al.* 2007a, b). As the impact energy is distributed over a longer time period, the maximum impact force and thus the amplitude of the lateral extension is reduced. At the same time the frequency spectrum emitted is shifted to lower frequencies because the oscillation period is prolonged. Hence, the reduced propagation velocity of the lateral extension directly decreases the sound emission. This would not only have a positive effect on sound in the water but also on the seismic component of radiated noise. The prolongation of pulse duration is a theoretical noise mitigation method, however, no practical and effective solutions for large piles have been presented

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

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yet (Koschinski & Lüdemann 2013). Piling cushions between hammer and pile are not suited for large monopiles and a coiled steel cable which revealed a prolongation of the pulse duration by a factor greater than 2 and a noise reduction by up to 7 dB was effective only for a few strikes (Elmer *et al.* 2007b).

A novel technology making use of this effect without using conventional hydraulic pile driving hammers is *BLUE Piling* by the Dutch company *FISTUCA BV* (Winkes & Genuit 2013). It uses a large water column to generate the driving force. *BLUE Piling* increases the pulse duration by a factor of 20. Sea water inside a steel tube closed at the bottom is pushed upwards by igniting a gas mixture in a combustion chamber at the bottom (Figure 11, left). The flue gasses are kept from freely expanding by the mass inertia of the water column. The pressure increase generates a downward force and lifts the water column at the same time. A second downward force pulse is produced when the water falls down again (Figure 11, middle). This cycle is repeated until the pile reaches its desired depth. Advantages are a lower noise emission of 25 dB or more (without external mitigation methods), a gradual force build-up, a low tension stress and also cost-effectiveness. The reduced propagation velocity of the lateral extension of the pile should not only decrease the underwater noise emission but also the seismic component of radiated noise which is often limiting external noise mitigation systems. The pile driving properties have been investigated in a successful near-shore test with a prototype (\varnothing 2.2 m, 35 t + 80 t of water) and a closed ended pile of \varnothing 0.66 meter and an open ended pile of \varnothing 2.25 meter (Figure 11, right). The blow duration was 80 ms for the primary and over 100 ms for the secondary blow. The maximum SEL for the 0.66 m pile was 152 dB re $1\mu\text{Pa}^2\text{s}$, the maximum peak level was 179 dB re $1\mu\text{Pa}$ at measuring distance of 70 m. A larger hammer (about 600 kJ) is to be built and tested near shore in 2014 before scaling up the technology for full-scale monopiles (projected for 2015) (J. Winkes, FISTUCA BV, Eindhoven, NL pers. comm.).

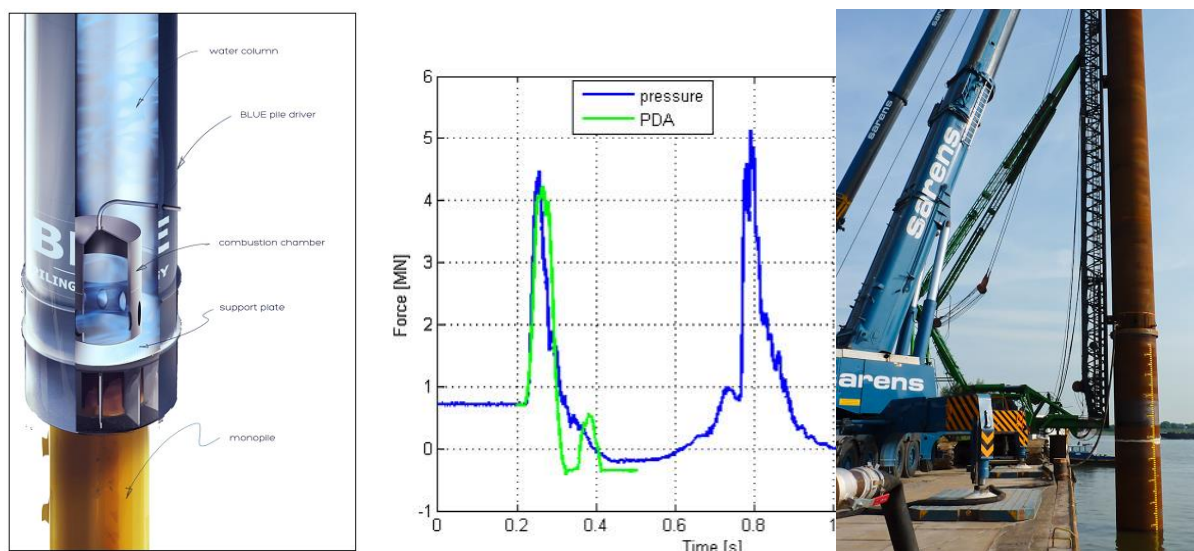


Figure 11: Left: schematic overview of the BLUE pile driver (left), middle: blow characteristics of primary and secondary pulses measured in the water column (blue) and with strain sensors in the pile (green), right: photograph from the nearshore test (Source (modified): Winkes & Genuit 2013).

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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)

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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 available 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 table⁵.

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).

