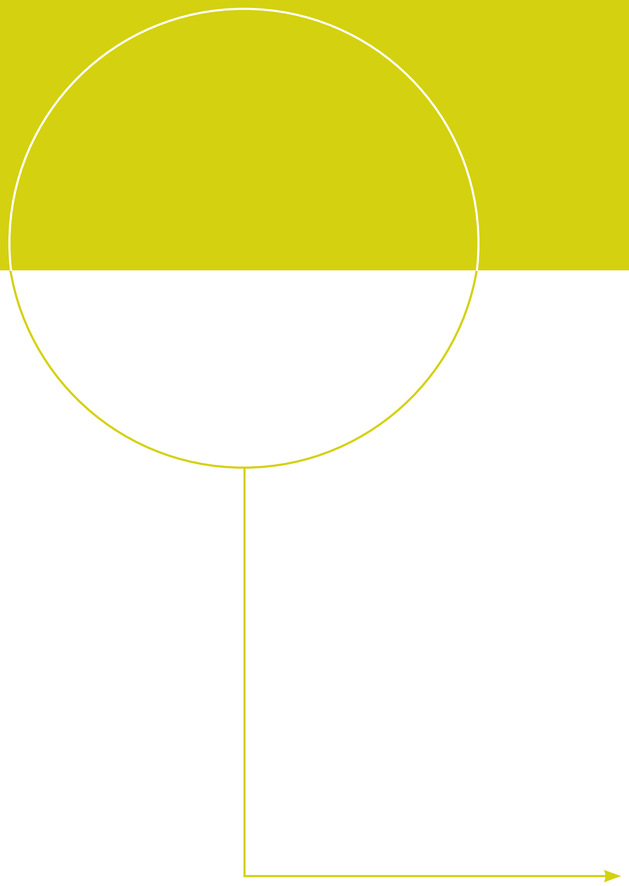

Master's thesis

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Master's thesis

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Feasibility Study of the Complete Removal of Monopiles Using Vibratory Pile Removal

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MASTER THESIS

MASTER OF SCIENCE IN OFFSHORE ENGINEERING

MASTER OF SCIENCE TECHNOLOGY - WIND ENERGY

28th June 2022
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Abstract

The offshore wind market is a fast growing market. Currently, 3 GW of offshore wind are installed in The Netherlands. However, the ambitions of the Dutch government are to have 30 GW offshore wind installed by 2030. The current installed offshore wind capacity of Europe is 28 GW. The EU ambitions are to install 60 GW by 2030 and to install 300 GW by 2050. Wind farms are designed to have a lifetime of 20 to 25 years. When wind turbines reach their end-of-life, they have to be decommissioned. The already installed capacity and the enormous amount of turbines that are to be installed in order to reach the offshore wind ambitions, eventually all have to be removed. To date, only a hand full of offshore wind farms have been decommissioned. This is due to the fact that not many wind farms have reached their end-of-life. The most used technique is partial removal, where a cut is made at a few meters below the mudline and the top part of the monopile is removed from the marine environment. However, this method leaves a significant part of the monopile in place after decommissioning, leaving behind tonnes of steel in the subsurface. Completely removing the monopile from the marine environment can be done by using vibratory pile removal. By modelling the forces and limits involved in vibratory pile removal, an estimation of the diameters up to which vibratory pile removal is technically feasible has been done. In addition, the costs and CO_2-eq. emissions have been modelled and examined. The opposed method uses vibration to reduce the soil resistance along the shaft of the monopile by creating soil fatigue. With the currently available tools, it is possible to extract monopiles up to a diameter of approximately 5.8 meters in clay and up to approximately 7.9 meters in sand. For a mixed soil profile, it is likely that the limit lays with these two numbers. Likely, it is possible to extend these limits by developing more powerful tools or by internally dredging the monopile before using vibratory pile removal. By retrieving extra steel from the soil by choosing complete removal over partial removal, more steel can be recycled. This leads to an extra emission reduction of approximately 100 to 830 mT CO_2-eq. per monopile, dependent on the diameter and the type of connection between the transition piece and the monopile. Whether complete removal is preferred from a economic point of view is dependent on the type of connection between the transition piece and the monopile and the diameter. Based on the results found during this research in can be said that all wind farms that reach their end-of-life up to 2039 can be decommissioned using vibratory pile removal. Dependent on the soil type of the subsurface, even wind farms reaching their end-of-life up to 2045 can be removed using vibratory pile removal. In many cases complete removal should be preferred over partial removal based on both economic and environmental grounds. In some cases a cost benefit analysis should be made in order to determine whether a higher reduction of CO_2-eq. emission is worth the extra costs involved in completely removal a wind farm with vibratory pile removal.

Preface

Proudly, I present to you my master thesis. I enjoyed researching this topic and I am very happy with the end result. The past two years of being a European Wind Energy Master student have been unforgettable. Studying at three different universities in three different countries has been an amazing experience where I have leaned so much. I am very proud with how I managed writing my thesis and I am very pleased to say that it has been quite a smooth journey. However, this would not have been possible without all the people who helped me get though it.

Hedzer, it has been a true honour to be the first student to graduate under your supervision. I could not have wished for a better supervisor. You challenged me to dig deeper and to take the extra steps. I have learned a lot form you, things that will inevitably help me throughout my carrier. Your honesty is much appreciated and it has helped me a lot during the past six months. I am truly happy to be able to say that we will be colleagues for the coming years.

Jeroen, I am grateful for your supervision. I always looked forward to our meetings, since they were not only extremely helpful, but they are also fun. Whenever I was stuck, you knew exactly how to help me. I am thankful for your positivity, constructive criticism and support!

Gary, you have been my supervisor throughout a large part of my master. I would like to thank you for everything. Your dedication to my work means a lot to me. The 7 hour time difference never made a difference and you were always there for me when I needed guidance. Unfortunately, we have never met in person. I hope that some day we will meet so that I can thank you in person for your great support and help.

Andrei and Stas, thank you for showing such interest in my research. Your support means a lot to me. Your humour and happiness made me look forward to our meetings, whereas I think most students dread their midterm and green light meeting. I always felt at ease, thank you for that. Besides the humour and happiness your comments were always very helpful and much appreciated.

Besides my great supervisors, I could not have done it without my wonderful colleagues at Heerema Marine Contractors. I am looking forward to officially joining the Heerema team!

My wonderful friend and family have been a great support throughout my masters, but also throughout writing this thesis. Thank you all for listening to my stories about wind turbines and thank you for providing the much needed distraction.

Lastly, I would like to thank everybody at CAPE Holland that have helped me throughout my research. I truly believe that a bright future awaits complete removal with your impressive Vibro Lifiting Tools.

Nomenclature

Abbreviations

AWJC	Abrasive Water Jet Cutting
CFC	Carbon Footprint Compensation
COG	Center of Gravity
DOT	Delft Offshore Turbine
DWC	Diamond Wire Cutting
EIA	Environmental Impact Assessment
EU ETS	European Union Emissions Trading System
GBS	Gravity Based Structure
GDP	Gentle Driving of Piles
IMO	International Maritime Organisation
IPC	Internal Pile Cutter
MCDA	Multi-Criteria Decision Analysis
MGO	Marine Gas Oil
MSL	Mean sea level
NAS	Noise Abatement System
NMS	Noise Mitigation Screen
OSV	Offshore Service Vessel
RNA	Rotor Nacelle Assembly
ROV	Remotely Operating Vehicle
SPIV	Self-Propelled Installation Vessel
TP	Transition Piece
UNCLOS	United Nations Convention on the Law of the Sea
VLT	Vibro Lifting Tool

Other symbols

ω	Angular frequency
ρ_F	Density of the fluid
F_c	Centrifugal Force

f_n	Natural Frequency
F_V	Centrifugal force
F_{ext}	Extraction force
G_i	Force due to weight of pile
k	Spring constant
L_{emb}	Embedded length
l_{eq}	Equivalent length
m_c	Mass of vibrating part VLT
M_e	Eccentric moment
m_e	Eccentric mass
m_p	Mass of the monopile
m_t	Total dynamic mass
$Q_{s,i}$	Inside shaft resistance
$Q_{s,i}$	Outside shaft resistance
r	Distance eccentric mass and the COG
R_v	Soil Resistance during vibration
s	Displacement amplitude
V_D	Displacement volume
W_{pile}	Gravitational force due to weight pile
W_{VLT}	Gravitational force due to weight VLT
ρ	Friction index
V	Constant volume
A	Amplitude
A_p	Cross-sectional area of monopile
E	Modulus of Elasticity

Physics constants

g	Gravitational constant

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Chapter 1

Introduction to Decommissioning of Offshore Wind Farms

1.1 The Offshore Wind Energy Market

In order to meet the European Union climate change targets, the European Commission proposes to increase Europe's offshore wind capacity. The EU ambitions are to increase the installed capacity up to 60 GW by 2030 and up to 450 GW by 2050. To realise this capacity increase, many wind farms have been and will be installed over the coming years. To date, the monopile remains the most popular substructure. It is the common substructure in operating offshore wind farms, Figure 1.3. The removal of a wind turbine is referred to as decommissioning. The design life time of an offshore wind farm is 20 to 25 years. Over the coming years several offshore wind farms will enter the decommissioning phase and with the ambition to increase the offshore wind capacity up to 450 GW many more offshore wind farms will need to be decommissioned in the coming decades.

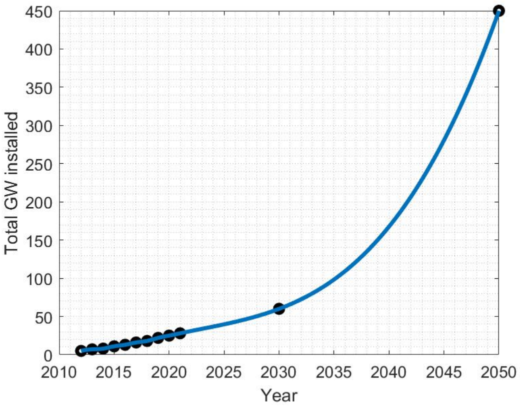


Figure 1.1: Offshore Wind ambitions European Union

An Offshore Wind Turbine consists of multiple components, as displayed in Figure 1.2. The figure displays three different types of substructures. This present report focuses on monopiles, which is the left most substructure in the figure.

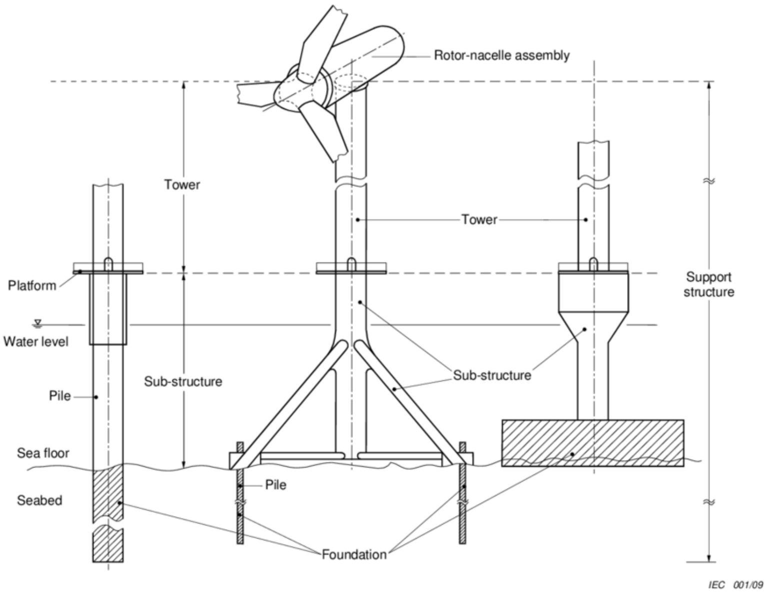


Figure 1.2: Components of an Offshore Wind Turbine [Natarajan et al., 2016]

Offshore wind turbines can be installed using various foundation types. With 81.2%, the monopile is by far the most used type of foundation to date. In 2020 over 80.5% of all installed installations were monopiles [Ramirez et al., 2021]. The offshore industry will face a large task decommissioning all the wind turbines. Due to the lack of experience it is important to clearly identify the challenges that the industry will face. According to Smith and Lamont [2017] the challenge lays in the removal of the turbine foundation. It is expected that the reverse of the installation procedure can be used for dismantling the blades, the nacelle and the tower.

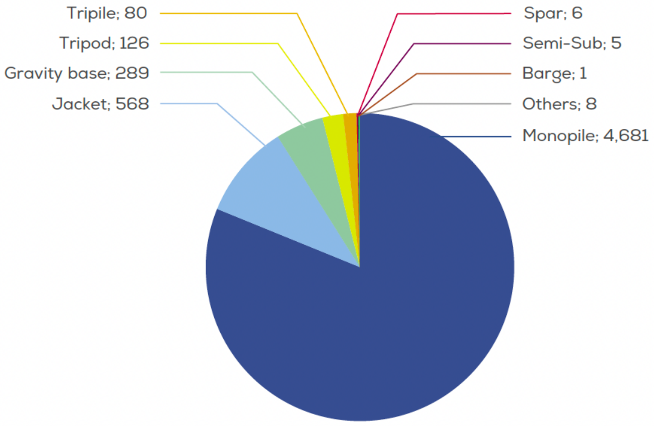


Figure 1.3: Overview of substructure types installed [Ramirez et al., 2021]

This present report focuses on the decommissioning of a monopile using vibratory pile removal. Figure 1.4 displays the number of turbines that have been installed up to 2010. These wind farms are to be decommissioned or re-powered over the next decade. The majority of these wind turbines are monopiles. Some wind turbines will face lifetime extension and some wind turbines will be re-powered. Lifetime extension is when a wind turbine operates longer than it was designed to. Replacing old technology with state of the art technology, extending the life time of a wind turbine is referred to as Re-powering [Bulder, 2016]. Many, and eventually all, will be have to be decommissioned. According to Smith and Lamont [2017] the decommissioning volume is estimated to be 2 GW per year by 2035. With an average size of 4 MW of the to be decommissioned wind turbines, this leads to 500 turbines per year. Up to now only a few offshore wind farms have been decommissioned and there is not much industry experience regarding the decommissioning phase. The amount of offshore wind farms that are to be decommissioned will be a significant opportunity for marine contractors.

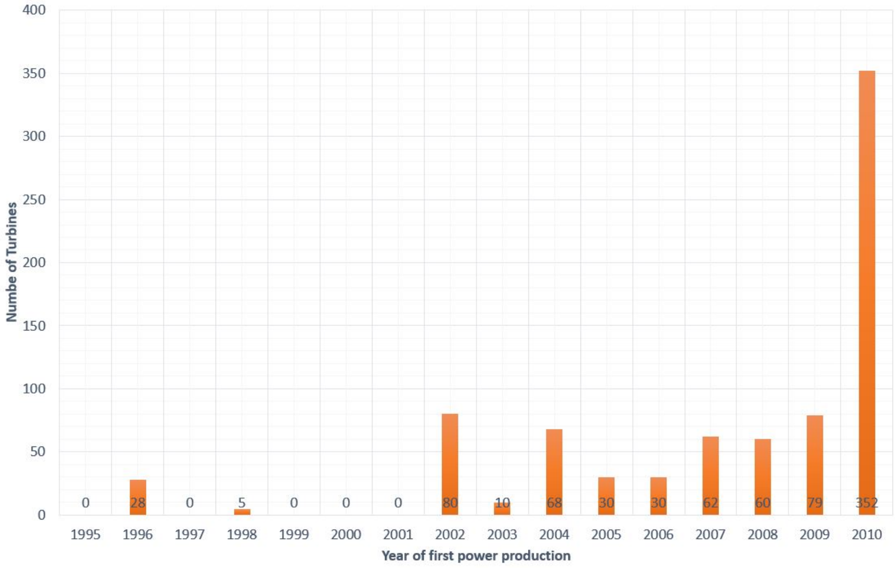


Figure 1.4: Number of turbines installed up to 2010

Table 1.1 displays the wind farms that are to be decommissioned up to 2035, based on an average lifetime of 25 years. These wind farms will be referred to as the soon-to-be decommissioned wind farms throughout this report. The average number of turbines is 43 wind turbines, with an average diameter of 4.52 meters. Looking at the diameter of the soon-to-be decommissioned wind farms, it can be seen that the diameter lays between 4.00 meters and 5.00 meters. Therefore, this present report will focus on the extraction of monopiles with a diameter between these two values. As technology keeps rapidly developing, the diameter of the monopiles installed after 2010 show a trend upward. Chapter 5 will touch upon the decommissioning of wind turbines with larger diameters.

Table 1.1: Soon-to-be decommissioned wind farms
* based on a lifetime of 25 years

Name OWF	Nr	Country	Number of Turbines	MW per Turbine	MW OWF	Diameter	Year of DeCom*
Horns Rev 1	1	Denmark	80	2	160	4.04 m	2027
Samsø	2	Denmark	10	2.3	23	4.50 m	2028
Arklow Bank - phase 1	3	Ireland	7	3.6	25.2	5.00 m	2029
North Hoyle	4	United Kingdom	30	2	60	4.00 m	2029
Scroby Sands	5	United Kingdom	30	2	60	4.20 m	2029
Kentish Flats	6	United Kingdom	30	3	90	4.30 m	2030
Barrow	7	United Kingdom	30	3	90	4.75 m	2031
Burbo Bank	8	United Kingdom	25	3.6	90	4.70 m	2032
Egmond aan Zee	9	Netherlands	36	3	108	4.60 m	2032
Prinses Amaliawindpark	10	Netherlands	60	2	120	4.00 m	2033
Inner Dowsing	11	United Kingdom	27	3.6	97.2	4.74 m	2034
Lynn	12	United Kingdom	27	3.6	97.2	4.70 m	2034
Rhyl Flats	13	United Kingdom	25	3.6	90	4.70 m	2034
Belwind	14	Belgium	55	3	165	5.00 m	2035
Gunfleet Sands	15	United Kingdom	48	3.6	172.8	5.00 m	2035
Horns Rev 2	16	Denmark	91	2.3	209.3	4.20 m	2035
Robin Rigg	17	United Kingdom	58	3	174	4.30 m	2035
Thanet	18	United Kingdom	100	3	300	4.70 m	2035

When looking at decommissioning techniques for monopiles used in the offshore wind industry, there are two main options. These options being partial removal and complete removal. Complete removal techniques take out the entire monopile from the sea bed, whereas with partial removal techniques a part of the monopile remains in place. The different removal techniques and methods are described in detail in Section 2.1.

1.2 The Need for Complete Removal of Monopiles

1.2.1 Environment

The effects of offshore activity on the environment are of great importance nowadays. By extracting the entire monopile from the soil, extra steel amounts are retrieved. The steel that remains in the soil during partial removal, is extracted during complete removal. These extra amounts can be recycled to secondary steel, which is done using electric arc furnaces. Producing this secondary steel emits one-fifth of the CO_2 emissions compared to primary steel making [The Crown Estate, 2019]. This is the case even when the majority of the electricity used in the electric arc furnaces comes from fossil fuels. If however renewable energy is used, the production of secondary steel can predominantly be decarbonised. Keeping this in mind, as much steel, if not all, should be retrieved from the seabed and used in order to produce secondary steel.

Offshore Wind Farms enhance the biodiversity of the surrounding marine environment, since they act as an artificial reef during their operational lifetime. Removing these structures, will affect the habitat of the species living in the artificial reef. The decommissioning method that has the least environmental impact and even so, has a positive impact, is leaving the substructures in place. This is referred to as "Renewables-to-reefs" [Fowler et al. [2020];Smyth et al. [2015]]. However, due to various reasons such as navigational hazards and hazards for fisherman, removing the wind farms partially or completely is the standardized option. Potentially the substructures of some wind farms will remain in the seabed post decommissioning. However, it is inevitable that many will be partially or completely decommissioned. This thesis focuses on partial and complete removal from the seabed.

