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Alternatives and modifications of Monopile foundation or its installation technique for noise mitigation

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Preface

This report is the result of a research carried out for North Sea Foundation as a part of an internship program, which is a component of the M.Sc. curriculum at the Delft University of technology.

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Executive Summary

This report reviews and proposed alternatives and modifications for the steel monopile foundation and its current installation technique for noise mitigation. The steel monopile is a cylindrical hollow tube that is used as a foundation for offshore wind turbines. The report identifies a number of different engineering solutions that are divided into two categories, solutions that can be used with the current installation techniques *(i.e. modifications)* and solutions that change the current methods *(i.e. alternatives)*.

Based on measurements the noise emissions for the installation of a 6 m diameter monopile using hydraulic impact hammers reach sound exposure levels of 174 dB re 1μPa at a distance of 500 meters. This value is above the Temporary Threshold Shift (TTS) of pennipeds *(163 dB)* and very close to that TTS of cetaceans *(183 dB)*. Moreover prolonged exposure to TTS sound levels can cause Permanent threshold Shift (PTS). The marine mammals depend heavily on their hearing to survive. Damaging the hearing of these animals can make it harder for these animals to survive and in extreme cases make it impossible.

Selecting a foundation type for an offshore wind turbine is not straight forward; as the choice depends on many variables that vary greatly from one offshore site to another. The general understanding is that there is not one perfect solution. The design method for each foundation also varies but general procedure is more or less similar. The data required for the design of these foundations is also analogous, which includes environmental data, turbine data and site data.

Methods that do not completely change the current pile driving methods are interesting as these procedures can be applied in the short term. These include changing of pile-toe shape, use of contact damping, skirt-pile support, modification of the parameter for pile stroke and sound isolation/damping. The noise reduction from these modifications is achieved either by reducing the sound at the source, for example changing the pile stroke parameter or by isolating/damping the sound, like using sleeves.

Alternatives for current techniques require a major modification either of the installation procedure or of the monopile itself. Alternative for hydraulic impact hammer include the use of Vibratory hammers and drilling, while the alternatives for the monopile foundation include, guyed support structure, concrete/drilled monopile, screwpile, jacket structure, gravity based supports structures (GBS), tripod/tripile foundation, floating structures and suction caisson. Few of these alternatives, like GBS, jackets and tripods have and are already being used in the offshore wind industry today.

Final comparison is based on two criterions, noise reduction achievable and time required for implementation. Even the best solution for a significant noise reduction is useless in the short term if it will take decades to implement. Therefore solutions with the quickest implementation time need to be considered and applied to reduce the harmful effects of impact pile driving in the near future. This will slightly lower the noise disturbance in the short-term while giving more effective solutions, time to be developed and tested.

Background

The Netherlands has currently two active offshore wind farms in the North Sea, with the total capacity of producing *228 MW*, however there are plans to increase this capacity to *6,000 MW* by the year 2020. In order to meet this challenge a considerable number of wind farms are expected to be built in the coming years.

So far both[1] the Dutch wind farms use the monopile[2] support structure for its Wind turbines and almost all the upcoming projects also plan on using the same approach. The monopiles are installed currently by hammering them directly into the seabed using powerful hydraulic hammers. This process generates a lot of noise and due to the properties of sound propagation[3] in water, can be heard by animals like seals as far as *80 km*. Closer to the site of hammering the sound pressure levels are incredibly high. Average sound exposure levels are estimated around 247 *dB re 1 μPa* (Lindeboom H. , 2010). Further as the size of the wind turbines is increasing so is the diameter resulting in even higher noises. This adversely affects the sea life in the North Sea causing deafness and forces many animals to flee.

The wind energy represents a green and environmental friendly future while the use of monopiles with current installation techniques is contradictory to the whole Wind energy philosophy and needs to be re-examined.

Aims and Objectives

The aim of the project is to analyse and propose alternatives for the monopile support structure and its installation techniques to minimalize or eradicate the noise production during the deployment of offshore Wind farms. This is to protect and preserve the sea life of the North Sea with a specific focus on the Dutch EEZ[4].

[1] Windpark Egmond aan Zee (OWEZ) and Princess Amalia Wind Farm.
[2] A hollow cylindrical steel tube used as a support for offshore wind turbines
[3] Sound travels 4.3 times faster in water than in air due to difference in the medium properties of the two fluids.
[4] Exclusive Economic Zone: A seazone over which a state has special rights for exploration and use of marine resources.

1. Problem Analysis

1.1. Marine life in the Dutch EEZ

The Dutch Exclusive Economic Zone (EEZ) is approximately 57,000 km^2, almost 1.5 times the Dutch land area. Sharing a sizable part of the North Sea, which is one of the buzziest seas in the world, the Dutch EEZ is home to a rich and diverse ecosystem. (Lindeboom, et al., 2008)

The marine life in this ecosystem consists of:

a. Microscopic life
b. Plants and algae
c. Marine invertebrates
d. Fish
e. Seabirds
f. Marine mammals

This problem analysis will mainly focus on the effects of pile driving on marine mammals with a brief look at the fish. The effects of noise on other types of underwater marine life mentioned are almost unknown and are therefore beyond the scope of this study. Seabird will also not be studied as the study focuses only on underwater noise.

a) Harbour Seal (Phoca vitulina) (© Andreas Trepte) *b) Grey Seal (Halichoerus grypus) (© Andreas Trepte)*

c) Harbour porpoise (Phocoena phocoena) (© Solvin Zanki)

Figure 1. Marine mammals found in the Dutch EEZ

There is a large variety of marine mammals that form a part of the North Sea marine life, the largest groups are;

a. *Harbour Seal (Phoca vitulina)*
b. *Grey Seal (Halichoerus grypus)*
c. *Harbour porpoise (Phocoena phocoena)*

These mammals can be seen in Figure 1.

Beside the marine mammals, there are a huge variety of fishes present in the Dutch EEZ. It would be difficult to list all these sorts of fish therefore only the prominent sorts will be listed; this list is in no particular order:

a. *European flounder (Platichthys flesus)*
b. *Yellow sole (Buglossidium luteum)*
c. *Spotted Ray (Raja montagui)*
d. *Thornback ray (Raja clavata)*
e. *Grey gurnard (Eutrigla gurnardus)*
f. *Atlantic herring (Clupea harengus)*
g. *Atlantic horse mackerel (Trachurus trachurus)*
h. *Atlantic mackerel (Scomber scombrus)*
i. *Atlantic cod (Gadus morhua)*
j. *Lesser weever (Echiichthys vipera)*
k. *Striped red mullet (Mullus surmuletus)*
l. *Common dab (Limanda limanda)*
m. *Haddock (Melanogrammus aeglefinus)*
n. *European plaice (Pleuronectes platessa)*
o. *Scaldfish (Arnoglossus laterna)*
p. *European sprat (Sprattus sprattus)*
q. *Turbot (Psetta maxima)*
r. *Dover sole (Solea sole)*
s. *Whiting (Merlangius merlangus)*

In the section 1.4 the effects of noise on these marine mammals and fish and their behaviour will be discussed.

1.2. Underwater acoustics

Before diving into the underwater noise levels of pile driving and its impact on the sea life it is vital to understand few fundamentals of underwater acoustics. It is vital to realise that underwater acoustics is a complex and vast subject and only a section on this topic doesn't do justices. However this section is intended to explain certain basic concepts needed for understanding noise generated from pile driving.

Sound is a mechanical disturbance that can move through any medium (gas, liquid or solid). This disturbance propagates in air and underwater by the compression and rarefaction, as depicted in Figure 2. Due to these compressions and rarefactions the sound is detected by a receiver as change in pressure.

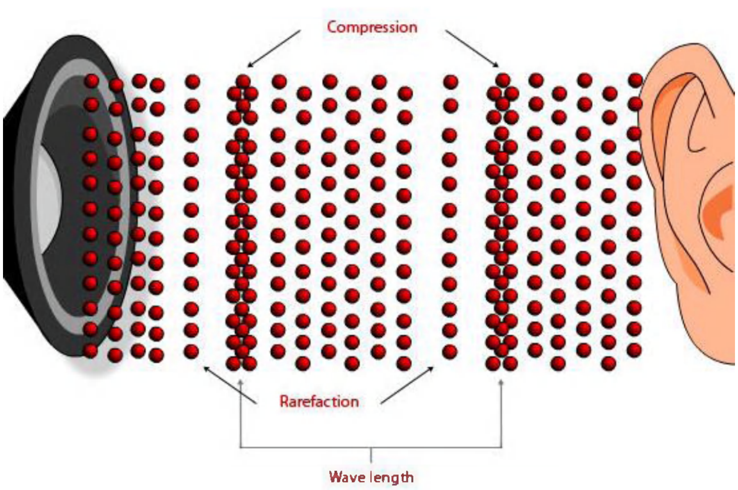


Figure 2. Compression and Rarefaction (What is Sound?, 2010)

One salient characteristic of sound propagation is the speed of sound. The speed of sound underwater varies significantly from speed of sound in air as the two mediums have very different properties. The sound travels faster through medium with higher incompressibility and/or lower density. As given by the equation:

$$c = \sqrt{\frac{K}{\rho}}$$

Where,

c represents the speed of sound in a medium
K is the Bulk modulus (incompressibility)
ρ is the density of the medium

The water has higher density than air but is harder to compress (higher bulk modulus) making the sound travel around 4.3 times faster in water than air. If the medium is more compressible then more sound energy is used up for compressions and rarefaction resulting in lower sound speeds. In fresh water, sound travels at about *1497 m/s* at *25 °C*, while at the same temperature the speed of sound in air at sea level is *346 m/s.*

This speed is also influenced by the temperature of water and furthermore in seawater, which is a non-homogeneous medium, there are other factors that affect the speed of sound namely salinity and water depth (pressure). The approximate sound speed variations as a function of temperature, salinity, and depth are given in Table 1 and further the sound depth relation is observable in Figure 3.

Table 1. Approximate sound speed variation (Urick, 1983)

Sound speed dependency	Coefficient
Temperature	*+ 4.6 m/s per °C*
Salinity	*+ 1.3 m/s per ppt (part per thousand)*
Depth	*+ 0.016 m/s per m*

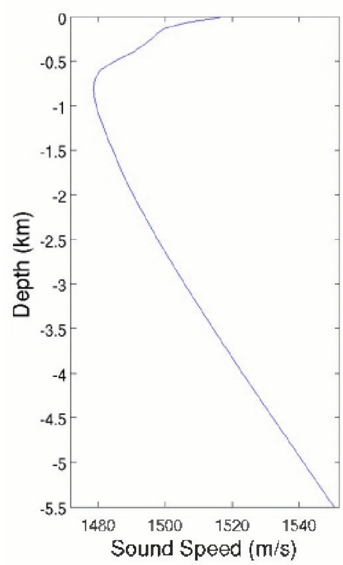


Figure 3. Speed of Sound vs. Depth

1.2.1. Sound levels in Air versus water

Sound levels and other acoustic parameters vary over a very wide range; the values relating to sound are therefore measured in a logarithmic unit, *decibels* [dB] to be specific. A *decibel* unlike other units is a dimensionless unit i.e. it is a ratio. To understand why a logarithmic is better suited for wide ranges consider a range of numbers from 0.001 to 10,000, this range is simply –3 to +4 on the logarithmic scale (values of the exponential 10^x). This makes it easier to handle the wide range of values.

As mentioned earlier, *decibel* is a ratio, and a ratio can only be calculated in relation to some reference value. The sound pressure level or intensity level are therefore calculated using some reference sound pressure level or reference intensity respectively, as can be seen in the equations

$$\text{Sound Intensity level (dB)} = 10\log_{10}(\text{Sound intensity}/\textbf{reference intensity})$$

$$\text{Sound pressure level (dB)} = 20\log_{10}(\text{Sound pressure}/\textbf{reference sound pressure})$$

Comparing the sound pressure levels in air and water is not straight forward as the reference pressures are different. For air the reference pressure is ***20 µPa*** while for water it is ***1 µPa***. (Bradley & Stren, 2008) This difference can be calculated as follows;

$$\text{Difference* (dB)} = 20\log_{10}(\text{air reference pressure/water reference pressure}) = 26 \text{ dB}$$

*in the numerical value to the same RMS pressure

A simple, but unscientific way to visualize the different values obtained from using different reference values might be to take the example of length or distance. Distance or length can be measured with respect to meters or inches/feet etc. The measured values i.e. 2 meters is the same as 508 inches, but the values are different depending on the reference used.

1.2.2. Sound Absorption

The sound absorption in seawater depends on properties like, temperature, salinity, acidity and the frequency of the sound. There are two main processes that play an essential role,

a. *Kinematic (Viscosity)*
   The sound propagation in water causes the molecules to 'rub' against each other because of the viscosity and results in the loss of sound energy as heat.
b. *Chemical (relaxation processes)*
   Seawater contains salts and acids, when considering absorption the most interesting are Magnesium Sulphate ($MgSO_4$) and Boric Acid (H_3BO_3). These can exist in two different physical shapes, when energy is provided by the sound they change shape, absorbing energy, and then return to their original forms after a certain period (relaxation time) releasing energy. This is the relaxation process. For Boric Acid, the conversion takes place when the sound frequency is low, and for magnesium sulphate, it occurs when the frequency is high. (Francois & Garrison, 1982)

The seawater sound absorption coefficient α can be computed using the Francois-Garrison equation. (Francois & Garrison, 1982)

Total Absorption		Boric Acid Contribution		Magnesium Sulphate Contribution		Pure water contribution
α	=	$\frac{A_1P_1f_1f^2}{f_1^2+f^2}$	+	$\frac{A_2P_2f_2f^2}{f_2^2+f^2}$	+	$A_3P_3f^2$

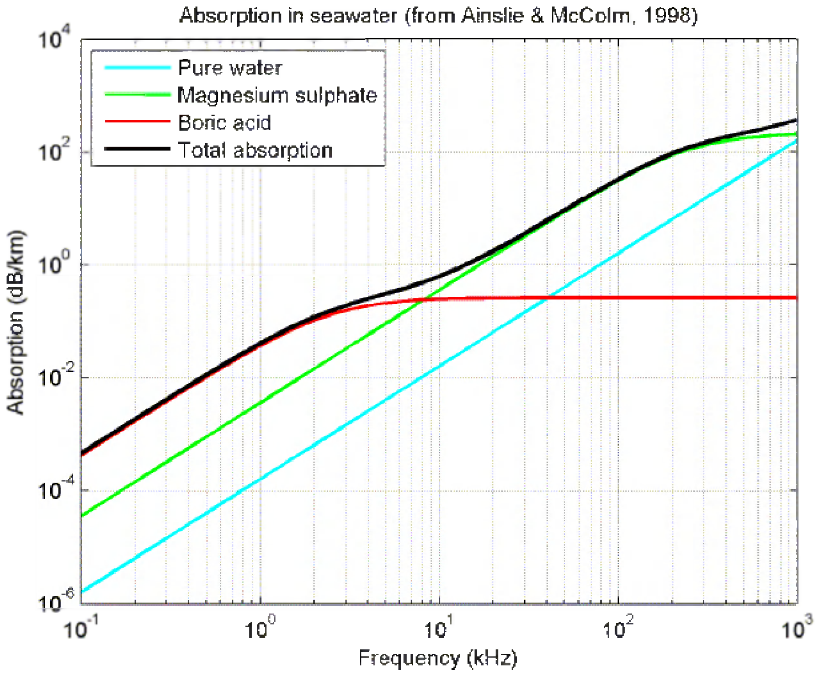


Figure 4. Sound Absorption in Seawater

1.2.3. Reflection

Another crucial aspect of sound propagation under water is the reflection of sound. Both the ocean surface and the ocean floor act as reflecting and scattering boundaries. Due to the different properties of the water and air only a small amount of energy is able to cross the ocean surface. And therefore for simplification sea-air surface is considered as a perfect reflector at times. The reflection from the seabed is more complex and dependent on the soil type, however the energy is generally transferred much easily in comparison with the sea-air surface.

The reflection is important to consider, as the sound doesn't escapes the water *(especially from the ocean surface)* and keep reaching the receiver again and again through different

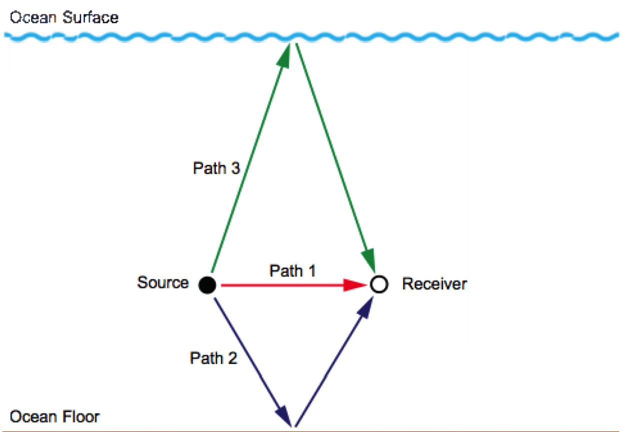


Figure 5. Different paths of sound due to reflection. (Bradley & Stren, 2008)

paths over a wider range of time.

