Sound Solutions

Construction of offshore wind farms without underwater noise

www.noordzee.nl/soundsolutions

Stichting De Noordzee

CBF KEUR VOOR GOEDE DOELEN

Together for a healthy North Sea

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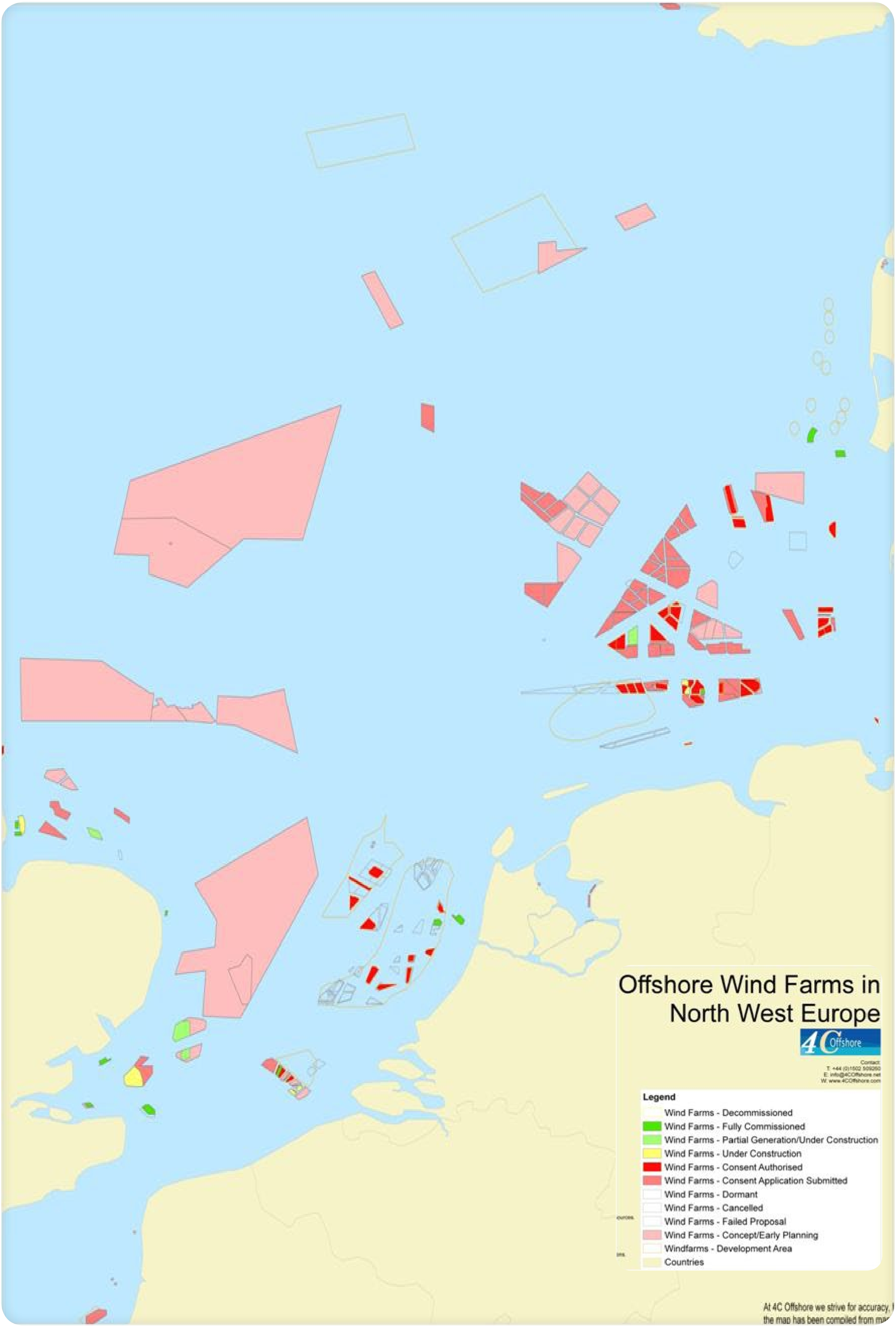
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Offshore wind is a growing industry

Reduce underwater noise caused by piling

The North Sea Foundation (NSF) is an environmental NGO advocating the protection and sustainable use of the North Sea. With regard to using the North Sea as a source for renewable energy production, we support offshore wind if the impact on marine life is taken into account seriously. Piling for offshore installations is one of the stronger sources for underwater noise. Our aim is to reduce underwater noise caused by pile driving for offshore wind farm construction. Our goal is to prevent the negative impact of underwater sound on marine life, and at the same time prevent delays in offshore wind farm development.

Introduction

Offshore wind is a growing industry. In the near future, a lot more offshore wind farms will be constructed, most of them in the North Sea. Those windfarms will probably be placed further offshore and generally the turbines will be larger and have a higher capacity.

There are several offshore foundation types. Currently the foundation most applied is the monopile (65%), followed by gravity based foundations (25%) and jackets (8%) (V.d. Walle, 2011).

Monopiles are generally being driven in the seafloor by a large hammer. This technique produces high-level underwater sound. These sound waves could have a large negative impact on marine life, especially if several large offshore wind farms will be constructed simultaneously.

Internationally there is awareness that the underwater sound of piling can cause serious problems. NGOs are concerned about the impact. Scientists conduct research to find out what the impact of piling is on the marine life. Governments put restrictions to the piling of offshore wind parks. These could lead to a delay in construction of future parks. Companies are therefore looking for engineering mitigation solutions or alternative construction methods.

Objective

The North Sea Foundation (NSF) is looking for solutions in reducing underwater noise during construction in order to:
1) reduce the impact on marine life like fish and marine mammals
2) prevent a delay in construction of future wind parks because of constrictions in relation to underwater sound.

More information: www.noordzee.nl/soundsolutions

About this report

In chapter 1 we give some information about pile driving of mono piles and the noise they generate. In chapter 2 we describe what the impact of this underwater sound is on marine life and we give some background information on underwater sound. In chapter 3 information on mitigation measures is given. Chapter 4 describes alternative construction techniques. Both chapters 3 and 4 are based on the report of Saleem (2011). Conclusions and recommendations are given in chapter 5.

Methods

For this report we reviewed literature, used news articles and interviewed experts on possible sound mitigation or alternative construction methods. We also interviewed several constructors/ suppliers on their practical experience applying mitigation measures, their opinions on the impact of underwater sound on marine life and the current regulations for pile driving and future perspectives. Several Dutch underwater acoustics experts have been involved in this project to support us on the complex underwater sound parts. NGOs in the Netherlands and abroad gave input on this project.

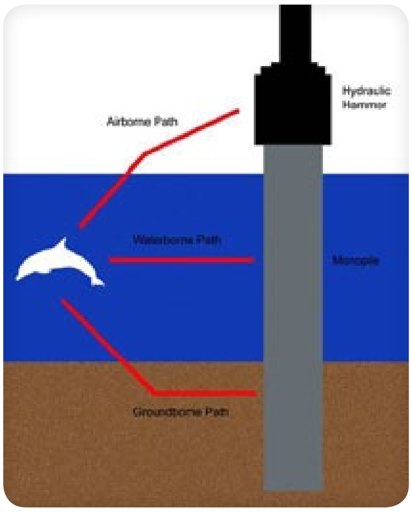
1. Pile driving and underwater noise

Piling has proven to be very effective

Pile driving causes high-level sounds

1.1 Pile driving

Mono pile foundation used for offshore wind farms is basically a cylindrical tube usually made of steel, which is directly installed into the seabed using hammering. This technique has been used in the offshore oil production before it made its way to wind energy and has proven to be very effective. It can be used for several soil types. Since its introduction in the offshore the mono pile has become larger and heavier. The diameter limit these days is around 6 meters and there are already concepts of 7 meters. It has been applied to water depths of 34 m.



Noise paths during impact pile driving

Pile driving causes sounds in serveral ways:

- When an impact hammer hits a pile the pile deforms and this deformation travels downwards to the lower end of the mono pile. This deflection disturbs the water, generating sound (Saleem, 2011).
- Also when the hammer strikes the pile the sound is generated in the air. A part of this sound energy enters the water and contributes to the overall noise levels.
- - Finally the impact force transmitted to the seafloor will also consist of the structural vibration energy, producing lateral waves in the seabed. Some of these waves also “leak” into the water. Models indicate that the sound transmitted by the mono pile (structure borne radiation path) in most cases is the dominant path. The seismic path (sea floor) is less important for the overall underwater sound. However, in a few cases it can be the controlling path at a few frequencies, if sound isolation (bubble screen or compliant layer treatments) is being applied. The airborn path is not a significant contributor to underwater sound (Stokes et al., 2010).

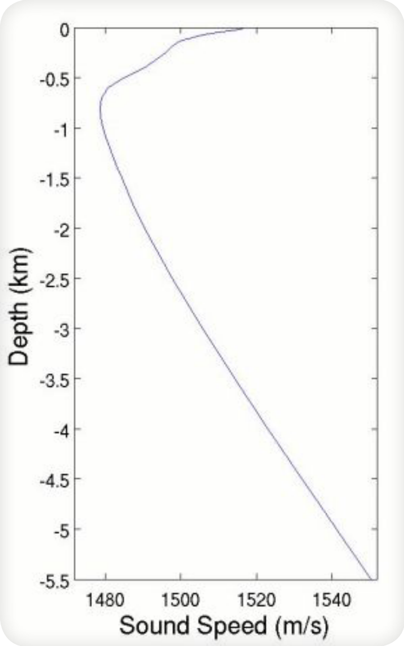
A part of the generated sound will be absorbed, by the seawater and the sea floor. Several factors influence how much sound is absorbed: substratum, water depth, salinity.

1.2 Underwater noise

I’ts never silent underwater

Sound propagates over longer distances underwater than in air. It’s also much faster: the speed of sound underwater is approximately 1500m/s against 340 m/s in air. It’s never silent underwater, there is always background noise. There are a lot of underwater sound sources. Natural sources like rain, storms and animal sounds. And unnatural, anthropogenic - or man made - sources. These sounds include construction activities, windfarms and shipping. Noise levels can vary quickly, depending on local circumstances.

Sound underwater and sound in air can't be compared



Speed of Sound vs. Depth

Underwater sound is expressed in dB. This is a logarithmic measure. An increase in acoustic energy by a factor 10 leads to an increase by 10dB, an increase of a factor 2 leads to an increase of approximately 3 dB (Ainslie et al., 2009). The amplitude of the reference pressure variation of underwater sound is by definition 1 μPa. In air it is 20 μPa. This makes, also due to the different acoustic impedances of both media, that underwater sound and sound in air can't be compared.

Several measures of sound are used to indicate characteristics of sounds.

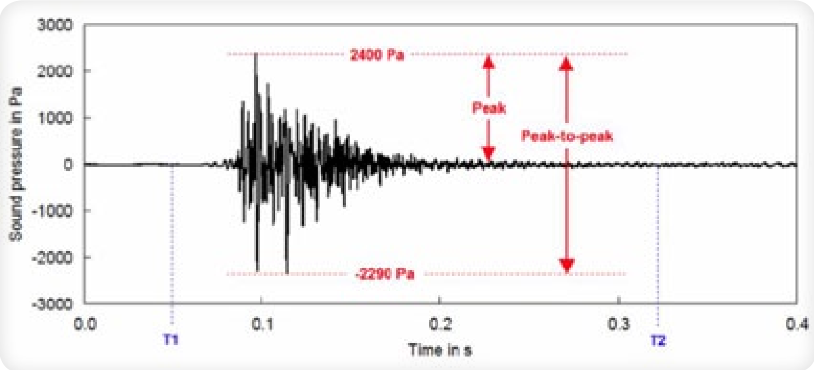
- The source level is the amount of sound energy of a source. A higher source level means a louder sound.
- The peak level is the maximum absolute pressure within a particular time interval.
- The Sound Pressure Level (SPL) is the level actually experienced at a particular location. It indicates an average level of sound and is indicative for the received level at that location.
- The Sound Exposure Level (SEL) refers to the total, accumulative amount of sound that is received during a particular time interval.