1.2.2 Potential hazards

If an offshore wind farm is partially decommissioned, the site needs to be monitored post decommissioning. Potential hazards for fishermen and the offshore industry can occur if the remaining part of the monopile comes to surface. Fishing nets can get stuck and jack-up vessels cannot be safely positioned [Hinzmann et al., 2018]. Complete removal mitigates these hazards and post decommissioning monitoring is no longer nescessary, saving money.

1.2.3 Future of Offshore Wind

The sites of offshore wind farms are carefully selected. The site selection is based on the wind characterised associated with the site, such as a high average wind speed. However, there are many criteria for site selection of offshore wind farms. A wind farm may not be located in territorial water and in military areas. It may not interfere with shipping routes, pipelines, underground cables and bird or marine mammal mitigation routes. In addition, it cannot be located to close to the shore, due to the visual and noise impact on civilisation. The water depth should also be taken into consideration. As the water depth increases, the foundation costs rapidly increase [Argin et al., 2019]. Having to deal with all these criteria, site selection is a difficult process and results in limited suitable sites for offshore wind farms. The wind farms that are currently operating, fulfill the requirements. Partially decommissioning these wind farms would limit the options of reusing the sites. A constrain would be added in the lay out design of a new wind farm, making sure that the new foundations are not placed where the old foundations are. Complete removal of the monopiles results in the option of opening the site for new tenders for offshore wind farms, on a site that fulfills all requirements.

1.2.4 Future of the Sea

After World War I and II, the surplus of chemical weapons and bombs were dumped in the worlds oceans. The sea bottom seemed like a suitable place to dump these items at the time. Nowadays, a UXO survey is performed prior to performing offshore operations. A UXO survey is a unexploded ordnance survey, which is the scanning of the subsurface and marine environment for unexploded items of ordnance such as unexploded bombs. Performing this survey minimises the risk involved with offshore operations. After both World Wars, nobody was thinking about building offshore wind farms in our marine environment or other offshore operations. And thus, they did not foresee any long-term problems with dumping their ammunition. Today, it cannot be predicted for what purposes the sea bottom or the marine environment might be needed in the future. Therefore, it is considered a wise decision to completely decommission offshore wind farms if possible. This way the future of the use of the marine environment is not limited by the decisions made now-a-days to use it for renewable energy purposes.

1.3 Research Objective and Research Questions

The overarching research objective of this thesis is to compare the feasibility of applying decommissioning by vibratory pile removal over conventional partial decommissioning techniques. The objective is reached by researching the following research questions.

- **Research Question 1:** What decommissioning techniques are currently used and what are their limitations?
- **Research Question 2:** What are the effects of various soil characteristics on using vibratory pile removal?
- **Research Question 3:** What are the limitations of using vibratory pile removal?
- **Research Question 4:** What are the advantages and disadvantages of using vibratory pile removal compared to partial removal?
- **Research Question 5:** For which soon-to-be decommissioned offshore wind farms is using vibratory pile removal feasible?
- **Research Question 6:** Will vibratory pile removal be feasible as the diameter of the soon-to-be decommissioned monopiles increases?
- **Research Question 7:** Should vibratory pile removal be favored over conventional removal by cutting?

The answers to these research questions are given in Section 6.1.

1.4 Outline of the Report

The state-of-the-art of the decommissioning of Offshore Wind Farms is described in chapter 2. This chapter explains the various decommissioning methods and techniques, the rules and regulations regarding decommissioning and the basic principles of vibratory pile driving. In addition, this chapter describes the need for noise mitigation and the noise mitigation system used in this present report. Chapter 3 describes how to create a model to calculate the extraction force that is required for the complete removal of monopiles using vibratory pile removal. This is done using the techniques and methods described in chapter 2. The modelling of forces relevant for the modeling of the monopile during extraction, such as shaft resistance and soil resistance during vibration, is described in chapter 3. The chapter also discusses the vibratory pile removal tools used in the model and how to determine which tool to use. The results for the calculated extraction force are also displayed in chapter 3. This calculated extraction force is needed for a complete removal using vibratory pile removal is used as an input to research the overall feasibility of complete removal versus partial removal, which is described in chapter 4. This chapter compares two decommissioning techniques, partial removal with a cut at 3 meter below the mudline, with complete removal using vibratory pile removal. A comparison is made based on execution time, overall costs and green house gas emissions involved in the decommissioning of the substructure. Since the main focus of this thesis lays on the decommissioning of monopiles with a diameter between 4 and 5 meters, chapter 5 focuses on the future of complete removal as the diameter of the to be removed monopiles increases. chapter 6 presents the discussion of the results, the conclusion and the recommendations of this thesis.

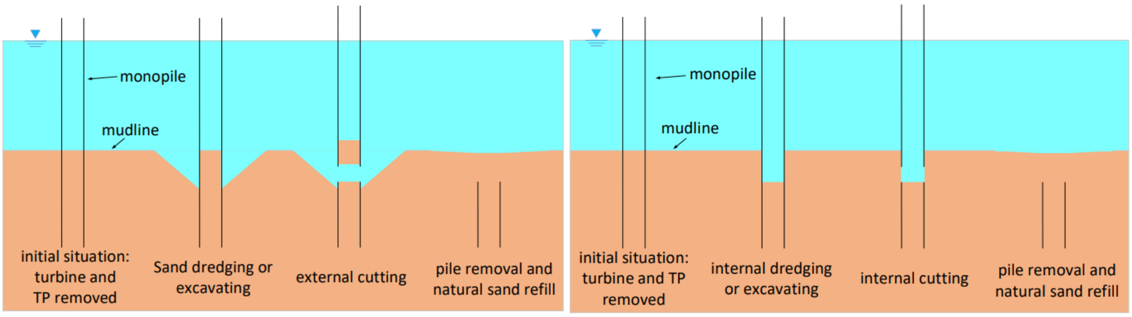
Chapter 2

State-of-the-art of Decommissioning Offshore Wind Farms

2.1 Decommissioning Offshore Wind Farms

This chapter describes the currently available decommissioning techniques as well as decommissioning techniques that are under development and might be developed in the future.

In the last case, the monopile is cut off below the mud line. Figure 2.1 displays external pile cutting and internal pile cutting, these are two methods of partial removal.



(a) External pile cutting (b) Internal pile cutting

Figure 2.1: Cutting techniques [Hinzmann et al., 2018]

The currently used techniques in decommissioning in offshore engineering are listed below.

- Partial removal
  - External Dredging
  - Diamond Wire Cutting (DWC)
  - Abrasive Water Jet Cutting (AWJC)
  - Explosives
- Complete removal
  - Vibration Techniques

2.1.1 Decommissioning Techniques

2.1.1.1 Internal and External Dredging

When using external pile cutting, external dredging is used to gain access to the cutting area. For every additional meter of excavating depth below the seabed, the excavation hole will increase with at least two meters in diameter at the sea floor [Winds, 2007]. Depending on the required depth of cutting below the seabed, it should be evaluated whether this method is feasible or not.

Internal dredging is a method used for both complete and partial monopile removal. Internal dredging removes the internal soil from inside the monopile. The soil inside is loosened by a high-pressure jet that pumps a water air mixture into the soil. The air-water mixture is less dense than the surrounding liquid and therefore is displaced upwards through the discharge pipe. The solids are entrained into the flow and are sucked upward and discharged along with the flow. An airlift tool creates suction and the loosened soil is sucked out of the monopile.[Hinzmann et al. [2017]; Hinzmann et al. [2018]].

2.1.1.2 Diamond Wire Cutting

Diamond Wire Cutting (DWC) is a method used for external pile cutting. The DWC is an abrasive method that cuts the structure. An advantage that is can be used on almost any size, which makes this technique useful for the soon-to-be decommissioned monopiles as well as for the to be decommissioned monopiles in the future, since they will have a much larger diameter. On the downside, this method requires good access to the cutting area. Dredging or excavating techniques need to be applied first to gain good access to the cutting area.

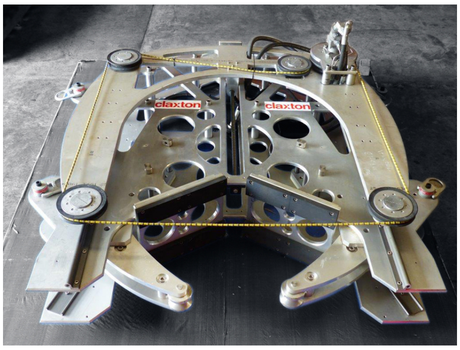


Figure 2.2: Diamond Wire Cutter [Claxton Engineering, 2021]

2.1.1.3 Abrasive Water Jet Cutting

Abrasive Water Jet Cutting (AWJC) can be used for both internal and external pile cutting. It uses high pressure water mixed with an abrasive at maximum 1000 bar. Hydraulic arms keep the tool at a fixed position inside the monopile. A cutting nozzle at the lower part of the tool is able to rotate 360°, performing the cut. The tool can be equipped with high resolution underwater cameras used during and after the cutting. A main advantage of this technique is that it can cut almost any material. Disadvantages are the relatively high costs and the hazard of components flying off and affecting the environment. The very high pressure used makes the use of this method a dangerous task. Unstable and changing weather conditions can be of high influence on using this method [Hinzmann et al. [2017];Topham and McMillan [2017]].

The hydro sounds emitted during internal AWJC were studied by Hinzmann et al. [2017]. The sound levels emitted are within the limiting values of hydro sound emission regulations for impact pile driving. However, regulations for sound emissions for decommissioning methods using vibrators or AWJC tools still need to be developed.

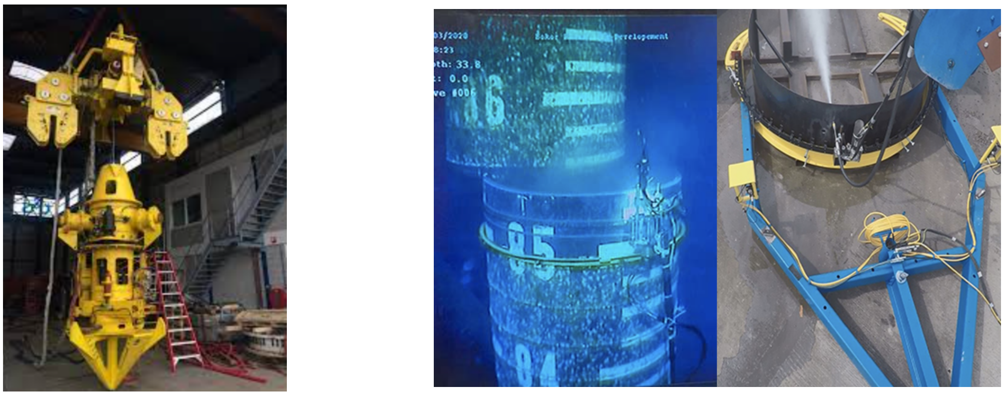

(a) Internal AWJC [TMS Supplies, 2021]
(b) External AWJC tool [Fisher offshore, 2021]

Figure 2.3: Abrasive Water Jet Cutting tools

2.1.1.4 Explosives

Papers by Bull and Love [2019] and Topham and McMillan [2017] describe the use of explosives used in the oil and gas industry. Compared to methods using explosives, the use of methods like AWJC and DWC is slow and may involve the use of additional personnel and equipment and they are therefore more costly. Explosives are used to cut tubular pipes, such as a monopile. The method has proven to be nearly flawless and reliable. A cylindrical explosive container is lowered down the monopile to the designated cut elevation and detonated from both ends. This creates a so-called collision charge. When the force of the detonation at the ends moves towards the middle, the force moves out horizontally when the two explosions collide. This force creates a cut in the pile [Bull and Love, 2019]. However, there is a massive downside to the use of explosives. Using explosives involves relatively high risks and more planning. Additionally, it causes more disruption to the marine environment including the risk of damage to marine mammals or fish kills near (meters) the blast zone compared to non-explosive methods.

2.1.1.5 Vibratory pile removal

According to Hinzmann et al. [2018], vibration is one of the most promising techniques for the decommissioning of offshore monopiles. The vibrating motion reduces the shear resistance on the pile shaft-soil interface. In the ideal situation a state of liquefaction is achieved by the continuous agitation of the soil surrounding the pile. Liquefaction is a state where the soil acts like a fluid-like substance. Previous to vibration, the voids between grains are filled with water. The grains are in contact with each other, the friction caused by these contacts keeps the sediments together. Once the soil starts to vibrate hard enough, the pore water pressure increases and the effective stress become zero. The pore water pressure is large enough to keep the particles apart and the soil acts like a liquid. This phenomena sometimes occurs during earthquakes and can cause significant damage. In reality, the shaft resistance is significantly reduced by applying vibration based on the same principle as liquefaction when installing and extracting monopiles.

In 2016, Offshore Wind Farm Lely was decommissioned using vibration technique. The 4 monopiles were 26 meters long and had a diameter of 3.20 up to 3.70 meters. Each pile was extracted from the soil in 45 minutes [Dieseko, 2016]. The Delft Offshore Turbine (DOT) also sees the use of vibration to decommission monopiles as a promising technique. One of their projects is focused on the extraction of a 4 meter diameter monopile. The offshore test phase for this project took place between 2018 and 2020 [van Dorp et al., 2021].

The advantages of using a vibratory hammer for the decommissioning of offshore structures are: the upending option, the self handling and pitching option causes significant time saving. The mechanics of a vibratory device and the soil behaviour under vibration will be discussed in more detail in Section 2.2.

Figure 2.4: Decommissioning Lely Offshore Wind Farm

2.1.2 Decommissioning Techniques Under Development

There are several studies on alternative decommissioning techniques[[Hinzmann et al., 2018];[GROW, 2022]]. Some of these techniques have been used and put to practice. Others are merely ideas and might be put to practice in the future. Alternative complete removal techniques are:

- Crane-uplift
- Internal Dredging
- Buoyancy Force
- External Jet Drilling
- Air-Pressure
- Press Construction
- Gentle Driving of Piles

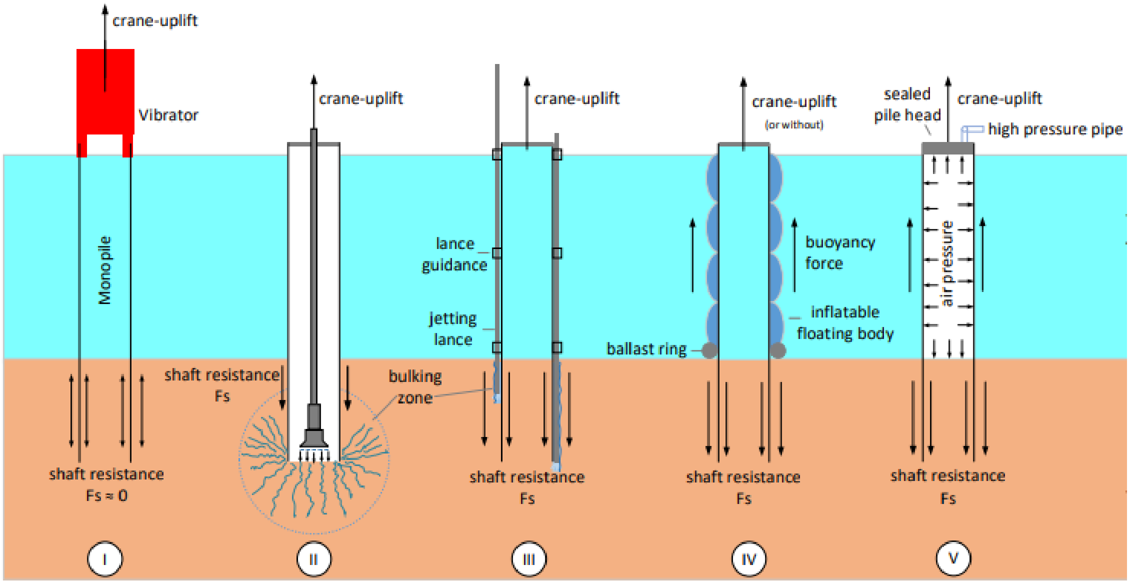


Figure 2.5: Possible Offshore decommissioning techniques [Hinzmann et al., 2018]

2.1.2.1 Crane-uplift

Crane-uplift is a theoretical method where the monopile is extracted from the seabed by pulling it upward with a crane.

2.1.2.2 Internal Dredging

Internal dredging is used for entire monopile removal in order to reduce the shaft resistance of the monopile. Additionally, a potentially formed soil plug can be removed. In case of rocks or other large hard obstacles that can not be dredged using the previously mentioned dredging method, a drilling tool can be placed at the suction end. As shown in Figure 2.5, the pile shaft resistance on the outside of the area above the pile toe can also be reduced if the dredging tool passes the pile toe, this way a bulking zone can develop [Hinzmann et al., 2018]. It should be noted that dredged the dredged soil should be utilized to shore and cannot be dumped back into the sea. Therefore, dredging costs can increase rapidly.

2.1.2.3 Buoyancy Force

Papers by Lehn et al. [2020] and Hinzmann et al. [2018] describe the decommissioning of a monopile using the buoyancy force. The total breakout resistance of the monopile can be overcome by using the buoyancy force. A tube of inflatable floating elements is pulled over the pile. While inflating the floating elements, the pile and the floating elements are more rigidly connected. Eventually, the buoyancy force pulls the monopile out of the seabed. The stress conditions in the soil and the pending soil should be taken into account.

Figure 2.6 schematically represents the set up of using the method. The buoyancy force needs to be large enough to overcome the shaft resistance, the mass of the pile and the mass of the system combined [Lehn et al., 2020].

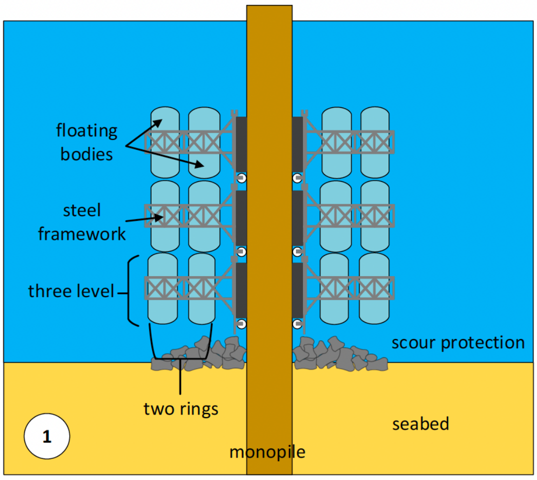


Figure 2.6: Initial phase of the buoyancy method [Lehn et al., 2020]

The main advantage of using the buoyancy method is the flexibility of the method. Additionally, the construction can be reused for the decommissioning of other wind turbines or even other wind farms. Another great advantage is that most of the preparations for using this method can be done on shore and only little work has to be done offshore. This will lower the costs of the use of highly expensive vessels. The costs of vessels can also be reduced by towing the monopiles to shore using much smaller and cheaper vessels than used in other methods. Finally, the removal of scour protection is not necessary in order to apply this method. Again saving time and money [Lehn et al., 2020].