1.3. Noise Levels for pile driving

Pile driving is a process of installing a hollow cylindrical steel tube into the

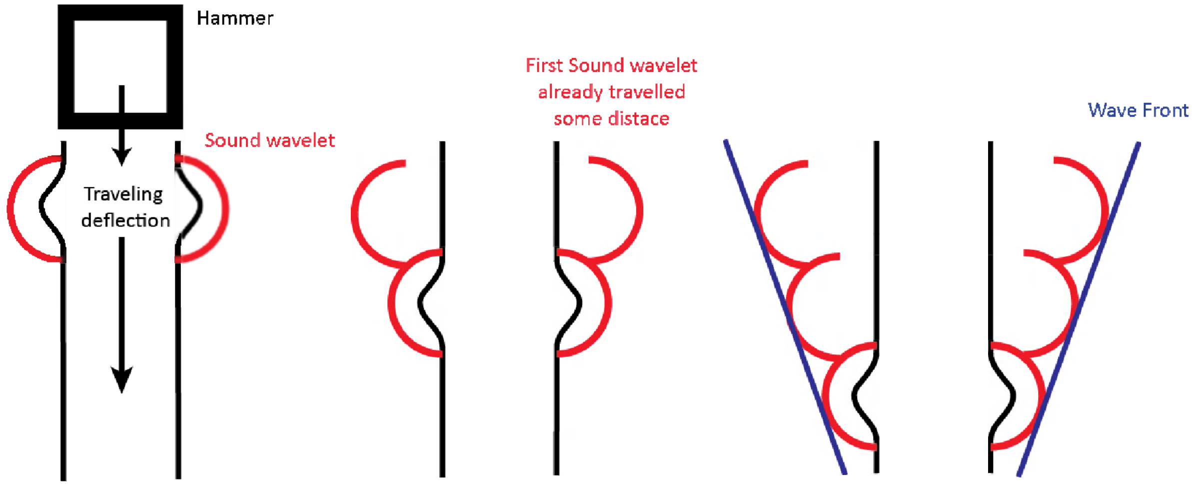


Figure 6. Sound generation by impact hammer (wave front)

ground/seabed, by impact or vibratory hammer. Impact driven monopiles seem to be the preferred method and to date the only method used in the Dutch EEZ to install offshore wind turbines. The hammering of the monopiles generates extremely loud noise; the exact values will be discussed in the lateral part of this section.

When an impact hammer hits a pile the pile deforms and this deformation travels downwards to the lower end of the monopile. This deflection disturbs the water generating sound. Therefore the sound is not produced simultaneously from the whole pile rather is generated first from the top part and moves downwards. The sound wavelet from the top part starts traveling first and therefore has already travelled a certain distance when the second wavelet is formed. Therefore the Huygen's wavelets front is not straight i.e. the sound energy is transmitted at an angle according to (Reinhall & Dahl, 2010) the deflection is around 18 degrees. Consequently a large part of the noise follows a zigzag path reflecting of the seabed and the ocean surface, like depicted in Figure 5.

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 significantly 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 and as speed of sound is higher in soil than in water the noise from this path will reach the receiver before any other path (Nedwell & Howell, A review of offshore windfarm related underwater noise sources, 2004) these paths are depicted in Figure 7.

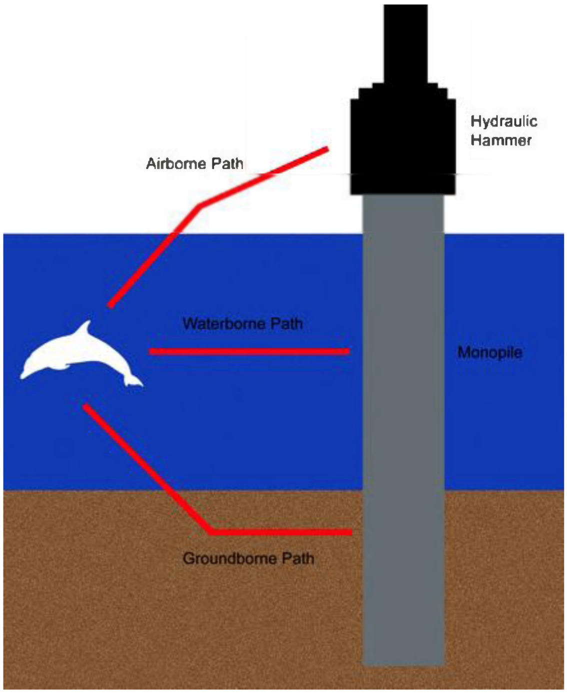


Figure 7. Noise paths during impact pile driving

As pile driving is an impulsive sound, a single dB value is not enough to define it. Other useful values that are needed for better interpretation of pile driving noise are explained below. The graph in Figure 8 generally represents the sound pressure impulse from a stroke for impact pile driving.

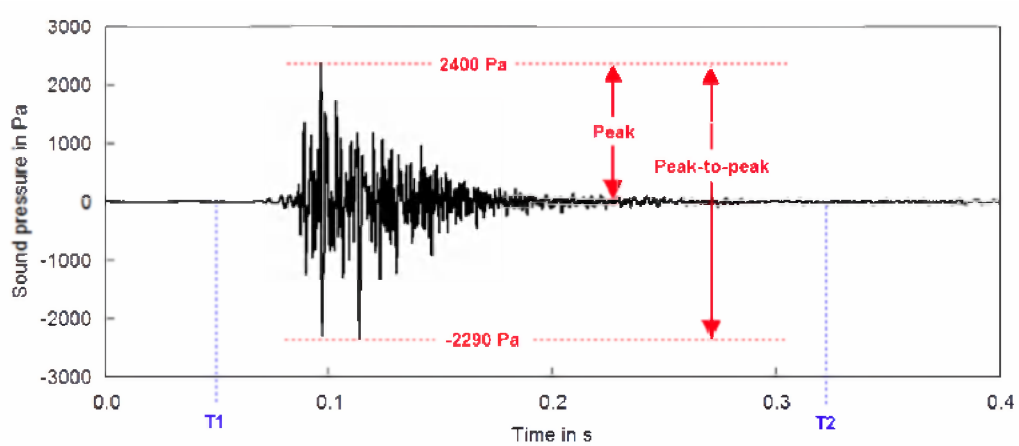


Figure 8. A typical Sound Pressure impulse of one hydraulic hammer stroke (Nehls, Betke, Eckelmann, & Ros, 2007)

1.3.1. Equivalent Continuous sound pressure level

It is also known as time-averaged level and is abbreviated as L_{eq} it is widely used as an index for noise, and is the average sound pressure level during a period of time in dB. Numerical it can be represented as:

$$L_{eq} = 10 \cdot \log\left(\frac{1}{T}\int_0^T \frac{P(t)^2}{P_0^2}\,dt\right) dB$$

Where,

$P(t)$ is the sound pressure,

P_0 is the reference pressure,

T is the averaging time.

1.3.2. Sound Exposure Level (SEL)

For sounds that are non-continuous like the pile driving noise, time averaging doesn't give an insight into the noise energy of a single noise event. Therefore to calculate the energy produced from a single noise event Sound Exposure Level is used. It is given by the equation:

$$L_{SEL} = 10 \cdot \log\left(\frac{1}{T_o}\int_{T_1}^{T_2}\frac{P(t)^2}{P_0^2}dt\right)dB$$

It can be seen that it is quite similar to L_{eq} and differs only on the time interval. The T_1 and T_2 are chosen arbitrarily such that the sound event lies between these limits.

1.3.3. Sound Pressure Level (SPL) for pile driving

The sound pressure level (SPL) for pile driving also depends on another key parameter namely the number of strokes per second N. (Ainslie, de Jong, Dol, Blacquière, & Marasini, 2009). The number of strokes vary between 0.8 – 1.5 sec and the whole cycle takes around 2 hours. (de Haan, Burggraaf, Ybema, & Hille Ris Lambers, 2007)

$$L_{SPL} = L_{SEL} + 10\log_{10} N$$

1.3.4. Peak Level

Another crucial value for impulsive sound is the peak level. As impulsive sounds can have moderate L_{eq} and L_{SEL} values while having a very high instantaneous pressure level, which can be harmful for different species. Peak level is calculated using:

$$L_{peak} = 20 \cdot \log\left(\frac{|p_{peak}|}{p_o}\right)dB$$

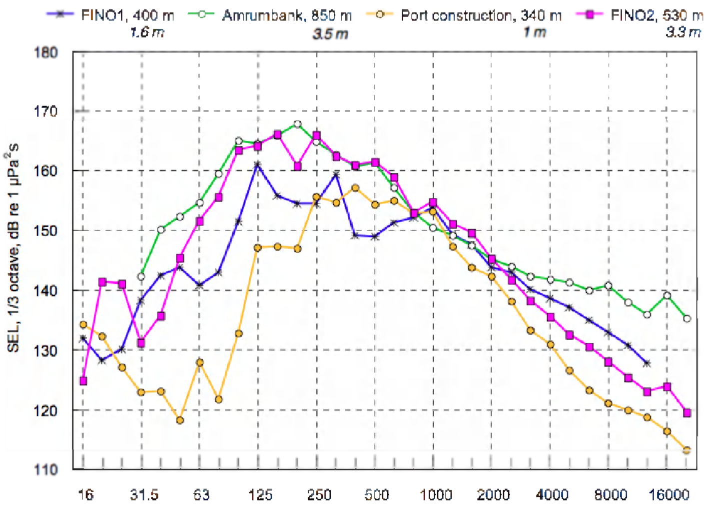


Figure 9. 1/3-octave band spectra of a single stroke SEL of some pile-driving operations (Nehls, Betke, Eckelmann, & Ros, 2007)

The peak level differs from L_{eq} and L_{SEL} as there is no time averaging. Now that the terms have been briefly explained data from different sites will be presented in the Table 2 and the corresponding spectra for these values in Figure 9.

Table 2. Summary of various measurement results for different pile driving operations (Nehls, Betke, Eckelmann, & Ros, 2007) & (Ainslie, de Jong, Dol, Blacquière, & Marasini, 2009)

Project	Pile diameter [m]	Water depth [m]	Measuring Depth [m]	Measuring distance [m]	Blow Energy [kJ]	Peak level [dB re 1 µPa²]	SEL [dB re 1 µPa²s]	Normalised Peak level [dB re 1 µPa²]	Normalized SEL [dB re 1 µPa²s]
Jade port construction work, Germany 2005	1.0	11	5	340	70 – 200	190	164	186	160
FINO 1, Germany, 2001	1.6	30	10	750	80 – 200	192	162	196	166
FINO 2, Germany, 2006	3.3	24	5	530	300	190	170	191	171
Amrunbank West, Germany 2005	3.5	23	10	850	550	196	174	200	178
Q7 Park, Netherlands, 2006	4	20–25	3 – 15	890 – 1200	800	195	172	198	175

1.4. Known Effects on Sea life

As discussed in the previous sections, sound transmission in water is much more efficient than sound transmission in air, it is therefore important to understand the effects that underwater sound, in particular from pile driving, has on sea life.

Before addressing this topic in detail it is essential to briefly address the importance of hearing for sea life in particular the sea mammals. Most of the sea mammals depend on their hearing to navigate underwater, this means that without their hearing they cannot survive. These animals need hearing underwater to perform basic survival functions like finding food, migrating, mating etc. if the animals are seriously impaired due to extremely high noise levels it is inevitable that they will not survive.

Moreover there is a general perception that sound doesn't have the capability to kill any animal, this is however a false perception. There are many cases of marine animals being killed by sounds especially by sonar used by different navies around the world. An example of such an incidence happened on the shores of North Carolina in early January 2005, when after the use of powerful sonar by the US Navy, 37 whales of 3 different species beached themselves and die along the shore. (Kaufman, 2005). Similarly, in October of 2005, during a search operation using high-frequency sonar, 145 long-finned pilot whales stranded and died in the Marion Bay region of Tasmania. (Marion Bay Whale Stranding, 2005)

Figure 10. Carcass of a harbour porpoise after the sonar incident at Haro Strait. (Balcomb, 2003)

The sound intensity of the sonar "pings" is around 230 dB @ 3kHz (Balcomb, 2003). According to (Ainslie M. , 2011) this value is the radiated power and not the received intensity, in other words, this value is a source level, which is not representative of likely sound pressure levels received at a distance from sonar source. Moreover the death of these animals is not a direct consequence of the sonar noise but rather an indirect consequence. The exact causes are unknown. One possible cause of death can be the result of the quick ascent to avoid the sonar noise and serve injury as a result of not being able to adapt to pressure differences during the process.

The North Sea has a diverse variety of sea life and each species has different hearing thresholds and example of this can be seen in Figure 11 where the hearing thresholds of harbour seals and harbour porpoises are plotted.

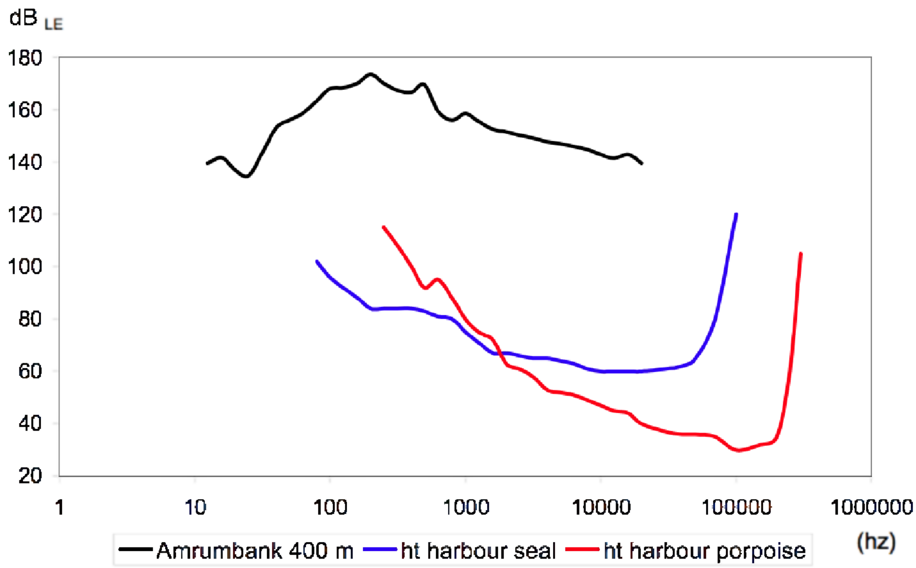


Figure 11. Hearing threshold of harbour seal and harbour porpoise plotted with the noise emission (SEL) from pile(3.5m) driving at Amrumbank at 400m. (Nehls, Betke, Eckelmann, & Ros, 2007)

Figure 11 also shows the spectrum similar to the ones found in Figure 9. It can be observed that the SEL from pile driving at Amrumbank are predominantly in the same frequency range as the hearing threshold of the two mammal species. If the threshold of these mammals are compared to the human hearing spectrum, it can be seen that the threshold do not contain the complete hearing spectrum of these animals. Further long-term sound pressure exposure might also cause hearing loss as is the case for human hearing. (Nelson, 2009). The wind parks are growing in size and usually consist of 80 - 100 wind turbines that need to be installed. So the effect is not only accumulated by the number of strokes but also by the number of turbines in the wind farm.