2. Pile driving noise

Pile driving is a short and loud sound

Piling for offshore installations is one of the strongest sources of underwater noise (Madsen et al. (2006) in Ainslie et al., 2009). It is one of the main contributions to anthropogenic sound energy in the North Sea, next to shipping, seismic surveys (airguns) and underwater explosions (Ainslie et al. 2009).

Pile driving is a relatively short and loud impulsive sound. Peak levels and sound exposure levels of pile driving are very high. Peak levels of 208 dB re 1 µPa have been measured (at 57 m distance) and SEL of 178 dB re 1 µPa.s. Normalised at 500 m distance and 20 m water depth show peak levels of 200 dB re 1 µPa and SEL 178 re 1 µPa.s. The highest sound pressures are reached at low frequencies between 100 and 300 Hz (Ainslie et al., 2009). During the hammering of monopiles, the repeated sound is separated by about 0.8-1.5s intervals, where a full hammering cycle takes about 2 hrs to complete. It is also repeated every 24 hrs (Kats, 2009).



A typical sound pressure impulse of one hydraulic hammer stroke (Nehls, Betke, Eckelmann &Ross, 2007)

The actual noise generated from pile driving depends on a lot of factors like: soil type, salinity, sea state, pile diameter, wind speed and power of the hammer. The exact relation between the blow energy and noise level is unknown, however it can be safely assumed that the noise will be higher with higher blow energy (Saleem, 2011).

2.1 Impact of pile driving noise on marine life

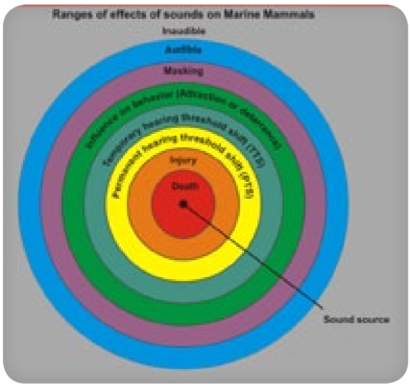
Every animal has it’s own hearing sensitivity

Introduction

Every animal has its own specific hearing sensitivity and hearing (frequency) range. Species do not hear all frequencies equally. Each species has hearing adaptation for its own vocalizations, those of its prey and sometimes those of its predators (Ainslie et al., 2009). Therefore, every species has its own zones of influence.

In general, pile driving discharges a certain amount of sound energy to the water that decreases with distance from the source, and eventually drowns out in the seas background sounds. Several zones of influence surrounding pile driving can be distinguished (Kastelein, 2011).

Larger turbines can increase the zones of noise influence



The sound source in the picture represents in this case pile driving (Kastelein).

- Far away from the source, the sound is inaudible to an animal, because the background noise in the sea masks the anthropogenic sound source.
- A bit closer to the source, there is a zone where the animal gradually perceives the sound. After reaching a certain level, the sound can cause masking of animal’s sound detection system. This is where noise is strong enough to drown out other biological sounds needed for i.e. communication.
- Closer to the source, there is a zone where behavioural responses occur.
- Even closer to the sound source, there is a zone where physical damage could occur: temporary threshold shift (TTS) and real closer to the source also, permanent threshold shift (PTS).
- In the immediate surrounding even lethal damage could occur.

Probably the size of turbines will increase in the future. The effects can not be assessed yet, but it is likely that larger turbines can increase the zones of noise influence (Thomsen et al. (2006) in Kats, 2009). However, a recent Belgian study found no statistically significant differences in maximum and mean SEL normalized at 750 m between piling of monopiles (5 m diameter) and pinpiles of jacket foundations (diameter 1,8m) (Norro et al., 2012).

Not all sounds carry the same effects. The higher the frequency of the sound, in general, the quicker it is absorbed by water. Therefore, sounds of higher frequencies, may affect animals at somewhat shorter distances than low-frequency sound. This effect, however, may be eliminated by the fact that many marine animals are more sensitive at higher frequencies. In contrast, loud lower frequency sounds like pile driving can travel many tens of kilometres and can be especially damaging to certain animals (Kats, 2009).

Marine mammals

Harbour porpoises hear sounds between 0-200 kHz

In the North Sea, the most common marine mammals are grey and harbour seals and harbour porpoises. Therefore, we focus on these species. It should be born in mind however that there are also other marine species like minke whales, bottlenose dolphins and white-sided dolphins.

(W.J. Strietman)

Harbour porpoises belong to the odontocete suborder of cetaceans. They can hear sounds between 0-200 kHz with a most sensitive hearing range (-10 dB) between 16 and 140 kHz, (Kastelein, 2011)

Mammals swim away from the pile driving location

Permanent threshold shift (PTS)

Brandt et al. (2009 in ICES, 2010) showed in a model that cumulated sound exposure over the duration of a single pile driving event suggests that levels sufficient to elicit PTS could be reached for both seals and porpoises at distances of around 1 km from the piling site. Verboom & Kastelein (2011) indicate an acute PTS due to one pile driving blow within 100 m from the source (for seals and porpoises).

Temporary threshold shift (TTS)

As level for masked TTS of harbour porpoises a SEL threshold of 164 dB re 1µPa.-/s and a peak level of 199 dB re 1µPa SPL are mentioned (based on Lucke et al (2009) in ICES, 2010). These values, including some safety adjustments are used to set thresholds for pile driving sounds in Germany (at 750 m 160 dB SEL and 190 dB SPLpeak) (Ices, 2010).

Verboom & Kastelein (2011) calculated lower TTS-onset levels at a SEL of 147-143 dB re 1 µPa.s for porpoises. for a distance of 0-14 km from the source.

Underwater sound measurements at BARD park Offshore 1 in the North Sea, the TTS levels of 164 dB re 1µPa.s (SEL) and 199 dB re 1µPa (SPLpeak) were exceeded at a distance over 5 km. Verboom & Kastelein (2011) calculated TTS-onset within 7.5 km from the source due to the cumulative sound energy of one pile driving series (to drive one 4 m monopile in the North Sea).

De Jong & Ainslie (2008) found from sound measurements at the Prinses Amalia park levels above discomfort thresholds at a distance of 5.6 km. At distances till about 1.5 km the levels are even well beyond the 'severe discomfort' threshold. Approaching the pile driving source at distances smaller than 500m is exceeding the TTS threshold. Verboom & Kastelein (2011) found that within 330 m from the pile driving location acute TTS due the one blow will occur in porpoises.

The impact of TTS to harbour porpoises and seals depends on the duration, recovery of hearing and the affected hearing frequency. It can influence their ability to find food, each other or navigation (Kastelein, 2011). Note that seals and porpoises – to some extent – are able to swim away from the location when pile driving starts. However, it is expected that they are not able to swim at high speed for such a long time that they can avoid TTS when they are relatively close to the pile driving location.

Behavioural response

Not injury, but behavioural impact is biggest problem

Experts do not expect that injury is the biggest problem, because marine mammals will avoid the pile driving location due to the noisy construction activities in that area. They fear the effects of behavioural impact on individual animals and even populations. Wind farm related noise can potentially affect the physiology and behaviour of harbour porpoises and harbour seals at great distances. Major disturbances can be described as one likely leading to a strong reaction in individual animals, such as through a noise level (peak to peak) of 155 dB re 1 uPa and higher (Bailey et al. in Haelters et al., 2012).

Discomfort occurs at a larger distance from the pile driving. Several studies confirm impact on the behaviour of harbour porpoises of at least 25 km of the piling sites (Ices, 2010). A recent Belgian study by Haelters et al. (2012) showed a decrease in harbour porpoise detection at a few kilometres from the piling site to virtually zero immediately upon the start of piling activities and did not recover during piling. After piling stopped, it took hours to days before new detections were made at this location. Aerial surveys showed an apparent impact at around 22 km. Part of the area was repopulated after one day without piling: a small number of harbour porpoises were observed.

A recent study by Verboom & Kastelein (2011) suggests that the behaviour of young porpoises and seals, with good hearing, can be affected up to tens of km away from offshore pile driving sites. To what degree, depends on the propagation conditions and background

The effect of behavioural disturbance is not clear yet

noise. How this would affect the seals' and porpoises' survival and reproduction depends on their time budgets for various ecologically important behaviour (such as foraging, suckling, and resting).

Harbour porpoises seem to be more vulnerable to disturbance than larger dolphin species (delphinids). There are indications that even short time disturbances can have an impact on the individuals. Haelters et al. (2012) describe that it can be expected that regular disturbance may at least have an influence on its condition and health.
Harbour porpoises need to eat relatively a lot (daily 10% of body weight) and often (approx. every 2,5 hours). Even a short disturbance (one piling event will take around 2 hours) can cause:

- less time for foraging
- potential displacement to less favourable foraging areas
- increased activity (displacement) leading to increased food requirement
- mother calf separation (Kastelein, 2011).

Even though the disturbance itself, i.e. a single pile driving event, is fairly short term (in the order of maximum 2 hours), it may take 1–2 days following an individual pile driving event before porpoises gradually return to the impact area. However this depends on the number of foundations being piled, and also the intervals between piling (Ices, 2010).

The effect of the impact of behavioural response on the individual long-time survival or on populations are not clear yet (Ices, 2010). A recent Belgian study (Haelters et al., 2012) also describes that the knowledge of impact of piling is limited and it will be very difficult to describe sub-lethal effects at the level of an individual animal and on a population level. Assessment of the effects on a population level is still lacking.

Nedwell (2007) mentions a SPL level of 140 dB re 1 µPa for behavioural response. Tougaard et al., 2011 (in Norro et al. 2012) mention a discomfort level (zero-peak) of 134 dB re 1 µPa and Norro et al (2012) a peak to peak level of 140 dB re 1 µPa. Verboom & Kastelein (2005) estimated level of serious discomfort at SPL = 125 dB re 1 µPa and discomfort between 97 and 111 dB re 1 µPa, with a frequency range between 10-14 kHz.

Seals

Seals hear sounds between 0-70 kHz

(Sarah Marx))

Pinnipeds can hear sounds 0-70 kHz. They have the highest sensitivity (-10 dB) for sounds between 0.5 and 40 kHz (Kastelein, 2011).

Permanent threshold shift (PTS)
Brandt et al. (2009 in ICES, 2010) showed in a model that cumulated sound exposure over the duration of a single pile driving event, suggests that levels sufficient to elicit PTS could be reached for both seals and porpoises at distances of around 1 km from the piling site.

Temporary threshold shift (TTS)
Verboom & Kastelein (2011) calculated TTS-onset levels at a SEL of 173-168 dB re 1 µPa.s for seals (for a distance of 0-14 km from the source). Acute TTS due to one blow is expected at 260 m from the pile driving location (North Sea conditions). TTS due to a pile driving series is calculated to be within tens of kilometres when the seals are not able to leave the 'danger' area.

Behavioural response
In seals, masking can occur at least up to 80 km and this raises the concern for hearing loss. It cannot be ruled out that severe injuries take place in the immediate vicinity of the source (Kats, 2009). During the construction of Egmond aan Zee seals did not approach within 40 km of the wind farm area (Ices, 2010).

Masking can occur at least up to 80 km

Fish and fish larvae

Fish species react different to sound frequency ranges

Close to pile driving, injury could occur

Fish
Studies have shown how different fish species can react to different sound frequency ranges. Most fish species hear sounds from below 50Hz up to 500-1500 Hz. A small number of species can detect sounds over 3 kHz, but this is very rare and only very few species can detect sounds over 100 kHz (Kats, 2009).

The highest sound pressures from pile driving are reached at low frequencies between 100 and 300 Hz (Ainslie et al., 2009). The piling noise is probably much higher than the TTS-onset level of fish. Research in the USA indicated that TTS-onset occurs in catfish and goldfish at mean sound pressure levels above 155 dB re 1 µPa or a SEL of 187 dB re 1 µPa.s (Verboom & Kastelein, 2011).