2.1.2.4 External Jet Drilling

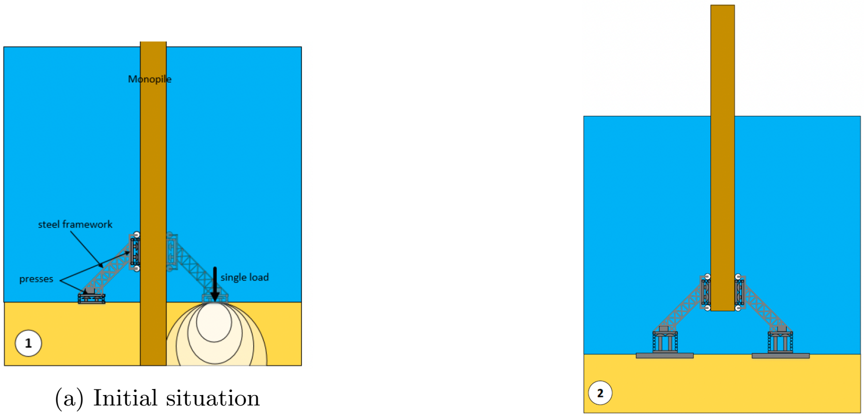
External jet drilling is a method used for partial removal. The jet drilling is used to loosen the particle structure along the external pile surface. This causes a reduction in the soil resistance [Hinzmann et al., 2018]. In case of partial removal, the soil is loosened up to a few meters below the seabed, where the cut is made. The reduction of soil resistance causes the lifting force required for extraction to decrease. However, this method can theoretically also be used for complete removal. If the soil is loosened up to the tip of the pile, the pile can be extracted completely. GBM works is a company that investigates the possibility of installing monopiles using the principle of reducing soil resistance along the shaft using jets. They claim to be able to install monopiles in a silent, efficient and fast way using a combination of water injection along the inside of a pile and a vibrating pile tip. Up to now, demonstrations have shown that a combination of these two principles results in a deeper and faster penetration than traditional piling methods. The method of GBM works has great potential, both for installation and decommissioning. The goal of the company is to have introduced and established this method of installing monopiles in the sea by 2025. Research on the possibility of the complete removal of monopiles using this technique might prove to be very useful for the future of decommissioning offshore wind farms.

2.1.2.5 Pressure

The use of water- or air-pressure can also be used to overcome the soil resistance. The pile head needs to be sealed, as well as all other existing holes and gaps. As pressure is created in the sealed monopile, an extraction force is created. If the pressure inside the pile is larger than the pile resistance, the monopile is pushed out of the seabed. The monopile needs to be guided and clamped by a gripper. If the pressure inside the monopile is not large enough, extracting the pile using a crane can speed up the process [Hinzmann et al., 2018]. A down side to this method is that sealing the pile requires more offshore activity compared to alternative methods, which leads to increasing costs. Hydraulic Pile Extraction is a method developed by GROW which uses water-pressure for complete removal. Scale tests for various soil configurations have shown promising results. The break-out pressure observed during the experiments was strongly depended on the soil type and soil configuration. Especially a soil layer with low permeability has a large effect on the required break-out pressure. According to GROW, this method becomes more efficient as the diameter of the pile increases. Therefore, this technique might be very promising for the future of decommissioning monopiles GROW [2020].

2.1.2.6 Press Construction

A method developed by Lehn et al. [2020] is the press construction method. This method is based on the principle of a force pressing the pile out of the soil. Figure 2.7a shows a schematic representation of this method. The skin friction of the pile is increase by the stress distribution caused in the soil from the press, as can be seen in Figure 2.7a. The press construction method will extract the monopile leading to the situation as shown in Figure 2.7b. The advantage of this method is that the speed can easily be regulated and that any high press forces can be used. However, there are more disadvantages. The dimensions of the structure are very large and due to the small stroke, many presses and lifting operations have to be performed in order to extract the monopile from the sea bed, resulting in a time consuming and therefore costly method [Lehn et al., 2020].



(a) Initial situation

(b) Final situation

Figure 2.7: Press construction [Lehn et al., 2020]

2.1.3 Gentle Driving of Piles

The method of Gentle Driving of Piles (GDP) aims to develop an installation method that is based on the simultaneous application of low and high frequency vibrators which excite in two different modes of motion on the monopiles. This method reduces the driving loads and the emitted noise during installation. The GDP method could also be used as a decommissioning method. In 2019, a full-scale test has been performed at Maasvlakte. A large-size pile has been successfully installed and removed from the soil using the prototype GDP tool. Currently, project teams is working on the upscaling of the GDP technology to large-size monopiles. This method could help realise fast en quite complete removal of monopile.

2.1.4 Rules and Regulations for Decommissioning Offshore Structures

According to Januário et al. [2007] many countries apply the offshore oil and gas procedures, rules and regulations to the offshore wind sector. The whole decommissioning process for offshore wind farms is insufficiently regulated and lacks relevant guidelines for recommended practices [Topham et al., 2019]. Januário et al. [2007] state that the countries that do have rules and regulations regarding decommissioning have based them on on the OSPAR convention and the UNCLOS convention. The OSPAR convention is the convention for the Protection of the Marine Environment of the North-East Atlantic [Commission, 1998]. It provides guidance to the European Commission and 15 European Countries on the construction of farms as well as on the environmental impact assessment and decommissioning. The UNCLOS convention is the United Nations Convention on the Law of the Sea. It entered force in 1994 and was agreed to by the European Community and most of the Member States. Article 60(3) of the UNCLOS convention states that:

Any installations or structures which are abandoned or disused shall be removed to ensure safety of navigation, taking into account any generally accepted international standards established in this regard by the competent international organization. Such removal shall also have due regard to fishing, the protection of the marine environment and the rights and duties of other States. Appropriate publicity shall be given to the depth, position and dimensions of any installations or structures not entirely removed.

The OSPAR decision 98/3 is on the disposal of disused offshore installations [Commission, 1998]. The decision 98/3 prohibits the dumping or leaving in place of installations in the marine environment. One of the rules following from decision 98/3 is that the minimal water clearance above any partially removed structure is 55 meter and the pile cute should be made at least 3 meters below the natural seabed. In addition, all steel installations weighing less that 10.000 tonnes in air must be completely removed from the marine environment [Department for Business, 2018].

The literature research performed prior to this research has shown that all the available decommissioning programmes of offshore wind farms plan on partial decommissioning the wind farms at their end-of-life. Most of the seas in Europe are subjected to UNCLOS. In addition, monopiles weigh well below 10.000 tonnes. Therefore, based on the OSPAR convention, all monopiles should be completely removed. However, due to a lack of enforcement power there are significant challenges in implementation and enforcement of the UNCLOS convention. Resolution A.672(16) of the International Maritime Organisation (IMO) guidelines and Standards for the Removal of Offshore Installations and Structures on the Continental Shelf and in the Exclusive Economic Zone [Lowe and Talmon, 2009] state the following: All abandoned or disused installations or structures standing in less than 75 m of water and weighing less than 4,000 tonnes in air, excluding the deck and superstructure, should be entirely removed. An on or after 1 January 1998, standing in less than 100 m of water and weighing less than 4,000 tonnes in air, excluding the deck and superstructure, should be entirely removed; The means of removal or partial removal should not cause a significant adverse effect on living resources of the marine environment, especially threatened and endangered species; The coastal State may determine that the installation or structure may be left (partially) in place if it will serve a new use such as enhancement of a living resource; Where entire removal is not technically feasible, would involve extreme cost, or an unacceptable risk to personnel or the marine environment, the coastal State may determine that it need not be entirely removed; Any remaining materials on the sea-bed may not move under the influence of waves, tides, currents, storms or other foreseeable natural causes so as to cause a hazard to navigation; On or after 1 January 1998, the design and construction of the installation or structure is such that entire removal upon abandonment or permanent disuse would be feasible.

Figure 2.8 displays the average water depth, distance to shore and size of the offshore wind farms in Europe. The size of the circle, represents the size of the wind farm. Based on the above regulations this implies that a very large portion of the wind turbines should be removed completely.

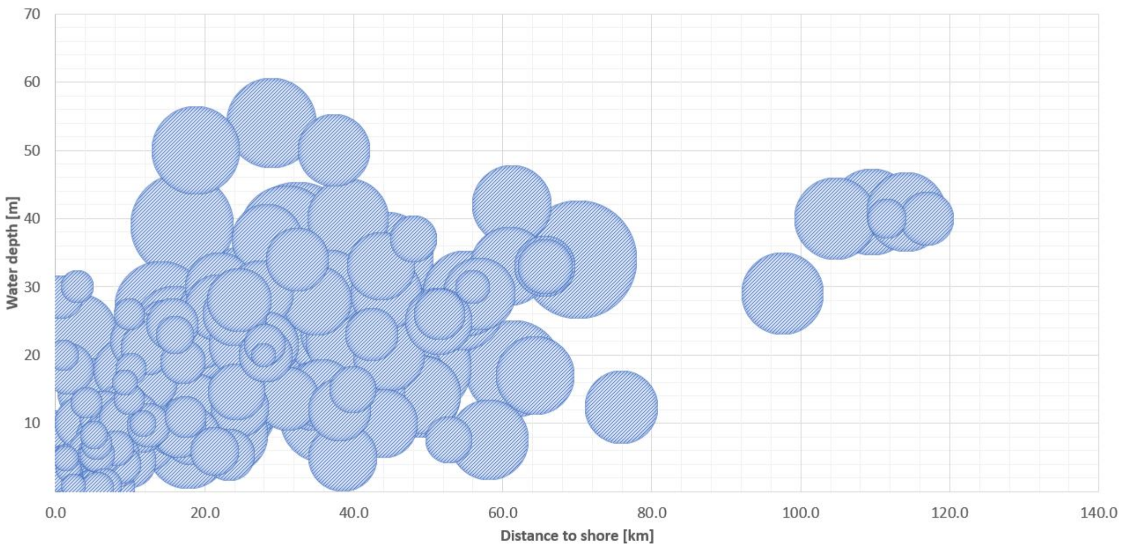


Figure 2.8: Average water depth, distance to shore and relative size of offshore wind farms in Europe

[4C Offshore]

However, in practice partial removal is the suggested decommissioning method [Statoil [2014]; Winds [2007]; OFTO [2013]]. And the previously decommissioned wind farms have mostly been decommissioned partially. Since UNCLOS does not require complete removal and the IMO guidelines and the OSPAR guidelines provide exception being made, most wind farm owners opt for partial removal Smyth et al. [2015].

Januário et al. [2007] states that the European Commission should take action to avoid future duplication of regulation. An international initiative is needed with binding minimum standard for the decommissioning of offshore wind farms. In addition, the paper states that the OSPAR guidelines should be adapted for this matter. Meaning that the remains of offshore installations should be removed unless there are strong reasons not to.

2.1.4.1 Rules and Regulations for pile removal in The Netherlands

The Dutch Ministry of Infrastructure and Water Management (Rijkswaterstaat) is currently developing guidelines for the decommissioning of offshore wind farms. The rules that apply to date are that the decommissioning has to start after maximum two years after shutdown and has to be finished at maximum 30 years after when the wind permit became irrevocable [Guides, 2018]. The scour protection can remain in place in order to enhance the artificial reefs. Whether the foundations and cables should be removed partially or completely is under discussion [Vattenfall, 2021].

2.1.4.2 Rules and Regulations for pile removal in Denmark

In the Danish law there are no specific requirements stated regarding the decommissioning of offshore wind farms. The environmental requirements will have to be assessed at the time of decommissioning. Whom ever is responsible for the decommissioning is regulated in the construction license of the wind farm. Usually the owner of the wind farm is obliged to restore the area to its original condition. In addition, the construction licence might state that the owner has to prepare a decommissioning programme that has to be approved by the Danish Energy Agency [Guides, 2017]. The scour protection may be left *in situ* or it may be removed. The cables should be removed from the site or they may be left *in situ* if they are burried safely. The foundations can be partially removed [Vattenfall, 2021].

2.1.4.3 Rules and Regulations for pile removal in The United Kingdom

In the UK the Department of Energy and Climate Change has developed a guidance on using the decommissioning scheme for offshore wind and marine energy installations based on the Energy Act 2004. The Department of Energy & Climate Change [2011] states that complete removal is preferred. However, partial removal may be considered. The decision for partial or complete removal will always be made on a case-by-case basis. Partial removal is considered if:

- Structures will be reused for renewable energy generation
- Structures will serve a purpose beyond renewable energy generation
- Foundations and structures are below sea bed level: *where an installation's foundations extend some distance below the level of the sea-bed, removing the whole of the foundations may not be the best decommissioning option, given the potential impact of removal on the marine environment, as well as the financial costs and technical challenges involved. In these cases, the best solution might be for foundations to be cut below the natural sea-bed level at such a depth to ensure that any remains are unlikely to become uncovered. The appropriate depth would depend upon the prevailing sea-bed conditions and currents. Contingency plans should be included in the decommissioning programme, to describe the action proposed if the foundations do become exposed.*

The methods of removal are also described in of Energy & Climate Change [2011]. The method should have regard to the best practicable environmental option, safety of surface and subsurface navigation, other uses of the sea and health and safety considerations.

2.2 The Basic Principles of Vibratory Pile Removal

This chapter discusses the basic principles of a Vibro Lifting Tool (VLT) and their specifications. In addition, this chapter focuses on the behaviour of soils under vibration and the effect this has on a reduction in soil resistance.

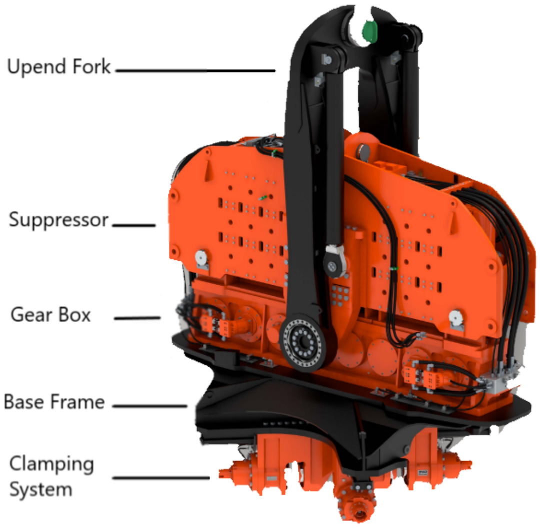


Figure 2.9: Vibro Lifting Tool

2.2.1 Working Principle of Vibratory Pile Removal Tool

Figure 2.9 displays a VLT from CAPE Holland. The eccentric masses within the gearbox generate the vibration. The suppressor minimizes the vibrations from the gearbox going into the crane by using dampers. The clamps at the bottom of the tool are used to form a rigid connection between the pile and the VLT. No extra horizontal support is needed due to these clamps. A gripper frame is no longer needed using this method, saving money, lowering offshore working time and saving deck space. The Upend Fork is used to rotate the tool. This way the VLT can be used to put the pile in a horizontal position on the deck after decommissioning.

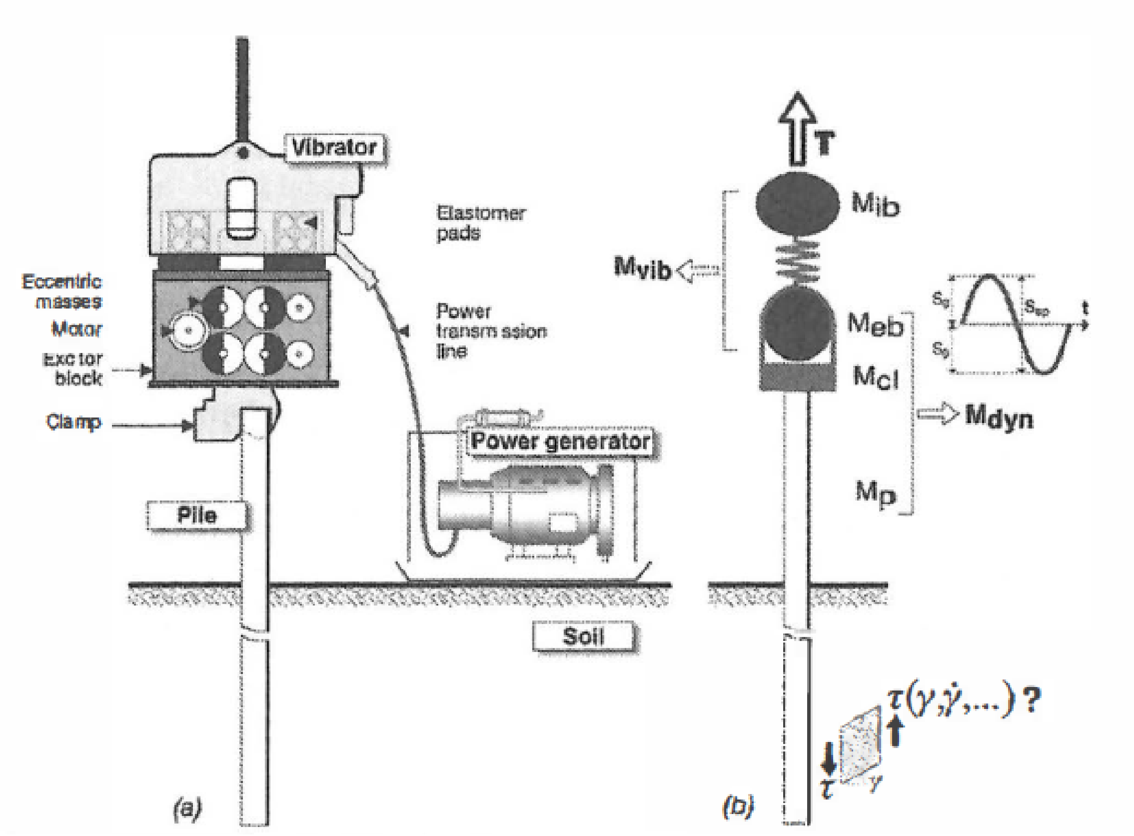


Figure 2.10: Mechanical action of a vibrator [Holeyman, 2002]

The vibratory action is generated by the counter-rotating eccentric masses. An even number of symmetrically moving masses results in a sinusoidal vertical forces $F_v(t)$, given in Equation 2.1. Where m_e is the eccentric mass off the vibrator in kg.m., where ω is the angular frequency of the vibrator in rad/s and where F_c is the maximum centrifugal force of the vibrator. The center of gravity of the masses remains at the neutral axis. As these masses are counter-rotating they cancel each other out in the horizontal direction and enhance each other in the vertical direction, leading to a purely longitudinal force [Holeyman, 2002]. The vibrator tool can be seen as a system with two degrees of freedom, as displayed in Figure 2.10 [Holeyman, 2002].

$$F_v(t) = me\,\omega^2 \sin\omega t = F_c \sin\omega t \tag{2.1}$$

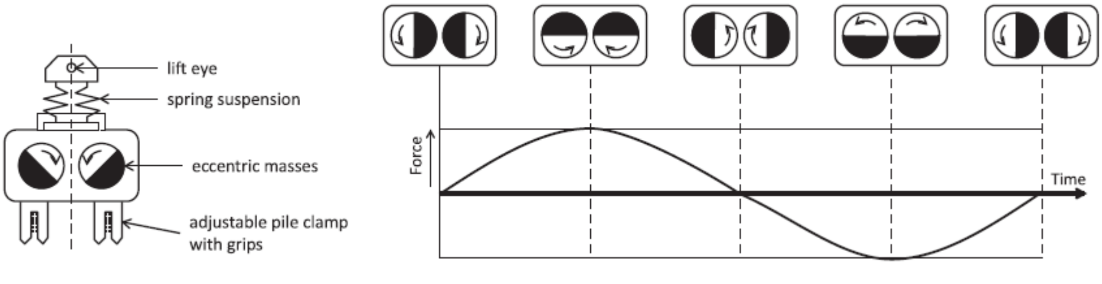


Figure 5.6-18 Working principle of a vibratory hammer

Figure 2.11: Working principle of a vibratory device [Vugts and Zandwijk, 2016]

VLT's have various parameters such as the eccentric moment, the maximum centrifugal force and the maximum amplitude. The eccentric moment M_e is dependent on the individual eccentric masses, the gravitational constant g and r, which is the distance between the centre of gravity of that individual mass and the axis of rotation in meters [Vugts and Zandwijk, 2016].

$$M_e = \sum_n m_e\, g\, r \tag{2.2}$$

The maximum centrifugal force F_c in N is dependent on m_e, r and ω, which is the rotational speed of a mass in rad/s.

$$F_c = \sum_n m_e\, r\, \omega_2 \tag{2.3}$$

The maximum amplitude A in m is dependent on M_e, g, the mass of the vibrating part of the hammer in kg m_c and m_p, which is the mass of the pile in kg.

$$A = \frac{M_e}{m_e\, g + m_p\, g} \tag{2.4}$$

The frequency at which the VLT vibrates is chosen to be close to the natural frequency of the pile-hammer system [Vugts and Zandwijk, 2016]. Where that natural frequency f_n is given by Equation 2.5. k is the spring constant in N/m, calculated using Equation 2.6. k is dependent on the modulus of elasticity of the monopile E in N/m^2, the cross-sectional area of the pile A_p in m^2 and the equivalent pile length l_{eq} in m. l_{eq} is taken as half the pile length[Vugts and Zandwijk, 2016].

$$f_n = \sqrt{\frac{k}{m_e + m_p}} \tag{2.5}$$

$$k = \frac{EA_p}{l_{eq}} \tag{2.6}$$

The diameter of the monopiles increases rapidly. The VLT already available are well suited for the piles that need to be extracted in the near future. As the diameter increases over the coming year to the so-called XXL monopiles with diameters larger than 10 meters are being installed. For the purpose of installation of larger monopiles, larger tools are designed. These VLT can be used for the decommissioning as well. As the tools are designed for the installation of the large diameter monopiles of today, they will be powerful enough for the relatively small diameter monopiles that have to be decommissioned in the near future.