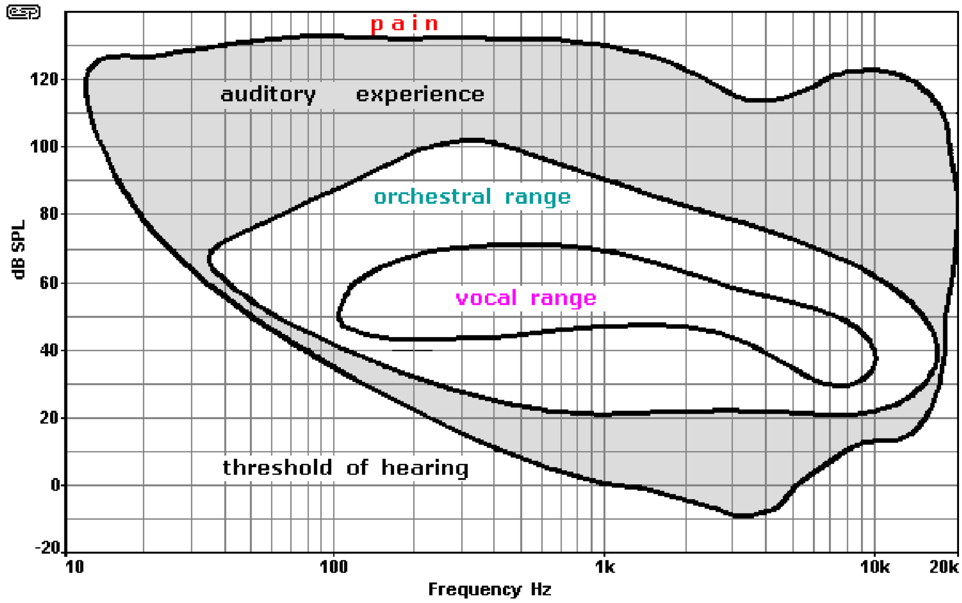


Figure 12. Human hearing spectrum (Elliott, 2006)

Moreover with every larger wind turbines the size of monopiles is also increasing and consequently the hammers needed to install them. This however also means that the noise levels for driving these bigger piles will be even higher. This fact can also be observed in Figure 13

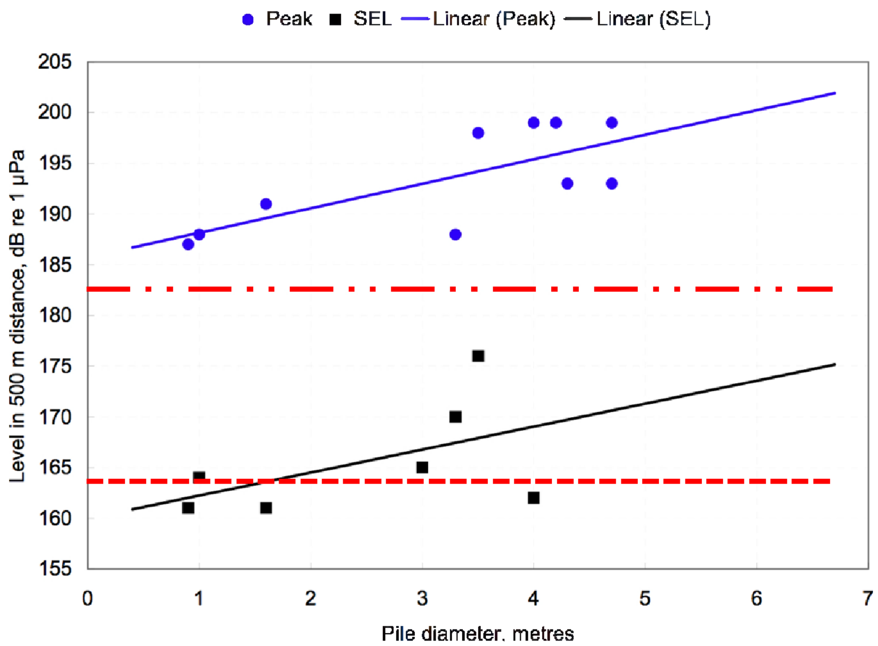


Figure 13. Peak and SEL levels at 500m as a function of pile diameter (Nehls, Betke, Eckelmann, & Ros, 2007)

For an underwater noise source different noise levels at different ranges are categorized and can be seen in Figure 14. In the immediate region of the sound source the

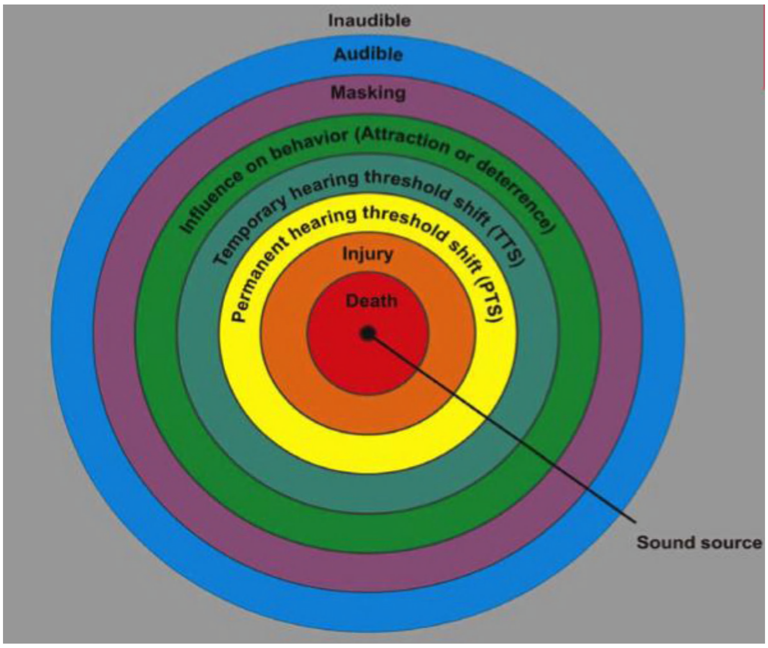


Figure 14. Range of effects of a sound source on marine mammals (Prins, Twisk, Van den Heuvel-Greve, Troost, & Van Beek, 2008)

marine mammals might die. This effect also holds for fishes of various sorts (Nedwell, Turnpenny, Langworthy, & Edwards, 2003). This region is followed by injury that can also result in death in certain cases. Beyond these hazardous regions are the Permanent hearing threshold shift (PTS) and the Temporary hearing threshold shift (TTS). PTS and TTS are Noise-Induced Hearing Loss, these concepts are not unique to animals but also human can experience these effects in certain conditions. As an example, TTS can more or less be explained by the temporary hearing loss experienced by most humans when a firecracker goes off nearby. PTS - Permanent hearing threshold shift is however permanent damage to the hearing threshold. Some of these values can be seen in Table 3. TTS of the two mammals groups are also plotted onto the Figure 13, it can be clearly seen that the TTS of Pinnipeds clearly exceeded even when driving a pile of 1.5 m diameter at a distance of 500 m.

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

After considering all the facts it can be safely said that the monopile driving with hydraulic impact hammers causes a hazard for the marine life in the North sea and alternatives need to be seriously considered and applied to maintain the balance of marine life in the North sea.

2. Offshore wind support structure Design Considerations

An offshore wind turbine represents a huge investment and needs to survive and operate in harsh sea conditions. Moreover a wind turbine cannot be installed offshore without a proper support structure to hold them in place. The support structures of the offshore wind turbines are a crucial part of the engineering project and need to be designed very carefully. The design philosophy mentioned in this section is based on (de Vries & der Tempel, 2007)

2.1. Data Required

There are many factors that need to be considered when starting an offshore support structure design; these can be categorized into three main groups. Each sort of data will be elaborated in the following sub-sections;

a. Environmental Data
b. Turbine Data
c. Site Data

2.1.1. Environmental Data:

The support needs to withstand and survive the harsh environmental conditions therefore these conditions need to be known so that the support can be designed to coop with these extreme loads. These include;

$H_{\max,50}$	$[m]$	50 years maximum wave height
$U_{c,50}$	$[m/s]$	50 years maximum current velocity
$V_{w,50}$	$[m/s]$	50 years maximum wind velocity
Δz_{tide}	$[m]$	Tidal range
Δz_{surge}	$[m]$	Storm surge

Beside the extreme loads there are cyclic loads that are needed for the calculation of the effects of fatigue. Some values of these parameters are given in Table 4.

2.1.2. Turbine Data:

Wind turbines are usually classified by their rated capacity, but even turbines with the same rated capacity has different characteristics. These parameters can include the diameter of the rotor, mass of the nacelle, etc. The wind turbine is placed in the wind and the wind speed influences the forces acting on the wind turbine therefore the turbine data is usually a function of the wind speed. Further the mass of the turbine and all the components need to be known for the calculation of the natural frequencies. Some of the main parameters include:

i. Thrust force as a function of wind speed
ii. Rotational velocity as a function of wind speed
iii. Rotor diameter
iv. Turbine mass.

2.1.3. Site Data:

This data unlike the turbine and environmental data is highly variable, as it can differ from one wind turbine to another even in one wind park, this includes;

i. Water depth
ii. Soil profile

The seabed is not a flat surface and varies in depth further the soil conditions are not constant. This can cause significant problems and costs, as these conditions are too costly to be measured for each wind turbine.

2.2. The design Process

Like any engineering project a certain design process need to be followed in order to achieve successful results. In the following sections the design process of an offshore wind turbine support will be discussed.

2.2.1. Platform level

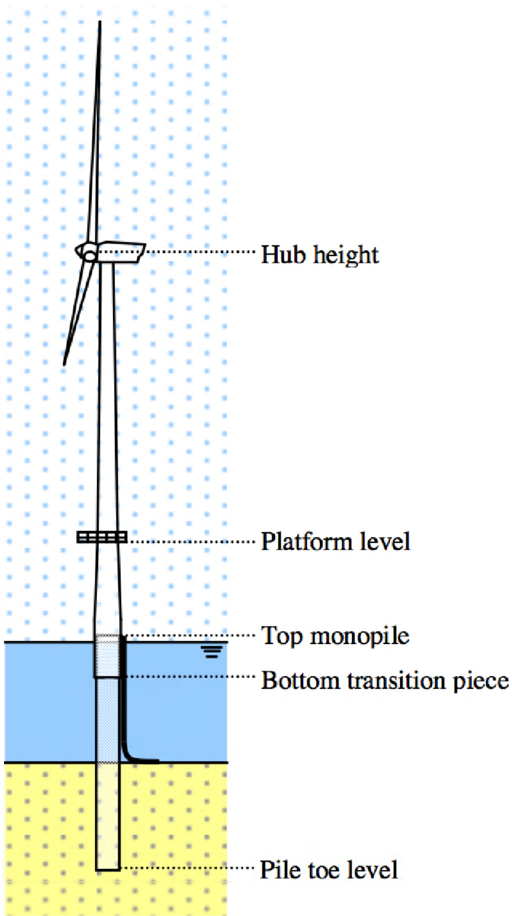


Figure 15. Design levels for an offshore wind turbine (monopile (de Vries & der Tempel, 2007))

The platform level *(depicted in* Figure 15*)* needs to have certain clearance from sea at all sea levels. The sea level however is not constant and is continuously fluctuating. In order to determine the height of the platform level the maximum conditions of sea are totalled.

$$z_{platform} = LAT + \Delta z_{tide} + \Delta z_{surge} + \Delta z_{air} + \zeta^*$$

Δz_{air}	$[m]$	Air gap
Δz_{surge}	$[m]$	Storm surge
Δz_{tide}	$[m]$	Tidal range
LAT	$[m]$	Lowest astronomical tide
ζ^*	$[m]$	Highest wave elevation above still water level

To get a better feel for these parameters, these values have been calculated for 3 different locations in the Dutch EEZ and presented in Table 4. The locations used for this analysis can be seen in Appendix II – Locations considered in the Dutch EEZ.

Table 4. Site Data and platform level calculation for 3 locations in the Dutch EEZ

	Ijmuiden (P5)	Noordzee 1 (K3)	Noordzee 2 (E15)
Coordinates	*3 °25'0", 52 °44'0"N*	*3 °55'0"E, 53 °54'0"N*	*3 °45'0"E, 54 °15'0"N*
LAT_{min}	18 m	36 m	37 m
LAT_{mean}	20 m	40 m	40 m
LAT_{max}	22 m	44 m	43 m
Tidal range	1 m	1,5 m	1 m
50-yr surge	3 m	2 m	1,5 m
50-yr crest	3,6 m	4,2	4,1
Platform level	**29,6 m**	**51,7 m**	**49,6 m**
$H_{s, max}$	7,1 m	8,3 m	8,3 m
$T_{s, max}$	9,5 s	10,5 s	11 s
50 yr sea level	26 m	47,5 m	45,5 m
current	1,5 m/s	1,5 m/s	1,5 m/s

2.2.2. Natural Frequency

The next crucial step is determining the required natural frequency. The turbine is constantly in motion and if the excitation frequency comes close to the natural frequency resonance occurs. This can have catastrophic consequences and needs to be avoided at all costs. An offshore wind turbine is in contact with two mediums; air and water and therefore the sources of excitation are winds and waves.

The waves, that are interesting for the excitation, are relatively short waves with a significant wave height H_s around 1 - 1.5m and a zero-crossing period T_z around 4 - 5 s. This excitation can be seen in Figure 16.

The wind excitations that are of concern are the frequencies that are close to the rotational frequencies of the rotor 1P and the blade passing frequency *(The blade/tower interaction)*, which depends on the number of blades. As most turbines these days have 3 blades therefore it is 3P. The natural frequency needs to be chosen to avoid these frequencies. The preferred region is the one marked in the Figure 16. Moreover the wind turbulence also causes excitations also plotted along other frequencies.

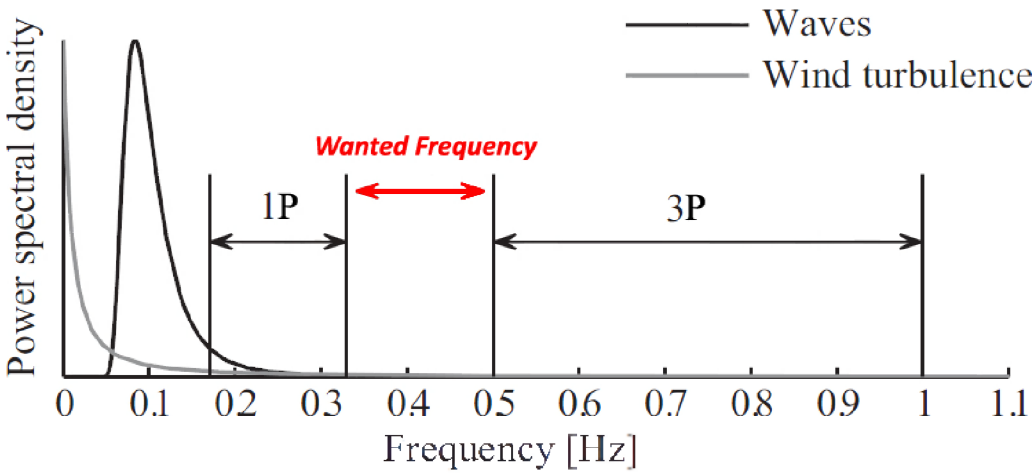


Figure 16. Excitation ranges of a modern offshore wind turbine. (LeBlance, 2009)

This region is sometimes called the "Soft – Stiff" region. The region before the 1P is called the "Soft – Soft" region while the region after the 3P is known as "Stiff – Stiff" region. If the natural frequency of the design lies in the Soft – Soft region it will be too flexible while in the Stiff – Stiff region it will be too rigid (Heavy/Expensive), making it unsuitable for the design. As evident from Figure 16 the "Soft – Soft" usually contains the wave and wind turbulence excitation frequencies this is another reason why this region is usually avoided.

2.2.3. Preliminary geometry

Based on the natural frequency and the design levels the initial sizing will be done, this will be different for different types of support structures. i.e. for a monopile support the pile diameter D and the thickness t will be determined.

2.2.4. Extreme loads

Now as the basic dimensions are known, the extreme hydrodynamic loads can be calculated on the support structure. This is achieved usually linear wave theory that gives a reasonable and quick approximation. But as mentioned before that there are two sources of loads, water and air.

The maximum wind load on the turbine is calculated by considering the thrust on the rotor at rated wind speed and incorporating a gust by multiplying the thrust by 1.5. Most modern wind turbines have adjustable pitching blades to maintain constant rotor speed, but a gust doesn't give enough time to the turbine's control system to change pitch, therefore there is a temporary increase of thrust by 50%.

There are other extreme loads such as ice but they are not relevant in the Dutch North Sea. Combining these loads in different ways gives load cases that are analysed during extreme load calculations.

2.2.5. Foundation Stability

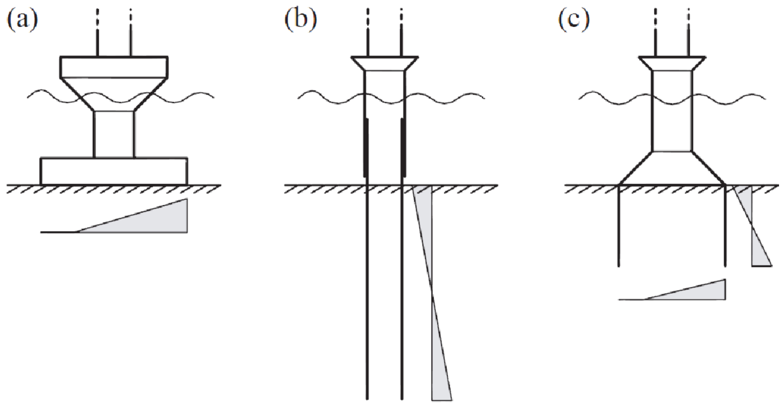


Figure 17. Soil Reaction forces for moments loading form the wind turbine. (a) Gravity based, (b) monopile & (c) Suction caisson (LeBlance, 2009)

The foundation needs to keep the wind turbine stabile so that it can operate safely and efficiently, therefore the foundation stability is an important issue.

The following step is to check the axial and lateral stability of the support. Generally the lateral stability is the main issue. The axial loads are mainly static (mass of the turbine) and much lower than the loads and moments in the lateral direction.

The foundation stability calculations vary for different types of supports structures. For example the main parameters for the stability of a monopile are penetration depth and the diameter of the pile. The soil properties are also a major player for foundations that penetrate the seabed. As the soil holds the foundation in place and if it is soft then it will allow for deflection. Different foundations handle the moment loads differently Figure 17 and Figure 19 give loading on few types of support structures.