⁵ 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 recommendations used by DEA	2011 (Mitigation guidelines) 2014 (MMO manual)	2016	2012	2007	2008	2013	2005 (could not access but reviewed in MaMaCoCoSE A, 2015)

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	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).	<i>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'</i>	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

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	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 1µPa ² 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 qualification requirements	All MMOs must be 'trained', defined as having undertaken a JNCC recognised training course and have some experience of visually spotting marine mammals. In areas of importance ⁶ , MMOs also required to be 'experienced', defined as having a minimum of 20 weeks experience implementing the guidelines in UK waters obtained over the previous ten years, preferably 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.
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	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

⁶ 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
Soft start procedure	<p>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.</p> <p>Airguns <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.</p> <p>Electromagnetic sources: where practical, ramp up in a uniform</p>	<i>ramp up over a minimum of 20 minutes and maximum 40 minutes depending on survey type</i>	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
Shut down procedures	<p>Delay soft start if marine mammal in mitigation zone.</p> <p>No shut down requirement during operations if marine mammal enters exclusion zone.</p>	<p>Delay soft start if marine mammal in exclusion zone.</p> <p>No shut down requirement during operations if marine mammal enters exclusion zone.</p>	<p>If marine mammals are detected with exclosure zone, firing shall be reduced ti mitigation gun</p>	<p>Reduce output to mitigation gun if mammal in 200 m injury zone.</p>	<p>Delay soft start if cetacean in exclusion zone.</p> <p>Immediate shut down if cetacean in exclusion zone.</p>	<p>Shut down if marine mammal within 500 m exclusion zone.</p>	<p>Delay soft start if cetacean in exclusion zone.</p> <p>Immediate shut down if marine mammal/turtle in exclusion zone.</p>	<p>Delay soft start if cetacean in exclusion zone.</p> <p>Immediate shut down if marine species enters exclusion zone.</p>	<p>Delay soft start if whale is in shut down zone.</p> <p>Immediate shut down if whale enters or is about to enter shut down zone.</p> <p>Power down to lowest setting if whale in low power zone.</p> <p>Require additional trained crew member or MMO if whale in observation zone.</p>	<p>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.</p>	<p>Delay soft start if marine mammal in exclusion zone.</p> <p>Immediate shut down if marine mammal enters exclusion zone.</p>

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	Country										
	UK	Ireland	Greenland	Denmark	Spain	Netherlands	USA (Gulf of Mexico)	Canada	Australia	New Zealand	Brazil
Night time or low visibility requirements	Soft start to commence in daylight hours if possible. PAM should be used during periods when visual mitigation not possible e.g. darkness, low visibility.	No soft start allowed.	It is recommended to initiate surveys when visibility is good	Not specified but PAM and other 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/delayed 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
Other requirements	Specific guidelines for high resolution surveys (e.g. sub-bottom profiling).		Systematic sampling of seabird and marine mammal data. Modelling impact areas of the noise before survey. If other 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.

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	Country										
	UK	Ireland	Greenland	Denmark	Spain	Netherlands	USA (Gulf of Mexico)	Canada	Australia	New Zealand	Brazil
Post survey requirements	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 1 st and 15 th 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 walrus. 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

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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.

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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).

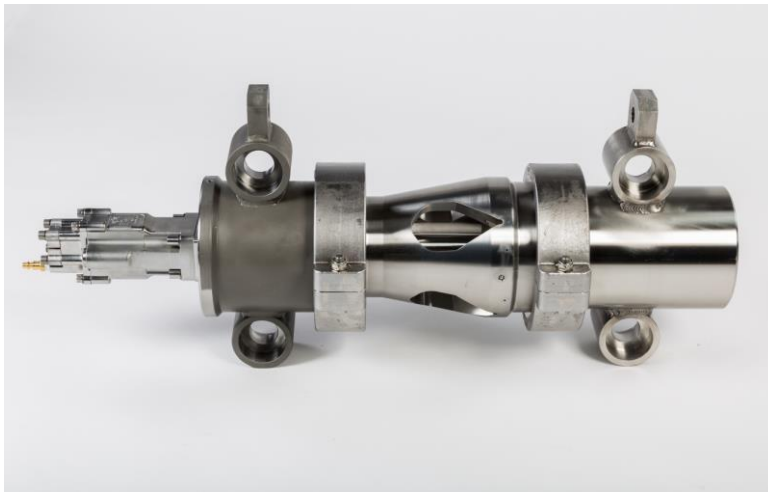


Figure 1: Bolt Technology eSource airgun design

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 (depending on 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 of 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

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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 operations. 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° 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.

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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 within 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).