Nowadays a large portion of the wind farms have a flanged connection between the transition piece and the monopile. Older monopiles have grouted connection in most cases. The VLT's often have the option to come with flange connections instead of offshore clamps. Standard offshore clamps can simply be placed on the monopile, whereas a flange clamps require a flange. The use of flange clamps slightly increases the dynamic weight and the total weight of the VLT, the other parameter remain the same. The currently available tools lead to a limit for F_{ext} of 2000 mT if there is no flange available. However, this is not a hard limit and therefore it is not taken into account in this research. The tools can be modified by using materials on the clamps with different friction coefficients. Since the monopile are being removed, damaging the piles will not lead to any trouble. The limit is a tool limitation and is the maximum line pull that can be exerted on the VLT.

2.2.2 Soil Behaviour Under Vibration

The soil resistance along the shaft of the pile is reduced due to the vertical motion of the pile. The soil behaviour under vibratory loading have been studied by Vucetic [1994] and Holeyman [2002].

The vertical motion induced in the pile due the vibration causes action in the neighboring soil shear stresses and shear strains. The static and cyclic stress-strain behaviour of a soil subjected to uniform cyclic strains is displayed in Figure 2.12. Where G_{max} is the initial shear modules, where τ_c is the shear stress at amplitude γ_c, where G_S is the secant shear modulus, where u is the pore water pressure and where N is the number of cycles. In Figure 2.12 these values are given for the first loop and for the Nth loop. It can be seen that the ultimate shear strength τ_{max} and G_{max} decrease for an increase in N, this is reffered to as soil fatigue[Holeyman, 2002].

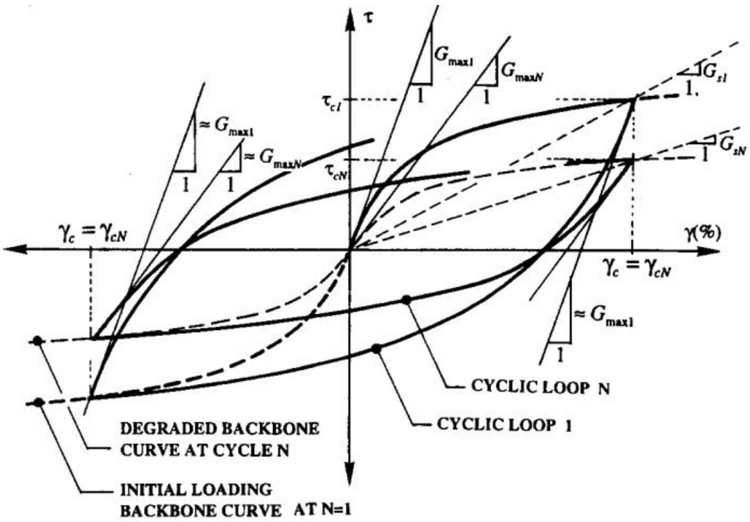


Figure 2.12: Soil behaviour under cyclic strain controlled simple shear test [Vucetic, 1994]

The vibration of the pile shears the soil back and forth, causing the particles to achieve a denser packing. This leads to a volume reduction. This volume reduction is immediate under drained conditions. In undrained conditions, the tendency for volume reduction causes an increase in the pore water pressure. This increase leads to an effective stress that is close to zero. The soil behaves in a fluid-like manner, called soil liquefaction [Holeyman, 2002].

As the weight of the monopile increases, so does the embedded length and thus the energy required to induce vertical vibration. The pulses of energy that are transferred from the VLT and the pile to the soil travel away from the pile will in three different types of waves. These waves being P-waves, S-waves and R-waves. P-waves are compression waves that are associated with a change in volume. S-waves are shear waves that involve distortion of the soil without a change in volume. R-waves are Rayleigh waves that radiate cylindrical away from the point of excitation whereas the P- and S-waves radiate hemispherically. These three waves change the stress-strain behaviour and other characteristic of the soil as they propagate through the soil, each at their own speed [Jonker, 1987]. In granular soils the stress waves cause continuous movement of the individual soil particles. This will reduce or even completely eliminate their contact pressure. The pile friction will be reduced to only a fraction of its maximum static value. In cohesive soils these waves will increase the pore pressures and reduce the friction. The soil failure is a result of loss of internal friction and or a built-up of excess pore pressure [Jonker, 1987].

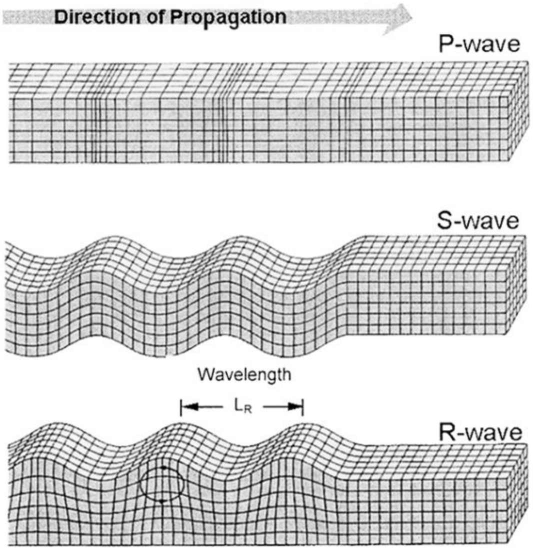


Figure 2.13: Types of seismic waves [Athanasopoulos et al., 2000]

2.2.3 Resonance Due to Vibratory Extraction

Resonance is a phenomenon that occurs when the frequency of an applied periodic force is equal or close to the natural frequency of the system. The system will oscillate at a higher amplitude than when the same force is applied at a different frequency. The frequencies at which this occurs are the so called resonance frequencies. Resonance is an unwanted phenomena during vibratory extraction. The VLT is designed not to have any natural frequencies in the range at which it will operate, which is in the range of 15 up to 25 Hz. However, the tool is connected to other systems. The system of the crane can have a natural frequency that lays within this range.

The VLT has a dynamic and a static part. The dynamic part is rigidly connected to the pile using clamps. There are suppressors between these two parts, that damps vibrations travelling from the dynamic part to the static part. As the tool starts or shuts down, it goes from zero to the operating frequency. It is possible that the resonance frequencies of a system connected to the VLT lay in this range. Under these circumstances, the crane or the crane drivers cabin starts to resonate. This is a highly unwanted situation, since it can be dangerous to personnel, it can damage the equipment, the crane and the vessel. Therefore, to avoid resonance, it is important to quickly get though this range up to a high enough frequency. This can be compared to starting or shutting down a car. During the start and a shut down, the frequencies quickly ramp up to above the resonance frequencies. But slight vibrations can be felt as the motor goes through these frequencies.

Another situation can cause resonance during extraction with a VLT. In order to avoid resonance, the tool should be able to vibrate the soil a while prior to applying an extraction force. Once the tool is started, it takes a couple of minutes before soil fatigue has occurred along the whole shaft. Once this has happened, the hook load on the crane starts to go up, since gravity tries to lower the pile into the soil. Once a large portion of the weight of the pile is in the crane, the pile can be extracted. If an extraction force is applied directly after starting the tool, the soil fatigue has not occurred yet. The monopile has to much resistance and is still stuck in the ground. If an extraction force is applied while the pile is still stuck in the soil, the vibrations cannot vibrate the pile and they will travel upward into the crane. It should be noted that the tools are designed in such a way that resonance will not occur. It is highly unlikely that if the tools are used as they are designed to and if all mechanisms work as designed, resonance will not occur.

2.2.4 Connection of the Transition Piece

The Transition Piece (TP) connects the monopile to the wind turbine tower, as shown in Figure 2.14. There are various ways in which the TP can be connected to the monopile. The two main types are a grouted connection or a bolted connection. There are also TP-less connections, where no transition piece is needed to connect the tower to the monopile. To date, a bolted or a TP-less connection is the most common connection used during installation. The older wind farms all have grouted connections, since the TP-less and bolted connections were not developed when these wind farms were installed. The type of TP connection is of influence on the decommissioning of the monopile with complete removal with a VLT. If there is a grouted connection, a cut has to be made below the transition piece. If the connection is TP-less or bolted, the VLT can be placed directly on the flange of the monopile after the tower or the transition piece has been removed. The effect of the extra time and costs involved in having to perform a cut when a grouted connection is present, is discussed in chapter 4.

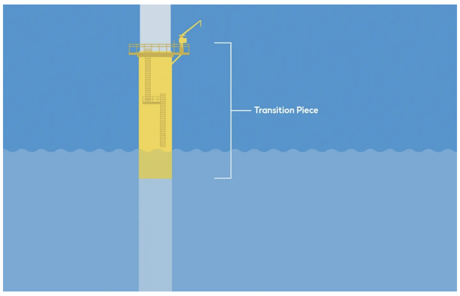


Figure 2.14: Transition Piece [Ørsted]

2.3 Noise Mitigation During Decommissioning

The potential environmental impacts of the decommissioning of offshore wind farms are less understood. According to Hall et al. [2020], the environmental impacts can not simply be defined by thinking it is simply a reversal of the construction phase. Introducing something into the marine environment is not the same as removing it. Therefore, mitigation measurements taken during the construction phase may not be appropriate or sufficient for the decommissioning phase. A lot of research has been done on the environmental impacts of the constructional and operational phase, but not so much on decommissioning [Diederichs et al., 2008]. Since, not many wind farms have been decommissioned so far, not much data is obtained. Therefore, it is of great importance to obtain as much data on the impact on marine life during decommissioning. The impact radii of the methods used need to be estimated in order to prevent the damage to marine mammals, to optimize the mitigation measures, to plan monitoring activities and to select the reference sites not influenced by activities. In addition, the environmental impacts should be well analysed during the planning phase of the wind farm. This will lead to the consenting authority to make an informed decision based on the impact that a certain decommissioning method will have [Hall et al., 2020].

Diederichs et al. [2008] describe the methodologies for measuring the changes in marine mammal behaviour, abundance or distribution arising from the decommissioning of offshore wind farms. Noise emissions from the construction, operation and decommissioning phase of an offshore wind farm can, under specific conditions, potentially harm marine mammals. This is due to the fact that sound waves have the ability to travel very well in water and therefore they can have an impact over a large distance. When using a noise mitigation system, the likelihood of the impact decreases. It should be noted that these studies are based on impact driving rather than on vibratory methods. The noise emitted and therefore the impact on the marine environment and the marine mammals is much lower compared to impact based methods. Whether the noise emitted during decommissioning using vibratory pile removal is strong enough to cause harm to marine mammals is yet to be researched.

Whether sound affects marine mammals is dependent on the loudness of the source and the frequency. A risk assessment should be made in order to check whether marine mammals are indeed affected by, in this case, sound emissions due to decommissioning. To investigate this, the following information needs to be gathered: The sound characteristics such as frequency, sound level and rise time of the emitted sound; the sound field of the source; the marine mammals likely to be in the area and whether these marine mammals are able to detect the sound emitted and the effects on them [Knowlton, 2017]. When vibration is used there is a continues sound emission.

As described by Diederichs et al. [2008], there are several types of effect on marine life. Firstly, hearing loss, discomfort or injury. Secondly, masking, which occurs when the signals that are of biological significance for hunting an communicating interferes with the signal emitted by decommissioning activities. This is called masking and it occurs when both signals have similar frequencies. Finally, the response in behaviour of mammals due to sound emissions or activities. This is regarded to as disturbance.

The impacts on the marine life are challenging to predict, since these impacts are dependent on a large number of factors. The factors being e.g. the acoustic qualities of the sound source, the oceanographic conditions in which the sound is produced, the hearing abilities of the species of interest and the behavioural context in which the marine mammals receive the sound [BOEM, 2020].

The environmental impacts of decommissioning may adversely dependent on the location of the offshore wind farm and on the decommissioning method used. However, the impacts that have been identified for and during the commissioning phase are likely still accurate. The disturbance of the seabed is unavoidable and therefore the turbidity will increase during decommissioning work [Hall et al., 2020].

The effects of vibration on organisms living in or on the seabed, benthic organisms, have not been studied. These organisms are for example starfish, worms, sea cucumbers and sea urchins. A noise mitigation system does lower the environmental impact in the water column. However, it does not lower the vibrations in the soil. The effect of vibration on these benthic organisms should be studied in more detail to get a clear picture of the environmental impact.

2.3.1 Bubble Curtains

In order to reduce the impact of noise emissions during decommissioning (and construction) mitigation measurements have been developed. A widely used mitigation measurement is the use of bubble curtains. A layer of air bubbles is created over the full length of the pile. Compressed air is pumped through a perforated hose which is positioned on the seabed around the pile. There are types of bubble curtains, big bubble curtains and small bubble curtains. Big bubble curtains enclose the entire construction site and are used at a radial distance between 70 and 150 meters from the pile. Another secondary mitigation measurement is the small bubble curtain, which is placed in the vicinity of a pile. The advantage of using the small bubble curtain is that no auxiliary vessel is needed to deploy the bubble curtain. Besides bubble curtains, hydro sound dampers can be used. The method is comparable to the small bubble curtain. However, the air bubbles are replaced by air filled balloons or foam elements of different sizes. The sound damping efficiency can be enhanced by adjusting the number and the composition of the elements in order to suit the peak frequencies of the emitted noise [Federal Ministry for the Environment, Nature Conservation, 2014]. Note that the bubble curtains experience effect form currents and tides, this influences the path of the bubbles.

It should be noted that an extra ship is needed to deploy the bubble curtains. Operating this vessel will result in additional CO_2-eq. emissions. In order to push the pressurised air thought the bubble curtain, green house gasses are emitted. The use of a bubble curtain does reduce the direct environmental impact on for example the marine mammals. However, there are additional CO_2-eq. emissions related to using such a system. In addition, currents can strongly influence the bubble curtain. If the current is to strong, the bubbles may not cover the intended radius.

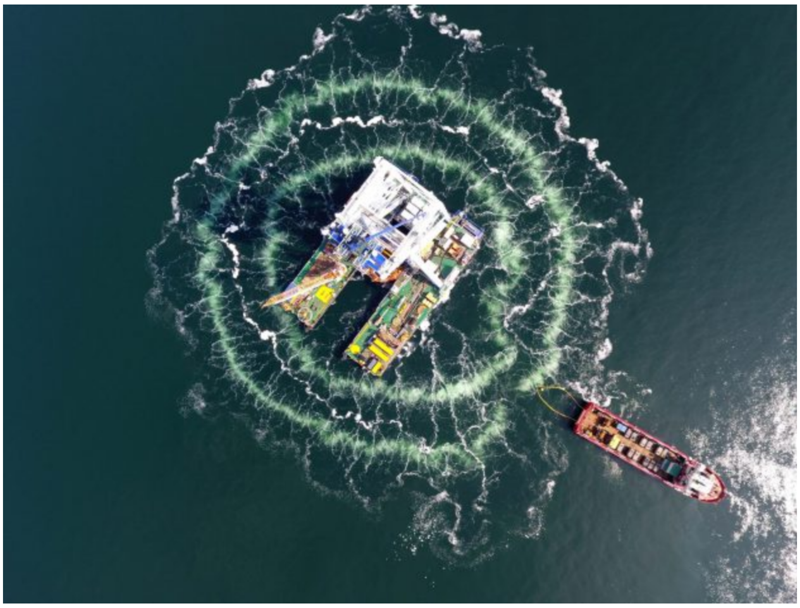


Figure 2.15: Big Bubble Curtain [Ramirez et al., 2021]

2.3.2 Noise Mitigation Screen

A Noise Mitigation Screen (NMS) is a noise mitigation system that consists of a double-walled steel cylindrical shell and it is shown in Figure 2.16. The NMS is placed around the to be decommissioned monopile. The space between the NMS and the monopile is filled with air. In case the NMS does not result in a sufficient noise reduction, the system can be combined with a bubble curtain.

Figure 2.16: Noise Mitigation Screen from IQIP [IQIP]

2.3.3 Noise Abatement System

The Noise Abatement System (NAS) is a system developed by AdBm Technology. The method absorbs the sound, where other methods merely contain the sound emitted. The system uses large arrays of Helmholtz resonators that are tuned to specific frequencies to capture and mitigate noise from various noise sources. Many resonators are placed upside down in the water, trapping air inside the cavities [Wochner, 2019]. Figure 2.17 displays such a system. The system can be deployed withing 10 minutes to a water depth of 40 meters.

Figure 2.17: Noise Abatement System from AdBm Technology

Using a VLT to extract a monopile emits a continuous sound on a specific frequency. The NAS can be tuned to this frequency, therefore this method has proven to be very effective. Using the NAS is the preferred option when using vibration offshore. Therefore, the noise mitigation system used in the model is the NAS. The NAS reduces the noise emissions with 8 up to 12 dB.

In the following chapters the offshore time, the costs and the emissions related to three different decommissioning scenarios are calculated. One of these scenario is complete removal using a VLT without noise mitigation and another scenario is that of using a VLT in combination with the NAS. Based on direct environmental impact, using a noise mitigation system is the preferred option. However, it is important to look a the bigger picture. Therefore, the effects on time, costs and emissions are calculated.

Chapter 3

Modelling the Extraction Force Required for a Complete Removal Using Vibratory Pile Removal

In order to determine the extraction force F_{ext} required for complete removal using vibratory pile removal, a soil-structure model is developed. The model is used to research the technical feasibility of the decommissioning method. This present chapter describes the development of the model and displays the results. The main focus of this thesis is to investigate the feasibility of using the VLT to completely remove the soon-be-decommissioned wind farms from Table 1.1. The smallest diameter is 4.0 m and the largest diameter is 5.0 m.

3.1 Developing a Soil-structure Interaction Model

3.1.1 Vibro Lifting Tools in the model

The VLT's used in the model are the tools of CAPE Holland. Their specifications are displayed in Table 3.1. The various tools are constructed by putting blocks with an M_e of 320 kgm or 640 kgm, where a single 320 VLT consist of one 320 block and where a triple 640 VLT consists of three 640 blocks and therefore has an total M_e of 1920 kgm. The maximum line pull is the maximum force that can be exerted on the VLT, which is very relevant for the extraction of piles. This relevance will be discussed in more detail in Section 3.1.3.