For a monopile support there are two limits that the design needs to fit, these limits are based on past experience and not on any scientific data or formulation. The values define the maximum allowable horizontal displacements;

i. Max. Horizontal displacement at mudline: *0.12m*
ii. Max. Horizontal displacement at pile toe level: *0.02m*

Pile toe level is the deepest point of the monopile underground as illustrated in Figure 15

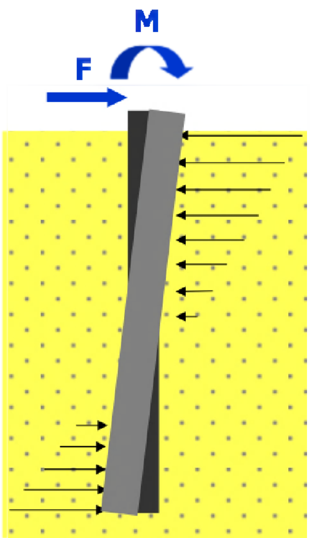


Figure 18. Monopile foundation lateral Stability

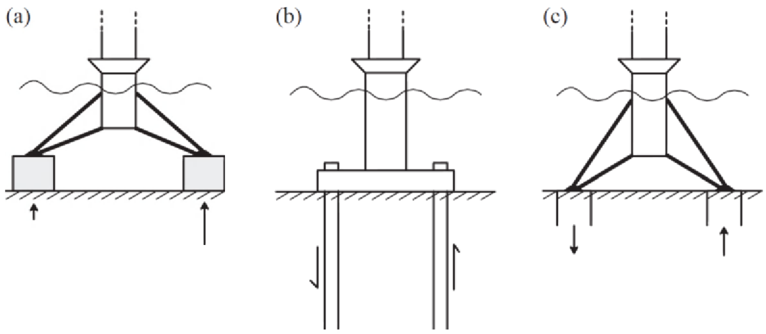


Figure 19. Soil reaction forces under moment loading. (a) Gravity based multipod; (b) piled multipod; (c) caisson based multipod. (LeBlance, 2009)

2.2.6. Stress and fatigue checks

Now that all the design dimensions and loads are known design is checked for maximum stress levels, buckling and stress location. Followed by the fatigue assessments based on all the excitations acting on the whole structure. These steps are advanced design steps and don't play a direct role in the selection of the type of the support structure, rather they are performed to verify and modify the design if required.

2.3. Cost

The viability of any technology depends on its economic feasibility. This also holds for offshore wind energy. The huge projects need to be profitable if the offshore wind energy is to expand further in the future. A lot of design decisions are also hugely influenced by the costs.

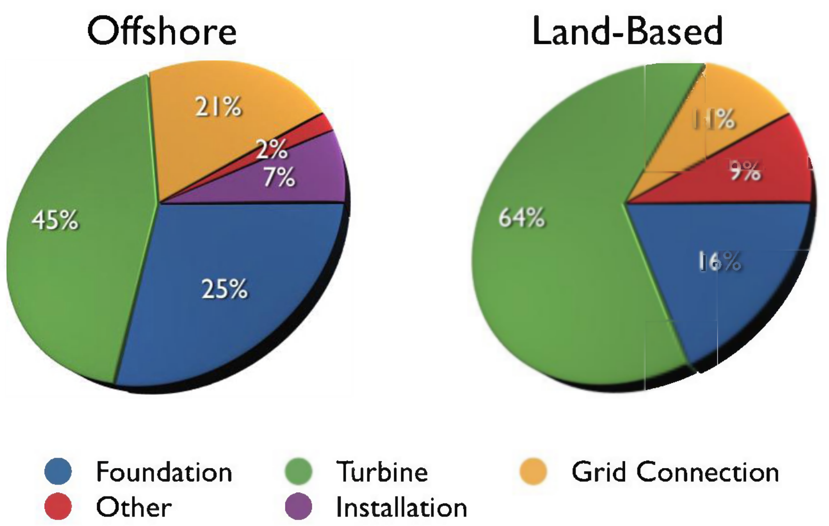


Figure 20. Typical cost comparison between onshore and offshore wind (Kühn, et al., 1998)

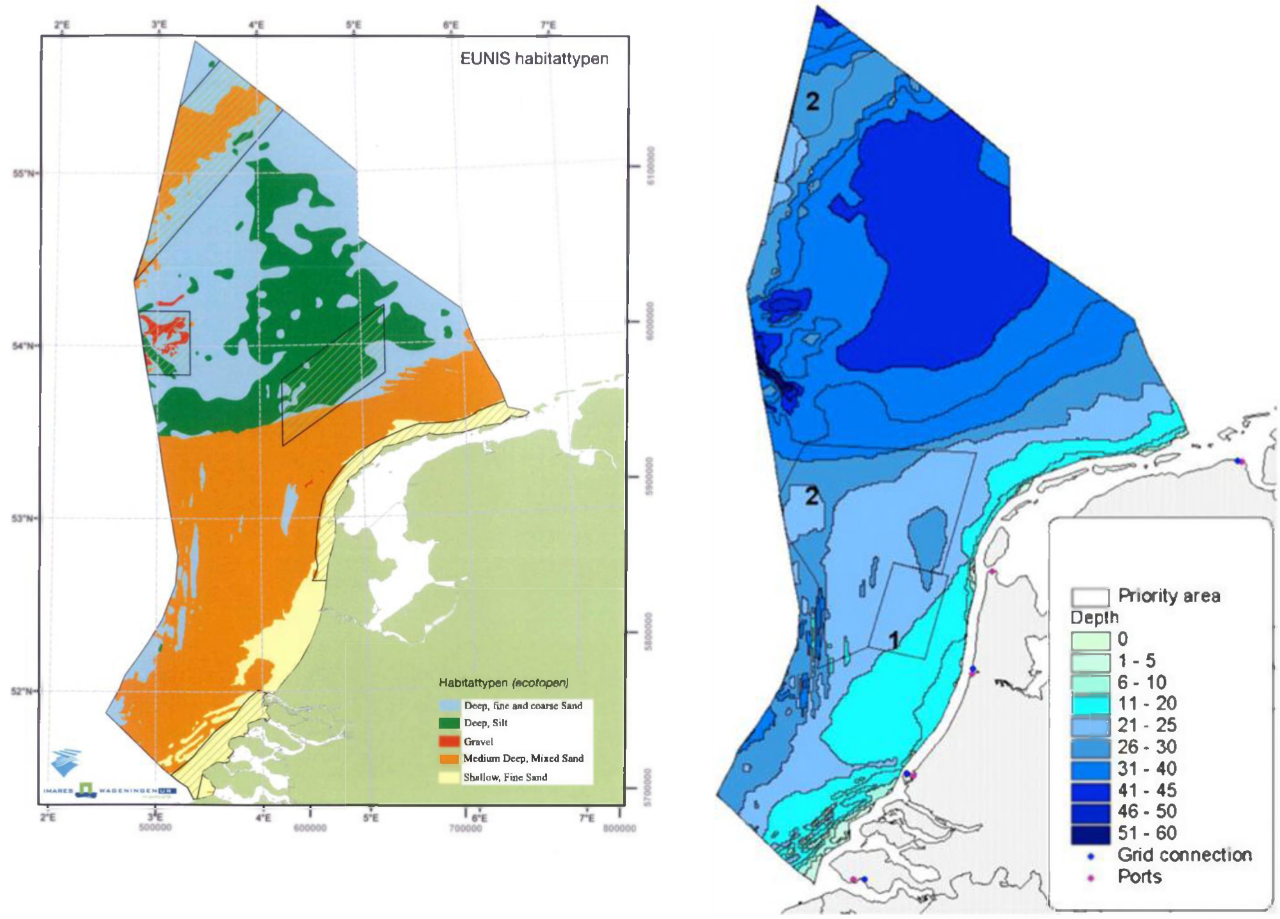
The land based wind turbines require a basic foundation to be installed whereas the offshore need a proper support structures; this changes the cost distribution for offshore and onshore projects and is illustrated in Figure 20. It can be seen that the support structure becomes a larger part of cost distribution i.e. 25%. (Kühn, et al., 1998)

The design and choice of the offshore wind support structure therefore plays a crucial role in the feasibility of an offshore wind project. Also from Figure 20(a) it can be seen that the installation costs are 7% of the totals costs, which are also heavily dependent on the type of support structure. Therefore it is safe to say that around 30% of the total costs are dependent on the support structure.

It is essential to mention here that the exact costs are really hard to come by, as they are trade secrets. Therefore it is impossible to get a clear image, but a general idea has been established on the bases of interviews with the experts. The costs of an offshore wind farm depend on a lot of factors and making it difficult to compare different types of supports. This is also evident in Figure 22. A certain foundation might be the cheapest solution for one site while another type of foundation might be more cost effective for another site. Some of the variables that influence the costs of the foundation include: *(The variables in 'grey' will not be discussed as they are generally independent of foundation type.)*

i. Distance to shore (Grid connection)
ii. Distance to the construction site
iii. Size of Turbines
iv. Soil type
v. Weather conditions
vi. Water depth
vii. Scour protection

The type of soil plays a huge role in the design and installation of wind turbine foundations. Different support structures and their dependencies on the soil types will be discussed in their respective section. The Dutch EEZ soil conditions can be seen in Figure 21 (a). It should be kept in mind that Figure 21 (a) is not a perfect depiction of the actual soil condition. The soil conditions are very irregular and may even vary within a wind farm.



a. Soil conditions in the Dutch EEZ (Lindeboom, et al., 2008)

b. Bathymetric map of Dutch continental shelf (Bulder, et al., 2003)

Figure 21. Bathymetry and soil condition in the Dutch EEZ

Further the depth also contributes significant to the design and the cost structure of the foundation. An overview of the bathymetry of the Dutch EEZ is presented in Figure 21 (b). It was explained in section 2.2 that the first step in the design process is the platform level determination which is directly related to the water depth. Deeper waters present a more complex challenge for engineers and complexity generally have a trend of increases the costs.

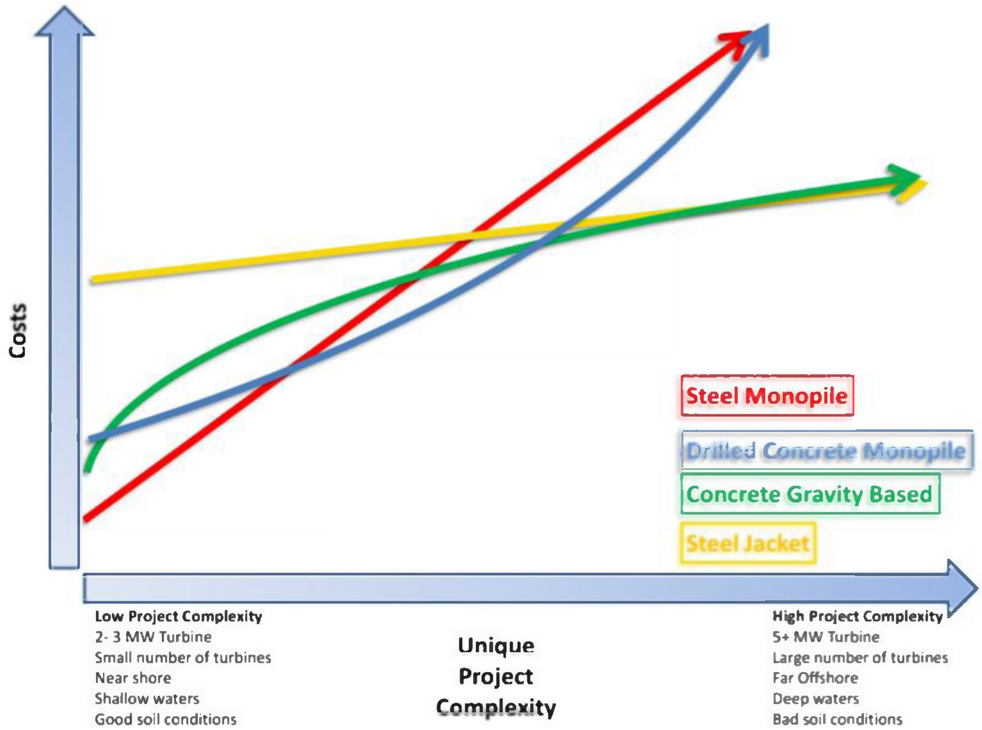


Figure 22. Cost analysis for a specific case in the Dutch EEZ (van de Brug, 2009)

Scour is the removal of soil around a submerged structure in moving waters (Figure 23). The removal of soil has an influence on the stability of the foundation and therefore a scour protection needs to be installed to overcome this effect. An example of scour protection can be seen in Figure 25

The famous quote, "Time Is Money" seems to be also highly applicable for the offshore wind projects. The offshore construction/repair can only take place when the conditions at sea are feasible. Different stages of construction can only be carried out if the wave height is lower than a certain level. Every installation vessel has a certain safe limit in which they can be operated. For example the HLV Svanen Figure 24. which was used during the installation of OWEZ can only operate at a maximum significant wave height H_s of 1m (Ballast Nedam, 2000). In Table 5 it can been seen that this operation can only be carried out on a good weather day during the summer months.

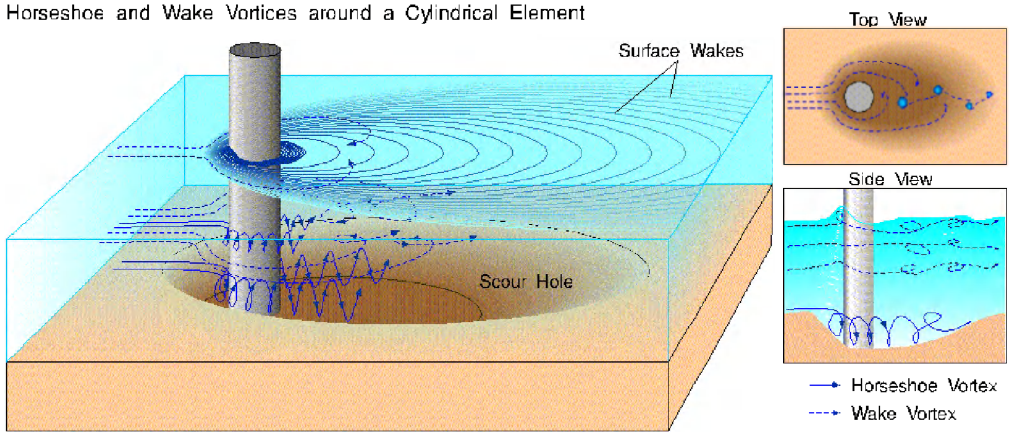


Figure 23. Scour around a cylindrical structure (Huizinga & Rydlund, 2009)

Figure 24. HLV Svanen at the Offshore Windfarm Egmond aan Zee in 2006 (© Edwin van de Brug)

The whole project planning is done to accommodate the wind and sea conditions. This introduces the limitation on the availability of time for a given project and increases the risks of delays. As a slight problem can cause the whole project to be late increasing cost drastically. Therefore the risk while construction for different types of support structures needs to be considered and weighed.

Table 5. Monthly Distribution of wave heights (Wave Climate, 2010)

Lower	Upper	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(m)		*Percentage %*											
7.5	**8.0**	0	0	0	0	0	0	0	0	0	0	0.02	0
7.0	**7.5**	0.07	0	0	0	0	0	0	0	0	0.05	0.02	0
6.5	**7.0**	0.19	0.10	0	0	0	0	0	0	0	0	0.10	0.02
6.0	**6.5**	0.26	0.10	0	0	0	0	0	0	0	0.02	0.10	0.17
5.5	**6.0**	0.45	0.29	0.05	0	0	0	0	0	0.10	0.14	0.15	0.36
5.0	**5.5**	0.95	1.09	0.38	0	0	0	0	0	0.47	0.45	0.34	0.40
4.5	**5.0**	2.04	1.72	0.83	0.12	0	0.12	0.05	0	0.47	0.71	0.93	1.42
4.0	**4.5**	3.72	3.20	1.54	0.74	0.07	0.34	0.19	0.14	0.88	1.16	2.21	3.25
3.5	**4.0**	7.21	5.38	3.39	1.15	0.05	0.20	0.38	0.21	1.45	3.39	4.68	6.07
3.0	**3.5**	9.99	7.85	6.48	1.59	0.57	0.93	0.85	1.42	3.14	6.48	7.16	8.80
2.5	**3.0**	12.45	10.65	10.10	3.60	2.40	2.01	1.83	3.37	6.37	10.84	10.81	11.55
2.0	**2.5**	14.42	15.15	13.85	9.66	7.64	6.27	3.56	5.98	10.59	13.45	15.69	13.92
1.5	**2.0**	16.15	17.26	21.54	17.84	17.24	13.06	11.53	12.67	15.29	20.30	20.78	16.51
1.0	**1.5**	16.51	14.89	20.21	27.16	27.61	27.77	23.34	24.72	23.55	22.32	21.15	16.70
0.5	**1.0**	12.36	19.00	17.81	30.17	34.27	36.30	38.50	36.43	29.63	16.63	14.90	15.99
0.0	**0.5**	3.23	3.33	3.82	7.97	10.15	12.99	19.78	15.06	8.06	4.06	0.96	4.84
Total		100	100	100	100	100	100	100	100	100	100	100	100

Additional important contributors to the costs are the Legal aspects. To get permission for a wind park in the Dutch is a long process and is only prolonged by the selection of a monopile support structure. Further there are limitations imposed by the Dutch government on pile driving operation that cannot be conducted from **1st January** to **1st July** and only take place for **one** windfarm at a time. (Besluit inzake aanvraag Wbr-vergunning offshore windturbinepark 'Breeveertien II', 2009)

2.4. Certification and Classification

Another aspect that governs the design selection is the certification process. Offshore wind farms need to be insured and as required by the insurance companies need to be certified. The certification standards are usually conservative to ensure safety.