Close to pile driving, injury could occur, especially in gas filled swim bladders. An assessment made by COWRIE reported that during a pile installation in Canada, the hammering of steel piles caused fish mortality in the vicinity of the pile driving area (Nedwell & Howell (2004) in Kats, 2009). Although it has been stated that fish close enough the pile driving sound might be killed, there is insufficient data available to give an indication of the percentage of fish killed. It is equally unknown which species are more susceptible to the sounds, and the distance from the pile driving source that kills fish (Kats, 2009). Moreover, it is not clear if each pile driving strike should be considered as a completely separate event in terms of damage to fish or if the problem lies in its cumulative damage resulting from multiple pile strikes (Popper & Hastings (2009) in Kats, 2009).

Fish eggs and larvae
There is also concern about the impact of pile driving on fish eggs and fish larvae. These eggs and larvae play an important role in the marine foodweb, so if piling has a large negative impact on eggs and larvae, this can affect the foodweb as well, including protected marine mammals and birds.

Concern about the piling impact on eggs and larvae

It is assumed that the loud sounds could kill the eggs and larvae in the immediate surroundings. Unless adult fish, they are not able to swim away from the sound source. Kostyuhenko (1973) studied the effects of air guns on marine fish eggs. The results reported damage to the eggs at up to 20 m from the air gun blasts. Similar studies were executed with cod, saith and Atlantic herring eggs, where significant mortality was found in a variety of ages. However, this was only the case when the eggs were located within 5 m from the source. The most important effects were found within 1-4 m from the source. Most studies were also performed using airguns or mechanical shocks that give a different stimulus than for example pile driving (but sound levels are in the same order of magnitude).

No evidence of mortality of larvae by piling

Recently, IMARES investigated the impact of piling sounds to larvae of sole (Damme, et. al., 2011). There was no evidence of additional mortality of the larvae by the piling. However, the impact of piling on eggs of other fish species is not known yet.

2.2 Conclusion & Discussion

Possible effects of piling on mammals should be taken seriously

Given the number of offshore windfarm projects that are being constructed and planned and the fact that effects of pile driving on marine mammals can occur at distance beyond 20 kms from the construction site, the possible effects of pile driving on marine mammals should be taken seriously (Ices, 2010).

Behavioural disturbance

For porpoises and seals the general conclusion regarding pile driving sound is that source levels exceed the level of temporary threshold shift (TTS) onset by more than a thousand times. Consequently, TTS is introduced at short distances (a few hundred metres) from the pile driving location. In practice, pile driving will most likely not cause mortality in marine mammals as these animals would avoid the area because of the underwater (noise) disturbance. However, because of the high sound pressure levels, natural behaviour will be influenced in a very large area. What the impact of this behavioural disturbance is, needs to be assessed.

Table 3. Threshold Shift levels for certain marine mammals (Nehls, Betke, Eckelmann, & Ros, 2007)

Animal Order	Layman name	Temporary Threshold Shift (TTS)		Permanent Threshold Shift (PTS)	
Cetaceans	Whales/Dolphins and porpoises etc.	183 dB SEL pulses	224 dB peak pressure	215 dB SEL	230 dB peak pressure
Pinnipeds	Walrus/seals etc.	163 dB SEL pulses	204 dB peak pressure		210 dB peak pressure

Threshold Shift levels for certain marine mammals (Nehls, Betke, Eckelmann, & Ros, 2007)

For fish and their eggs and larvae it's hard to draw a general conclusion. Pile driving levels are that high, that effects in the immediate surroundings of the piling site can not be excluded. Effects on marine fish can influence the marine food web. Therefore, it is important to take fish into account when pile driving.

NSF: apply precautionary approach to reduce noise pollution

Cumulative impact

It is obvious that research into the actual impact of pile driving on fish and marine mammals is urgently needed. Special attention should be paid on the cumulative impact. However, North Sea Foundation believes that based on current knowledge the precautionary approach must be applied to reduce noise pollution. NSF urges the need to diminish underwater noise. Noise reduction during the construction of offshore wind farms is necessary and possible. In the short term mitigation measures should be applied. On the longer term more silent construction techniques should be used.

3. Mitigation of underwater noise

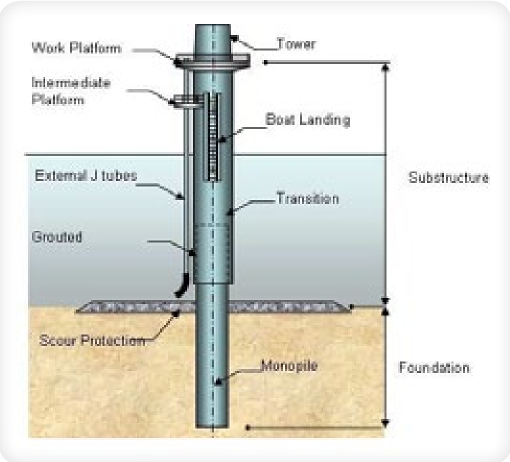
The general principle of mitigation of underwater noise is to reduce the impact of the sound on the environment. The impact of noise depends on the properties of both the sound as the receiver: each animal has its specific dose-response relationship and its sensitivity to sound differs (frequencies and levels).

Mitigation means reduce impact of piling noise

Mitigation measures could be focused on the ecological impact or on reduction of the noise itself. These different approaches will be described here. However, it is important to bear in mind that the sound levels due to pile driving are so high that mitigation will never prevent negative impact entirely.

Focus on ecological impact or reduction of noise itself

Mitigation will never prevent negative impact entirely



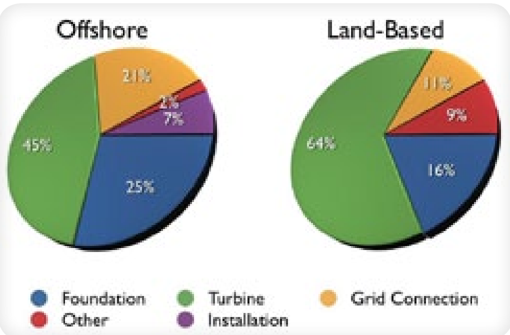
Various components of a monopile foundation (Iuga)

Conditions to mitigation measures

Several constructors indicated the importance of applicability of mitigations in the harsh offshore environment. Stokes et al. (2010) mention factors to be considered for treatment design including the ability to install the treatment effectively, survivability in the ocean environment, cost, and side effects such as pollution. Koschinski and Lüdemann (2011) also state that the measures must be technical, practical and scientifically proved to really reduce sound significantly.

Mitigation measures could lead to increase of costs

A lot of mitigation measures could be applied, but potentially will lead to an increase of costs for offshore wind electricity. Several constructors indicated that the challenge is to incorporate mitigation measures in such a way, that it will not lead to extra time and costs for the installation. However, it is important to bear in mind practical considerations for treatment design.



Typical cost comparison between onshore and offshore wind (Kühn, et al., 1998)

Reduce ecological impact by avoiding essential habitats

International alignment in applying seasonal or spatial restrictions is

3.1 Mitigation measures to reduce ecological impact

Avoid essential habitats and avoid ecological important seasons.

A relatively simple way to mitigate ecological impact, is to avoid essential habitats for endangered species, or areas with a high species abundance, and to avoid piling in periods of ecological importance (like spawning). Marine spatial planning is an important tool that helps selecting areas more of less suitable for offshore wind farms.

Natura 2000 areas

This principle is already being applied. In the UK for example there is a Strategic Environmental Assessment before each round of permits. In Denmark areas with high densities of harbour porpoises are excluded. In the Netherlands some areas have been selected as areas for wind farm development. These areas are outside Natura 2000 areas. In the Appropriate Assessment, possible impact of offshore wind farms build outside Natura 2000 sites on protected species and areas has been taken into account as well.

According to Jasny (2005) areas with high species abundance, marine sanctuaries and MPAs should also be avoided. Only in Germany, offshore wind farms are not allowed in Natura 2000 areas. In Denmark it is allowed and in Belgium, the Netherlands and the United Kingdom it is not a priori forbidden (Ices, 2010).

Seasonal restriction

Seasonal restriction to pile driving is also applied by several countries. In the UK there are some seasonal restrictions in relation to spawning fish. In the Netherlands, no piling is allowed between January 1st and July 1st. This restriction is mainly to reduce the risk of additional mortality of juvenile fish and the follow-up impact on protected bird species in Natura 2000 sites. Moreover, in winter and spring concentrations of harbour porpoises are higher (Ministerie van Verkeer en Waterstaat, 2009). In Belgium there is an advice not to pile between January 1st and May 1st. Denmark and Germany do not apply seasonal restrictions (Ices 2010).

Advantages & Disadvantages:

The North Sea Foundation considers mitigation by geographical or temporal restriction very useful to reduce ecological impact of the construction of offshore wind farms. If it is applied in an early stage (planning period) it doesn't lead to extra costs to a project. However, this measure will only reduce the impact. There are some serious constraints to this measure:

- Which habitats and species should be taken into account? Only Natura 2000 or also OSPAR? Only marine mammals or also fish species?
- There is a lack of knowledge in abundance and distribution of species
- Which distance should be taken into account for geographical exclusion? PTS/TTS levels or behavioural impact levels?
- What will the threshold be for seasonal restriction? Will it be determined by number of animals in a certain area, or by important stages in the life cycle of a species (like breeding)
- International alignment in applying seasonal or spatial restrictions is crucial.

Avoid physical harm of animals

Reduce ecological impact by marine mammal observers

In the UK yet another measure is being applied. Before and during pile driving there are marine mammal observers (MMO). They also use passive acoustic monitoring (PAM) as a supplement to visual observations. Piling cannot commence during periods of darkness, poor visibility, or when the sea state is not conducive to visual mitigation (above Sea State 4). This is only because otherwise marine mammal observers can't do their job properly. The MMO observe a 'mitigation zone' around the pile before (pre-piling) and during piling. The extent of this zone will be determined by factors such as the pile diameter, the water depth, the nature of the activities and the effect of substrate on noise transmission. In any situation the mitigation zone should have a radius of no less than 500 metres, The extent of this zone should be agreed with the regulatory authority. Piling should not be commenced if marine mammals are detected within the mitigation zone or until 20 minutes after the last visual or acoustic detection. It is considered that 20 minutes is a sufficient period of time to allow animals to be at a distance where risk of injury or death is minor.

No considera-tion with pos-sible non-lethal behavioural effects

The Joint Nature Conservation Committee (JNCC) recommends that the pre-piling search should be a minimum of 30 minutes. If no mammals have been observed, piling can start by a soft start of not less than 20 minutes. If there is a pause in the piling operations for a period of greater than 10 minutes, then the pre-piling search and soft-start procedure should be repeated before piling recommences. If a watch has been kept during the piling operation, the MMO or PAM operative should be able to confirm the absence of marine mammals, and it may be possible to commence the soft-start immediately. When piling at full power there is no requirement to cease piling, or reduce the power if a marine mammal transits into the mitigation zone. In this situation, the marine mammal is deemed to have entered the mitigation zone "voluntarily". It is also acknowledged that, for engineering reasons, it may not be possible to stop piling at full power, or until the pile is in its final position.

Noise generated from piling activities has the potential to cause non-lethal behavioural effects on marine mammals at a considerable distance from the activity. The JNCC protocol does not document measures to mitigate those effects.

Advantages & Disadvantages:
This mitigation measure is only aimed at minimising the potential risk of injury or lethal effects to marine mammals in close proximity to piling operations. It does not consider non-lethal behavioral effects.

Other disadvantages of MMO are:
- are the mammals really absent or just not visible?
- other factors such as food availability, may result in marine mammals approaching piling operations. In particular, the availability of prey species stunned by loud underwater noise may attract seals into the vicinity of piling operations.
- the mitigation zones will be generally too small to prevent TTS and PTS (from a series of strokes)
- If the mitigation zone is large enough (0-14 km from the piling) to prevent PTS and TTS, the area is too large to be covered by MMO and PAM.

