A Method for the Hooking of Floating Monopiles

H. J. van Gelder

Technische Universiteit Delft

TU Delft

A Method for the Hooking of Floating Monopiles

by

H. J. van Gelder

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on February 8th, 2022 at 3:00 PM.

Student number:	1518615	
Thesis committee:	dr. ir. P.R. Wellens,	TU Delft
	ir. A.D. Boon,	TU Delft
	dr. ir. P. de Vos,	TU Delft
Document number:	MT.21/22.015 M	

TU Delft

Abstract

To facilitate the installation of larger monopiles multiple players in the offshore wind market are investigating the floating transport of monopiles to installation locations. This brings the challenge that when these floating monopiles are to be installed by heavy lift vessels, they must safely be handed over to the installation vessel and hooked onto the main crane of the installation vessel for installation.

Current literature mainly focusses on two topics. Some studies exist on the behaviour of a floating monopile near a heavy lift vessel. Studies also exist that study the behaviour of a monopile hanging on the crane of a heavy lift vessel. The step between these two moments in time, where the floating monopile is handed over from the tug towing the monopile to installation vessel, is the focus of this study.

This thesis presents a method for the hooking of a floating monopile to the crane of heavy lift vessel Oleg Strashnov and a model for the hooking operation. This model is used to determine a maximum allowable sea state for this operation.

Two methods for hooking a floating monopile to the crane of a heavy lift vessel were defined. In the first option, the monopile would be moored alongside the vessel and kept in position by a supporting tug while the rigging is handed over to the heavy lift vessel and the rigging can be hooked onto the vessel crane. The second option entails positioning the monopile perpendicular to the heavy lift vessel, with fenders placed between the monopile and vessel.

The ANSYS AQWA software was used to model the response of the system in irregular waves during a critical moment of the installation procedure, the handover of the monopile from a towing tug to the heavy lift vessel. A variation study was carried out where the orientation and relative position of the monopile with respect to the heavy lift vessel were varied. Based on the relative vertical motion between the monopile and heavy lift vessel and the maximum tensions in the slings used to connect the monopile and heavy lift vessel, the perpendicular option was selected for further study.

Using the ANSYS AQWA software the response of the system in irregular waves during a three hour period was modelled in various sea states. Three incoming wave directions were considered: Head waves, beam waves and bow-quartering waves. The peak period of the wave spectrum was varied between 5.0 seconds and 7.0 seconds. Two significant wave heights were considered, 1.0 meter and 1.5 meters. Two limiting factors for the workability of the operation were studied: The vessel and monopile must not collide during the operation, and the relative vertical motion between monopile tip and vessel sideshell must remain below 1.8 meters to ensure a safe environment for personnel working on the deck of the vessel.

Based on the simulations it can be concluded that under the assumptions as shown in this report the chosen solution is a workable solution in the sea states shown in Table 1 and Table 2.

Wave angle / Tp	5.0s	5.5s	6.0s	6.5s	7.0s
090d	Ok	Ok	Ok	Ok	-
135d	Ok	Ok	-	Ok	-
180d	-	-	-	-	-

Table 1: Allowable sea states Hs 1.0m

Wave angle / Tp	5.0s	5.5s	6.0s	6.5s	7.0s
090d	Ok	Ok	-	Ok	-
135d	-	-	-	-	-
180d	-	-	-	-	-

Table 2: Allowable sea states Hs 1.5m

Contents

1 Introduction

Driven by both economic growth and population growth, the worldwide demand for energy keeps increasing (Figure 1.1a). In 2017 the global population has grown to 7.5 billion and it is expected to grow further to more than 9.5 billion in 2050 [11]. The world energy consumption is at an all-time high and is expected to keep increasing in the coming years (Figure 1.1b).