Table 3.1: Specifications of Vibro Lifting Tools

		Single	**Tandem**	**Tripple**	**Quad**
CAPE VLT-320	**excentric moment [kgm]**	320	640	960	1280
	max linepull [mT]	500	1000	1500	2000
CAPE VLT-640	**eccentric moment [kgm]**	640	1280	1920	2560
	max linepull [mT]	500	1000	3000	4000

3.1.2 Generic Monopile Sizing

A paper by Arany et al. [2017] gives the dimensions of monopiles as given in Equation 3.1, Equation 3.2 and Equation 3.3. These formulas are used to generate the input for the calculations performed. As a rule of thumb, the embedded length of the pile L_{emb} is taken as one third of L_{mp}.

$$WT_{mp} = (6.35 + 10d_o) \cdot 10^{-3} \tag{3.1}$$

$$L_{mp} = 14d_o - 17 \tag{3.2}$$

$$L_{emb} = \frac{1}{3}L_{mp} \tag{3.3}$$

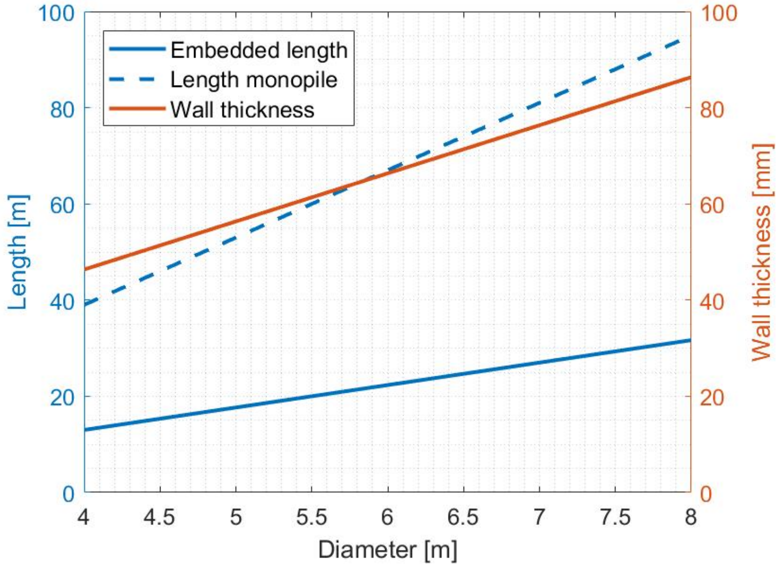


Figure 3.1: Dimensions monopile

Marine growth is the attachment of organisms such as shellfish to offshore structures. It has an effect on the weight of the monopile. The marine growth thickness t_{mg} in the Central and Northern North Sea up to a depth of 40 meters below mean water level is 100 mm. Below 40 meters the marine growth is 50 mm [DNV, 2016]. The weight of the monopile m_{pile}, including the marine growth, is given in Equation 3.4. It is assumed that marine growth only occurs on the outside of the monopile an above the mudline, up to the water level. z_{water} is the average water depth, which is taken to be 14 m in this report.

$$m_{pile} = \frac{(D_o^2 - D_i^2)\pi}{4}\rho_{steel}\, L + \frac{((D_o + t_{mg})^2 - D_o^2)\pi}{4}\rho_{mg}\, z_{water} \tag{3.4}$$

3.1.3 Modelling of Forces Acting on the Structure During Extraction

The force F_{ext} needed to extract a monopile must be large enough to overcome the downward force, Equation 3.5 [Vugts and Zandwijk, 2016]. The upward force is equal to the force with which the crane pulls the monopile, also referred to as the line pull. The downward force consists of three components, the soil resistance during vibration R_v, gravitational forces due to the pile weight W_{pile} and gravitational forces due to the weight of the VLT W_{VLT}. The soil resistance is related to the shaft resistance acting on the inside and the outside of the pile. These are the so-called the inside shaft resistance $Q_{s,i}$ and the outside shaft resistance $Q_{s,o}$. This chapter shows the calculations of these forces.

$$F_{ext} > R_v + W_{pile} + W_{VLT} \tag{3.5}$$

The line pull needed to extract the monopile from the soils increases as the weight of the VLT increases. This force, W_{VLT} is calculated by multiplying the weight of the VLT times g, as shown in Equation 3.7. Table 2 in the Appendix displays the weight of the various VLT's considered in this thesis.

$$W_{pile} = m_{pile} \cdot g \tag{3.6}$$

$$W_{VLT} = m_{VLT} \cdot g \tag{3.7}$$

3.1.3.1 Shaft Resistance

The outside shaft resistance $Q_{s,o}$ and the inside shaft resistance $Q_{s,i}$ are calculated using Equation 3.8 and Equation 3.9 [Vugts and Zandwijk, 2016]. The unit skin friction $f(z)$ is dependent on the type of soil and the depth z. Two methods for calculating $f(z)$ are used, one for cohesive soils and one for non-cohesive soils. A non-cohesive soil is a granular soil where the grains do not stick together but remain separate, such as sands. A cohesive soil is a fine grained soil in which particles tend to stick together, such as clays and silts. The effective unit weight γ' is calculated using Equation 3.12. For cohesive soils $f(z)$ is calculated using Equation 3.10. The adhesion factor α, given in Equation 3.13, is dependent on the consolidation factor Ψ, given in Equation 3.11. For non-cohesive soils $f(z)$ is calculated using Equation 3.14. Where f_{lim} is the limit skin friction in kPa. At large values of z $f(z)$ no longer increases linearly, therefore Equation 3.14 is limited to a maximum value of f_{lim} [Vugts and Zandwijk, 2016]. When calculating Q_{so} and Q_{si} for complete removal Equation 3.14 does not hold, since z is to large. Therefore, $f(z)$ needs to be calculated using Equation 3.15. Where p_a is the atmospheric pressure in kPa, where $\sigma'_v(z)$ is the effective vertical stress at depth z, where A_r is the pile displacement ratio given by Equation 3.16 and where a, b, c, d, e, u and ν are parameters as given in Table 3.2.

$$Q_{s,o} = \pi D_o \int_0^{L_{emb}} f(z) dz \tag{3.8}$$

$$Q_{s,i} = \pi D_i \int_0^{L_{emb}} f(z) dz \tag{3.9}$$

$$f_c(z) = \alpha c_u(z) \tag{3.10}$$

$$\Psi = \frac{c_u}{\gamma'_s z} \tag{3.11}$$

$$\gamma'_s = \gamma_s - \gamma_w \tag{3.12}$$

$$\alpha = \begin{cases} 0.5\Psi^{-0.5} & \text{for } \Psi \leq 1.0 \\ 0.5\Psi^{-0.25} & \text{for } \Psi > 1.0 \end{cases} \tag{3.13}$$

$$f_{nc}(z) = \beta \gamma'_s z \leq f_{lim} \tag{3.14}$$

$$f(z) = u\, q_c(z) \left[\frac{\sigma'_v(z)}{p_a}\right]^a A_r^b \left[\max\left(\frac{L_{emb} - z}{D_o}, \nu\right)\right]^{-c} (\tan\delta)^d \left[\min\left(\frac{L_{emb} - z}{D_o} \cdot \frac{1}{\nu}, 1\right)\right]^e \tag{3.15}$$

$$A_r = 1 - \frac{D_i}{D_o}^2 \tag{3.16}$$

Table 3.2: Parameters Equation 3.15

a	b	c	d	e	u	ν
0.1	0.2	0.4	1	0	0.023	$4\sqrt{A_r}$

Figure 3.2 displays $Q_{s,o}$ and $Q_{s,i}$ for both cohesive soils and non-cohesive soils. The input for the soil profiles is given in Table 3.3. It can be seen that for non-cohesive soils, $Q_{s,i}$ and $Q_{s,o}$ are higher compared to cohesive soils.

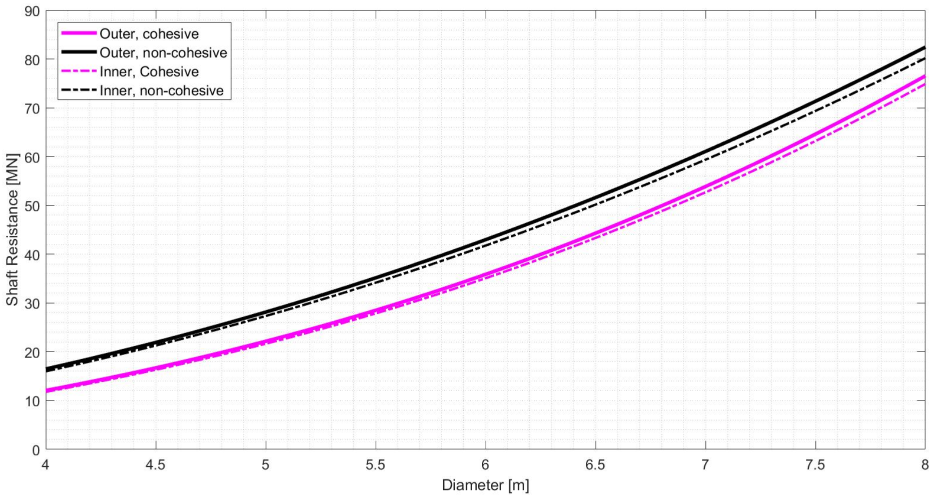


Figure 3.2: Soil resistance of cohesive and non-cohesive soils

Soil 1: Cohesive	**Symbol**	**Value**	**Soil 2: Non-cohesive**	**Symbol**	**Value**
Type of soil	-	Stiff Clay	**Type of soil**	-	Medium Dense Sand
Undrained shear strength	c_u	200 kPa	**Dimensionless skin friction factor**	β	0.37
Saturated unit weight	γ_s	21 kN/m^3	**Limit unit skin friction**	f_{lim}	81 kPa
			Saturated unit weight	γ_s	20 kN/m^3

Table 3.3: Soil Characteristics Used as Input for the Calculations

As mentioned in Section 2.2.2 the soil resistance can be reduced by using vibration. The soil resistance during vibratory extraction R_v in kN is calculated using Equation 3.17. R_v is dependent on β. This β factor is the residual strength after cyclic loading divided by the initial strength, as displayed in Figure 3.3. β_o and β_i are the ratio of static outside- and inside skin friction during vibratory extraction, respectively. These values are dependent on the type of soil, the typical values are given in Table 3.4 [Vugts and Zandwijk, 2016]. The values of β are based on the post analysis of vibratory driving and extraction records [Vugts and Zandwijk, 2016]. As vibration technique is used more frequently, β values can be predicted more accurate. Hence, extractability predictions will be more accurate.

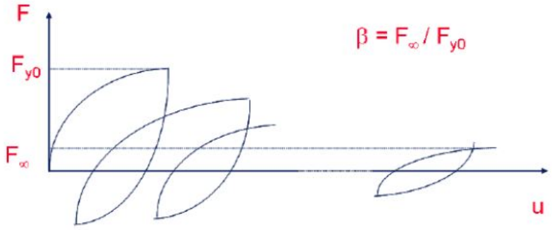


Figure 3.3: Soil fatigue due to cyclic loading

$$R_v = \beta_o \cdot Q_{s,o} + \beta_i \cdot Q_{s,i} \tag{3.17}$$

Table 3.4: Typical values for β_o and β_i

Type of Soil	β
Round Coarse Sand	0.10
Soft Loam/Marl, Soft Loess, Stiff Cliff	0.12
Round Medium Sand, Round Gravel	0.15
Fine Angular Gravel, Angular Loam, Angular Loess	0.18
Round Fine Sand	0.20
Angular Sand, Coarse Gravel	0.25
Angular/Dry Fine Sand	0.35
Marl, Stiff/Very Stiff Clay	0.40

The calculations will be done for the two extreme cases. The static shaft resistance for non-cohesive soils is higher than that of cohesive soils, as previously shown. However, R_v is lower for non-cohesive soils, as can be observed from Figure 3.4. This is due to the fact that for cohesive soils under vibration, a larger fraction of the soil resistance remains compared to non-cohesive soils. Resulting in an overall lower soil resistance during vibration for non-cohesive soils. This results in a larger F_{ext} needed in order to extract monopiles from cohesive soils. In reality, the soil profile most likely consists of multiple soil layers. Since the calculations are done for the two extreme soil conditions, the soil resistance and therefore the F_{ext} for a mixed soil profile lays between that of the two extremes.

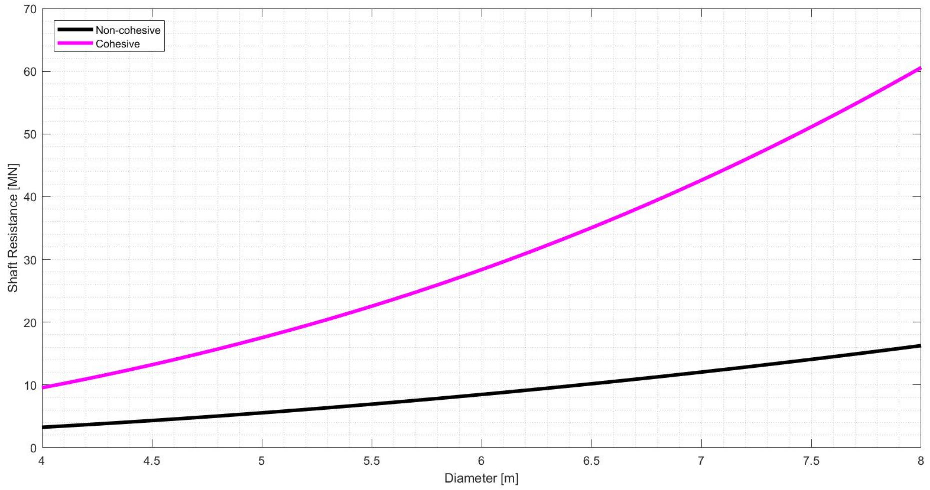


Figure 3.4: Soil resistance during vibratory extraction

3.2 Results Obtained from the Soil-structure Model

Figure 3.5 displays the outcome of the model using a β of 0.10 for the non-cohesive soil and a values of 0.4 for the cohesive soil. The jumps observed in the figure are caused by selecting a larger VLT. This causes an increase in W_{VLT} and therefore in F_{ext}. Figure 3.6a shows M_e for the VLT's needed for the extraction. Figure 3.6b displays the corresponding number of VLT as given in Table 3.5.

The largest VLT considered for this thesis has a maximum line pull of 4000 mT. Therefore, once F_{ext} becomes larger than 4000 mT, the line stops. Indicating, that extraction is not possible using the currently available tools. Larger tools can and most likely will be developed in the future, which would make the extraction of monopile with a larger monopile possible.

Looking at the figure, it can be seen that with the currently available VLT's piles up to a diameter of approximately 7.9 meters in non-cohesive soils, sand in this case. For cohesive soils, clay in this case, the piles with a diameter up to approximately 5.8 meters can be extracted. The limiting factor is the maximum line pull of the VLT. The largest VLT has a maximum line pull of 4000 mT. As the weight of the pile increases as a result of an increasing D_o, the line pull needed in order to extract the pile exceeds this maximum.

It should be noted that these outcomes are strongly dependent on the input of the soil parameters. Different soil conditions greatly influence the limit of extractability. This influence can be seen by the difference in extractability between sand and clay. Therefore, in order to determine the technical feasibility of decommissioning a wind farm using a VLT, the site specific soil conditions should be taken into consideration. Based on these soil conditions, this technical feasibility can be calculated. In addition, it is more likely to encounter a soil profile made up from various soil layers. The limit for cohesive soils in Figure 3.5 represents the worst case scenario encountering the most difficult soil along the entire embedded length. In order make a more accurate extractability prediction, a vibratory cone pentrometer test can be performed. The vibratory local sleeve frictions can be used to determine an accurate β factor [Jonker, 1987].

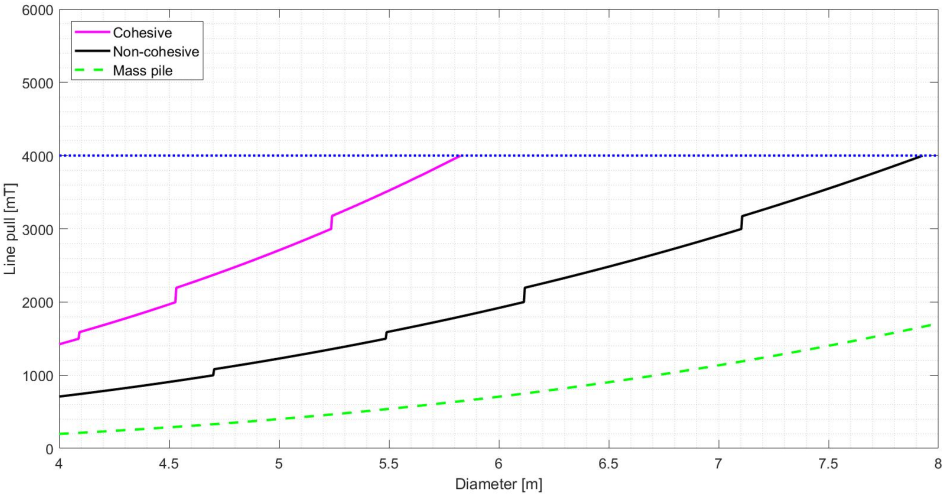
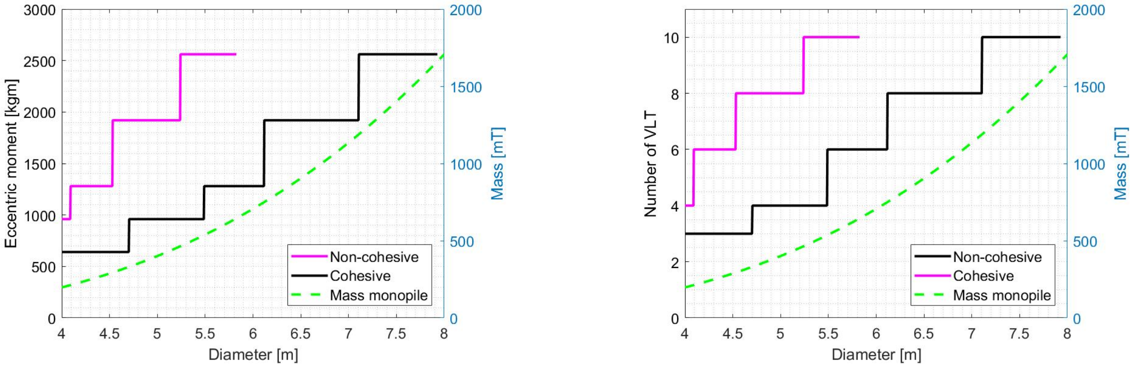


Figure 3.5: Results from model given as line pull



(a) M_e of VLT

(b) Number of VLT

Figure 3.6: Eccentric moment and number of VLT used as given in Table 3.5

This thesis focuses on the decommissioning of the wind farms that will reach their end of life phase in the years up to 2035. The diameter of the wind farms lays between 4.00 m and 5.00 m. Based on the outcome of this model it is technically feasible to completely remove all these monopiles using the VLT's currently available. Even if all monopiles were to be extracted from a full clay profile, which is the least favourable situation, extraction would still be possible for all considered wind farm.

Table 3.5: Information of the VLT's of CAPE Holland

Number	**Model name**	**Eccentric moment [kgm]**	**Maximum line pull [mT]**
1	Single CV-320	320	500
2	Single CV-640	640	500
3	Tandem CV-320	640	1000
4	Triple CV-320	960	1500
5	Tandem CV-640	1280	1000
6	Quad CV-320	1280	2000
7	Triple CV-640	1920	1500
8	Triple CV-640	1920	3000
9	Quad CV-640	2560	2000
10	Quad CV-640	2560	4000

3.3 Comparison to Other Methods

Now that the F_{ext} for using a VLT has been calculated, these values can be compared to other complete decommissioning situations. These methods correspond to certain load cases, as listed below.