The designers therefore stick to proven and matured technologies and are hesitant of adopting new techniques in order to overcome delays and other problems while certification. Major players in the certification and classification include:

Det Norske Veritas (DNV)
Headquarters: Bærum, Norway

Germanischer Lloyd SE
Headquarters: Hamburg, Germany

An example relating to certification is the Bearing capacity. **Bearing capacity** is the measure of the capability of the soil to support the applied to the ground. For impact driving piles there are models to verify the bearing capacity i.e. guaranteeing that the support will sink no more into the soil and will be able to hold the weight. One model that is used is the Hiley's formula: (Finnish National Road Administration, 2000)

$$P_u = \frac{e_f E_j}{s + \frac{1}{2}c} \frac{W_h + n^2 W_p}{W_h + W_p}$$

Where;

E_j driving energy, [kNm]
e_f driving efficient coefficient
n factor, which is 1 for steel
s permeable settlement of the pile, [mm]
c temporary compression, [mm]
W_p weight of the pile, [kN]

The effectiveness of the pile is directly checked on the site, which is a requirement in the standards. This is done on values evaluated from models such as the Hiley's formula.

Bearing Capacity (tonnes) = Blow Efficiency x E/(s+2.54)

Where,

E *Hammer Energy (kg.m)*
s *Final Set per Blow (mm/blow)*

Blow efficiency for a hydraulic hammer is typically around 80% and after adding a safety factor of 2 the formula to becomes

Bearing Capacity (tonnes) = 0.4 x E/(s+2.54)

According to the standards the pile driven will have sufficient bearing capacity if 10 hammer blows will not make the pile penetrate more than 25 *mm.*

3. Possible Engineering Solutions

In the first chapter of this report monopile driving in relation to underwater noise was analysed and the problem was outlined. This chapter will analyse the available alternative and suggest other possible alternatives.

The alternatives have been divided into two main categories namely;

1. *Reducing noise using hammering*
   i.e. modifying the current method to reduce the noise
2. *Alternatives for current techniques.*
   i.e. Replacements for the current method.

Different aspects of these methods will be analysed like cost, complexity, Noise reduction etc. The analysis will be done with the help of material available on the web from authentic sources, consulting the experts in the field, interviews, books, articles and magazines.

Before proceeding to the alternatives engineering solutions, the monopile support structure and its characteristics will be discussed ignoring the underwater noise, as these aspects have already been addressed in section 1.3.

3.1. Monopile foundation from an engineering perspective

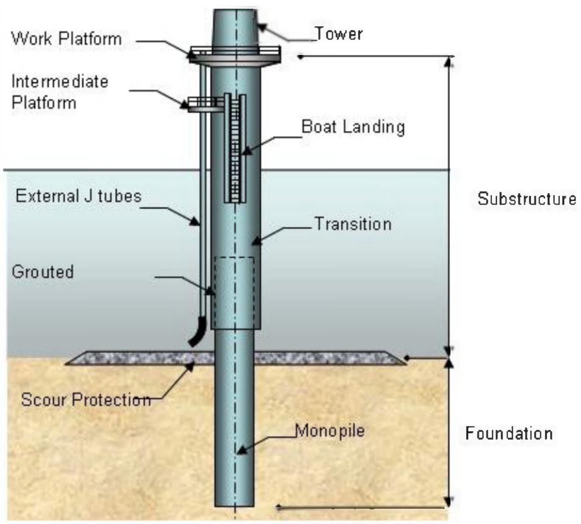


Figure 25. Various components of a monopile foundation (Iuga)

Monopile foundation used for offshore wind farms is basically a cylindrical tube usually made of steel, which is directly installed into the seabed using hammering or vibration. 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.

So far the monopile support structure is the most popular support structure used for the construction of wind farms. It is estimated that 75% of all installed offshore wind turbines use the monopile support (Moeller, 2008). There are a lot of factors that contribute to the popularity of monopile. Firstly it is a very simple design, which can also be manufactured in two straightforward steps, rolling and welding. The calculation and analysis of this structure are also easy and always the first step while designing any type of support structure.

Since its introduction in the offshore the monopile has become larger, heavier and has been installed in deeper depths. The diameter limit these days is around 6 meters and there are already concepts of 7 meters (Iken, If I had a hammer...*, 2010). The maximum weight is around a massive 1,000 tonnes. It was believed that monopile could only be installed in water depths up to 25 meters but monopiles are currently being installed up to depths of 34 meters at the Greater Gabbard wind farm, which is currently under construction (Iken, Movement in foundations, 2010). This development can be associated to the increasing diameters of the monopiles. According to experts (Erkel, 2011) an increase in the diameter of the monopile by 1 meter generally means that the pile can be installed in water depths 10 meters deeper. This could mean that a *7 [m]* diameter monopile might be installable in water depths around *40[m]*.

The hydraulic impact hammers have also grown in size with the piles and currently one of the biggest hammers on market is the IHC Hydrohammer S-2300 which can be seen in the Figure 26. This hammer is capable of providing a maximum blow energy of *2300 [KJ]*. This hammer is used for driving piles around *6 [m]* but can be modified for even larger diameter if there is a need (Erkel, 2011). It might also be interesting to briefly compare the maximum blow energy of Hydrohammer S-2300 with the blow energy of the hammer used to install monopiles in Q7 Park given in Table 2. The Hydrohammer S-2300 is capable of 3 times more blow energy. 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.

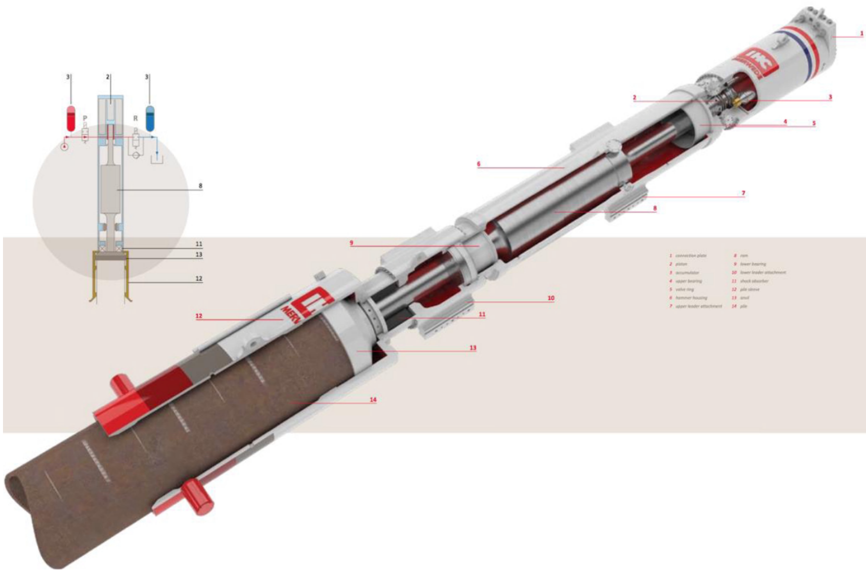


Figure 26. IHC Hydrohammer S-2300 cut-out

During 1996 and 1997 two Danish power company groups and three engineering firms conducted a research on the design and costing of offshore wind turbine foundations and concluded that the monopile foundation provided the most cost effective solution (Danish Wind Industry Association, 2003). Its simple global design is attributed to its cost-effectiveness and popularity in the offshore industry (Biehl & Lehmann, 2006).

Advantages:

i. Simple Design

Monopile is a simple and straight forward design, making it easy to manufacture and very handy to transport (in comparison with other supports).

ii. Proven Technology

The monopile has been used for many years and like discussed before proven to be a cost effective and straight forward solution.

iii. More versatile (Soil types)

Steel monopile driving using a hydraulic hammer can overcome problems faced by other installation techniques. For example the suction caisson can only be installed in certain soil conditions.

iv. Bearing capacity easily measurable

As discussed in section 2.4. the bearing capacity needs be verified. This process is straight forward for impact pile driving unlike other pile driving techniques.

Disadvantages:

i. Economic feasibility at greater Depths

Monopile is made up of steel and steel is not cheap. As the depth increase so does the diameter and the thickness, resulting in a huge mass of steel. This makes monopile not the best solution financially for greater depths. There are however on-going research to optimise the monopile to be more economical feasible on larger scales.

ii. Becomes really heavy for greater depths

Also the handing of such a huge structure adds to costs and complexity of the project. The stiffness of a monopile can only be obtained by introducing a huge amount of additional steel to the structure.

iii. Not removed completely after service lifetime

The monopile support is not completely removed after the lifetime has finished, the standards require the support to be removed at or 1.5m below the seabed. These structures if cut at the sea bed level can possibly prove dangerous for the sea life and add to the sea pollution.

3.2. Methods for reducing noise using current pile driving methods

Impact pile driving is vastly used in offshore wind farm construction as mentioned before. This section will analyse possible options, modifications and techniques of reducing noise generation using the current methods. This approach is important to consider as it can provide a short term solution without modification of current installation techniques.

3.2.1. 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. This idea of changing the pile-toe shape is inspired by medical syringes. The tip of the medical syringes/injections is modified to have less resistance force. If the resistance force is decreased this will imply that 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. Much like a nail with its tip shape. 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. These tests were conducted on steel piles with very small diameters (102 mm), moreover these bevels were implemented to the walls of the piles, for dimensions of these piles see Figure 27. Further research is needed to find out how this phenomenon will translate to large scale and full toe bevel.

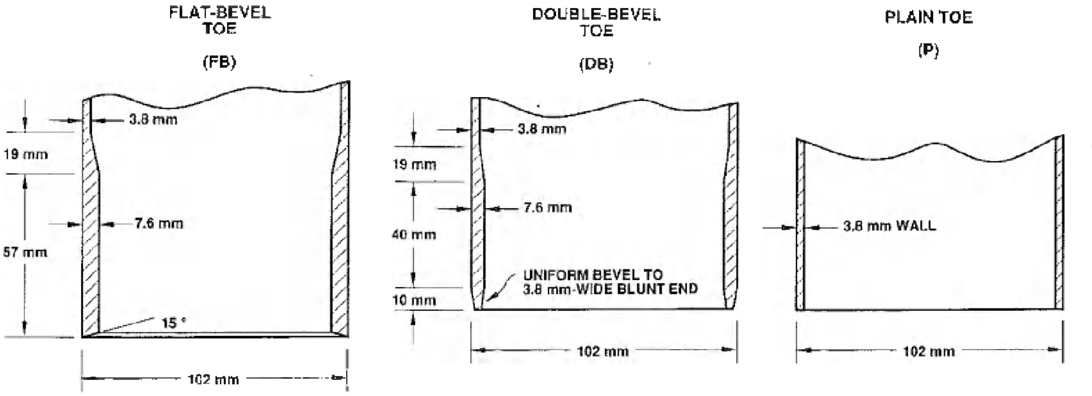


Figure 27. Dimensions of tested piles (Raines, Ugaz, & O'neil, 1992)

The shape change is not that significant, as it only requires the introduction of a bevel. As illustrated in the Figure 28. This change will only marginally increase the production cost of the monopile but can reduced installation costs, as less energy will be required during installation. The reduction of the noise that can be achieved this way is unknown and is beyond the scope of this research, but from the reduction in the required kinetic energy from the hydraulic hammer and the fewer amounts of blows required will significantly contribute to noise reduction.

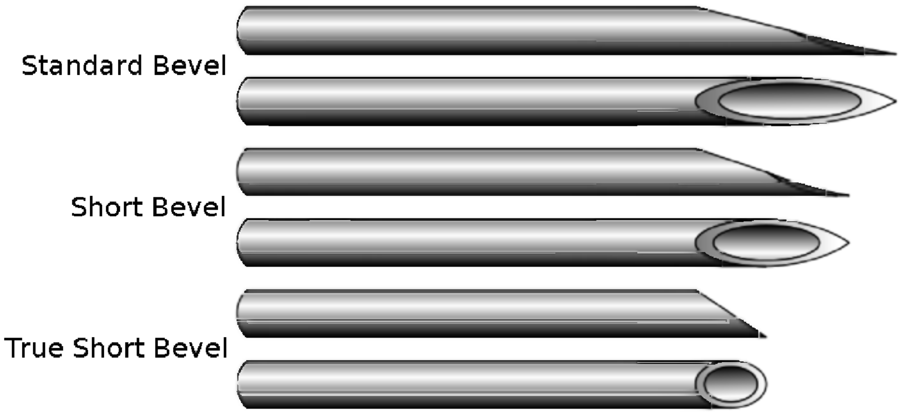


Figure 28 Different Bevels used for Hypodermic needle

An aspect that might be important is the bevel preservation as shown in Figure 29, as damage to the tip will increase the energy required for penetration.

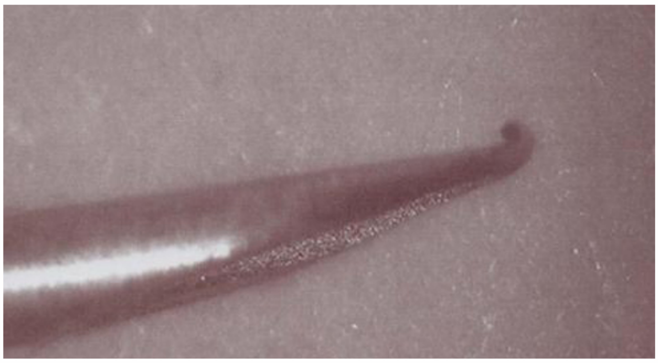


Figure 29. Tip damage

Advantages:

i. 27% Less hammer Kinetic Energy

Cheaper/lighter hammers can be employed to drive pile saving costs.

ii. 29% Less blows required

Fewer blows mean less strokes and less overall noise moreover less time required to install the pile.

iii. Lower installation costs

The lower energy and blows required would result in lower installation costs further the installation time will also be reduced.

Disadvantages:

i. 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.

ii. Increased production costs (Slightly)

Slightly more material would be required to produce the bevelled shape with the desired penetration.

iii. Potential problems with Bearing Capacity

Increasing the penetration would have consequences for the bearing capacity but it needs to be researched and verified.

3.2.2. Using contact Damping

This method is not generally used in the industry. Additional material is added to that contact between the pile and the hammer to absorb some of the energy. The method actually has a counterproductive, damping the contact might lower the sound peaks but in turn more blows are required to achieve the penetration required as less energy is transferred from the hammer to the pile. It is claimed (Erkel, 2011) that an 8 dB to 10 dB reduction is achievable but more blows also imply longer sound durations. The cost of using this approach is also higher as extra time and energy is required to drive the pile into the ground.

Advantages:

i. Lower sound pressure peak

The damping absorbs some of the energy from the hammer making the sound amplitude lower.

Disadvantages:

i. More blows required

As a result of the lower energy more blows would be required to achieve the desired penetration.

ii. 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.

3.2.3. Skirt-pile support

In the section, 2.2.5 Foundation Stability, it was explained that the penetration length of a monopile foundation depends on the lateral stability of the wind turbine, therefore if the lateral stability is somehow increased the penetration depth will be reduced as a consequence. The concept suggests adding a “skirt” to the monopile in order to increase the lateral stability and hence reducing the penetration. The skirt can be made from any material steel or concrete, but from a cost perspective concrete might be a better option.

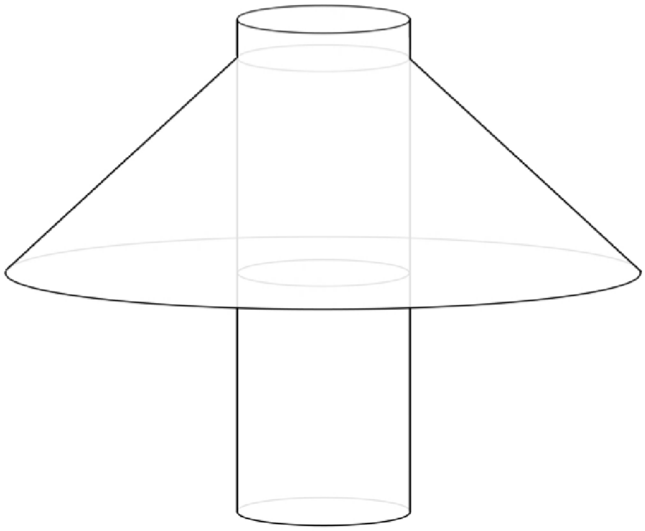


Figure 30 Skirt-pile support concept

Advantages:

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

Disadvantages:

i. Extra manufacturing costs
   The skirt would need to be separately manufactured and would require extra material and labour and therefore increasing costs.
ii. Significant scour protection needed
   The larger structure the larger the vortex it would generate (see Figure 23). As the skirt would add to the diameter of the monopile more scour protection would be required.
iii. 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.
iv. 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.