Deter vulnerable animals before piling
This is a mitigation measure aimed at preventing injury, PTS and TTS. According to Ices (2010), this measure is an option if effect on populations is not likely. Most countries require the use of deterring devices (ADD) before and during piling.

Reduce eco-logical impact by accoustic deterring de-vices

Besides this, a soft start ramp up will scare marine mammals away and thus prevent injury. However, a soft start for pile driving is necessary from an operational point of view. It is not possible to start piling at a maximum level. North Sea Foundation therefore doesn't consider it a real mitigation measure.

Acoustic deterring devices
Although the use of acoustic deterring devices is quite common, it is not clear if they work well. Kastelein et al. (2010) tested the functioning of 3 acoustic mitigation devices on grey seals and harbour porpoises. Audibility of and reaction to the devices depends strongly on e.g. weather conditions. It is hard to predict how animals will react to the device: it depends on sexe, experience, context (group or alone, fouraging or not, distance to shore, etc.) (Kastelein et al. 2010). In addition, there is a risk of habituation (Ices, 2010). Moreover, to deter animals in a sufficiently large area, the source level of the ADD must be high, potentially leading to PTS or TTS themselves.

Each species asks for a specific ADD

Since every species has its own hearing sensitivity and dose-response relationship, probably different sounds will be needed for different species. Therefore, the efficacy should be tested on all species of concern.

Example of deterring device, used in fisheries

Advantages & Disadvantages:

The North Sea Foundation wonders if this measure is useful:

- it is not sure if they work well. More research is needed.
- each species asks for a specific ADD (from very low-frequency for fish to high-frequency for porpoises)
- the use of acoustic deterring devices doesn't reduce the size of the zone of impact
- it is only applicable for moving animals and not for e.g. fish and fish larvae
- the device itself is a source of underwater noise. Noise levels are high and possibly cause negative effects.

Lower noise levels to prevent harm to marine life

A way to mitigate effects on marine life is to adjust noise levels to levels that do not harm animals. Technical possibilities to reduce levels will be described in the next paragraphs.

In Germany this principle is applied: there is a threshold to piling noise. From the piling onwards the limit at a distance of 750 m is 160 dB SEL and 190 dB SPLpeak, based on masked TTS levels of harbour porpoises including a safety adjustment.

Reduce ecological impact by threshold to piling noise

NSF sees advantages, but not for behavioural effects

Advantages & Disadvantages

The North Sea Foundation sees advantages and disadvantages to this approach:

- The values are broadband. This means that noise reduction will be at the entire spectrum and not is related to the specific hearing sensitivity of the various species.
- The values are stringent and relatively easy to measure
- The values are based on single stroke SEL. Cumulative SEL should be taken into account as well.
- The values are based on the harbour porpoise. Other animals have different hearing sensitivity. Maybe other thresholds for other species are needed.
- Behavioural impact is considered to be a larger problem. Even if this threshold is met, behavioural effects will occur in a large area.
- It is not clear, what the consequences are if these values are not been met. Will the construction stop?
- Verboom & Kastelein (2011)) calculated lower TTS-onset levels at a SEL of 147-143 dB re 1 µPa.s and the PTS at 180 dB re 1 µPa.s. for porpoises and TTS-onset levels at a SEL of 173-168 dB re 1 µPa.s for seals (for a distance of 0-14 km from the source). This means that the German criteria do not prevent marine mammals from hearing damage.

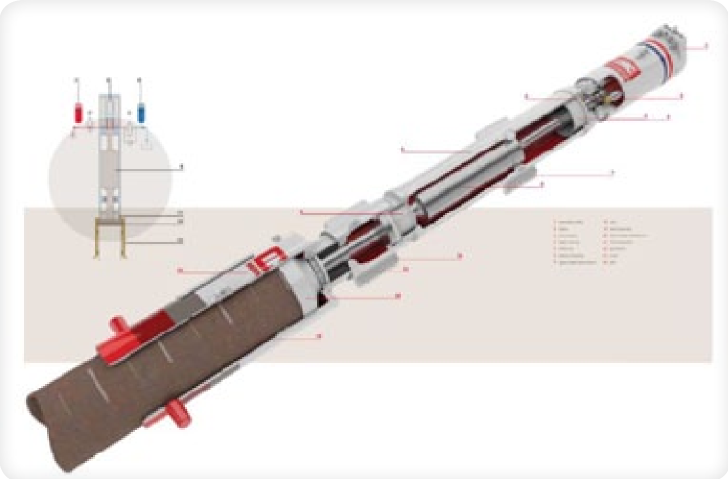
3.2 Mitigation measures to reduce underwater noise

The description of measures and techniques in this section is based on the report of Saleem (2011). The information of Saleem's report is updated in this report.

See report Saleem (2011) on www.noordzee.nl/soundsolutions

3.2.1 Reduction of source level

Measures to mitigate the source level of driving a mono pile, require modification of the blows applied by the driver to the top of the pile (Stokes et al., 2010).



IHC Hydrohammer S-2300 cut-out. Used for driving piles around diameter of 6 meter.

Contact damping

Reduction of source level by contact damping

This method is not generally used in the industry. Additional material is added on top of the pile to reduce noise. This could potentially lead to 8-10 dB reduction. However, the cap absorbs energy, reducing the ability to drive the pile into the soil (Stokes, 2010). It will take more time to hammer the pile, and more energy, which will increase the cumulative SEL value. This measure is therefore considered not effective by Stokes (2010) and several constructors. The cost of using this approach is also higher as extra time and energy is required to drive the pile into the ground.

Advantages:

1. **Lower sound pressure peak**
   The damping absorbs some of the energy from the hammer making the sound amplitude lower.

Disadvantages:

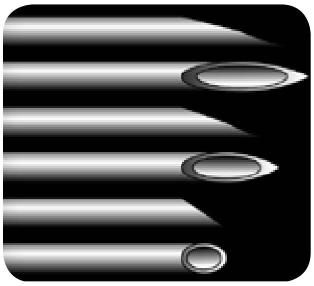
1. **More blows required**
   As a result of the lower energy, more blows would be required to achieve the desired penetration.
2. **Extra costs as the installation takes longer and more energy**
   This is kind of self-evident as longer installation time and higher blow energy would translate to higher costs. The exact increment in costs is unknown.

Changing pile-toe shape

Reduction of source level by changing pile-toe shape

The first point of contact of the monopile support on the seabed is the pile-toe and the energy is directly transmitted to the ground via this contact. If the resistance force is decreased, less energy will be required to push the pile into the ground, meaning less production of sound.
The shape of the tip can play a role in the energy required during installation. According to (Raines, Ugaz, & O'neil, 1992) bevelled piles require about 20% less pile-head energy, 27% less hammer kinetic energy per unit length and require 29% less blows to reach the same depth as a no modified pile. This could result in lower noise levels, but the reduction is unknown yet. The technology is not proven. Tests have only been conducted on piles with very small diameters (102mm). More research and development is needed to investigate its feasibility, especially the effect on the cumulative SEL.

Could lower noise levels, but reduction is unknown yet



Different Bevels used for Hypodermic needle

Advantages:

1. **27% Less hammer Kinetic Energy**
   Cheaper/lighter hammers can be employed to drive pile saving costs.
2. **29% Less blows required**
   Fewer blows mean less strokes and less overall noise, moreover less time required to install the pile.
3. **Lower installation costs**
   The lower energy and blows required would result in lower installation costs, further the installation time will also be reduced.

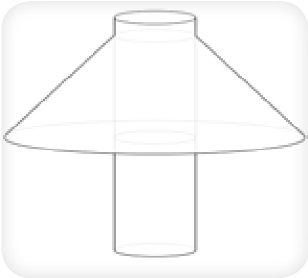
Disadvantages:

1. **No large scale application**
   So far no large scale testing has been done, therefore its feasibility for large scale application is doubtful and will take a long time to find its way into the industry.
2. **Increased production costs (Slightly)**
   Slightly more material would be required to produce the bevelled shape with the desired penetration.
3. **Potential problems with Bearing Capacity**
   Increasing the penetration would have consequences for the bearing capacity but it needs to be researched and verified.

Reduction of source level by skirt-pile support

Skirt-pile support

The penetration depth of a monopile foundation depends on the lateral stability of the wind turbine. If the depth is reduced, less piling is needed, meaning less sound. Adding a "skirt" (from steel or concrete) to the monopile will increase lateral stability. However, extra material and labour is needed to make the skirt and to install it. More scour protection is needed. No testing or data is found on this concept. More research and development is needed to investigate its feasibility.



Skirt-pile support concept

Advantages:

1. **Lower ground penetration**
   The ground penetration would be reduced by the increment of lateral stability from the skirt
2. **Less blows required to install**
   The lower the penetration the lower the blows required to achieve the required depth.

Disadvantages:

1. **Extra manufacturing costs**
   The skirt would need to be separately manufactured and would require extra material and labour and therefore increasing costs.

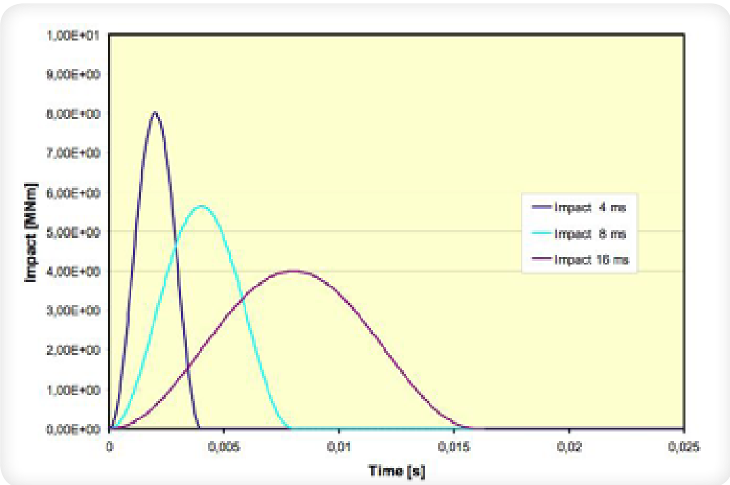
2. **Significant scour protection needed**
   The larger structure the larger the vortex it would generate. As the skirt would add to the diameter of the monopile more scour protection would be required.
3. **Extra installation to install the skirt**
   From talking with expects, it was found that attaching skirt before pile driving is not a good solution. The pile driving loads may cause damage to the skirt and therefore it should be installed after the pile has been driven into the ground. This however will add another step to the installation of the foundation, resulting in additional costs.
4. **Unproven technology**
   No testing or any data is available on such a concept. A case study needs to done to check if this concept has any promise.

Changing the parameter for pile stroke

The sound pressure depends on the velocity of the vertical pile vibrations. Prolonging the contact time of the hammer could reduce the amplitude of the pile vibration, reducing the noise generated. Theoretically this method could mitigate noise by 10-13 dB and have virtually no impact on the installation time. However, the signals are of longer duration, potentially still leading to masking marine mammal communication (Kats, 2009).

Reduction of source level by changing the parameter

Currently, an offshore supplier is investigating the hammer design. Changing parameters for pile stroke is possible. However, shorter hammer blows are expected to ramming the pile into the sea floor more effectively. This implies that more blows will be needed and the question is if noise reduction will be achieved overall. However, it seems worth to be investigated further.



Impact forces of different impulse contact times with the same ram energy. (Elmer, Neumann, Gabriel, Betke, & Glahn, 2007)

Advantages:

1. **Lower noise generation**
   This technique tackles the problem of noise at the source by changing the way the noise is produced, rather than damping it afterwards.
2. **No difference in the installation technique**
   This is the biggest advantage of using this technique, as virtually no change is required in the equipment and techniques used currently only a slight modification of the hammer settings. For the very short term this method should be used till more effect sound mitigation techniques can be employed.