- Load Case 1 represents a situation where the pile loading capacity consists of the weight of the pile and the shaft resistance on both the inside and the outside of the pile, this corresponds to a crane-uplift situation as discussed in Section 2.1.2.
- Load case 2 is that of a internally dredged monopile. Internally dredging the monopile results in eliminating the inside shaft resistance.
- Load case 3 resembles the use of a VLT.

$$F_{ext,1} = Q_{s,o} + Q_{s,i} + W_{pile} \tag{3.18}$$

$$F_{ext,2} = Q_{s,o} + W_{pile} \tag{3.19}$$

$$F_{ext,3} = R_v + W_{pile} + W_{VLT} \tag{3.20}$$

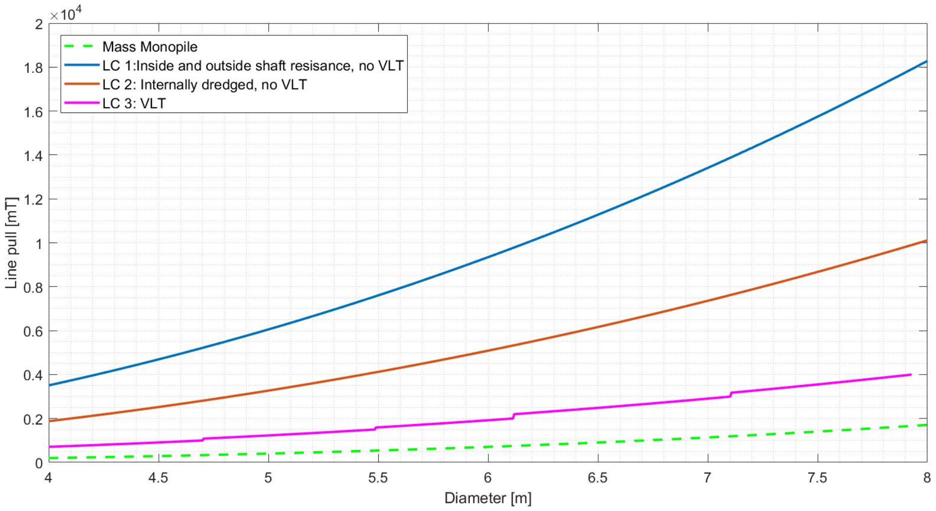


Figure 3.7: Line pull needed for the various load cases in Sand

By looking at the results, a large reduction in F_{ext} can be achieved. The force needed to extract a pile weighing 200 mT by simply pulling it is approximately 3500 mT, almost 18 times the weight of the pile. This can be reduced to 700 mT for that same pile, which is approximately 3.6 times the weight of the pile by using VLT. A lower F_{ext} is relevant due to the costs of the vessel. A higher F_{ext} results in a larger vessel, which results in higher day rates. These day rates will be discussed in the next chapter. For a relatively small monopile a large vessels would be needed for load case 1 and 2. Whereas when using VLT, a much smaller vessels and thus cheaper vessel can be used to extract the monopile from the soils.

Chapter 4

The Feasibility of Complete Removal Using Vibratory Pile Extraction Compared to Partial Removal

The overall feasibility of the method is without question of great importance. It contributes to the answers whether a method should be preferred over another. In this present report, the overall feasibility covers the costs, the green house gas emissions and the time it takes to decommission a wind turbine. It has been concluded that for the diameters of interest, it is technically feasible and possible to extract the monopile entirely using a VLT. However, this does not necessarily mean that complete removal is preferred over partial removal. If the costs involved in complete removal are much higher compared to that of partial removal, the method of complete removal might not be more feasible than that of partial removal. This chapter focuses on comparing both methods based on execution time, green house gas emissions and costs involved.

In order to analyse the overall feasibility of using a VLT for a complete removal, the timeline of the offshore phase is made for various scenarios. The duration of the offshore phase has a large impact on the costs and on the green house gas emissions of the project. The scenarios analysed are:

1. Partial removal with cut at 3 meter below the mudline
2. Complete removal using VLT without noise mitigation
3. Complete removal using VLT with noise mitigation

To date there are no rules and regulations in place regarding using noise mitigation when using a VLT offshore. However, in the future it is likely that rules and regulations will be in place make the use of noise mitigation obligatory. In addition, based on ethical grounds it is the preferred option to limit the environmental impact of the decommissioning phase. Therefore, noise mitigation should be used regardless of the rules and regulations in place. A scenario with and without noise mitigation is researched in order to investigate the effect on costs, emissions and execution time. And whether regardless of the lack of regulations the scenario with noise mitigation is the favoured option. The type of noise mitigation used is the AdBm Noise Abatement System Technology, as has been discussed in more detail in Section 2.3.

Scenario 2 and 3 are researched for both a grouted connection as well as for a bolted or TP-less connection. The bolted or TP-less connection are treated as the same, since the procedure for decommissioning is the same for both connections. The three scenarios mentioned above are compared with each for a grouted connection and for a bolted or TP-less connections.

4.1 Vessel Choice

The choice of vessel is of importance for calculating the emissions and the costs. The vessels have a different fuel consumption and different day rates.

For complete removal using a VLT of a 5 m diameter monopile a vessel with a lifting capacity F_{lc} of approximately 1230 mT is needed, as can be observed in Figure 4.1. For the partial removal of the same piles F_{lc} is approximately 390 mT. For the same diameter, vessels with a larger lifting capacity are needed when opted for complete removal. Figure 4.1 also displays a steeper increase in F_{ext} for complete removal compared to partial removal. This will lead to a steeper increase in vessels costs and green house gas emissions, as will be discussed later on. The effect of the need for larger vessels on the costs and the emissions are described in the following sections.

Different types of vessels are used for different water depths. At relatively low water depths a Jack-Up vessels is used and at relatively high water depths Semi Submersible should be used.

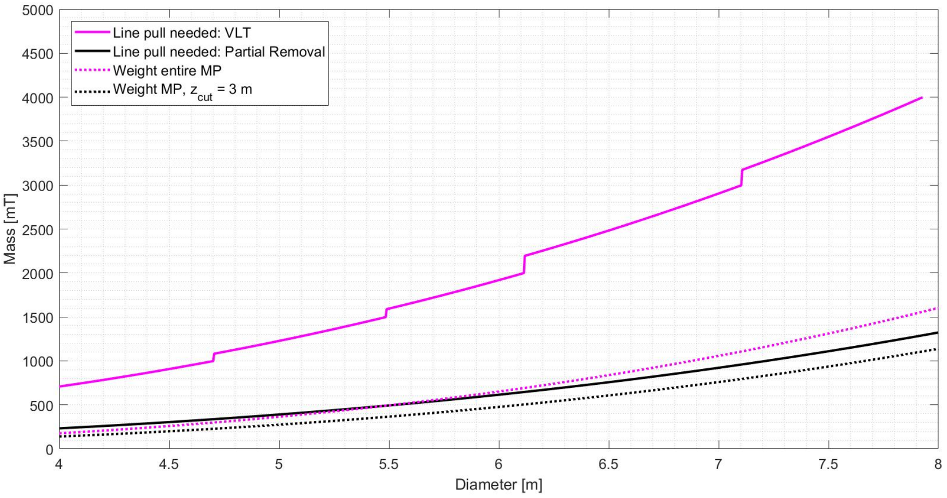
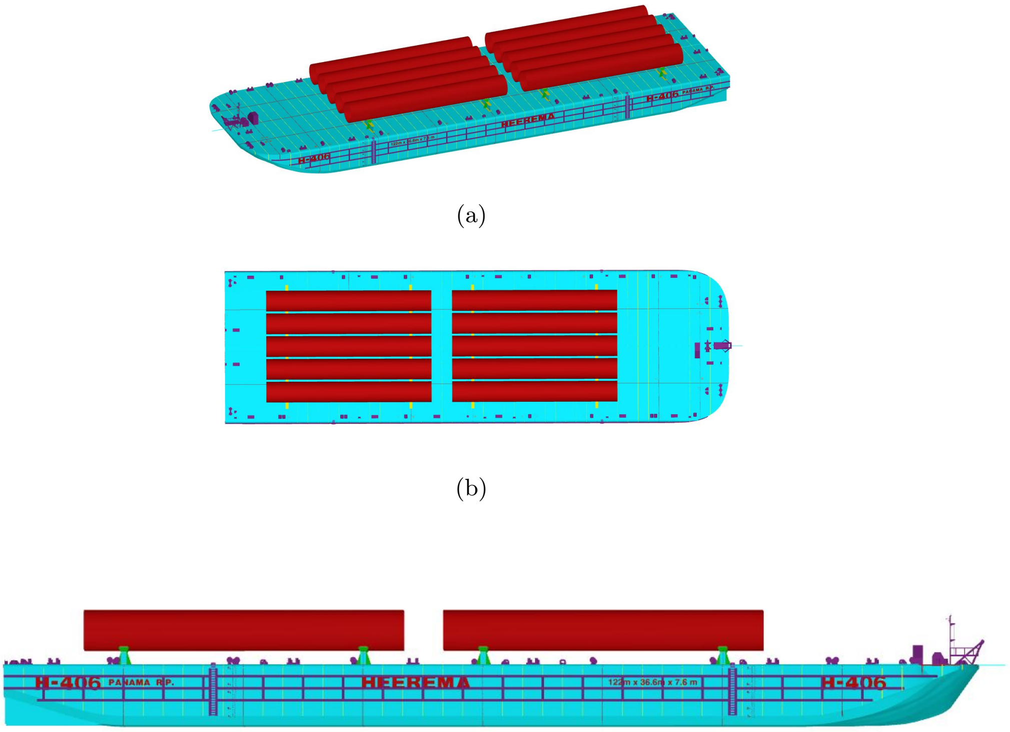


Figure 4.1: Line pull for partial removal and complete removal using VLT

Once the monopiles have been lifted from the seabed, they can be placed on a barge. In Figure 4.2 the layout of the 10 extracted 52 m monopiles is depicted on Heerema's H-406 barge. The dimensions of the barge are 122 m by 36.6 m and the monopiles are put on a grillage.



(a)

(b)

(c)

Figure 4.2: 52 m monopiles on barge H-406

4.2 Execution Schedule

The execution time per monopile for the various scenarios has been calculated by constructing a complete execution schedule for decommissioning a turbine with a diameter of 5 m. An equation for the execution time dependent on D_o is constructed as given in Equation 4.1 up to Equation 4.5. Where $t_{grouted,i}$ is the execution time for when a grouted connection is present for scenario i and where $t_{bolted,i}$ is the execution time for when a TP-less or a bolted connection is present for scenario i. Table 4.1 displays a brief summary of the execution time for a wind turbine with a diameter of 5 m. Figure 4.3a and Figure 4.3b display the execution times for all three scenarios as a function of D_o.

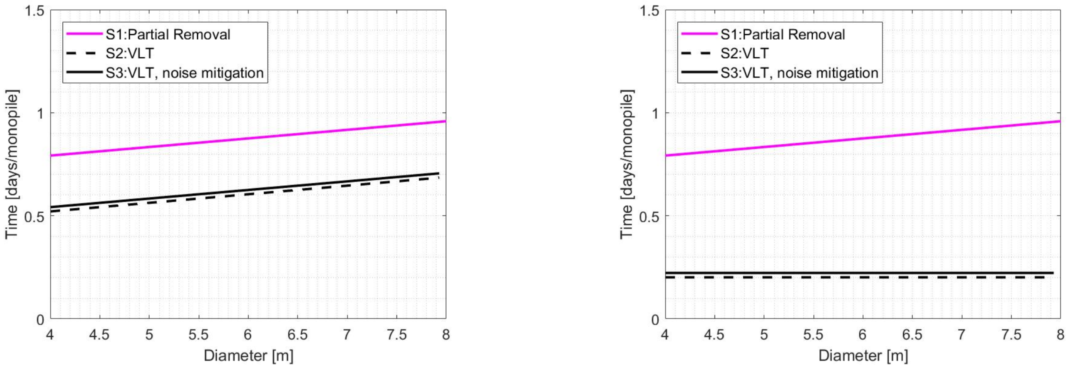
$$t_{grouted,1} = t_{bolted,1} = 0.0417 \cdot D_o + 0.6250 \tag{4.1}$$

$$t_{grouted,2} = 0.0417 \cdot D_o + 0.3542 \tag{4.2}$$

$$t_{grouted,3} = 0.0417 \cdot D_o + 0.3750 \tag{4.3}$$

$$t_{bolted,2} = 0.1875 \cdot D_o + 0.0139 \tag{4.4}$$

$$t_{bolted,3} = 0.2083 \cdot D_o + 0.0252 \tag{4.5}$$



(a) $t_{grouted,i}$ (b) $t_{bolted,i}$

Table 4.1: Execution time for $D_o = 5$ m

Connection	**Scenario 1**	**Scenario 2**	**Scenario 3**
Grouted [days/mp]	0.83	0.56	0.58
TP-less or bolted [days/mp]	0.83	0.20	0.22

Comparing the results of the schedule with each other, it can be seen that time needed for partial removal compared to complete removal is higher for both types of connection. The two main reasons for this difference are: Firstly, for partial removal multiple tools need to be used. This results in the need for changing of rigging and the connection and disconnection from the different tools. Whereas for the complete removal option, only one or two tools are needed. For grouted connections, a cutting tool and the VLT and for bolted of TP-less connections only a VLT is needed. The VLT is used for the vibration, the lifting and the down ending of the monopile. Not having to change the rigging and the tools saves a lot of time per pile. Secondly, by looking at the schedule for partial removal and for complete removal for a grouted connection, it can be seen that t is dependent on D_o. This is due to the fact that as the diameter increases, the cutting time also increases. For a monopile with a diameter of 5 m it takes 8 hours to perform a cut. For a monopile with a diameter of 8 meters, the cutting time is 11 hours. Whereas vibration takes only 0.5 hours. It is expected that for an increase in diameter the time for using VLT will increase significantly. So for an increasing diameter, the difference in time between the two methods increases.

The potential of waiting on weather has not been incorporated in the results. This is due to the fact that this is very site specific. However, partial removal contains more weather sensitive activities compared to complete removal. For a complete removal, the weather sensitive activities are the vibrating, the lifting and the down end activities and potentially the cutting. Whereas for partial removal the weather sensitive activities are lifting and installing the dredging tool, dredging, inserting the cutting tool, performing the cut, lifting the monopile and the down ending. A larger weather window is needed for partial removal, resulting in a higher risk of delays.

Some assumptions have been made when construction the equations for the execution time. More soil needs to be dredged as the diameter increases. However, larger dredging tools can be used. Therefore, it is assumed that the time for dredging t_{dredge} remains the same per diameter. For complete removal using VLT a similar assumption is made. As D_o increases, the soil resistance increases. However, a larger VLT is used. So it is assumed that the time it takes to vibrate t_{VLT} the soil remains the same.

Execution time is used as an input in order to calculate the costs and green house gas emissions. In Section 4.1 it was mentioned that larger vessels are needed for complete removal. As will be shown in Section 4.4, larger vessels correspond to higher day rates. The costs might be higher if a more expensive vessel is needed for a shorter time. The same holds for green house gas emissions, as will be described in Section 4.3. Larger vessels have higher emissions. Therefore, conclusions based on soley the time per monopile are irrelevant.

4.3 CO_2-eq. Emissions of Decommissioning a Offshore Wind Farm

4.3.1 Fuel use of the vessels

The CO_2 equivalent, CO_2-eq, is a measure for the emissions based on the global warming potential. One kg of CO_2-eq. emission has the same effect as that of one kg of CO_2-eq. emissions. The emissions for the three scenarios are calculated based on the execution schedule. Where ϵ denotes the emission factor for a specific fuel type. It is assumed that the vessels use Marine Gas Oil as a fuel, this fuel has an ϵ_{MGO} of 3.762. This means that for every mT MGO used, 3.762 mT CO_2-eq. is emitted.

For the total fuel consumption use Equation 4.6 is constructed. This formula is based on the data from various vessels, as shown in Figure 4.4. It can be seen that a larger lifting capacity corresponds to a higher fuel use in mT/day. It is assumed that a tug boat uses approximately 10 mT/day of fuel when towing a loaded barge through ocean conditions.

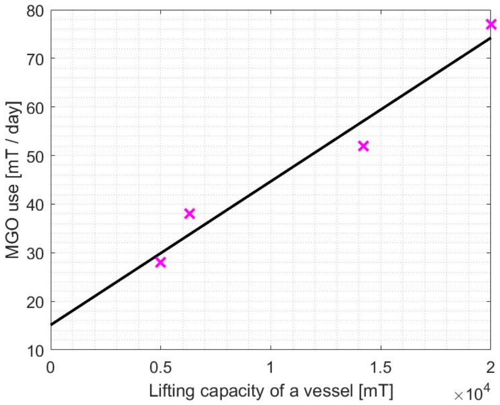


Figure 4.4: MGO use versus F_{lift} of vessels

$$C_{fuel,i} = (0.003 F_{lc} + 15.1317) \cdot + \frac{10 \cdot t_{tug}}{n_{turbines}} \tag{4.6}$$

$$CO_2\text{-eq.} = C_{fuel}\, \epsilon \tag{4.7}$$

4.3.2 Secondary steel production

Recycling steel by producing secondary steel is done using electric arc furnaces. Producing this secondary steel emits one-fifth of the CO_2 emissions compared to primary steel making. This is the case even when the majority of the electricity used in the electric arc furnaces comes from fossil fuels. If however renewable energy is used, the production of secondary steel can predominantly be decarbonised. Keeping this in mind, as much steel, if not all, should be retrieved from the seabed and used in order to produce secondary steel [The Crown Estate, 2019].

Completely removing a wind farm with instead of partially removing it results in an extra amount of extra steel that are to be recycled. This leads to a reduction in CO_2-eq. emissions. This can be calculated using the data given in Table 4.2 and Equation 4.8 and Equation 4.9.

$$M_{steel} = \frac{\left(D_o^2 - D_i^2\right)\pi}{4} \left(L_{emb} - z_{cut}\right) \rho_{steel}\, n_{turbines} \tag{4.8}$$

$$CO_2 \text{ Reduction per tonne} = \frac{M_{steel}}{1000} \, E_{CO_2,ps} \, E_{CO_2,ss} \tag{4.9}$$

Table 4.2: Input values for calculation reduction in CO_2-eq.

	Symbol	**Value**
Density of steel	ρ_{steel}	7850 kg/m^3
CO_2-eq. emission per tonne of primary steel produced	$E_{CO_2,ps}$	1.89 tonnes
CO_2-eq. emission per tonne of secondary steel produced	$E_{CO_2,ss}$	0.378 tonnes

As the diameter of the monopiles increases, so does the potential amount of steel that is to be extracted from the soil. Figure 4.5 displays the extra steel the is to be retrieved from the soil by choosing complete removal over partial removal as well as the CO_2-eq. reduction that can be realised by recycling this steel to secondary steel.