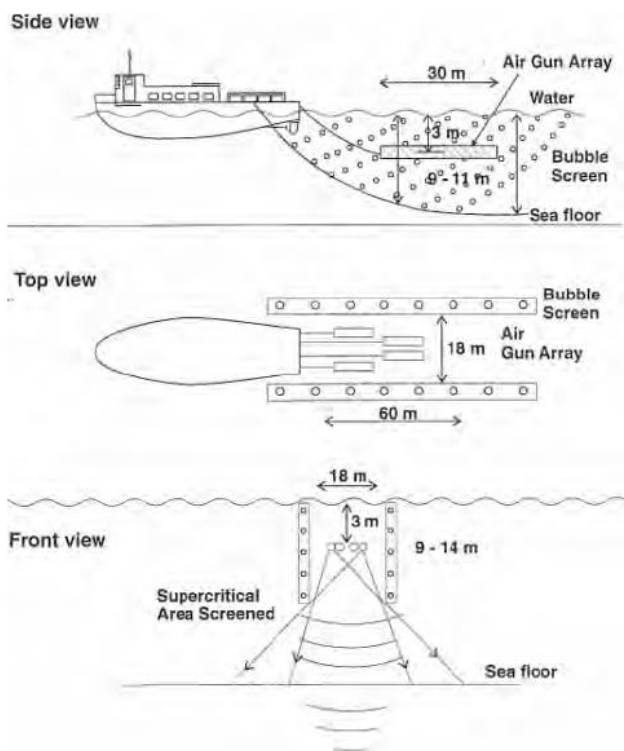


Figure 2: Example of bubble curtain used during a seismic survey 1996

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.

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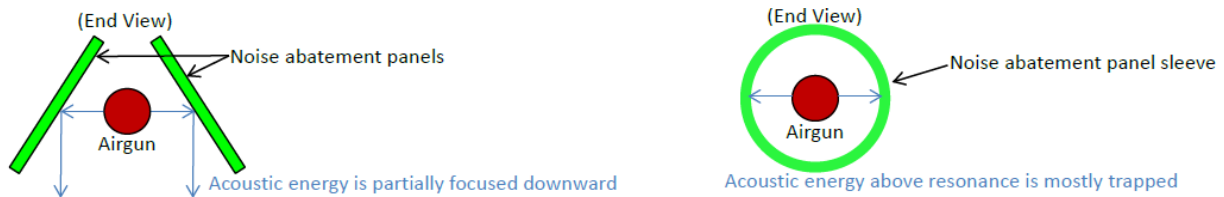


Figure 3: Helmholtz resonator technology for airgun sound suppression

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 observations 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

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(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.

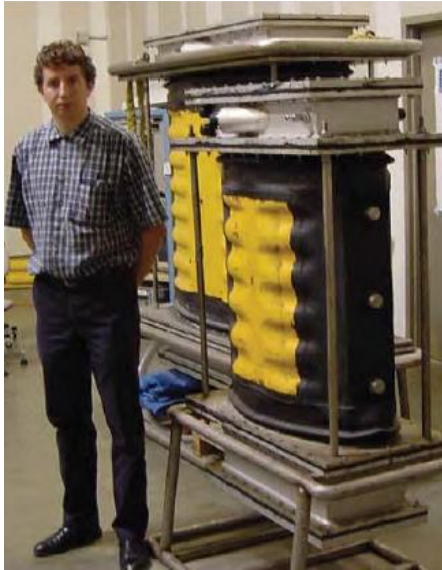


Figure 4: PGS Marine vibrator.

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).

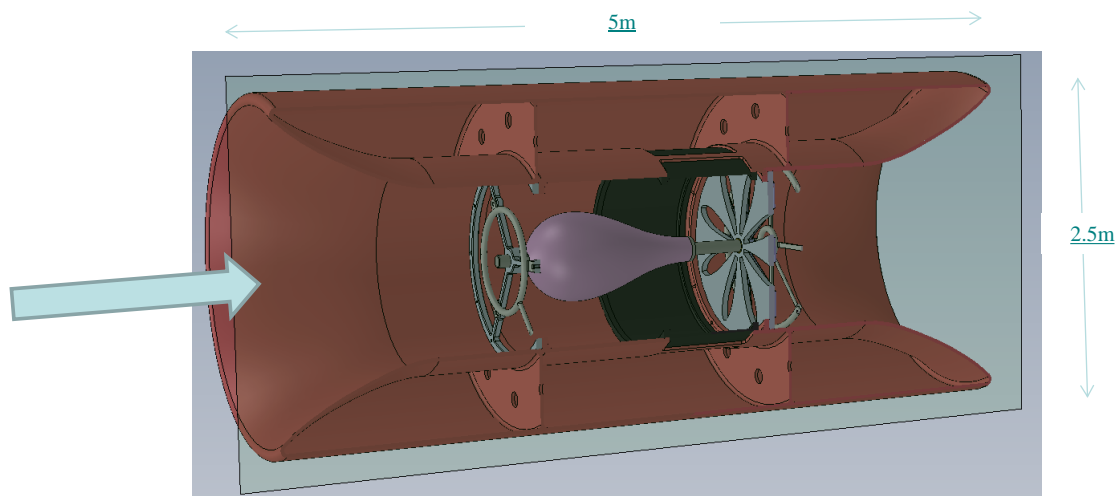


Figure 5: Design of the “Teles” marine siren (Cambridge Applied Physics Ltd., 2015)

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 μ Pa 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 piezoceramic 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 μ Pa 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 μ Pa 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).

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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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ISBN 978-1-911458-46-3
Publication Number: 706/2016

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