3.2.4. Changing the parameter for pile stroke

Observing Figure 6, one can easily deduce that the sound pressure depends on the velocity of the vertical pile vibrations. The idea of changing the parameter of the pile stroke suggests prolonging the contact time of the hammer and in turn reducing the amplitude of the pile vibration which will reduce the noise generated. Theoretically this method predicts a reduction of 10-13 dB (Nehls, Betke, Eckelmann, & Ros, 2007).

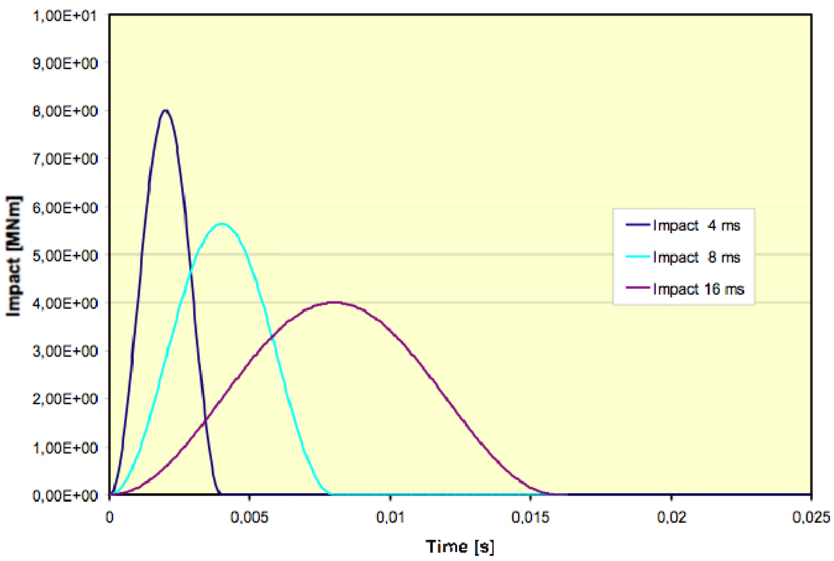


Figure 31. Impact forces of different impulse contact times with the same ram energy. (Elmer, Neumann, Gabriel, Betke, & Glahn, 2007)

Advantages:

i. Lower noise generation

This technique tackle problem of noise at the source by changing the way the noise is produced, rather than damping it afterwards.

ii. 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:

i. 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.

3.2.5. Sound isolation/damping

Sound damping as the name suggests calls for the isolation and dampening of noise during the hammering operation. This is achieved by using different techniques such as:

i. Confined Bubble curtains
ii. Pile Sleeves

One of the great benefits of using such an approach is that the existing installation techniques don't need to be changed. The two largest hydraulic impact hammer producers IHC-Merwede and Menck are looking into possible solution of sound isolation and have developed and testing prototypes for such applications. The trends in the industry seem to prefer pile sleeves rather than confined bubble curtains.

Confined Bubbles curtain

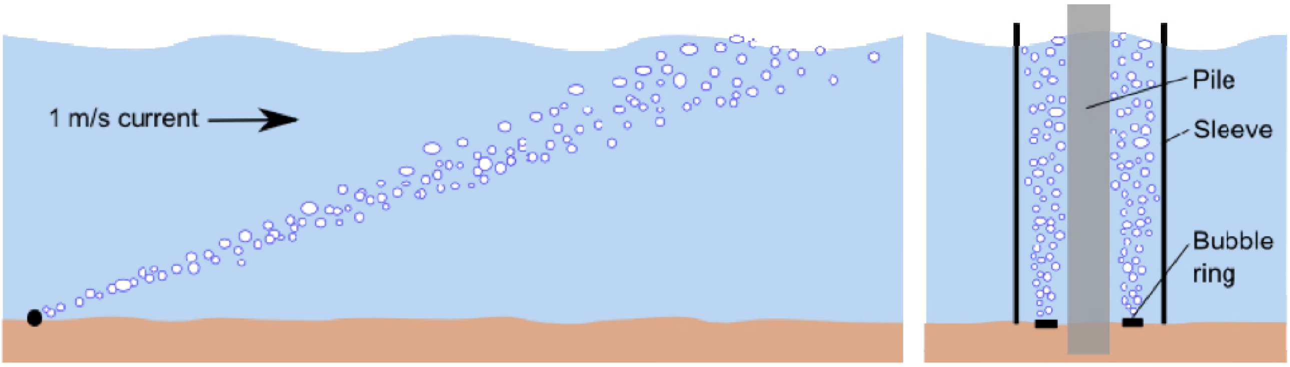


Figure 32. Confined bubble curtain (Nehls, Betke, Eckelmann, & Ros, 2007)

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. Different bubble sizes therefore dampen every sound spectrum in a different way this is evident in Figure 33. It can be noted that air bubbles with smaller diameters are only effective against sounds with higher frequencies, while bubbles with larger diameter cover a much larger part of the spectrum. It is difficult to produce large bubbles and moreover these larger diameter bubbles are less stable and break up into smaller bubble while travelling to the water surface. It is however very hard to predict the exact sound reduction.

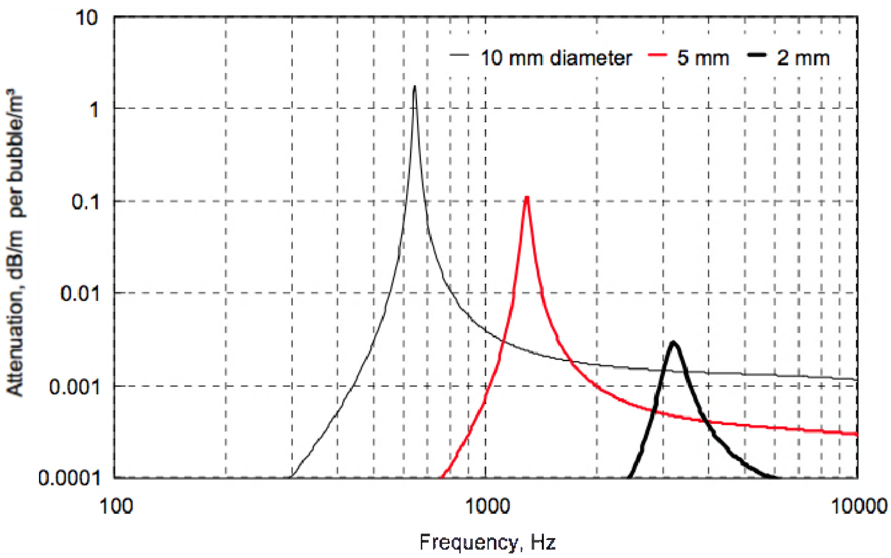


Figure 33. Sound reduction for various bubble sizes in the sound spectrum (Nehls, Betke, Eckelmann, & Ros, 2007)

The ocean is in constant motion and therefore if bubbles are generated on the sea bed they will travel with the water current as depicted in Figure 32. Therefore having unconfined bubbles is not effective and might completely nullify the noise reduction.

Advantages:

i. 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.

ii. Current methods don't need to changed

As mentioned in the start of this chapter techniques which do not change the current installation techniques would make it easier for the main player in offshore to adopt and employ this methods. Therefore can providing a solution for the underwater noise in the short term.

iii. 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:

i. Need 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.

ii. Unproven technology

The technology is still in initial phase of it development and will require some effort and confidence before it can become conventional.

iii. Extra costs

Due to the extra infrastructure and the longer time needed to install the foundation; this technology will incur extra costs. But the cost increment is not significant in comparison to other alternatives.

iv. 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.

Pile sleeves

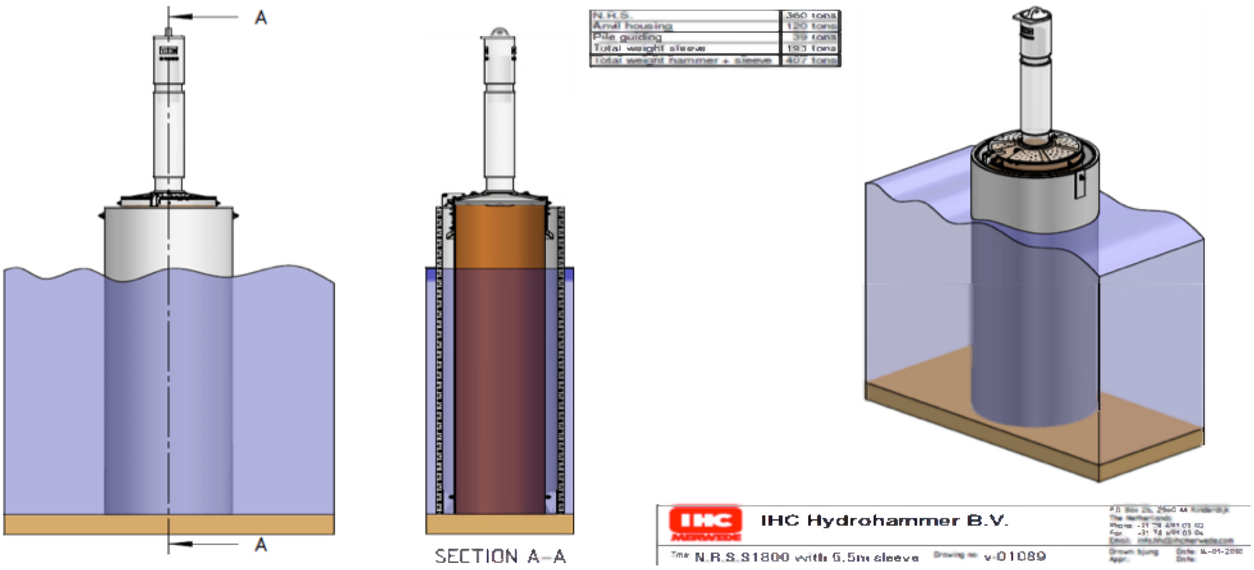


Figure 34. IHC Noise Mitigation System (NMS) for monopile foundation (IHC Hydrohammer B.V., 2011)

A pile sleeve is a physical sound barrier placed surrounds the source, in the case of the pile driving it encompasses the monopile. The pile sleeve utilized the principle of acoustic impedance. When sound in a medium, say for example water, encounter another material with different acoustic impedance a part of the sound I reflected and therefore reducing the total noise transmitted. Valves for different materials have been calculated to see how much noise is isolated and are depicted in Figure 35. It can clearly be seen that air provides the best possible solution. In order to achieve the most reduction in noise levels it is inevitable not to use air. More effective mitigation system can be made by using the air for noise damping by trapping it in between sleeves. Further damping can also achieved by adding extra layers of foam.

An example of such an application is a concept developed by IHC imagined in Figure 34, which can be applied to any water depth and is currently designed for a pile diameter of *5.5 [m]*, but can easily be expanded up to *7 [m]* diameter. Testing this concept has yielded a noise reduction of 25 dB especially in the low-frequency area where reduction is mainly needed. (Erkel, 2011)

Advantages:

i. 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.

ii. 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.

iii. Is in an advance stage of development

This concept is already being tested and can soon be applied on full-scale.

iv. 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:

i. Need extra infrastructure

Handing the huge monopile presents a problem itself and to add an extra sleeve

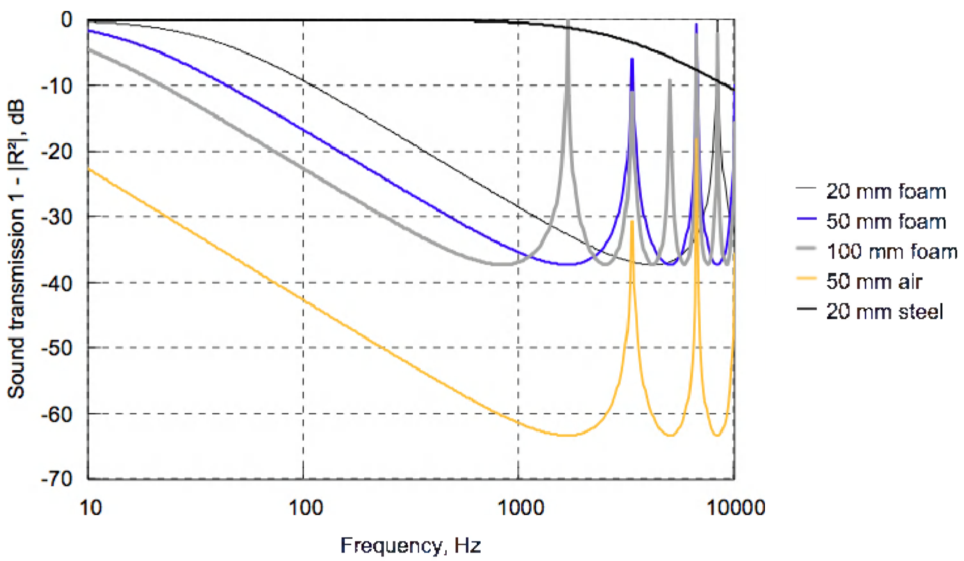


Figure 35. Sound level reduction achievable for different materials (Calculated values) (Nehls, Betke, Eckelmann, & Ros, 2007)

to it requires more infrastructure. This makes the whole operation more complicated

ii. 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

iii. Extra costs

The longer the installation process takes the more it cost and this is especially true for offshore operations.

3.3. Alternatives for monopile and/or current pile driving techniques

This section will look at alternative that replace the pile driving using hammering and/or replace the monopile support structure. It should be noted that the steel monopile is not the cause of the problem, which is discussed in section, 1. Problem Analysis, but rather the combination of the steel monopiles and hydraulic impact hammers is.

3.3.1. Pile driving using Vibratory Hammers

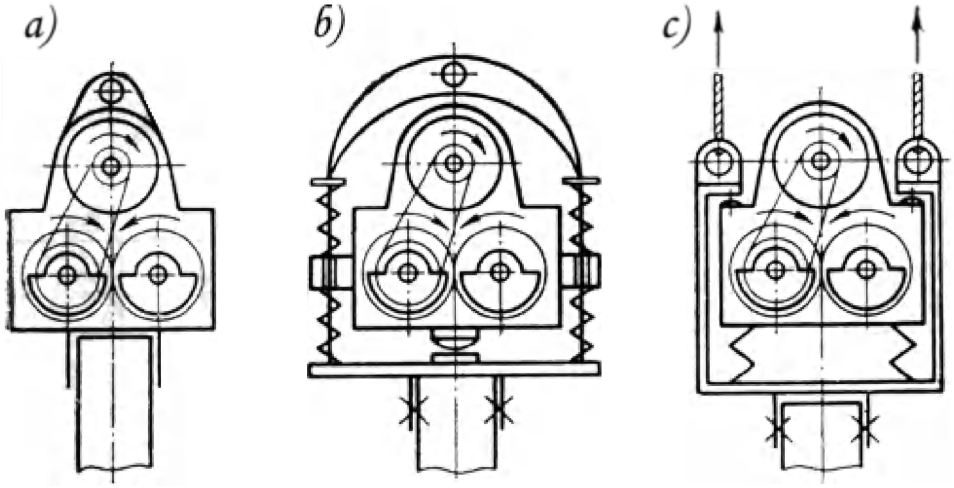


Figure 36. Technical drawings of various vibratory hammers configurations (Tseitlin, Verstov, & Azbel, 1987)

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 (see Figure 37) and therefore make the pile handing much more efficient, while saving time and costs.

Figure 37. PVE 300M Vibratory hammer clamped directly to a monopile. (Starre & Boor, 2011)

Figure 38. Two PVE 200 M vibratory hammers joined together (Dieseko Groep B.V., 2009)

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)**:**

i. Practically no diameter limitation unlike hammering[5]

   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.

ii. 3-4 times faster installation compared to hammering

   Disregarding the monopile handing which takes longer compared to vibratory hammer 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.

iii. 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.

iv. 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.

v. Can be used to remove/reinstall piles

   Unlike impact hammers, vibratory hammers can be used to remove pile. There is a therefore more room for correcting mistakes and completely removing pile after service life-time.

vi. 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, this can

[5] This is however not really an issue for offshore wind turbine monopiles as diameters currently do not exceed 6m.

also be seen in Figure 39. 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 as evident from Figure 11, therefore using vibratory hammer can considerably reduce the noise within the hearing spectrum of marine mammals.