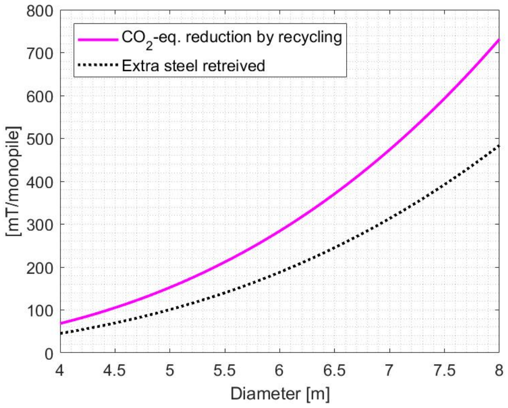
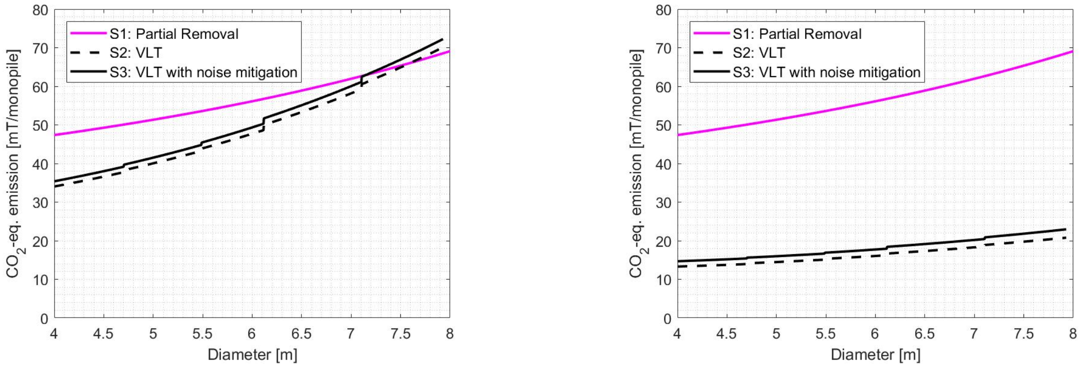


Figure 4.5: Effect of extra steel that can be retrieved by choosing complete removal over partial removal

Figure 4.6 displays the CO_2-eq. emissions for the decommissioning of the monopile. By looking at Figure 4.6a is can be seen that the emissions for partial removal are higher compared to complete removal up to approximately a diameter of 7 meters. Initially, the CO_2-eq. emissions are lower for complete removal since less offshore time is involved in complete removal, leading to less emissions. However, as the diameter increases, the CO_2-eq. emissions increase relatively fast for complete removal. This is due to a steeper increase in lifting capacity needed for complete removal, as mentioned before. Figure 4.6b displays that for TP-less and bolted connections the emissions are lower for complete removal compared to partial removal for all diameters researched. This is due to the relatively low offshore time and the independence of D_o of $t_{bolted,i}$.

By looking at both figures below, it can be seen that the effect of including noise mitigation to complete removal leads to an increase in emissions of approximately 1.3 mT CO_2-eq. emission per monopile.



(a) Grouted connection

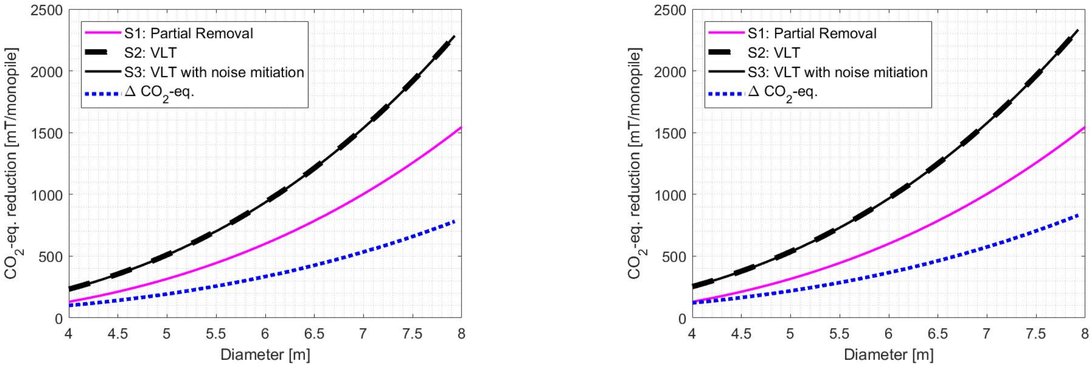
(b) TP-less or bolted connection

Figure 4.6: CO_2-eq. emissions decommissioning

4.3.3 Overall emission reduction

Figure 4.7 displays the overall emission reduction that can be realised by choosing complete decommissioning with a VLT compared to partial removal. This is calculated by adding the reduction in emission the vessel to the reduction in emission by recycling the extra steel retrieved from the seabed. It should be noted that this comparison is done based soley on the decommissioning of the substructure. In reality, the steel from the tower can also be recycled and thus, the overall emission reduction will be lower. Since this is the same for both scenarios this is left out of the equation. These number represent an extra emission reduction.

When comparing the three scenarios with each other the following can be concluded for all types of connection. Firstly, a extra reduction of emissions between 100 and 830 mT CO_2-eq. per monopile can be realised by choosing complete removal over partial removal. Secondly, as the diameter of the monopiles increases, the extra emission reduction increases. Hence, as the diameter of the to-be-decommissioned monopiles increase, so does the importance of completely removing the structures. Thirdly, the effect of including the NAS does not have a significant effect on the overall CO_2-eq. emissions. Based on the CO_2-eq. emissions, scenario 3 is the preferred option. Partial removal is the least optimal option. Since the reduction is large compared to the emission, the two graphs in Figure 4.7 look similar.



(a) Grouted connection

(b) TP-less or bolted connection

Figure 4.7: Overall CO_2 emission reduction

4.4 Costs of Decomissioning a Offshore Wind Farm

The largest portion of the cost is due to the day rates of the vessel. In order to find a value for the day rates of various vessels have been used to estimate the costs based on the lifting capacity of a vessel F_{lc}. Figure 4.8 displays the day rates versus the lifting capacity. The total vessel costs c_{vessel} can be calculated by multiplying the day rate times t_{total}. It should be noted that the fuel costs are not a part of c_{vessel}, these costs are calculated separately.

$$c_{vessel} = (94.5F_{lc} - 7971.3) \cdot t_{total} \tag{4.10}$$

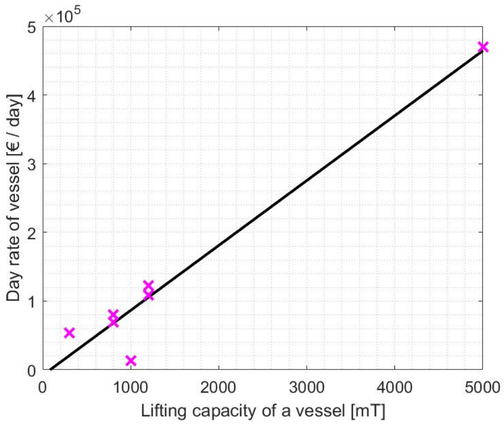


Figure 4.8: Day rates versus F_{lift} of vessels

The day rate of a tug boat c_{tug} is approximately €25.000. Again, the fuel costs are not part of these costs. The fuel costs c_{fuel} are calculated using C_{fuel} from Section 4.3 and the fuel costs. The average fuel costs $c_{avg,fuel}$ are taken as €800 per mT.

The costs of the barge c_{barge} consist of the day rate of the barge and the costs of outfitting the barge for transport. These outfitting costs consist of putting the grillage on the barge and making it suitable for transporting the removed monopiles. These outfitting costs are estimated to be €380.000, c_{barge} is taken as €4.500. Based on this, Equation 4.16 is constructed.

The costs of the tools c_{tools} are dependent on the type of method used. For partial removal it consists of the day rates of the dredging tool, the cutting tool and the lifting tool, c_{dredge}, c_{cut}, and c_{lift}, respectively. c_{dredge} is estimated as €16.000, c_{cut} is estimated as €24.000 and c_{lift} is taken as €15.000. The day rates of a VLT is estimated at €45.000. It should be noted that this is an estimated based on overall information found on the day rates of vibratory pile removal tools. It is not a day rate specifically for the VLT's of CAPE Holland. The costs of the NAS system are defined per monopile and are given in Equation 4.17. In addition to the day rates, the mobilisation costs have also been taken estimated en taken into account, as can be seen in the equations.

$$c_{tug} = \frac{25.000 \cdot t_{tug}}{n_{turbines}} \tag{4.11}$$

$$c_{fuel} = \frac{C_{fuel} \cdot c_{avg,fuel}}{n_{turbines}} \tag{4.12}$$

$$c_{dredge} = \frac{220.000 + 16.000 \cdot t \cdot n_{turbines}}{n_{turbines}} \tag{4.13}$$

$$c_{cut} = \frac{90.000 + 24.000 \cdot t \cdot n_{turbines}}{n_{turbines}} \tag{4.14}$$

$$c_{lift} = \frac{90.000 + 15.000 \cdot t \cdot n_{turbines}}{n_{turbines}} \tag{4.15}$$

$$c_{barge} = \frac{380.000 + 4.500 \cdot t \cdot n_{turbines}}{n_{turbines}} \tag{4.16}$$

$$c_{NAS} = \frac{250.000 + 10.000 \cdot n_{turbines}}{n_{turbines}} \tag{4.17}$$

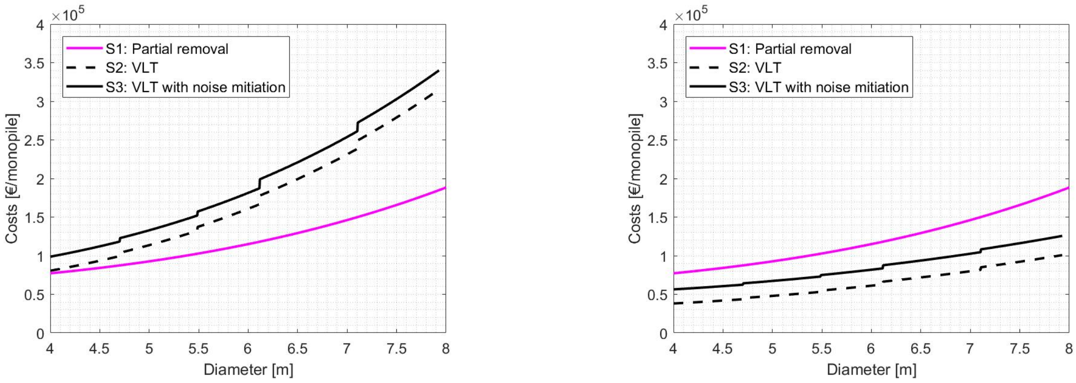
$$c_{VLT} = 45.000 \cdot t \tag{4.18}$$

The total costs of decommissioning c_{total} can be calculated using Equation 4.19, where i is 1, 2 or 3 dependent on the scenario for which c_{total} is calculated. Where c_{tools} is dependent on the tools used for the decommissioning of the monopile. For partial removal c_{tools} costs of c_{dredge}, c_{cut}, c_{lift}. For complete removal of a grouted connection c_{tools} consists of c_{cut}, c_{lift} and c_{VLT}. And for a TP-less or bolted connection c_{tools} consists of c_{VLT}. Whether c_{NAS} should be included in c_{tools} depends on whether noise mitigation is used.

$$c_{total,i} = c_{vessel} + c_{tug} + c_{barge} + c_{tools,i} + c_{fuel} \tag{4.19}$$

Figure 4.9 displays the costs involved in decommissioning for the three scenarios for both connections. Figure 4.9a show that for a grouted connection, the costs of decommissioning are higher compared to partial removal for all diameter researched. Figure 4.9b shows the opposite, for all diameters researched the costs for complete removal are lower compared to partial removal. From both figures it can also be concluded that adding noise mitigation to complete removal leads to an increase in costs of 15.000 €per monopile.

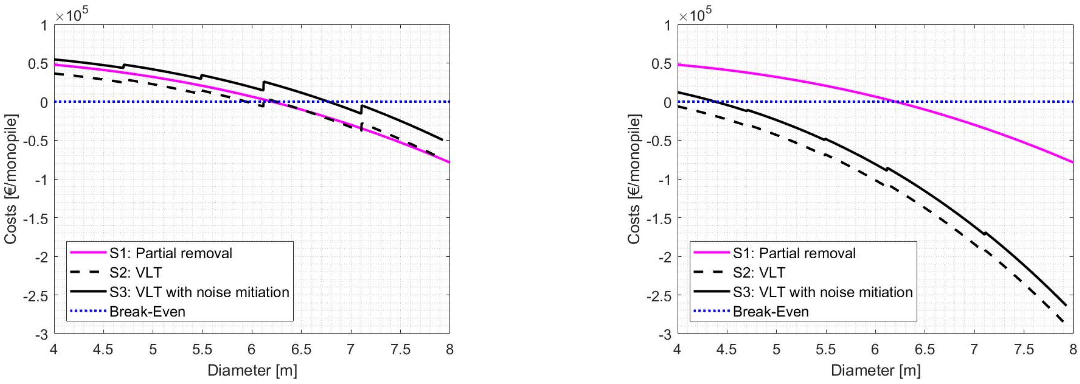
However, Figure 4.9 does not show the complete overview of the costs involved. The extra steel that is retrieved by choosing complete removal over partial removal has an effect on the overall costs. When this scrap steel is sold at a price of 0.25 €/kg, the overall costs are as displayed in Figure 4.10. Figure 4.5 displays the extra steel that is to be retrieved when completely removing a monopile. Adding the revenue made on the recycled steel has a great influence on the total costs. This is due to the fact that for complete removal, extra steel is retrieved and thus extra scrap steel can be sold, lowering the overall costs significantly more compared to partial removal.



(a) Grouted connection

(b) TP-less or bolted connection

Figure 4.9: Costs of decommissioning



(a) Grouted connection

(b) TP-less or bolted connection

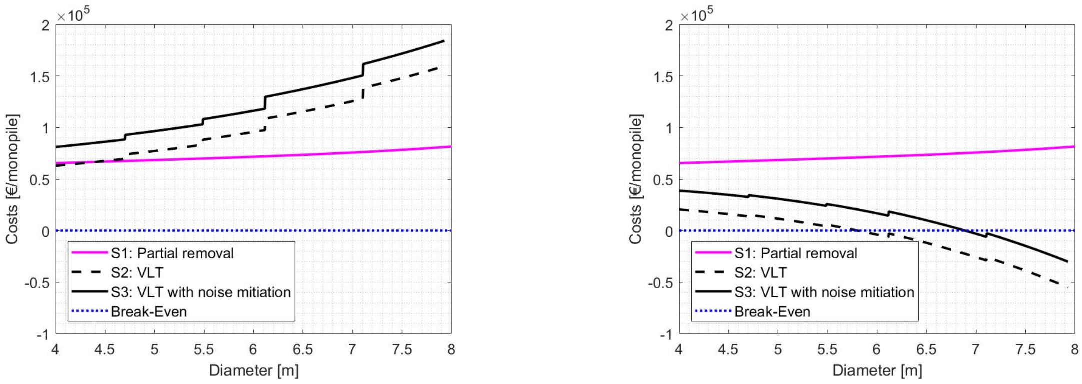
Figure 4.10: Total costs of decommissioning, including revenue made on scrap steel

Figure 4.10a displays the costs including the revenue made on the selling of scrap steel for a grouted connection. By looking at this figure it can be seen that the costs for choosing complete removal with noise mitigation over partial removal results in an increase in costs of €7.000 euro per monopile at a diameter of 4 meters up to an increase of €25.000 at a diameter of 8 meters. Complete removal without noise mitigation involves lower or equal costs compared to partial removal.

Comparing the scenarios based on overall costs for a bolted connection in Figure 4.10b, it can be said that complete removal is preferred over partial removal. For all values of D_o complete removal without noise mitigation is significantly lower in costs compared to partial removal. As the diameter increases, the difference increases rapidly in favour of complete removal. For a D_o of 4 meters, the costs of complete removal with noise mitigation are €35.0000 per monopile lower compared to partial removal. As the diameter goes to 8 meters, this difference increases to €190.000 per monopile! The rapid increase in difference between partial removal and complete removal is due to the fact that as D_o increases, the scrap steel that is to be sold increases, and thus the overall costs lower. Without including the noise mitigation, the reduction is €15.000 euro larger compared to the scenario with noise mitigation.

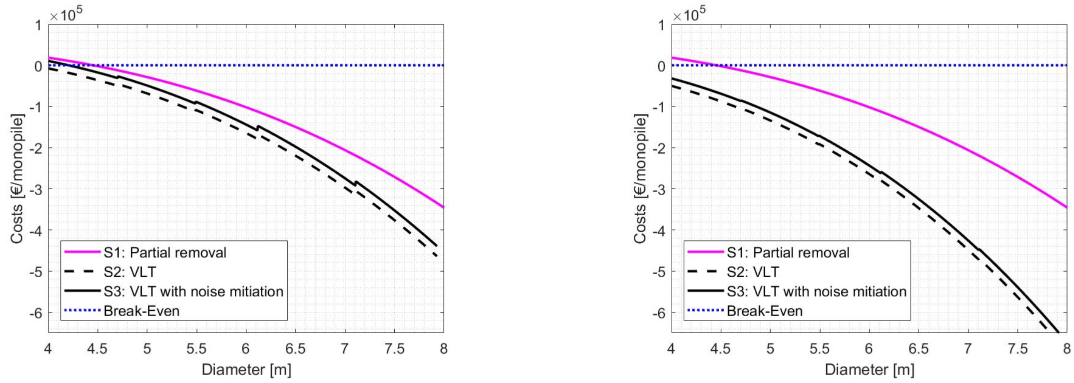
Figure 4.10 display that revenue can be made during the decommissioning of the substructure. It should be noted that this does not indicate that revenue is made during the decommissioning of an offshore wind turbine. Since the decommissioning of the tower, the RNA and blades are not taken into account here. In order to research the overall costs of decommissioning a complete offshore wind turbine, the decommissioning of the other parts should be researched and the revenue made on selling the scrap steel of the tower should also be taken into account. Since it is assumed that this is the same for all three scenarios, this is not taken into account.

The price at which the scrap steel is sold also is of great influence on the overall costs. The price of 0.25 €/kg steel is the current steel price. However, these prices tend to fluctuate over time. The effects on overall costs of a drop in the scrap steel price to a value of 0.10 €/kg, are displayed in Figure 4.11. The effect of an increase in scrap steel price to 0.50 €/kg is displayed in Figure 4.12.



(a) Grouted connection (b) TP-less or bolted connection

Figure 4.11: Total costs with scrap steel sold at 0.10 €/kg



(a) Grouted connection (b) TP-less or bolted connection

Figure 4.12: Total costs with scrap steel sold at 0.50 €/kg

Figure 4.11a displays that if the scrap steel price would drop, the total costs for complete removal will be significantly higher compared to partial removal. Especially at higher D_o, the difference in costs is high. At diameters close to 8 meters, scenario 3 costs 100.000 €more per monopile compared to scenario 1. The effect on the costs for TP-less or bolted connections is much less. For all diameters researched, complete removal involves lower costs compared to partial removal. The difference increases as the diameter increases, making complete removal even more favourable at higher D_o. At a D_o of 4 meter the costs of complete removal with noise mitigation are €28.000 lower compared to partial removal. At a D_o of approximately 8 meters, the costs are €110.000 lower.

If the scrap steel price increases to 0.50 €/kg, the costs of decommissioning are lower for complete removal with noise mitigation compared to partial removal for all diameter research. This hold for both a grouted connection, a TP-less connection and a bolted connection.

4.4.1 EU Emission Trading System

$$CFC = CO_2 - eq \cdot c_{CO_2} \tag{4.20}$$

The European Union Emissions Trading System (EU ETS) has been established in 2005. This global emissions trading system works according to the cap and trade principle. A maximum amount of allowances, these are appointed to participants. If however these allowances are insufficient to meet its needs, the participant can either reduce the carbon emissions in order to meet its allowances or it can purchase further allowances which are traded on a secondary market [NRF, 2021].

Up till now the shipping industry has been exempt from joining the EU ETS. From 2023 on, the shipping sector will be included. However, a number of shipping segments have been exempt. One of these exemptions are offshore vessels. It is expected that in the near future the offshore vessels will be included in the EU ETS. Once the offshore industy is included in the EU ETS, potential in reduction of emission by choosing a different method can play a significant role in decision making.

Figure 4.13 displays the trend in carbon pricing. It is expected that at the end of 2022 the carbon price will be 73.63 €/mT [TE, 2022]. If the offshore industry would indeed be included in the EU ETS, as expected, choosing partial removal over complete removal using VLT would result in much higher prices.