Disadvantages:

1. **Still very loud**
   Reduction of around 10 dB is significant, but still not good enough with the ever increasing size of the monopiles. However using this in combination with other methods might provide a superior solution.

Pile isolation can limit sound transmission

3.2.2 Reduction of transmission: isolation

Stokes et al. (2010) describe as promising mechanism for treating the noise transmission path decoupling. This will isolate the pile from the water. The principle is that sound will be partly reflected by the isolating material, limiting sound transmission. Different techniques can be used to isolate the pile: cofferdam, bubble curtains and pile sleeves.

Isolation by using a cofferdam

Cofferdam

A cofferdam covers the mono pile. The space between the pile and the sleeve is dewatered and filled with air. In a model study, Stokes et al. 2010 used a very massive dewatered cofferdam to calculate possible noise level reductions. In their study, they predicted a reduction in noise level of approximately 20 dB. They consider this as the upper bound on possible noise mitigation performance. However, this is only theoretically. They expect that in the offshore field, it will be virtually impossible to create a dewatered cofferdam. Koschinski & Ludermann (2011) describe the use of sheet pile walls as cofferdam in shallow waters, and several prototypes cofferdams. A reduction of over 20 dB would be possible.

Dewatered Cofferdam by Advanced Offshore Solutions Aps

Isolation by using a pile sleeve

Pile sleeves

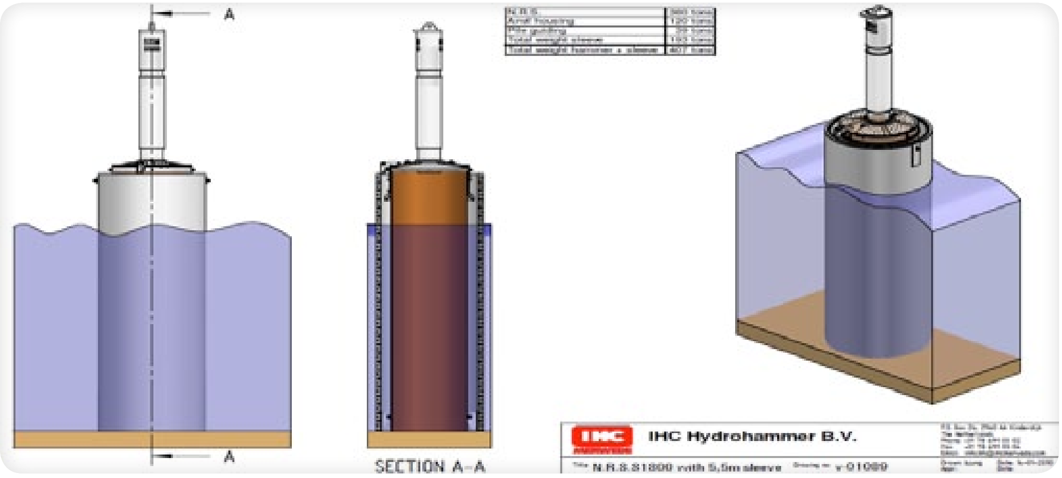
A pile sleeve is a physical sound barrier placed around the mono pile. The advantage of using pile sleeves is that the existing installation techniques don't need to be changed. Models predict a reduction of 10 dB (Stokes et al. 2010). Some small scale tests showed even larger reductions (up to 30 dB) in some 1/3 octave bands (Koschinski & Ludermann, 2011).

There are different pile sleeves: inflatable, telescopic, steal. This summer field tests of several variations of sleeves were executed in Germany (ESRA) and also at a met mast in the Netherlands (FLOW). Results of ESRA experiment showed a reduction of different systems around 6 dB (SEL). Damping was lowest in the frequency range 100-300 Hz (0-10 dB SEL) but higher in higher frequencies (5000 Hz up to 25 dB).

Pile sleeves can be applicable in the short-term (Saleem, 2011). This technique (unlike the confined bubble curtain) can provide more reliability and be effective even in rough weather conditions. An advantage of the use of pile sleeves is that they are relatively easy to handle. Current piling methods do not have to be changed. However, installation of the pile sleeve around the pile adds an extra step to the pile installation process. This will take extra time and extra costs.

IHC

An example of a Noise Mitigation Screen is a concept developed by IHC. It consists of two steel layers with air inside. Between the pile and the sleeve, a confined bubble screen is applied. A small scale test showed a reduction in several 1/3 octave bands of 27 dB (Koschinski & Ludermann, 2011). However, field tests in deeper water reduced the sound by approximately 10 dB. Meanwhile the design has been proven, leading to a third prototype (NMS-6900). This NMS can be applied for mono piles with a diameter of almost 7m. There is no mechanical contact between pile and screen. No field tests with this NMS have been conducted yet.



IHC Noise Mitigation System (NMS) for monopile foundation (IHC Hydrohammer B.V., 2011)

Prototype 2 Geluidsscherm IHC Hydrohammer_Project ESTA_Picture IHC Hydrohammer

BEKA schale

Another pile sleeve is the 'BEKA schale'. This sleeve is in a pilot stadium.
It consists of two shells, which are hydraulically put together around the pile. Both sound in water and in the sea floor will be damped. Between the pile and the sleeve, a confined bubble screen is applied.There is no direct contact between Beka shell and pile. The shells consist of two metal double layers, separated by10cm water with a bubblecurtain. The double layers are completely filled with a specific composition, which will absorb the sound. The innershell and outside
shells are acoustically completely separated by industrial vibration dampers. In addition, the inner shell is equipped with a 20 cm thick sound absorbing (Koschinski & Ludermann, 2011).

BEKA schale - BEKA-Schallschutzsysteme

Significant noise reduction, short-term use possible, but extra costs

Tube sleeve
Another variation of the pile sleeve is the 'Schlauchhülle (Tube sleeve). This sleeve consists of a packaging of fire hoses. These are attached in multiple rows on a framework from the ground to the piling frame. Before piling, air is blown into the hoses by compressors. This creates an air wall directly on the pile (Koschinski & Ludermann, 2011) Small scale experiments show a reduction of 10-30 dB in several 1/3 octave bands (between 800-20.000 Hz). A prototype has been tested in the ESRA project.

Advantages:
1. **Up to 25 dB noise reduction**
   This is a significant noise reduction. A recommendation might be to use this in combination with changing the pile stroke parameter, to achieve even further noise reduction.
2. **Current methods don't need to changed**
   This is a huge advantage as this method can be used in the short-term, retaining the advantages of monopile, while getting rid of the noise.
3. **It is in an advance stage of development**
   This concept is already being tested and can soon be applied on full-scale.
4. **All weather capability**
   This technique (unlike the confined bubble curtain) can provide more reliability and be effective even in rough weather conditions. This is a great advantage as rough weather conditions prevail at sea most of the times.

Disadvantages:
1. **Need extra infrastructure**
   Handing the huge monopile presents a problem itself and to add an extra sleeve to it requires more infrastructure. This makes the whole operation more complicated.
2. **Increased installation time**
   As mentioned, increasing complexity means more time is needed to achieve the pile driving. Installation of the pile sleeve around the pile adds an extra step to the pile installation process.
3. **Extra costs**
   The longer the installation process takes, the more it costs, and this is especially true for offshore operations.

Isolation by using a bubble curtain

Difficult to install in the harsh offshore environment

Bubble curtains
The principle of using air bubbles for noise reduction is based on the physical phenomenon of sound scattering and on the resonance of vibrating air bubbles. These parameters depend on the diameter of the air bubble in the path of the sound and of course the characteristics of the sound.

According to Nehls et al., a reduction of 10 dB is possible. Stokes et al. also predicted a noise reduction level of approximately 10 dB. This reduction depends on the size of the bubbles. Attenuation seem to occur from frequencies from 300 Hz and higher. The smaller the bubbles, the lower attenuation at lower frequencies. It is very hard to predict the exact sound reduction.

Nehls et al. conclude in their report that bubble curtains can efficiently reduce underwater sound. However, they considered it to be impossible to install bubble curtains in the offshore environment at greater water depths and tidal currents.

Currently, the use of bubble curtains is one of the options which are considered as a useful and applicable mitigation measure. Several technical realisations are possible: a large curtain, surrounding an entire jacket / pile, a confined bubble screen or a little bubble screen in a system with several rings at different heights.

Large bubble screen - Noise mitigation during the construction work of offshore wind farm Borkum West II

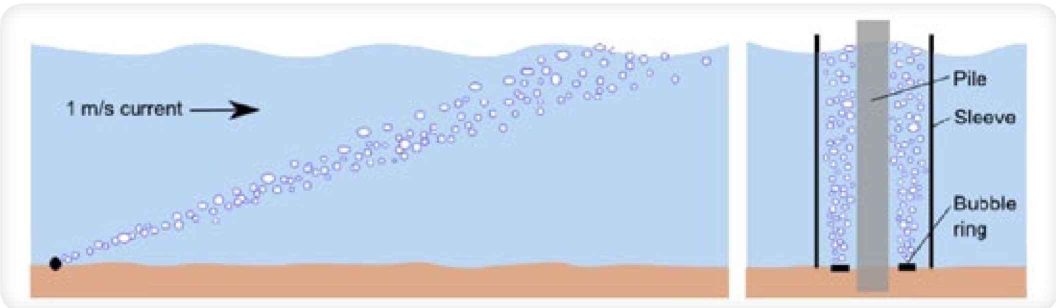
Large bubble curtain

A large bubble curtain consists of a perforated tube ring put on the seafloor around the pile. Air is generated by compressors on a ship or platform. Air flows out of the little holes in the tube, forming a bubble curtain. Koschinski and Lindemann (2011) describe results from a test in the German North Sea at the Fino platform. These showed a sound reduction of 12 dB broadband and 14 dB peak. At frequencies up to 200 Hz, noise reduction was limited: at 1kHz it was 20-25 dB and at 2 kHz even 35 dB (Koschinski & Ludermann, 2011).

Currently bubble curtains are being tested in the field at Borkum West 2. This method is being used since it is one of the available techniques and probably not too expensive in the future. The bubble curtain has a perimeter of approx. 400 m and is installed before the piles of the tripods are being hammered. The bubbles are generated on the sea bottom by compressors and are adjusted to currents and water depths of 25-30 m. During pile driving another bubble curtain is put in place on the next location. In this way, no working time of the expensive jack-up is lost. At this moment the use of the bubble curtain is expensive, but this project is considered as a pilot and a lot of research is carried out. 14 foundations will be measured and results will be evaluated, maybe leading to adjustments for the other foundations.

Confined bubble curtain

At a confined bubble screen, a shell prevents the bubbles to drift away. It is often applied in combination with a pile sleeve, like the IHC noise mitigation screen.



Confined bubble curtain (Nehls, Betke, Eckelmann, & Ros, 2007)

Little Bubble curtain

A little bubble curtain consists of perforated tubes in several levels in circles around the pile. There are several concepts for telescopic systems to prevent extra time for installation. (Koschinski and Lüdemann, 2011) When the air bubbles drift away, they can form sound bridges reducing the effectiveness of sound isolation. With tripods or jackets structure-borne noise can be a problem.

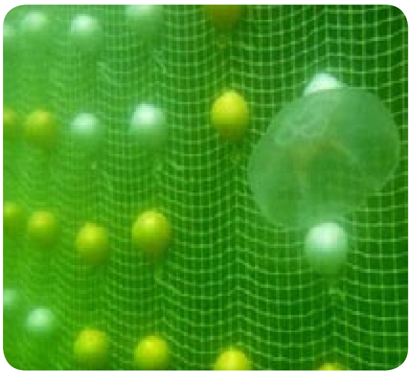
Tests in the German North Sea showed a reduction of ca. 12 dB (SEL) and 14dB peak. In shallow waters larger reduction has been measured.