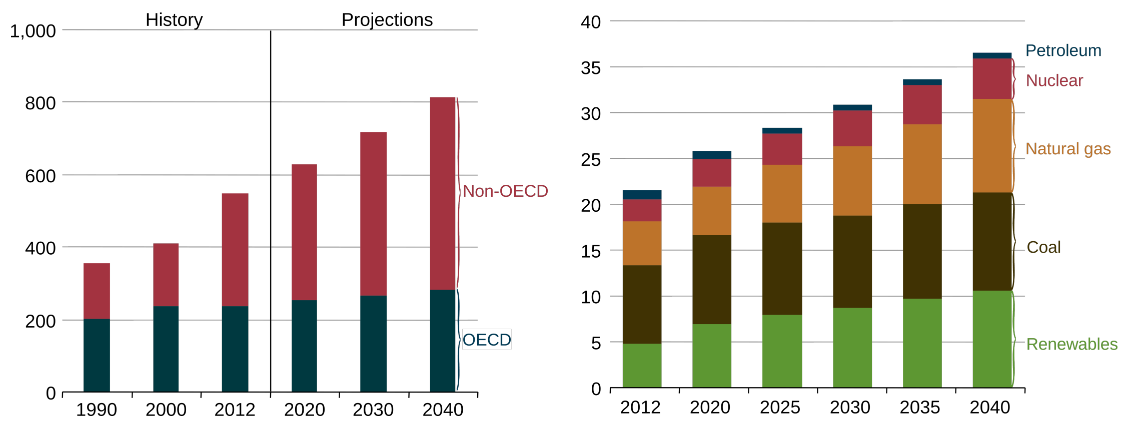

Figure 1.1: Predicted future energy use and electricity generation [5]

In light of this, the electricity demand is also increasing. A part of the increase in electricity generation is expected to come from renewable sources, wind energy being one of the main contributors.

1.1. Wind Energy

The first wind turbine for generating electricity was built in 1887 [12]. By the 1930s wind turbines were becoming more common on farms, especially in the United States due to the lack of an electricity grid. Over the years these turbines have continued to develop and increase in size and power output. It is not uncommon for modern wind turbines to deliver over 8MW of power.

”The entry into large-scaled wind farm installation” is what Thomson (2014) called the Middelgrunden wind farm off the coast of Copenhagen. In 2000, twenty turbines were installed at this site using makeshift equipment to keep the cost low. It was realised that this way of working was not sustainable and as a result, the industry needed to evolve and mature.

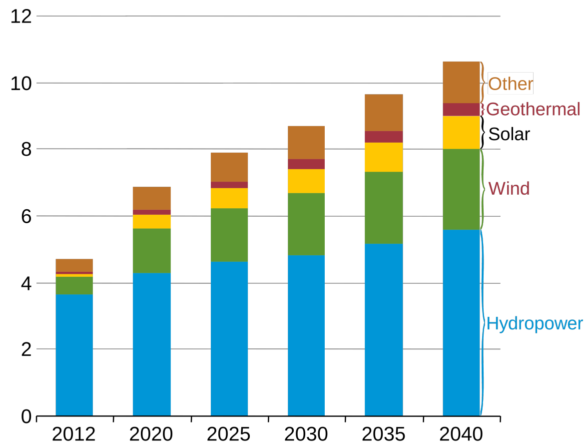

Figure 1.2: Renewable electricity generation outlook [trillion kWh] [5]

1.2. Offshore wind turbine foundations

The offshore wind turbine can be subdivided into two main components.

The superstructure, or tower, consists of all working parts of the turbine that are above the waterline. This includes the nacelle, the tower and the turbine blades.

The substructure, or foundation, is the connection of the wind turbine to the environment. Various foundation types for wind turbines have been explored over the years. Figure 1.3 shows most commonly used foundations. Of these the monopile has the largest share, making up 87 per cent of all new installations in 2017 [16]. The remaining 13 per cent is mainly made up of jacket structures, tripods, and tripiles. Furthermore, there is ongoing research into novel foundations, namely tension leg foundations, floating foundations and gravity-based foundations.