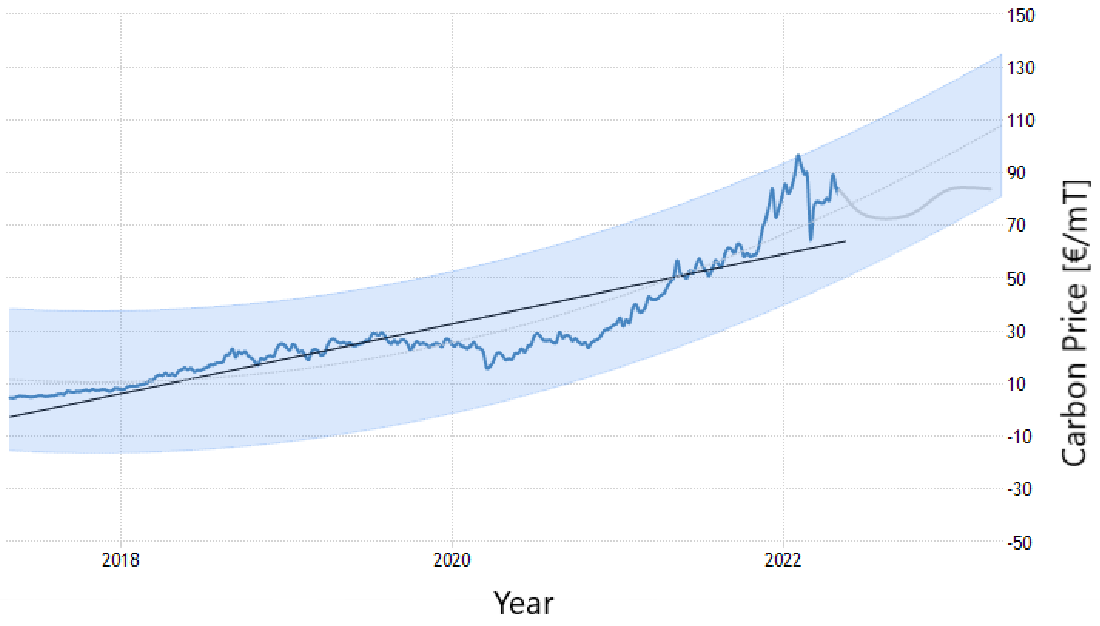


Figure 4.13: Trend in carbon price [TE, 2022]

Chapter 5

Outlook Towards Future Decommissioning Projects With an Increase in Monopile Diameter

This thesis mainly focuses on the extraction of piles with a diameter between 4 and 5 meters. However, the diameter of the monopiles that have been installed the past decade and at present day are much higher. Figure 5.1 displays the trend in the average D_o of the to be decommissioned monopiles. Ideally, these monopiles can be completely removed once they reach their end of life. As the diameter increases, so does the amount of steel that can be recycled. Based on the outcomes of this study all monopiles up to a diameter of approximately 5.7 meters can be completely removed using vibratory pile removal, regardless of soil type. In sand, monopiles with a diameter up to approximately 7.9 meters can be extracted. Given these limits and given the trend in average diameter from Figure 5.1 the following can be concluded. All monopiles that have to be decommissioned up to 2039 can be completely removed using vibratory pile removal. Up to 2046 monopiles can be completely removed using vibratory pile removal, dependent on the soil of the subsurface.

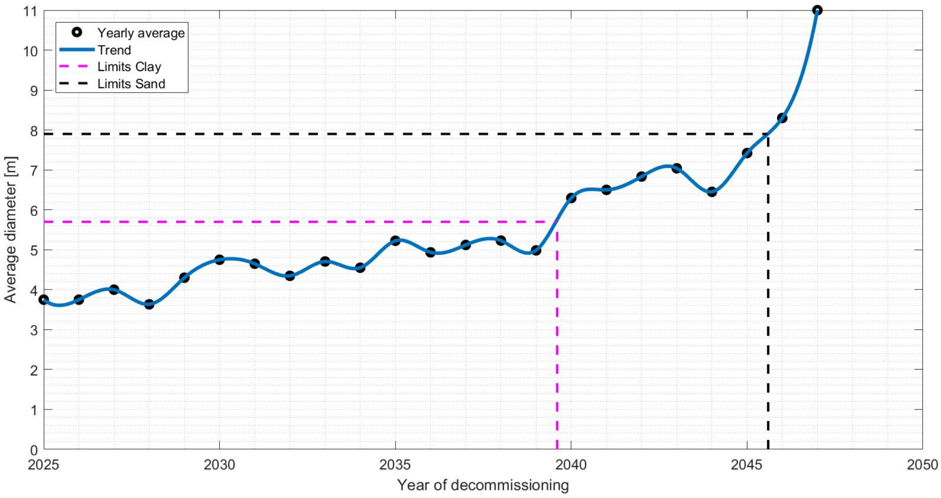


Figure 5.1: Diameter monopiles produced by SIF

There are several options to extend the technical feasibility of complete removal using a VLT up to larger diameters. One of these methods is to develop larger and more powerful VLT's. Potentially, the maximum line pull can be increased. However, using the tools available to date, internal dredging is a potential solution. By internally dredging the inside of the monopile, the internal shaft friction $Q_{s,i}$ goes to zero. Leading to a new the equation for R_v, as given in Equation 5.1. The elimination of $Q_{s,i}$ from the equation leads to a lower R_v. A lower R_v means that for the same monopile, a lower F_{ext} is needed in order to extract the pile. Therefore, with the currently available tools, monopile can be extracted up to a larger D_o. The effect of internal dredging on is given in Figure 5.2.

4. Complete removal using VLT in combination with internal dredging, without noise mitigation
5. Complete removal using VLT in combination with internal dredging, with noise mitigation

$$R_{v,dredge} = \beta \cdot Q_{s,o} \tag{5.1}$$

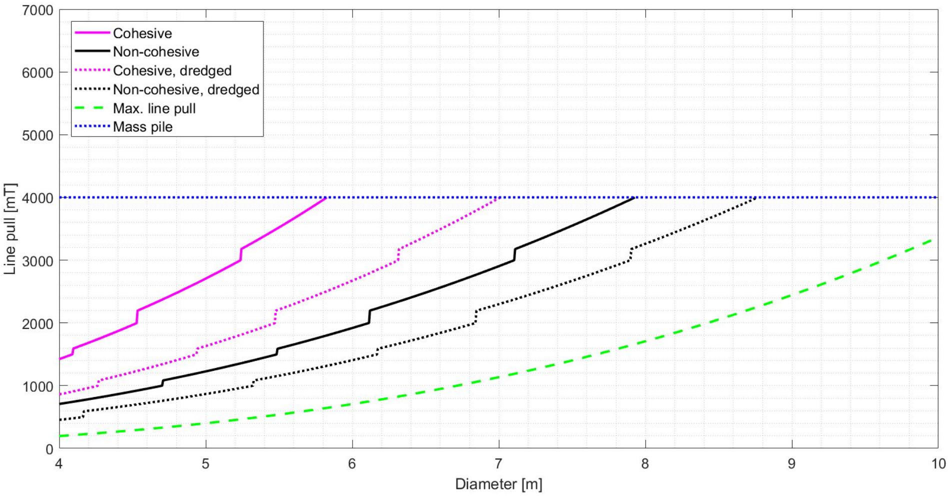


Figure 5.2: Line pull needed when internal dredging is used

Chapter 6

Discussion, Conclusions and Recommendations

6.1 Discussion

Research Question 1: What are the currently used decommissioning techniques and their limitations?

The two main decommissioning techniques are partial removal and complete removal. For partial removal, methods such as internal and external dredging, Diamond Wire Cutting, Abrasive Water Jet Cutting and Explosives can be used. The limitations of partial removal are that multiple actions and methods have to be used in order to decommission a monopile. The changing of tools and rigging is time consuming and therefore adds to the overall costs. The actions itself, such as cutting the monopile, are also very time consuming and increase with an increasing D_o. In addition, more tools needed lead to higher rental costs. The limitations for a complete removal are the lack of experience and the lack of methods. Only one wind farm, wind farm Lely has been completely decommissioned. This wind farm consisted of only 4 monopiles. Some experiments have been done with complete removal of monopiles. All these have proven to be successful. However, these complete decommissioning techniques were all related to the vibration method. Conventional method such as complete removal using pressure, buoyancy or external jet drilling have not been yet put to practice and currently remain theoretical methods.

Research Question 2: What are the effects of various soil characteristics on using vibration technique?

The effects of soil characteristics on using vibration technique are significant. If a monopile is extracted from a uniform clay layer, the limit up to which extraction is possible with the currently available tools lays at a D_o is 5.8 meters. In a uniform sand layer, extraction is possible up to 7.9 meters. This difference is due to two phenomena. Firstly, different soil characteristics lead to different shaft resistances. Secondly, the soil fatigue that will occur due to vibration is dependent of the soil type. Therefore, the soil characteristics are of great influence on the F_{ext} needed for a monopile.

Research Question 3: What are the limitations of using vibration technique?

The limitations for using vibration technique are the availability of tools that are powerful enough once the D_o of the monopiles increases. In addition, the influence of soil on the extractability is a limitation. Good data of the subsurface is needed in order to make accurate predictions on which VLT is needed and to estimate F_{ext}.

Research Question 4: What are the advantages and the disadvantages of using vibration technique compared to partial removal?

One of the great advantages of using vibration technique is the relatively small time it takes to decommission a turbine compared to other methods. This is due to the fact that only one tool or two tools are needed for the whole decommissioning process. Limiting the execution time and therefore the costs and emissions involved in the process. In addition, the whole monopile is extracted from the soil. This leads to tonnes of extra steel to be recycled. Reducing the carbon footprint of an offshore wind farm over its entire lifetime. The disadvantages are that currently there are limitations on the size of the monopile. However, this limit will not be reached any time soon. Since the monopiles that are to be decommissioned in the coming decades will have a D_o well below these limits.

Research Question 5: For which soon-to-be decommissioned offshore wind farms is using a vibration technique feasible?

Using vibration technique is technically feasible for all soon-to-be decommissioned offshore wind farms. Their diameters are between 4 and 5 meters. Even if the entire soil profile consist of clay, all monopiles can be extracted using a VLT.

Research Question 6: Will the vibration technique be feasible as the diameter of the to-be- decommissioned monopiles increases?

The vibration technique will remain feasible as the diameter increases. In clay, complete removal is technically feasible up to a diameter of 7 meters and 8.76 meters, dependent on the soil characteristics of the subsurface. Looking at the production trend of monopiles and assuming an average lifetime of 25 years for offshore wind turbines, this would imply that all monopiles that have to be decommissioned up to 2045 can be completely removed using vibration technique. As it is expected that new, more powerful tools will be developed, it is likely that monopiles with a larger D_o can also be decommissioned in the future.

Research Question 7: Should vibration technique be favored over conventional removal by cutting?

Vibration technique should be favoured over conventional removal by cutting based on environmental impact, costs and CO_2-eq. emissions. This will be further elaborated in Section 6.2

6.2 Conclusions

The technical feasibility study has shown that all offshore wind farms that are to be decommissioned up to 2035 can be completely removed using vibratory pile removal, regardless of the soil characteristics and regardless the type of connection of the TP.

Based on ethical arguments, a noise mitigation system should be used in order to reduce the environmental impact of the decommissioning phase. The most suitable noise mitigation system when using vibration is the Noise Abatement System by AdBm Technologies. This system can be tuned specifically to the frequency at which the sound is emitted. Another large advantage of this system is that no extra vessels are needed to deploy the noise mitigation system, saving time, money and emissions. When using a the noise mitigation system, slightly more CO_2-eq. is emitted. Based on the overall CO_2-eq. reduction, it can be said that the including a noise mitigation system should be favoured over not using a noise mitigation system. The extra CO_2-eq. emitted is significantly low compared to the positive effect a noise mitigation system has on the environmental impact of the operation.

All monopiles that are to be decommissioned, regardless of the soil type of the subsurface, up to 2039 can be completely removal using vibratory pile removal.

With the currently available VLT's the monopiles that are to be decommissioned up to 2045 can potentially be completely removed using vibratory pile removal, depending on the soil types in the subsurface.

With the use of internal dredging, monopiles with diameters up to approximately 8.8 meters can potentially be completely removed using vibratory pile removal, dependent on the soil types in the subsurface.

For grouted connections, complete removal with a VLT without noise mitigation should be preferred over partial removal for diameters up to 8 meters. Since at $D_o = 4$ m, a reduction in costs of 25% leads to a extra CO_2-eq. reduction of 80%. At $D_o = 8$ meters equal costs lead to a CO_2-eq. reduction of 50%.

For grouted connections, complete removal with noise mitigation should be preferred over partial removal for small diameters. Since at $D_o = 4$ m, a cost increase of 15% leads to a extra reduction in CO_2-eq. emissions of 50%.

For TP-less or bolted connections complete removal without noise mitigation should be preferred over partial removal up to a diameter of 8 meters. Since at $D_o = 4$ m a cost decrease of 125% leads to a increase in reduction of 95%. At $D_o = 8$ m, a cost decrease of 330% leads to a extra reduction of CO_2-eq. of 50%. Since vibratory pile removal is only technically feasible up to approximately 8 meters, no predictions on the costs are made.

For TP-less or bolted connections complete removal with noise mitigation should be preferred over partial removal up to a diameter of 8 meters. Since at $D_o = 8$ m, a cost decrease of 300% leads to a extra reduction of CO_2-eq. of 50%.

Table 6.1: Complete removal compared to partial removal for various scenarios

Grouted	**TP-less or bolted**	**Noise mitigation**	D_o	**Costs**	**Emission reduction**
x			4 m	-25%	+80%
x			8 m	Equal	+50%
x		x	4 m	+15%	+80%
x		x	8 m	+50%	+50%
	x		4 m	-125%	+95%
	x		8 m	-330%	+50%
	x	x	4 m	-70%	+95%
	x	x	8 m	-300%	+50%

This study has shown the impact on extractability of different soil characteristics. The soil profile in which the to be extracted monopile is located is of influence on the technical feasibility of complete removal using vibration technique. In order to determine an accurate extraction force, the soil profile across the entire embedded length should be modeled.

As more extractions are done using vibration, a more accurate extractability prediction can be done. The actual measured reduction in soil resistance can be compared to the predictions done based on β-factors. As vibration technique is used more frequently, the reliability of predictions will increase.

6.3 Recommendations

Due to the fact that this is one of the first studies regarding complete removal of monopiles using vibratory pile extraction, many assumptions have been made, leading to uncertainties in the limits calculated and the outcomes. In order to have a more accurate estimation of the limits and results it is highly recommended to investigate the margins of error for this study. The margins of error can be used to determine a range of the limits and calculations rather than a fixed approximate number as is the case in this report. Adding a safety factor to the calculations could also result in a more conservative results.

The potential effect of plugging has not been taken into account in this research, whether plugging is likely to happen during vibration should be investigated in order to get a more accurate result.

While constructing the execution schedules, the following assumptions were made: t_{dredge} remains constant over D_o due to the use of a larger, more powerful dredging tool; t_{VLT} remains constant over D_o due to the use of a larger, more powerful VLT. To increase the accuracy of the predictions of decommissioning time per monopile, the exact t_{dredge} and t_{VLT} can be modelled and implemented.

The extra time it might take to lead to soil fatigue in a clay layer has not been taken into account. It has been assumed that it takes approximately 5 minutes to achieve soil fatigue along the embedded length of the pile, regardless of soil type. It is recommended that the time it takes to achieve soil fatigue along the entire bedded length is researched for various soil types.

The CO_2-eq. emissions calculated in this report are based on the assumption that the vessels and tug boats use Marine Gas Oil as a fuel. As technology develops over time, it might be possible that vessels and tug boats use less pollutant fuels. These less pollutant fuels will have a emission factor ϵ that is lower than that of MGO. This will have a slight effect on the emissions during the decommissioning phase. Once these technologies are implemented on ships, it is recommended to update the calculations. However, the emissions from partial removal will remain higher compared to those of complete removal. Since a change in emission factor will effect both methods in a similar manner.

The reduction of overall carbon footprint due to the recycling of steel is based on the fact that the electric furnaces used for the recycling run on electricity generated from fossil fuels. However, if these electric furnaces will run on renewable energy such as wind farms, the reduction of overall carbon footprint will be even larger. Therefore, as more renewable energy is added to the grid in the future, a new calculation can be performed to see the enlarged positive effects of choosing complete removal over partial removal.

The CO_2-eq. emissions from the tools have not been taken into account, due to a lack of data. In order to get a more accurate estimation of the emissions of the decommissioning of the monopile, these should be researched and taken into account. It is expected that including these numbers would lead to a even larger difference in emissions between complete and partial removal. Since for complete removal one single tool is needed and for partial removal multiple tools are needed.

The calculations made in the report are focused on the decommissioning of the substructure, in order to get a clear image on the costs and emissions of decommissioning an entire monopile, the decommissioning of the tower, the RNA and the blades etc. should also be taken into account.

The day rates of the vessels are estimated based on data points. However, the accuracy of these estimations can be increased by including more data points. Due to the lack of transparency of offshore company's on the day rates of vessels, it is not easy to get access to this data. This also holds for the estimated day rates of the tools and tugboats.

In order to determine up to which year of decommissioning the currently available VLT's will be sufficient two assumptions have been made. Firstly, the lifetime of an offshore wind farm is 25 years. Secondly, the production of of monopiles of Sif is representative for the whole production of monopiles. In order to increase the knowledge on the D_o of the to be decommissioned wind turbines, the design lifetime and diameter of each specific wind farm can be implemented in the model. Creating a more clear overview of which size turbines are to be decommissioned at which moment in time.

The environmental effects of using vibration to extract piles from the seabed on benthic fauna are unknown. In order to see whether these species are impacted and if so, to what extend, a study should be performed.

To avoid resonance and to understand better which frequencies to avoid, it can be useful to research the dynamics of the whole system of crane, vessel, VLT and monopile. The dynamics of the whole system can provide information on which situations to avoid.

The β factor that is used to calculate the residual soil resistance is an empirical value that is typical for each soil type. However, not much is know about this β factor. It is suggested that more research is done to the reliability of these values.

Not much is known about the influence of time on the β factor. For example, is there an effect on the β factor as a monopile remains in the soil for a longer period of time. And if so, what is the influence of time. Therefore, it is suggested that this is further research is performed on this.

The β factor for the inner- and outer shaft resistance during vibration is taken as the same value, based on the soil type. It is suggested to research whether this assumption is correct. Perhaps, β_i differs from β_o since β_i regards a confined volume of soil withing the monopile and β_o regards the non-fined soil on the outside of the monopile.

The fact that the dredged soil cannot be dumped into the sea, but has to be transported to shore has not been taken into account in the dredging calculations. In order to get more precise cost and emission calculations, this should be taken into account in further calculations.

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Appendix

Table 2: Specifications VLT's of CAPE Holland.

No.	**Model name**	**Eccentric moment [kgm]**	**Dynamic mass [kg]**	**Eccentric mass [kg]**	**Eccentric radius [mm]**	**Maximum frequency [Hz]**	**Total mass VLT [kg]**	**Maximum line pull [t]**
			m_{dyn}	me		f	M_h	
1	CAPE VLT-320	320	55.021	3.327	96.2	23.3	89.138	500
2	CAPE VLT-640	640	89.464	6.654	96.2	23.3	123.582	500
3	CAPE VLT-320 Tandem	640	115.284	6.654	96.2	23.3	179.678	1000
4	CAPE VLT-320 Triple	960	166.526	9.982	96.2	23.3	261.196	1500
5	CAPE VLT-640 Tandem	1280	161.729	13.309	96.2	23.3	226.122	1000
6	CAPE VLT-320 Quad	1280	223.668	13.309	96.2	23.3	348.616	2000
7	CAPE VLT-640 Triple	1920	264.393	19.963	96.2	23.3	359.063	1500
8	CAPE VLT-640 Triple	1920	357.200	19.963	96.2	23.3	541.400	3000
9	CAPE VLT-640 Quad	2560	345.857	26.618	96.2	23.3	470.805	2000
10	CAPE VLT-640 Quad	2560	477.400	26.618	96.2	23.3	713.200	4000

Matlab Code