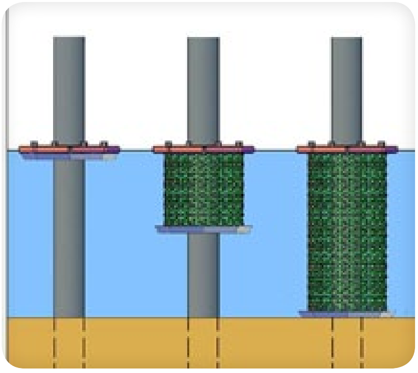
Isolation by using a Hydro sound damper

Hydro sound damper

The concept of hydro sound dampers is based on the same principle as bubble curtains. Instead of free air bubbles (as in the bubble curtain), gasfilled balloons are used. The balloons are attached to a frame or network and completely surround the piling. Several types have been tested (ESRA). A maximum reduction of over 10 dB SEL is reached at frequencies between 200 and 1000hz has been measured. At lower frequencies (0-125) there is hardly no reduction and at higher frequencies (over 2000 Hz) even increase of SEL occurred.

The use of bubble screens is mostly in a pilot phase. Tests show sound reductions of 12 dB broadband and 14 dB peak (Koschinski & Ludermann, 2011). Attenuation seem to occur from frequencies from 300 Hz and higher. The highest sound pressures from pile driving are reached at low frequencies between 100 and 300 Hz (Ainslie et al. , 2009). A large bubblescreen has been used as mitigation at the construction at Borkum in Germany. Results are expected to be published soon.





Hydro sound dampers by Offnoise-solutions

Advantages:

1. **Up to 10 dB broadband noise reduction**
   According to Nehls, Betke, Eckelmann, & Ros (2007) a noise reduction of up to 10dB is achieved using this method.
2. **Current methods don't need to changed**
   Techniques which do not change the current installation techniques, would make it easier for the main players in the offshore industry to adopt and employ. And therefore can provide a solution for the underwater noise in the short term.
3. **Freq. range damping**
   One major advantage of using bubbles is that it dampens the whole spectrum of noise and not just one particular frequency.

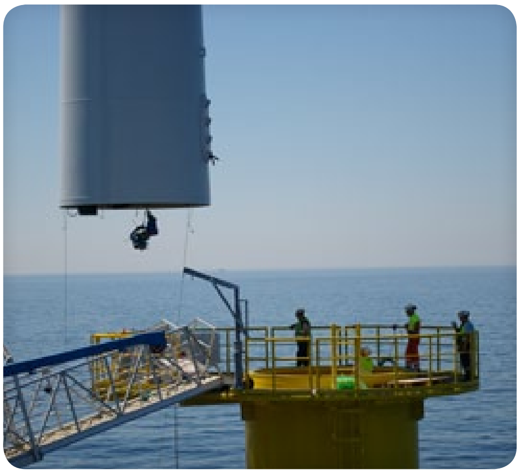
Disadvantages:

1. **It needs extra infrastructure**
   The bubbles need to be generated a somehow constrained. This calls for extra infrastructure. The extra infrastructure also results in longer handling time and eventually higher installation costs.
2. **Unproven technology**
   The technology is still in initial phase of its development and will require some effort and confidence before it can become conventional.
3. **Extra costs**
   Due to the extra infrastructure and the longer time needed to install the foundation; this technology will have extra costs. But the cost increment is not significant in comparison to other alternatives.
4. **Limited weather application**
   The bubbles are usually confined using water permeable fabrics which cannot be effective to contain the bubble in significant currents. Therefore this technique can only be used in clam weather conditions.

3.3 Conclusion & Discussion

Mitigation of underwater sound is possible. There are some options to reduce the source level or transmission. In all cases more research is needed. Special attention should be paid to the effect of the measures on the cumulative SEL. If research indicates that these measures will reduce the sound emission (incl. cumulative SEL), some of these measures can be applied relatively easily. A combination of several measures is also possible.

A combination of several measures is also possible



Placement of wind turbine on top of monopile

The sound of piling is still very loud

To what extent are extra costs justifiable?

There are several measures that can be applied in a short term. However, even if there is sound reduction by the measures, the sound of piling is still very loud. There will be still a large zone in which behavioural impact may occur and maybe even TTS. The question remains whether the sound reduction is sufficient to prevent the marine life from severe harm. Special attention should be paid to the low frequencies, which seemed to be very hard to reduce.

Delay

In several conversations with constructors or wind companies, the question was raised to what level the application of the precautionary approach in reducing underwater sound emission is reasonable. Especially because the reduction is relatively small. Offshore wind energy is sustainable energy and helps to reduce the impact of climate change. Delay in offshore wind farm development is not desired. It is important to find a good balance between these two aspects.

Costs

In these conversations another aspect was also mentioned: to what costs should measures be taken to reduce noise pollution of pile driving? These costs will be passed on to the costs of offshore wind energy. Offshore wind energy is already very expensive. Extra costs for noise reduction can make the project potentially not economically feasible. To what extent are extra costs justifiable and what are the ecological limits? These are good questions which should be taken into account seriously.

NSF: avoid pile driving altogether, use alternative techniques

North Sea Foundation finds it important to reduce man made underwater sound. Maybe the best approach to reducing impact from construction of offshore windfarms is to avoid pile driving altogether.

See report Saleem (2011) on www.noordzee.nl/soundsolutions

Alternative technique: vibratory hammers

Vibratory hammers make the pile handing more efficient

4. Alternative construction techniques

The description of measures and techniques in this section is based on the report of Saleem (2011). The information of Saleem's report is updated in this report.

Pile driving using vibratory hammers
Vibratory pile hammers contain a system of rotating eccentric weights, powered by hydraulic motors. The eccentric weights rotate in direction counter to one another to cancel out the horizontal vibrations, while only the vertical vibrations are transmitted into the pile. The vibratory hammers are directly clamped to the pile and therefore make the pile handing much more efficient, while saving time and costs.

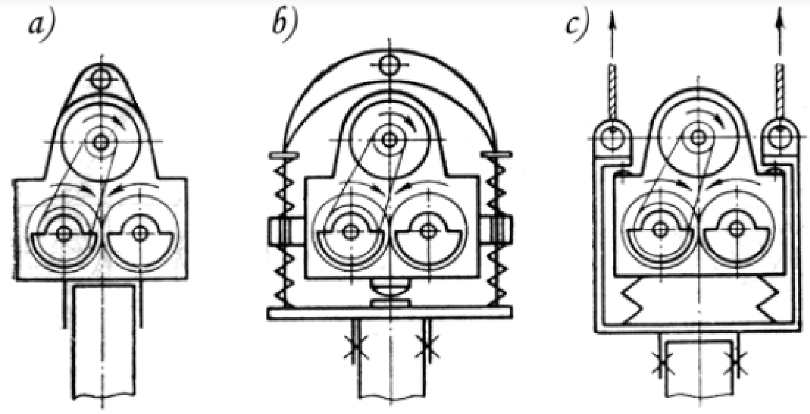


Figure 36. Technical drawings of various vibratory hammers configurations (Tseitlin, Verstov, & Azbel, 1987)

technical drawings of various vibratory hammers configurations (Tseitlin, Verstov, Azbel 1987).

Hydraulic fluid that is needed to operate the vibratory hammer is delivered to the system by "Power Units" through a set of long cables. Vibratory pile drivers are often selected when the construction is very close to residential area in order to minimalize the noise disturbance. The size of the vibratory hammer required to install a monopile is determined on the bases of soil conditions at the site and the size of the pile to be installed.

Advantages (Starre & Boor, 2011):
1. **Practically no diameter limitation unlike hammering.**
   Vibratory hammer have a very unique property that they can be joined together to form bigger hammer. This is shown is Figure 38, where two PVE 200 M hammer each capable of generating a centrifugal force of 4400 kN can deliver 8800 kN of centrifugal force in the "Twin" configuration.
2. **3-4 times faster installation compared to hammering.**
   Disregarding the monopile handing which takes longer compared to vibratoryhammer the time required to pile driving itself is 3-4 time faster. If the process of handling the monopiles is also taken into consideration than the whole process is even faster.
3. **1/2 the cost compared to hydraulic hammering**
   The vibratory hammers require less energy and time to install piles which directly translates to lower costs.
4. **Easy pile handling**
   As mentioned earlier direct clamping makes the pile handling easier and skips the step of placing/aligning the hammer from the installation process.
5. **Can be used to remove/reinstall piles**
   Unlike impact hammers, vibratory hammers can be used to remove pile. There is therefore more room for correcting mistakes and completely removing the pile after service life-time.
6. **Low noise emissions**
   One of the greatest advantages of employing vibratory hammers to install monopiles is that the noise produced during driving is greatly reduced. It is evident that the shape of the spectrum significantly changes and especially for frequencies ranging

from 300 – 1250 Hz sound pressure goes from around 150 dB re 1μPa to around 130 dB re 1μPa which is a reduction of around 20 dB re 1μPa for these frequencies. The frequencies between 300 – 1250 Hz are within the hearing range of marine mammals, therefore using vibratory hammer can considerably reduce the noise within the hearing spectrum of marine mammals.

Disadvantages (Starre & Boor, 2011):

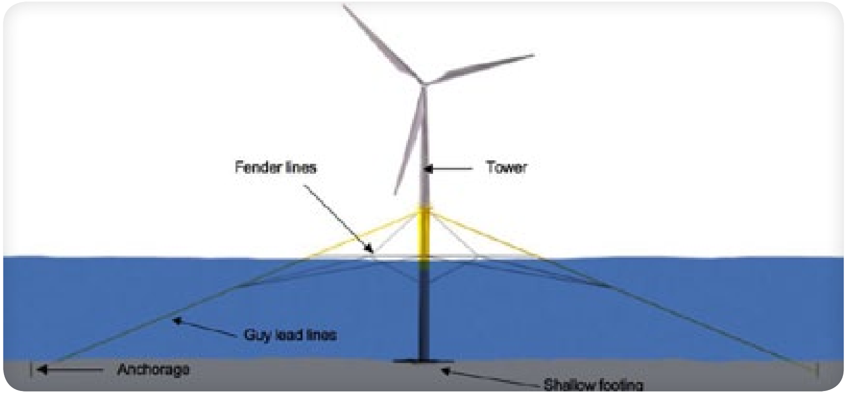
1. **Bearing Capacity cannot be measured**
   One major hurdle that faces the use of vibratory hammers to completely install monopiles is the lack of an accepted method to relate the hammer performance to the bearing capacity of the driven pile.
2. **Still not certified by the classification society**
   Bard, a major player in the offshore wind industry, uses the vibratory hammer to install its triple support structure. The last few meters of the piles is driven using impact hammers to verify the bearing capacity. However Dieseko's rented vibratory hammers were successfully used to install 5 meters diameter monopiles for an offshore wind farm in China as the regulations there are not as strict as in the Netherlands.
3. **Cable handing more complex**
   A lot of cables are attached to the vibratory hammer and they need to be carefully handled. This does cater for some complexity.
4. **Less reliability**
   The pile driving using vibratory hammers is less reliable when compared with the hydraulic impact hammer. Hydraulic impact hammers are more versatile and can guarantee the required depth and bearing capacity will be achieved, while a similar guarantee cannot be given for vibratory hammers.

Guyed support structure

The guyed support structure is a concept where an offshore turbine is supported by guy-wires or guy-ropes. These guys-wires provide the lateral stability and the need for penetration is completely voided. This principle has been used on land and offshore oil production facilities, but the concept calls for a larger scale implementation for offshore wind.

Alternative technique: guyed support structure

Support the offshore turbine by guywires or guy-ropes



Guyed Support Structures For Offshore Wind Turbines (Carey, 2002)

One of the best ways to peg the guy wires has to be the screwpiles, which can not only minimize noise during installation, but also handle tension loads much better. The report (Carey, 2002) claims that this support structure has many advantages over conventional structures.

Advantages

1. **More efficient handling of horizontal forces**
   Due to large distance to the anchors the bending moments and horizontal forces on the turbine can be supported in a more effective way.
2. **Lower installation costs**
   The concept proposes a unique installation technique where the whole wind turbine is installed in one step. The advantage of using such a process is that the whole turbine can be assembled onshore safely and saving costs. Further, single step installation can reduce the time at sea, making this concept more feasible.
3. **Relatively light**
   The guy wires provide structural strength that are virtually weightless in comparison to other support structures.