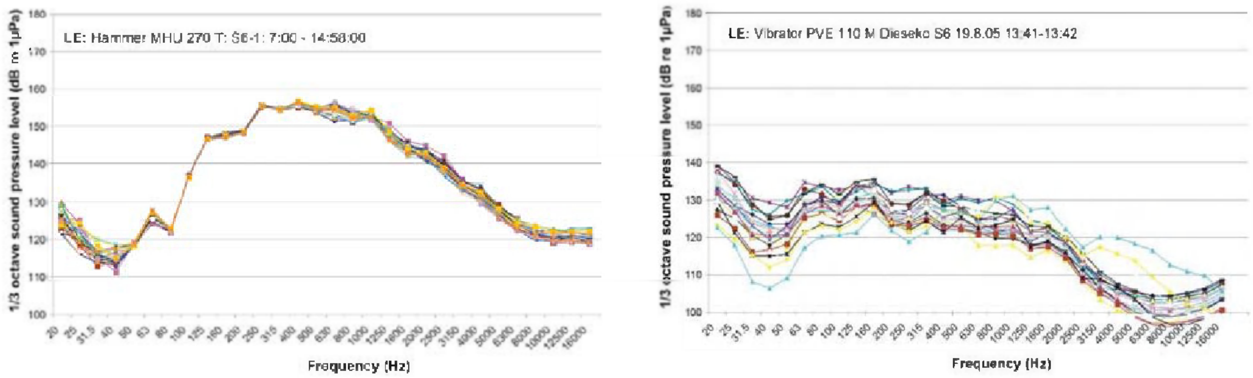


Figure 39. Noise Spectrum of a Vibratory hammer vs. Impact hammer (Elmer, Neumann, Gabriel, Betke, & Glahn, 2007)

Disadvantages (Starre & Boor, 2011)**:**

i. 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.

ii. 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 (see Figure 53). 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.

iii. Cable handing more complex

As noticeable in Figure 38 and Figure 37, a lot of cables are attached to the vibratory hammer and they need to be carefully handled. This does cater for some complexity

iv. 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.

3.3.2. Guyed support structure

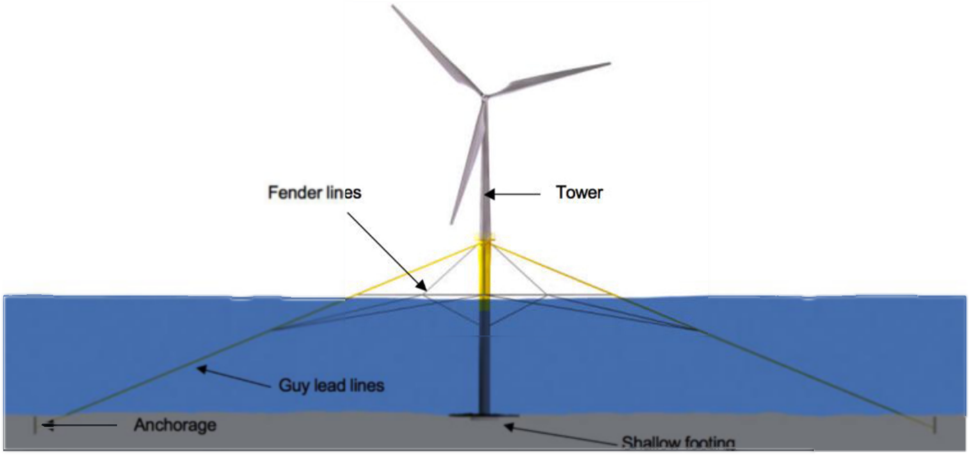


Figure 40. Guyed Support Structures For Offshore Wind Turbines (Carey, 2002)

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. One of the best way to peg the guys wires has to be the screwpiles, which can not only minimize noise during installation, but also handle tension loads much better, as described in section 0. The report (Carey, 2002) claims that this support structure has many advantages over conventional structures that include:

Advantages:

i. 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

ii. Lower installation costs

The concept proposes a unique installation technique where the whole wind turbine is installed in one step. This is depicted in Figure 41. 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.

iii. Relatively light

The guy wires provide structural strength that are virtually weightless in comparison to other support structures.

iv. 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.

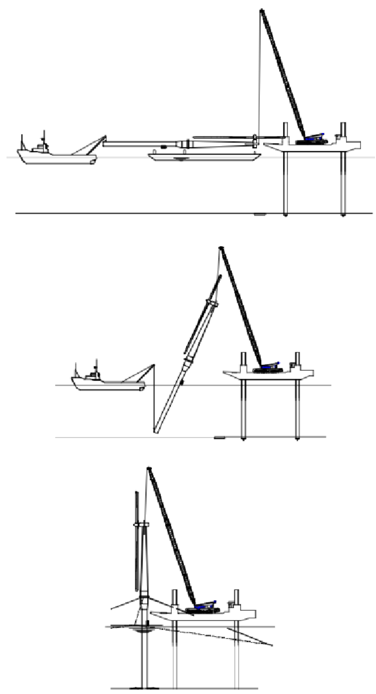


Figure 41. Proposed installation technique for guyed support for offshore wind turbine (Carey, 2002)

Disadvantages:

i. New unproven technology

Like many other technologies mentioned in this section this is an innovative idea and has not been tested and needs to be seen if the concept is actually practical.

ii. Cranes don't exist which can lift a completely assembles wind turbine

A significant drawback of the installation technique mentioned in the (Carey, 2002) is that there are currently no cranes available offshore capable of lifting an entire wind turbine. With the ever increasing size of wind turbines this would become increasingly difficult.

iii. 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.

iv. 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.

3.3.3. Concrete monopile/Drilling

Figure 42. Drilled concrete monopile concept by Ballast Nedam (van der Meer & van Bergen, 2009)

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 impact pile driving, this can be observed in Figure 42.

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:

i. Very versatile

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.

ii. 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.

iii. Lower CO_2 emission

The CO_2 emission during the production of the concrete monopile are much lower that for a standard steel monopile

Disadvantage:

i. The drilled hole needed to be filled after the installation

The soil hold 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.

ii. 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.

iii. 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.

3.3.4. Screw-pile

(Also referred to as: Helical Anchors, Screw Anchors, Torque Piles and Helical Piles or Piers)

Figure 43. Middle Bay Light in Mobile Bay, Alabama. First constructed in 1885. (Anderson, 2011)

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. Some of these lighthouses still survive like the Middle bay light shown in Figure 43.

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. Screwpile are even used to install small-scale wind turbines on land. Offshore applications include small screwpiles that are used to fasten petroleum pipes to seabed (MacLean Dixie HFS).

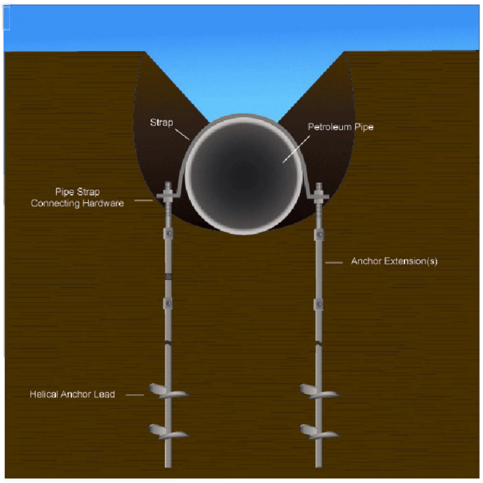


Figure 44. Helical screw anchors to prevent pipe uplift (buoyancy control) (MacLean Dixie HFS)

Surprisingly the screwpiles are also being used as supports for land-based wind turbines. Different configurations for different sizes of wind turbines can be seen in Figure 45. 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 Figure 46. This will however require the filling of ballast once the pile has been installed.

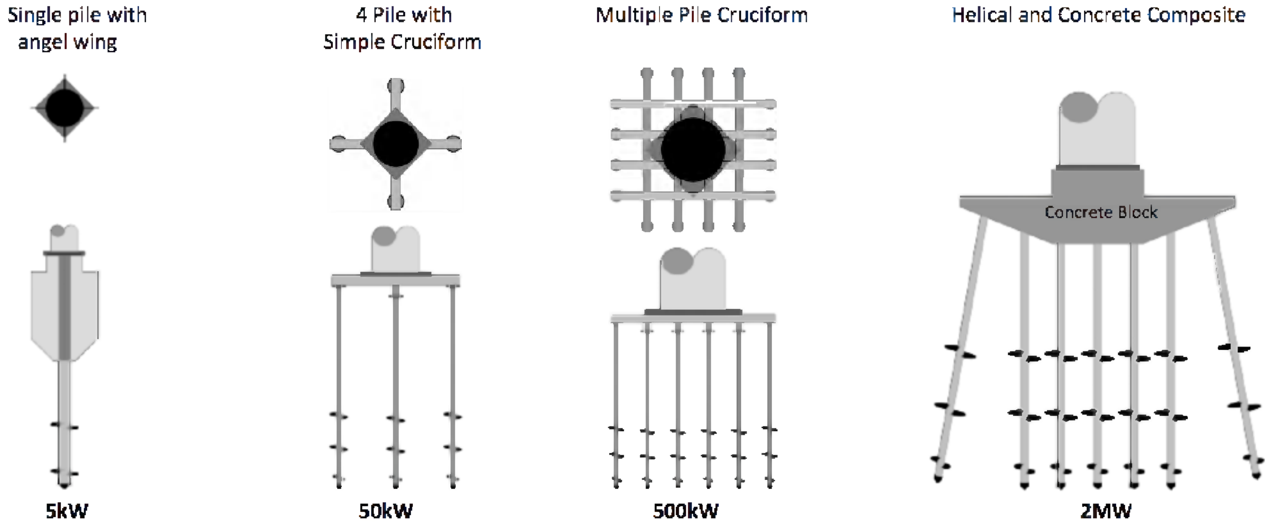


Figure 45. Screwpiles support solution for land bases wind turbines (ScrewFast Foundations Ltd, 2009)

Advantages:

i. 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 (see Figure 19) where the members also need to carry tension loads.

ii. Easy and fast installation
   The installation of screwpile 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 screwpile

iii. Reduced installation cost
   Due to the time saving during installation and the flexibility to remove and reuse, the screwpile can reduce installation costs.

iv. 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.

v. 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.

vi. No Curing Time required (after installation)
   Usually when a foundation is installed it required some time before the soil settles and get back to full strength. This is however not the case for the screwpile, which doesn't require any cure time.

vii. No scour protection required

If the configuration given in Figure 45 is used need for scour protection can be avoided. The concrete block would need to aligned with the seabed

Figure 46. Tip-screw

Disadvantages:

i. 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. However the using the configuration shown in Figure 45, can change this. As it combines the screwpiles with the cheap concrete block.

ii. 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.

iii. Unproven technology on large scale

This concept has never been applied on a large-scale monopile despite the many advantages that the screwpile provides. The largest diameter for a screwpile found in during the research is 24 inches (610 mm) with 30 inches (760 mm) helices. (Franki Foundations Belgium, 2008)

3.3.5. Jackets foundations

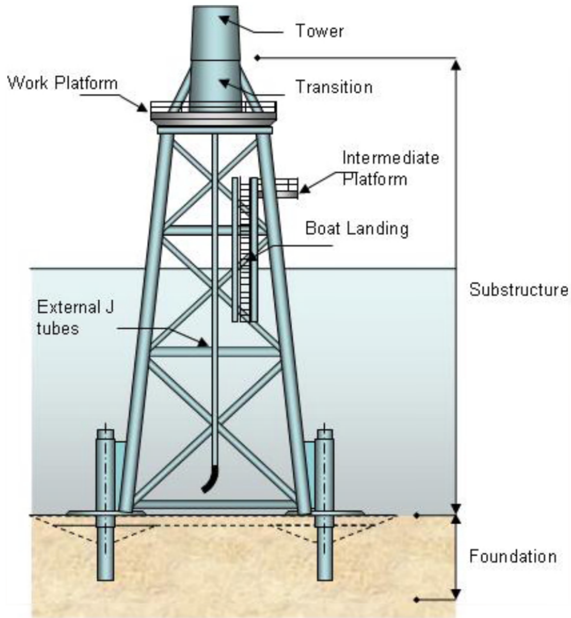


Figure 47. Jacket support structure for offshore wind farms (Iuga)

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 increases other solutions had to be considered. 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.

Figure 48. Oilrig jacket support for Bullwinkle oil platform (© Bettmann/CORBIS)

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.

Advantage:

i. 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.

ii. 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

i. Higher manufacturing costs

Unlike monopile, jackets consist of many parts and they need to be put together, increasing complexity, time required and costs. The material used is nevertheless lower.

ii. 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.

iii. Stress checks

Increasing parts also increase the risks of failure. Additional stress checks (See Figure 49) are required for the joints and members. The design of jackets and its analysis is more complicated and time consuming than a simple monopile.

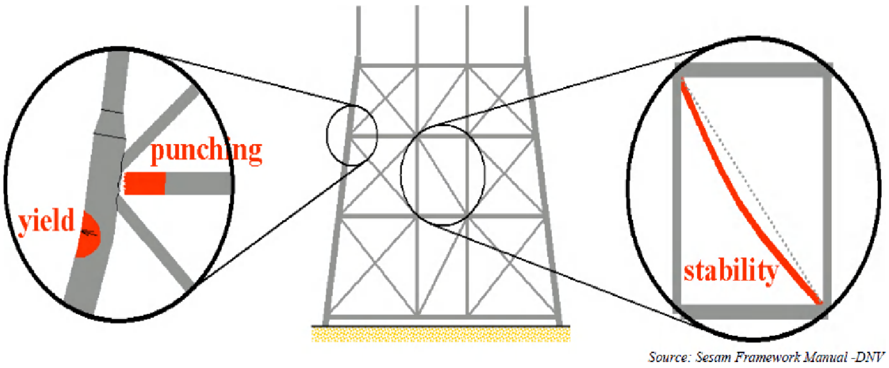


Figure 49. Stress checks for Jacket support

3.3.6. Gravity based support structures

Gravity based foundations are huge concrete structure 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 as seen Table 6. One of the deepest applications of gravity based foundation is the Thornton Bank in Belgium where water depths ranged 12 – 27 meters.

Table 6. Offshore Wind Projects with Gravity based Foundation

Project Name	Water Depth *[m]*	Country	Year
Vindeby	2 – 4	Denmark	1991
Tunø Knob	3 – 7	Denmark	1995
Middelgrunden	3 – 6	Denmark	2000
Nysted	10 – 20	Denmark	2003
Rødsand II	7.5 – 12.8	Denmark	2008
Thornton Bank	12 – 27	Belgium	2009

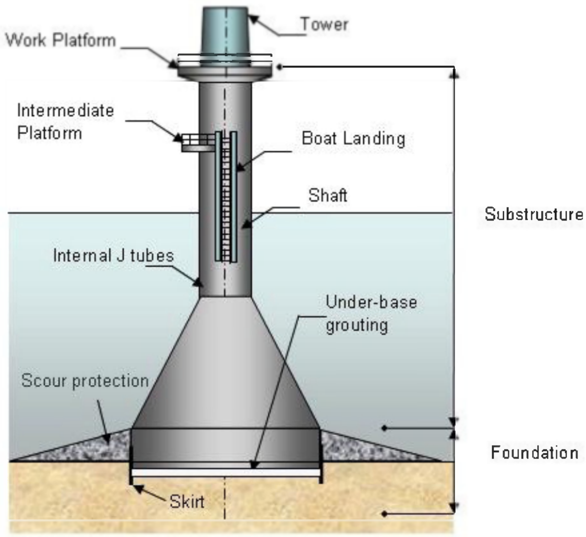


Figure 50. One possible Gravity base structure solution (Iuga)

The gravity based foundations that are used for wind turbine usually do not penetrate the sea bed and are generally supported by the seabed.

Advantage:

i. 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

ii. 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 (Figure 51).

iii. 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.

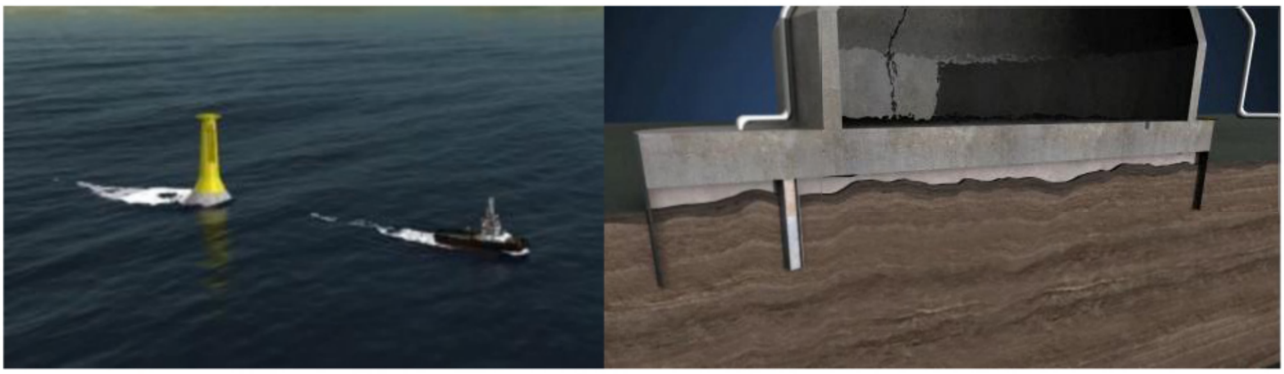


Figure 51. Cranefree Gravity foundations concept of SeaTowers (© SeaTowers)

Disadvantage:

i. Overturning moments

As the gravity based structure doesn't penetrate the seabed the overturning moments need to be considered and designed for. The soil resistance force for a gravity based structure can be seen in Figure 17.

ii. Seabed preparation needed

The gravity based structure needs to placed directly onto the seabed therefore the seabed needs to be levels so that the foundation is completely upright. This additional procedure increases installation costs. However the Cranefree Gravity foundations (Figure 51), offers a unique feature that fills the lower part of the foundation with concrete making a full contact with the seabed.

iii. 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.

iv. 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.