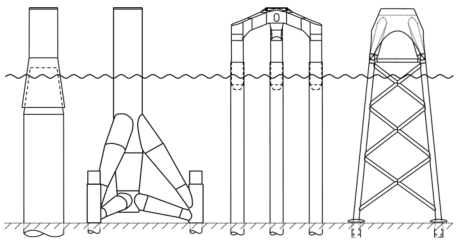

Figure 1.3: Foundation options for offshore wind turbines: monopile, tripod, tripile and jacket [13]

1.3. Floating monopile installation

Seaway Heavy Lifting is an offshore contractor in the global Oil&Gas and Renewables industry offering tailored T&I and EPCI solutions. They operate globally focussing on the North Sea, Mediterranean, America's, Africa, Asia Pacific and the Middle East. Seaway Heavy Lifting operates two heavy lift vessels (HLVs), the Stanislav Yudin and the Oleg Strashnov. These vessels are equipped with respectively a 2500 tonne and a 5000 tonne fully revolving crane and are amongst others used for the installation of Offshore Wind Turbine foundations, namely monopiles.

Currently, the conventional way of installing monopiles by Seaway Heavy Lifting entails transporting the monopiles on the deck of the HLV. This method may not be sustainable in the future due to the increasing size of monopile designs. These monopiles with diameters larger than seven meters are referred to as XL or extra large monopiles [7]. These larger monopiles will increase the difficulty of transport on the deck of the vessel. Therefore Seaway Heavy Lifting is researching alternative methods for transporting the monopiles to the project location.

Several companies have experimented with an alternative method for monopile transportation, the floating transport of monopiles. This entails making the monopile buoyant and towing the monopile to the installation location. At the installation site, the monopile is then handed over to the installation vessel. The monopile will be hooked onto the vessel crane after which the vessel crane will lift the monopile into an upright orientation (upending). Subsequently, the vessel will then lower the monopile to the seabed.

1.4. Literature review

Various studies have been performed related to the installation of monopiles using heavy lift vessels as well as studies investigating the floating transport of monopiles:

Li et al. [8] provided an analysis of lifting operation of a monopile for an offshore wind turbine considering vessel shielding effects. The study investigates the situation where the monopile is suspended from the vessel crane.

Acero et al. [1] includes an assessment of the dynamic responses and allowable sea states for an offshore wind turbine installation concept based on the inverted pendulum principle.

Sarkar and Gudmestad [14] studied a new method for installing a monopile by using a subsea frame to position the monopile during installation.

Maliepaard [9] studied the installation of floating monopiles in heavy weather conditions and includes numerical analyses of the ”touch down” of the bottom of a floating monopile on the seafloor as well as analysis of a coupled monopile-vessel system while the monopile is partly supported by the seabed.

Birkeland [4] provides numerical simulations of installation of XL monopiles by a HLV by evaluating the response of the coupled system where the monopile is suspended from the vessel crane.

There are more master theses in the TU Delft repository related to this topic. These studies are under embargo until 2023 or later and can therefore not be of use for this study.

The focus of the studies mentioned above has been two folded. Maliepaard [9] has focused on the behaviour of a floating monopile near a HLV. Other studies (Li et al. [8], Birkeland [4]) investigated the behaviour of a monopile that was attached to the crane of a HLV. This study will focus on the step between these two moments in time, where the floating monopile is handed over from the tug towing the monopile to the installation site to the HLV and hooked onto the crane for upending

One of the things that these studies do not investigate is the transport of the monopile and the handover from tug to vessel. This study will investigate how the handover can be made in a safe way as well as the behaviour of the monopile and vessel during handover. The behaviour of the monopile and vessel during handover is critical since during this moment the relative motions between monopile and vessel may result in snap load in the rigging connecting the monopile to the vessel crane. Large relative motions might also pose a risk for any crew of the HLV tasked with performing the handover. To minimise risk to the crew a solution should be found where the monopile can be safely handed over from the towing tug to the HLV. This solution should include an estimate of the operating limits of this solution.