4. **Virtually no noise during installation.**
   The use of this support structure will immensely reduce the noise production during installation, as no hammering is required at all.

Disadvantages:

1. **New unproven technology**
   Like many other technologies mentioned in this section, this is an innovative idea and has not been tested, and it needs to be seen if the concept is actually practical.
2. **Cranes, which can lift a completely assembled wind turbine, don't exist.**
   A significant drawback of the installation technique mentioned is that there are currently no cranes available that are capable of lifting an entire wind turbine offshore. With the ever increasing size of wind turbines this would become increasingly difficult.
3. **Soil preparation needed**
   As the foundation needs to be placed directly on the seabed, certain seabed preparation is needed. This would add to the overall costs. Moreover scour protection would be needed and would be more crucial as the complete vertical loads are supported by the seabed.
4. **Storm surges**
   Some experts doubt that such a support could hold up again storm surges at the sea. Scaled testing is needed to verify if this support could handle the harsh sea conditions.

Concrete drilling

Alternative technique: concrete drilling

Ballast Nedam, a construction and engineering company, proposed a drilled concrete monopile solution for offshore wind application. The concept integrates the cheap concrete material and the simple monopile shape. Further, as a part of the concept, a new installation technique is proposed. Unlike the steel monopiles which are driven/hammered into the seabed, the Concrete monopile will be installed using a drill inside the monopile. This installation process is chosen to eliminate risks associated with the impact of pile driving.

Using a drill inside the concrete monopile shape

Drilled concrete monopile concept by Ballast Nedam (van der Meer & van Bergen, 2009)

The Concrete monopile seems to be a promising concept, but – at this stage – is unproven and will require sometime before it can be applied on full-scale projects. However, it is being developed by a company with a lot of experience in the offshore, and can utilize its resources to accelerate the whole process.

Advantages:

1. **Very versatile**
   A pile cannot be driven into a rock seabed, while drilling can overcome this problem. Moreover the concept proposes the use of concrete rings increasing the flexibility of the foundation so that it can be installed in any depth using the appropriate number of rings, reducing cost while construction and easy handling compared to one huge concrete structure.
2. **Concrete is much cheaper than steel and more readily available**
   This is a major advantage of this support structure as steel continues to become more expensive.
3. **Lower CO2 emission**
   The CO2 emission during the production of the concrete monopile is much lower than for a standard steel monopile

Disadvantages:

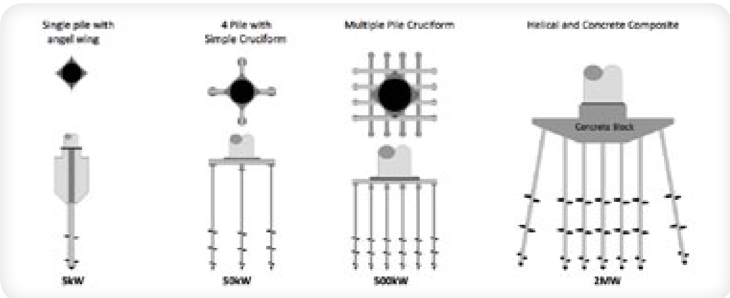
1. **The drilled hole needs to be filled after the installation**
   The soil holds the support in place and the soil resistant will act only on the outer wall if the inside of the pile will be hollow, therefore it would need to be filled adding an additional installation step, hence increasing the installation costs.
2. **Longer installation time in comparison to standard pile driving**
   Drilling is a generally a slower process in comparison to impact driving. The exact time required and comparisons are unknown.
3. **Need curing time after installation**
   Curing time is the time required by a material to reach its full strength after installation, assembly or construction. Concrete needs time to set and reach its full strength. The rings need to be joined using concrete and would need some curing time before the turbine can be installed on top.

Screw-pile

Screw piles are also referred to as: Helical Anchors, Screw Anchors, Torque Piles and Helical Piles or Piers.
Screw piles have been in use for a long time. One of the first applications was for Maplin Sand lighthouse constructed in 1838. This lighthouse was erected in shallow waters. During the 19th century many screw-pile lighthouses where built.
Screw pile is fundamentally a steel monopile, which is attached with helices. Screw piles are used for multiple on-and-offshore applications. However the diameter of these piles is very small. Offshore applications include small screwpiles that are used to fasten petroleum pipes to seabed (MacLean Dixie HFS).
Surprisingly, the screwpiles are also being used as supports for land-based wind turbines. A similar support could possibly be used for offshore turbines and could possibly remove the need for scour protection (as the support will share the seabed level). Furthermore, another application can be just be a tip screw. This will however require the filling of ballast once the pile has been installed.

Alternative technique: screw-pile

Screw-piles have been in use since 1838



Screw piles support solution for land bases wind turbines (ScrewFast Foundations Ltd, 2009)

Advantages:

1. **Can handle Compression and Tension loads much better**
   Owing to the presence of the helices the screw piles can not only take compression loads better but are also capable of handling tension loads unlike a simple monopile. This can very useful for multi-pod support structure where the members also need to carry tension loads.
2. **Easy and fast installation**
   The installation of a screw pile is very simple and fast, present piles can take less than 30 mins per pile to install. It is however hard to say how that will change with the size of the screw pile
3. **Reduced installation cost**
   Due to the time saving during installation and the flexibility to remove and re-use, the screw pile can reduce installation costs.
4. **Vibration and virtually noise free installation**
   This technique is probably the most environment friendly technique of installing piles. There is almost no noise or vibration produced during installation.
5. **Easy complete removal and Reusable**
   The screwpiles can be easily removed and reused. This is really handy as errors during installation can be easily corrected.
6. **No Curing Time required (after installation)**
   Usually, when a foundation is installed, it requires some time before the soil settles

and gets back to full strength. This is however not the case for the screw pile, which doesn't require any cure time.

7. **No scour protection required**
   Need for scour protection can be avoided. The concrete block would need to aligned with the seabed.

Disadvantages:

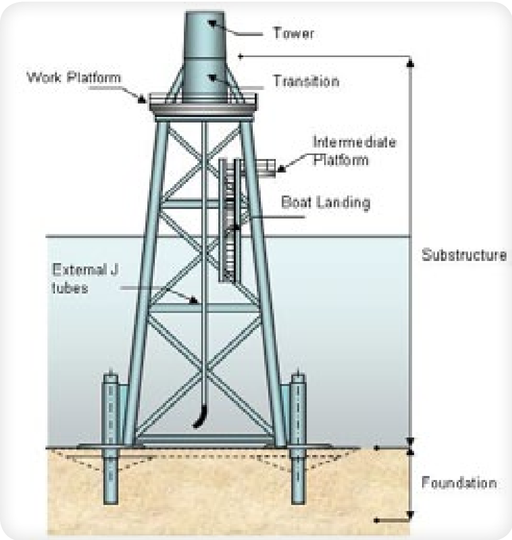
1. **Increased initial manufacturing costs**
   In single pile configuration the extra material is needed to make the helices and install them onto the pile meaning higher initial costs.
2. **Can only be installed in certain soil types**
   Unlike monopiles that can be impact driven into almost all soil types, the screwpile can only be installed in soft and medium soil types.
3. **Unproven technology on large scale**
   This concept has never been applied on a large-scale monopile despite the many advantages that the screw pile provides. The largest diameter for a screw pile found is 24 inches (610 mm) with 30 inches (760 mm) helices. (Franki Foundations Belgium, 2008)

Alternative technique: jacket foundations

The basic truss structure gives stability and strength

Jacket foundations

The Jacket support structures are a combination of smaller components and are therefore easier to be built into large sizes. Jackets utilize the basic truss structure to give stability and strength. Jackets have been used and were the preferred offshore support structure, but as the water depths of the offshore rigs increased other solutions had to be considered.



Jacket support structure for offshore wind farms (Iuga)

As the wind turbines grew heavier, larger and had to be deployed in deeper waters, the engineers turned to the jacket support structure. The jacket support structures are fixed to the sea bed using piles that are driven through pile sleeves. Both impact and vibratory hammers are used for this purpose.
Shell's Bullwinkle oil platform located in the Gulf of Mexico is a testament to the capability of the jacket support structure. 412 meters of this oilrig's jacket support structure is below the waterline. Size is therefore not an issue for the jacket foundation when it comes to wind farms.

Oilrig jacket support for Bullwinkle oil platform - (C) Bettmann/CORBIS

Generally, the pinpiles for jackets will be much smaller than monopiles. It could be expected that the piling of the smaller pins is less noisy. However, a recent study in Belgium by Norro (2012) showed no significant differences between mono- and pinpiling. The pinpiling took 2,5 more times than monopiling and has a prolonged impact onto the marine fauna. Standardised to megawatt installed, both types score about equally.

Advantages:

1. **High global stiffness**
   The stiffness of a monopile can only be obtained by introducing additional steel to the structure. However, jackets can easily be designed to fulfil stiffness requirements.
2. **Low structural mass**
   Comparing jackets with monopiles, it can clearly be seen that the jackets are not one solid mass like monopiles. This greatly reduces the amount of material needed and the weight of the support.

Disadvantages:

1. **Higher manufacturing costs**
   Unlike monopiles, jackets consist of many parts and they need to be put together, increasing complexity, time required and costs. The material used is nevertheless lower.
2. **Scour protection harder to install**
   To install scour protection for the jacket support structure is more complex as the inner parts of the piles are hard to reach.
3. **Stress checks**
   Increasing parts also increase the risks of failure. Additional stress checks are required for the joints and members. The design of jackets and its analysis is more complicated and time consuming than a simple monopile.

Gravity based support structures

Alternative technique: gravity based support structures

Gravity based foundations are huge concrete structures, designed to support offshore installations. These foundations have been particularly popular in the early days of offshore wind energy in Denmark. The depths of these early wind parks were also very low. One of the deepest applications of a gravity based foundation is the Thornton Bank in Belgium where water depths ranged 12 – 27 meters. The gravity based foundations that are used for wind turbines usually do not penetrate the sea bed and are generally supported by the seabed.
Plaatje en bijschrift:
One possible Gravity base structure solution (Iuga)

Advantages:

1. **Cheaper material and more availability**
   Concrete is a much cheaper material and more readily available as mentioned before and hence gravity based support has a clear advantage in terms of raw material.
2. **Towable**
   The concrete foundations are made hollow, to keep the weight low for handling. This also makes the gravity based structure towable in certain cases. An example of such a concept is the "Cranefree Gravity foundations" concept of a company called, SeaTower.
3. **Dry Dock**
   Gravity based foundations for smaller wind turbines can even directly be fabricated on dry dock for easy transportation after completion, this is however hard with the ever growing size of wind turbine foundations.

Disadvantages:

1. **Overturning moments**
   As the gravity based structure doesn't penetrate the seabed, the overturning moments need to be considered and designed for.
2. **Seabed preparation needed**
   The gravity based structure needs to placed directly onto the seabed therefore the seabed needs to be leveled so that the foundation is completely upright. This additional procedure increases installation costs. However, the Cranefree Gravity foundations, offers a unique feature that fills the lower part of the foundation with concrete making a full contact with the seabed.

3. **Extensive scour protection needed**
   The lower part of the gravity based support structures are much larger that a steel monopile and there the vortex generated cause a deeper scour. Moreover due to no penetration scour protection is more crucial.
4. **Depth limitations/feasibility**
   Practicality of concrete structures in 50m water depth is questionable. As the size and weight of the foundation makes it increasingly difficult to handle.