3.3.7. Tripod/ Tripile support structures

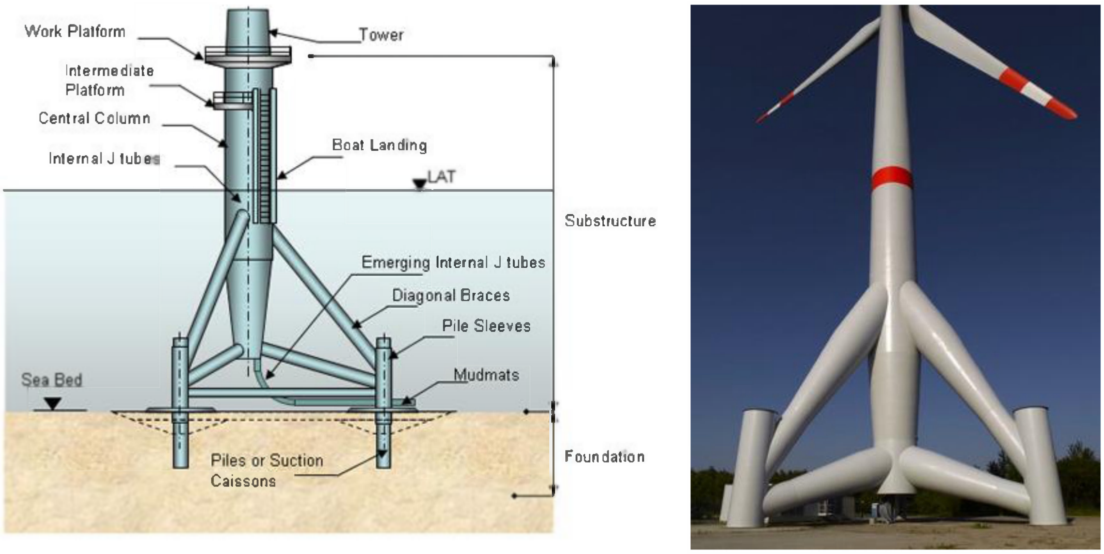


Figure 52. Tripod foundation for offshore wind turbines (Iuga)

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

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 (see Figure 53). 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)

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 mentioned in the section 2.4 Certification and Classification

Figure 53. Tripile foundation used by BARD GmbH for it offshore wind parks (© BARD Engineering GmbH)

Advantages:

i. 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.

ii. Better lateral stability than a single monopile.

Better lateral stability and stiffness can be achieved than monopile foundation. See Figure 19.

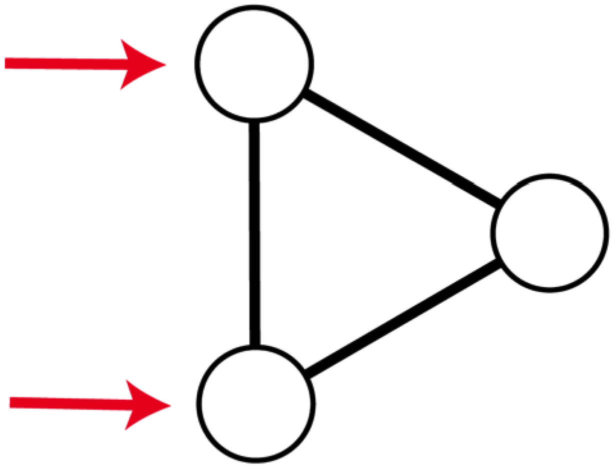


Figure 54. A possible Load case for tripod foundations

Disadvantages:

i. 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.

ii. One member need to bear load in certain load cases

Wind and waves come from every direction and are constantly changing. When the waves are coming in the direction depicted by the red arrows in Figure 54, the member at the back has to take all the loads. This means that all the members need to be designed for the extreme load case making the whole structure heavier and more expensive.

iii. More complex to transport

Tripod and tripiles are huge structures as evident from Figure 52 and Figure 53, transporting these structures is more complex than standard monopile. Monopile can even be made airtight and towed to the location.

3.3.8. Floating foundations

(a) Floating Wind Turbine Concept (Mitchell, 2009)

(b) Principle Power's WindFloat Concept

(c) Blue H – installed in 113 meters water depth

Figure 55. Few floating wind turbine concepts

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 Figure 55(a).

Some concepts try to overcome this problem by adding extra floater like the Blue H – prototype Figure 55(c) . This increases the area underneath the turbine making it stable. Other concepts suggest using active balancing like the Principle Power's WindFloat Concept shown in Figure 55(b)

Figure 21 (b) shows the bathymetric map of the Dutch EEZ, it can be seen that maximum depth reach *60m*, while a large part has depths around *50m.* This part might be used for floating supporting support structure as this technology matures.

Advantages:

i. 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.

ii. Can also be used in the deepest part of the Dutch EEZ

   Even though the Dutch EEZ is not one of the deepest sea in the world still the depth in a large part reaches almost 60 meters. For such depth the floating might prove to be a more feasible solution

iii. 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

iv. 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.

v. 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:

i. 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.

ii. Stability a major concern

   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.

iii. 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 noise problem

3.3.9. Suction caisson/Buckets

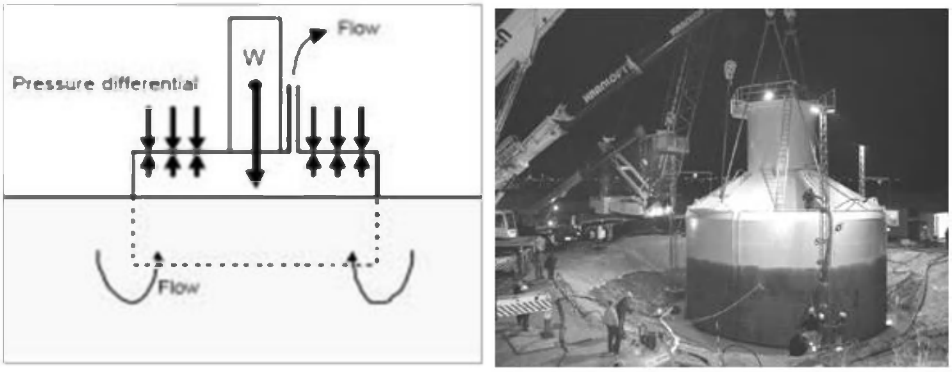
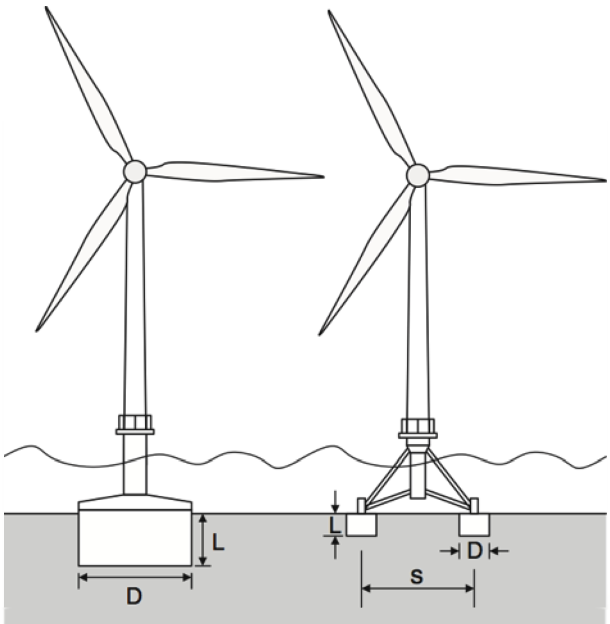


Figure 56. Suction caisson (Houlsby, Ibsen, & Byrne, 2005)

Suction buckets are tubular structures that are installed by applying suction inside the caisson/bucket. The hydrostatic pressure and the weight of the structure cause the foundation to penetrate the soil. The penetration is very low compared to the monopile, while the diameter is much larger. The lateral stability is provided with the combination of both the large diameter and the walls of the foundation this is evident from Figure 17.



(a) (b)

Figure 57. Possible foundation configuration with suction caisson (Houlsby, Ibsen, & Byrne, 2005)

There are two possible methods that the suction caisson can be applied for wind turbines. These two concepts are depicted in Figure 57. Using a single large bucket is referred to as 'Monopod' while the configuration with 3 and 4 smaller buckets are titled tripod/tetrapod respectively.

Advantages

i. Can be completely removed on decommissioning

Unlike monopile that are chopped 1.5 meter below the seabed, suction caisson can be completely and easily removed.

ii. 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.

iii. Less weather dependant

For impact pile driving the pile needs to be held in place plus the hammer need to also need 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:

i. 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.

ii. 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.

iii. 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.

iv. Overturning moments

Similar to the gravity based foundations, overturning moments is 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.

v. Limited application

Unlike the monopile, suction caisson cannot be used in all soil types rather are only applicable in sand and clays of intermediate strength. Making them unsuitable for harder soil types and increasing risks during installation.

3.4. Comparative Analysis

During the process of research a lot of interesting solutions for the offshore wind energy were found. There are many ways that the alternatives/modifications can be compared to each other, but this analysis will mainly focus on the noise mitigation aspects of all the solutions and other practical issues associated with that.

Finding on perfect solution is impossible as every foundation provide certain advantages and disadvantages. This whole issue of the best foundation for offshore wind energy has been beautifully summarised in a magazine (Iken, Movement in foundations, 2010) that says:

"After many year of discussion, it is gradually being accepted that there is no individual foundation type which is equally suitable for all locations."

One of the main reasons for using monopile foundation is that it is the cheapest and most reliable solution. Various cost analysis has proven that there is not one perfect solution when it comes to cost. It does seem to be one of the most reliable solution and more versatile than most other alternatives. The drilled concrete monopile however might prove to be even more reliable then steel monopile.

As far as noise mitigation is concerned there are a lot of interesting and effective options. These can be categorized by the *noise reduction achievable* and *the time that is required for implementing* them. The reason why *'time required for implementation'* has been chosen beside the *'noise reduction achievable'* is to be able to highlight the alternative that can provide a solution in the short-term. A method that is highly effective at noise reduction and takes 50 years to develop, for example, is useless currently. The problem is serious and needs to be dealt with immediately with solution that can provide some relief to the sea life while the more effective solutions are being developed. Table 7 gives a comparative overview of all the alternatives and modifications discussed in this report.

Table 7. Comparative Overview

	Technique	Noise reduction achievable	Time required for implementation	*Comments*
Modification of current techniques	Changing pile-toe shape	Medium	Short	*This method can reduce the noise levels and their duration and required a short time for execution and should be seriously considered. There could however be a problem with bearing capacity.*
	Using contact Damping	Low/minimal	Short	*Even though this method can be implemented very quickly but due the low noise reduction is not a recommended solution.*
	Skirt-pile support	Low/minimal	long	*This is a purely conceptual modification and needs to be tested ıf it can have particle benefits, in the short-term however it is not an option.*
	parameter for pile stroke	Low	–	*This method does not require any time to implement, as mentioned before, just the slight modification of hydraulic hammer controls. The noise reduction independently from this method is not significant however combining this technique with other methods might help mitigate even more noise. For example combining it with sound isolation*
	Sound isolation/damping	Medium – High	Medium	*Depending on the technique used medium or high noise reduction can be achieved, it is also encouraging to see that the biggest Hydraulic hammer companies, IHC-Merwede and Menck taking interest in these techniques and testing them for full scale use.*
	Vibratory Hammers	High	Short*	**Missing standards for bearing capacity can cause significant hurdles in implementation. But using it for the initial stage of driving can also have a huge effect in the short term. Like Bard is currently doing.*

Alternatives for monopile and/or current pile driving techniques	Guyed support structure	High	Long	*Still in concept phase, would take very long to develop and be approved. Many experts seem to doubt the practicality of this solution, however more testing is required to check this.*
	Concrete monopile/Drilling	Medium	Medium	*This solution is also in concept phase, but as the idea is backed but a huge player in the offshore wind sector, it has potential of becoming ready in reasonable period.*
	Screw-pile	High	Medium/Long	*A promising implementation of this method could be configuration depicted in* Figure 45. *This application could be made available on medium term. However single screwpile support would take very long and is not even certain ıf it can be applied at large scales, as required for offshore wind.*
	Jackets foundations	Medium – High	–	*Depending on the methods used for pile driving. Vibratory pile driving or screwpiles are certainly the best options in terms of noise reduction.*
	Gravity based foundations	High	–	*This foundation is already being used therefore there is no implementation time required. Combining this support with screwpiles might further optimize this support.*
	Tripod/ Tripile foundation	Low/minimal	–	*The tripod/tripile foundations use 3 smaller piles rather than one huge monopile, this implies that the construction takes longer. Therefore The noise levels are lower but the sound is produced for a longer duration of time. Therefore the accumulative noise reduction is minimal. Using vibratory hammers like Bard does mitigate a huge amount of sound.*
	Floating foundations	Very high	Long	*This foundation might be the future of wind energy but will take a long time to become main stream. This foundation will almost completely be noiseless to install.*
	Suction caisson/Buckets	high	Medium/Long	*This method also can be a promising solution for noise mitigation but still needs extensive testing and standardization before it can be used commercially.*

From this analysis following conclusions can be derived:

Engineering solutions that can be used for noise mitigation in the *immediate short-term* without significantly changing to the current methods include: (i.e. ***Modification***)

- ✓ 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

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.

Conclusions

Noise produced during steel monopile driving using hydraulic hammer generates extremely high noise levels which effect animals within a large area, therefore alternatives and modifications of current method is needed. After examining and comparing a number of possible engineering solutions, some were found to be more effective than others. However it is impossible to identify a single best solution.

Possible engineering solution do exist to reduce noise in the immediate short-term and should be encourages by the government to be employed in all upcoming projects. Further research is needed to realise some alternatives still in the development or concept phase.

Wind Energy cannot be seen as a completely green alternative as long as it keeps disturbing the eco-systems of the seas, with the ever growing number of windfarms installed using hydraulic impact hammer. Cutting CO_2 emissions is not the ultimate aim of green energy but to preserve the environment of which animals form an integral part.

Recommendation

i. The underwater sound needs to understood better and standardized
ii. Innovative noise mitigation solutions need to be stimulated by the Government and classification societies
iii. Methods for noise isolation need to be tested further and applied on full scale.
iv. Solutions like Vibratory hammer for pre-installation should be used as long as other alternatives are being finalised.
v. Further testing and research should be focused on high potential solutions mentioned in this report.

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Appendix I - interview - Tim van Erkel IHC-Merwede

What kinds of methods are used by IHC-Merwede to reduce underwater noise during pile driving?

Damping

How are the IHC Hydrohammer damped?

The IHC Hydrohammers are not damped. The IHC Hydrohammer design is based on steel-to steel energy transmission. IHC Hydrohammers are accelerated resulting in a high impact velocity creating a relative short impact time which creates a strong shock wave which is perfect for driving steel piles. It would be possible to change the characteristics of the hammer, i.e. increase the impact time of the ram weight on the anvil. However this will have an impact on drivability results. We do not believe that this will bring enough reduction.

How much more energy/time/money is lost due to the damping?

There is loss in energy. We did not calculate how much since the reduction is not significant. If you use the same hammer type it will result in more blows thus time to drive the pile to the required penetration. In case the soil resistance is too strong you have to take a larger hammer which will lead to higher costs as well.

How much noise reduction is achieved in this way?

We expect this will bring approximately 8 dB to 10 dB reduction

Noise reduction package

How does the Noise reduction package work?

IHC Hydrohammer has developed a so-called double wall Noise Mitigation Screen (NMS). This is a construction made out of two piles with air between them. The NMS is placed completely around the mono-pile and is resting on the sea-bed and reaching out above the water level. Furthermore we create a special bubble curtain between the mono-pile and the inner wall of the NMS. We have also developed concepts for the installation of tri-pods and jackets, both post and pre-piling.

Has the "Noise reduction package" been applied for offshore wind, so far?

This NMS has been tested in a real water environment however only at a water depth of 6 meters and in a river. We are planning to have a full scale test in the North Sea later this year. We have made a full FEED for a NMS suitable for 30 meters of water depth, mono-pile diameter of 5.500 mm and average North Sea conditions.

What is the maximum depth that the "Noise reduction package" can support?

Basically no limitations, however the weight and thus how to handle the NMS will most likely the limiting factor. At this moment the mono-pile is used in water depth up to 35 meters and that is no problem. The concepts for tri-pods and jackets can go up to 60 meters and beyond.

What is the maximum pile diameter that the "Noise reduction package" can support?

We have a full design ready for mono-piles 5.500 mm but this can easily be increased to 7.000 mm or larger.

How much cost/time is incurred by using the "Noise reduction package"? How much noise reduction can be achieved?

The additional time and thus costs depends on too many factors such as weight of the NMS, how to handle the NMS, type of vessel used and piling procedures set by the contractor. IHC has developed various concepts how to handle the NMS in different applications. It is likely to expect an increase in installation time and thus costs.

The full scale test in the river application showed a reduction of over 25 dB especially in the low-frequency area where reduction is mostly required. The tests have been monitored by TNO.

Appendix II – Locations considered in the Dutch EEZ