1.5. Thesis goal

Conventional transportation of monopiles from the fabrication yard to the project location is done by either transporting the monopiles on the deck of a heavy lift vessel or transporting the monopiles on barges. Seaway Heavy Lifting is investigating the feasibility of installing monopiles by instead floating them out to the project site.

Previous studies have investigated the behaviour of a coupled HLV/monopile system with the monopile suspended from the vessel crane. The behaviour of a grounded monopile has also been studied. The handover of the monopile from a towing tug to a HLV and the hooking of the monopile onto the vessel crane however is a challenge that has not yet been studied in the available literature.

This thesis will investigate the feasibility of handing over a floating monopile from a towing tug to HLV Oleg Strashnov. The goal of this thesis is:

To formulate a method for the hooking of a floating monopile to the crane of HLV Oleg Strashnov and to model the hooking operation to determine a maximum allowable sea state for this operation.

Based on this the following sub-objectives have been formulated to achieve the main goal:

- Formulate two methods for safely hooking the floating monopile onto the vessel crane.
- Develop a model of the vessel and monopile to estimate hydrodynamic responses of the monopile and vessel and make a selection between the two proposed solutions

- Determine allowable sea states for the proposed solution based on simulations of the vessel and monopile

1.6. Thesis outline

This thesis has been split up into various chapters per the thesis objective:

- chapter 2 discusses the current method of installing monopiles used by Seaway Heavy Lifting and how it differs from floating monopile installation. It then proposes two methods for hooking the monopile onto the main hook of the vessel crane.
- In chapter 3 the boundary conditions and assumptions are presented for a model which will describe the behaviour of the monopile and vessel during installation.
- chapter 4 will compare the two proposed methods of monopile installation and select the optimal method to be used for further investigation.
- Detailing of the operation and behaviour of the system in the time domain will be discussed in chapter 5.
- Lastly, chapter 6 will list the conclusions that can be drawn from the presented results and will give recommendations for future research.

2

Monopile installation methods

The first part of this chapter will describe the conventional method of installing monopiles. After this, the alternate method of installation by floating the monopiles to the project location will be described.

A critical part of the installation procedure is the hooking of the monopile onto the main hook of the vessel crane. In order to safely hook the monopile onto the vessel crane a method needs to be designed to make a controlled handover from the tug to the vessel. Internal studies at Seaway Heavy Lifting have resulted in two solutions, which are also described in this chapter.

2.1. HLV Oleg Strashnov

This study focuses on monopile installation by the Oleg Strashnov, a heavy lift vessel (HLV) owned and operated by Seaway Heavy Lifting. The Oleg Strashnov is equipped with a 5000 tonne fully revolving crane. Key dimensions of the Oleg Strashnov can be found in Table 2.1. Figure 2.1 gives an impression of the HLV.

Figure 2.1: HLV Oleg Strashnov [15]

The Oleg Strashnov is equipped with a DP3 class positioning system and an eight-point mooring

Description	Unit	Value
Length overall	m	183.0
Working draught	m	13.5
Breadth	m	47.0
Displacement	m^3	51,200.0

Table 2.1: Dimension HLV Oleg Strashnov

system. Currently, Seaway Heavy Lifting uses the eight-point mooring system for positioning while installing monopiles. The installation of monopiles using dynamic positioning is under investigation but presents its own problems, which fall outside of the scope of this thesis and will therefore not be discussed further.

2.2. Conventional monopile installation

The procedure for installing monopiles can be split up into four steps: Loading and transport, upending of the monopile, outrigger assisted positioning, and hammering.

The following section expands on these four steps during conventional installation of a monopile. The procedure for floating monopile installation will diverge from this method for the first two steps.