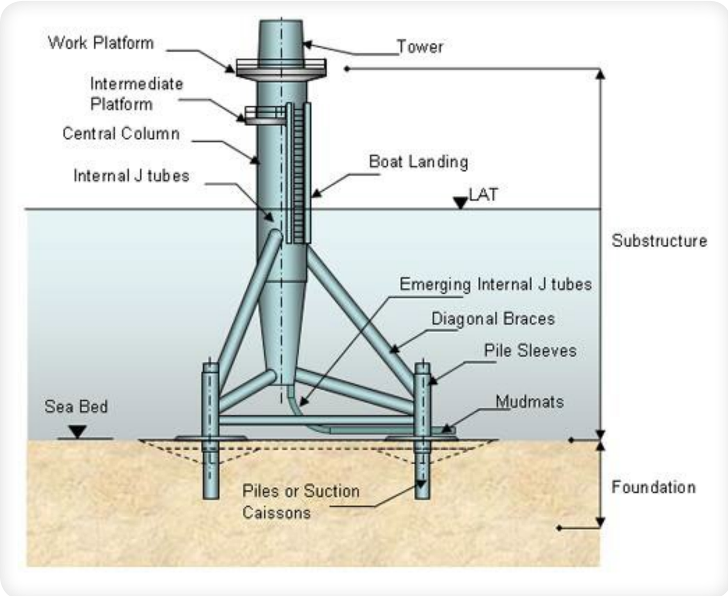
According to a.o. Gravitas, some of the disadvantages are tackled in the new generation Gravity based constructions. There is for instance for no need for seabed preparation, it can be used in waterdepths up to 60 m, large turbines (up to 8 MW) can be installed and no special heavy lift vessels are needed.

Alternative technique: tripod or tripile support structure

The tripile foundation is used by Bard Engineering GmbH

Tripod

Tripod - as the name suggests - is a three-legged support. Like the jacket support structure, the tripod is capable of providing greater stiffness and lateral stability than a single monopile.



Tripod foundation for offshore wind turbines (Iuga)

A variation is of the tripod is the tripile support structure, which is employed by Bard Engineering GmbH. The installation of this type of foundation requires three monopiles to be driven into the ground. The diameter of these three monopiles is however less than a single monopile that would be required to support the same turbine. This particular support is designed for water depths from 25 to 50 meters. During the installation of the tripile foundation, the three piles are first preinstalled using a vibratory hammer to a depth of 21 meters and the rest of the depth is achieve by a hydraulic hammer (Deutsche Welle, 2008).

Tripile foundation used by BARD GmbH for it offshore wind parks (BARD Engineering GmbH)

During an interview with experts (Starre & Boor, 2011), it was found that the last part of these piles is hammered in order to prove the bearing capacity of these piles required by the certification bodies.

Advantages:

1. **Can be installed in depths up-to 50 m**
   So far monopile support structure has not been installed in water depths greater than 34 m. Even though the monopiles have the capacity to installed in deeper waters, the tripod can still provide better lateral stability and use less material to be manufactured than a single monopile for greater depths.
2. **Better lateral stability than a single monopile.**
   Better lateral stability and stiffness can be achieved than monopile foundation.

Disadvantages:

1. **Still require pile driving**
   Since impact pile driving alternatives are being searched for, this support structure might not be the best possible option. As this type of installation still need the installation of piles. The diameter of each pile is smaller but the number of piles increase i.e. three per turbine.
2. **One member need to bear load in certain load cases**
   Wind and waves come from every direction and are constantly changing. This means that all the members need to be designed for the extreme load case making the whole structure heavier and more expensive.
3. **More complex to transport**
   Tripod and tripiles are huge structures, and transporting these structures is more complex than a standard monopile. The monopile can even be made airtight and towed to the location.

Floating foundations

With the advent of the floating oilrigs, it was soon that experts thought of floating wind turbines. Floating oilrigs, however, cannot be compared to floating wind turbines. An oilrig covers a huge area and therefore be easily laterally stabilized, unlike a wind turbine that is just supported by a single tower with a huge mass on its top, making them inherently unstable (inverted pendulum). The mass of the nacelle need to be balanced with a huge mass that is submerged underwater to achieve stability.

Alternative technique: floating foundations

A wind turbine needs a huge mass underwater for stability

Floating Wind Turbine Concept (Mitchell, 2009)

Some concepts try to overcome this problem by adding extra floaters like the Blue H – prototype. This increases the area underneath the turbine making it stable. Other concepts suggest using active balancing like the Principle Power's WindFloat Concept.

Principle Power's WindFloat Concept

Advantages:

1. **Easy to transport**
   As the bases of the floating wind turbines are floatable they can just be towed to the location, where they need to be installed, saving heavily on transportation costs. Which usually require loading and unloading the parts on to huge ships/barges.
2. **Can also be used in the deepest part of the Dutch EEZ**
   Even though the Dutch EEZ is not one of the deepest seas in the world, still the depth in a large part reaches almost 60 meters. For such depths the floating might prove to be a more feasible solution.
3. **No scour protection needed**
   The floating turbine is just held in place by anchors installed into the seabed and there is no real structure on the seabed. This overcomes the need for scour protection and therefore saving time, costs and noise produced during the installation of scour protection.
4. **Onshore construction and repairs**
   Most types of floating wind turbines can be constructed and assembled completely onshore and just towed to the location to be moored to the seafloor. This is a big cost saver as spending more time offshore translates to higher costs. Further floating turbines can also be brought to shore for repairs, unlike fixed base turbines.
5. **No noise**
   A great advantage of using the floating wind turbines is that their installation almost generates no noise. Further the underwater environment is also minimally disturbed.

Disadvantages:

1. **Not financially feasible in shallow waters**
   In shallow waters the floating are so far believed to be too expensive. Maybe as the technology evolves these trends would change.
2. **Stability a major concern**
   The sea is one of the most hostile environments in the world. Unstable loads on turbine can reduce its fatigue life. The stability of the turbine is vital for reducing fatigue loads on the turbine and smooth turbine operations.
3. **Unproven technology**
   This technology is in the early phase of development and will take some time before it will become readily available. Therefore this cannot provide a short-term solution for the noise problem.

Alternative technique: suction buckets

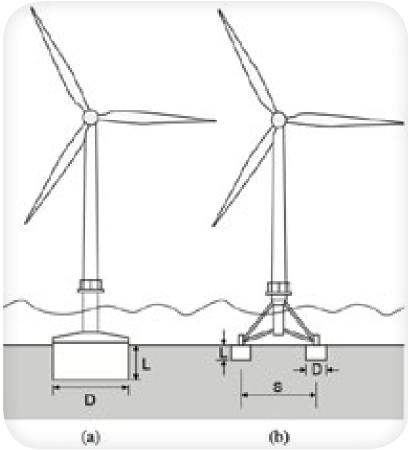
Suction buckets

Suction buckets are tubular structures that are installed by applying suction inside the bucket. The foundation initially penetrates the seabed by means of its own weight. In the next phase, suction is added by means of hydraulic pumps. The operation is finalized by applying cement slurry to ensure full soil contact if needed. If needed the dead load can be increased by filling the shaft with e.g. sand (Harland & Wolff, 2011). The penetration is very low compared to the monopile, while the diameter of the bucket is much larger. The installation process is estimated 12-24 hours. The ideal situation is sand or softer clay to a depth of 12-17 m, but it can be used in water depths up to 55 m and seabed consisting of clay, sand and silt.

The only sound produced is by the power packs for suction. Harland and Wolff (2011) don't expect it to be harmful to sea mammals. The production is more expensive, but faster installation and use of lighter vessels makes suction buckets cheaper than piling monopoles.

The only sound produced is by the power packs for suction

Production is more expensive, but installation is faster



Possible foundation configuration with suction caisson (Houlsby, Ibsen, & Byrne, 2005)

Advantages:

1. **Can be completely removed on decommissioning**
   Unlike monopiles that are chopped 1.5 meter below the seabed, suction caisson can be completely and easily removed.
2. **Quicker installation**
   As the penetration is lower and there is no hammer required to install, the whole process goes faster. As mentioned before hammering requires more time as the hammer needs to be aligned to the foundation and held in place.
3. **Less weather dependant**
   For impact pile driving the pile needs to be held in place plus the hammer also needs to be held on top of the pile. This operation requires good weather conditions; this is not the case for suction caisson and is therefore less weather dependant.

Disadvantages:

1. **Extensive scour protection needed**
   The suction caisson has a huge diameter and the penetration depth is low. The huge diameter causes a huge scour, while the lower penetration makes to more crucial to provide sufficient protection again scouring as due to the lower penetration that scour can greatly reduce the foundational properties.
2. **Liquefaction**
   Liquefaction is the phenomenon when soil loses its strength and stiffness. This can be caused by earth quakes or the change in the water pressure in the soil. This can be crucial for suction caisson and there is not a lot supporting the structure and a failure of soil will result in the failure of the support.
3. **Unproven technology**
   Since this is a new technology, it still needs to be extensively tested and approved before it can be applied on full-scale.
4. **Overturning moments**
   Similar to the gravity based foundations, overturning moments are a serious issue as the penetration is very low. However, this problem is only limited to the monopod configuration. The tripod/tetrapod can handle the overturning moments much more effectively.
5. **Limited application**
   Unlike the monopile, suction caisson cannot be used in all soil types. They are only applicable in sand and clays of intermediate strength. Making them unsuitable for harder soil types and increasing risks during installation.

5. Conclusions & Discussion

Underwater sound levels of monopile driving cause a problem

1) Underwater sound levels of monopile driving cause a problem to the marine environment. However, it is not clear how big the problem is. There is a lack of knowledge on the impact of underwater sound on marine life. Research is urgently needed to make a set useful set of regulations for the construction of wind farms.

There are mitigation measures and alternatives for offshore wind

2) Underwater sound levels of monopole driving can be reduced. Various techniques are being tested. A reduction of at least 10 dB re 1 μPa is possible. These mitigation measures can be applied offshore. This will cost extra handling time and thus money. At the same time, a reduction of costs for offshore wind is urgently needed. This represents an extra challenge for the technical implementation.

3) There are alternatives for offshore wind foundations which produce less underwater sound than pile driving which are already being applied: Gravity Based structures, suction buckets. There are other concepts which need further technical development (like drilling).

4) International collaboration is needed. Countries should have the same regulations for underwater sound for construction of and operational offshore wind farms, based on the best available knowledge.

5) Sustainable energy is important, but marine life is important as well. Negative impact of offshore wind on the local environment should be as low as possible. However, there should be a good balance between measures to reduce impact and costs of renewable energy. Therefore, research and cooperation are key factors.

6) Piling is not the only strong underwater sound source. Other ones, like seismic surveys, should be considered as well.

Promising measures and alternatives (Saleem 2011)

Promising measures: changing parameter & vibratory hammer

Engineering solutions that can be used for noise mitigation in the immediate short-term without significantly changing to the current methods include:
- Changing the parameter for pile stroke
- Vibratory Hammer for pre-installing the monopile

Other solutions that can follow to further reduce noise in the short/medium-term include:
- Sound isolation/damping
- Changing pile toe-shape

Promising alternatives: jacket foundation & gravity based

Alternatives for steel monopile can also provide for some very effective solutions, in the short term these solutions can be:
- Jacket foundation with vibratory pile driving
- Gravity based support structures

These techniques are currently in use and should be given priority over using hydraulic impact hammering without noise migration techniques. Other alternatives that can play a vital role in noise mitigation include:
- Concrete monopile/drilled
- Screwpile
- Floating foundations
- Suction caisson/buckets

Some of these methods are in concept phase and need further development and time, but can provide significant noise reduction for future wind farms. The government and the classification societies should further encourage wind farms developers to pay more attention to noise mitigations and using alternatives that significantly reduce installation noise.

Concluding

Internationally there is increasing awareness that underwater sound of piling for the construction of offshore wind farms is a problem. During this project, North Sea Foundation gathered a lot of information on underwater noise of piling, possible solutions, biological impact of underwater noise but also on the views of different stakeholders involved. This information was combined and discussed with all relevant stakeholders (constructors, marine biologists, acoustics, technicians, policy makers etc). It is evident that the problem and solution is complex, but all stakeholders are willing to look for a solution. Cooperation between countries and disciplines is needed.

Countries should have the same regulations for underwater

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