2.2.1. Loading and transport

The monopiles are fabricated onshore and are loaded either on deck of the vessel (Figure 2.2a) or on a barge (Figure 2.2b). If the monopiles are transported on the HLV, the vessel sails out to the project location and positions itself on the design location of the monopile using its eight-point mooring system. If barges are used for the transportation of the monopiles the HLV stays at the project location.

(a) Monopile transport on HLV

(b) Monopile transport on barge

Figure 2.2: Monopile transportation [15]

2.2.2. Upending of the monopile

To begin the installation procedure the vessel crane is used to transfer the monopile from the deck or barge to the upend cradle on deck. This cradle is used to rotate the monopile from a horizontal to a vertical position, a process referred to as upending of the monopile. The cradle supports the monopile during upending to reduce internal stresses during the operation and to limit the freedom of motion of the monopile during the upending procedure.

With the monopile in the upending cradle, the main hook of the vessel crane is attached to the top of the monopile. The vessel crane then lifts the top of the monopile, rotating the monopile from a horizontal position until the monopile is vertical (Figure 2.3).

2.2.3. Outrigger assisted positioning

Using the vessel crane the monopile is placed in an outrigger fitted on the side shell of the HLV Figure 2.4 This outrigger is actively compensated to ensure that the monopile stays vertical and touches down on the seabed on the designated location.

2.2.4. Hammering

The top of the monopile is released and a hammer is placed on the monopile which then drives the monopile to the desired seabed penetration (Figure 2.5) while the outrigger ensures the verticality of the monopile.

Figure 2.3: HLV Oleg Strashnov upending a monopile [15]

Figure 2.4: Outrigger assisted MP installation by HLV Oleg Strashnov [15]

Figure 2.5: Monopile hammering [15]

2.3. Floating monopile installation

The floating monopile will be towed to the project location by a tug and upended while in the water. The installation of floating monopiles will differ from the procedures used for conventional installation. Installation of floating monopiles can be split up into various steps to describe the full process:

1. Loading and transport
2. Hooking of the monopile

3. Upending
4. Outrigger assisted installation
5. Hammering

Of these steps, steps four and five will the same as with conventional monopile installation and will therefore not be elaborated upon again.

2.3.1. Loading and transport

A previous study in this field [9] has shown internal floatation devices in combination with liftable end caps to be a viable solution for the floating transportation of monopiles. The internal flotation devices are large inflatable bladders that provide buoyancy to the monopile. The use of multiple of these internal flotation devices, as well as the liftable endcaps, ensures redundancy and limits the possibility of a single point of failure. The monopile is then towed out to the project location where it will be handed over to the heavy lift vessel for installation. Options for storage of monopiles on location to ensure that the HLV will not have any downtime due to delays in the monopile delivery are also being investigated. This thesis however will focus on the floating handover of the monopile to the HLV.

Figure 2.6: Floating delivery of monopiles using monopile end caps [15]

2.3.2. Hooking of the monopile

When the monopile arrives at the project location it must be handed over to the HLV and hooked onto the vessel crane for upending. One of the main requirements for this operation is to limit the exposure of the vessel crew to potentially dangerous situations. Therefore the aim is to make the handover with as little manual intervention as possible. Furthermore, the hooking method should have a high workability to keep project costs down and minimize delays due to waiting on weather windows. Internal studies at Seaway Heavy Lifting have yielded two options for safely hooking and upending the floating monopile, which are discussed in the next section of this chapter.

2.3.3. Upending of the monopile

After the monopile has been hooked to the main hook, the vessel crane is used to upend the monopile while it is floating. After or during the upending procedure the buoyancy of the monopile will be reduced to reach a vertical position of the monopile in a controlled manner. After this step, the vessel crane will guide the monopile into the outrigger for installation. From this point, the installation no longer differs from the conventional installation method.

2.4. Proposed installation methods

A critical part of the installation procedure is the hooking of the monopile onto the main hook of the vessel crane. In order to safely hook the monopile onto the crane a method has to be designed to facilitate a controlled handover of the monopile from the towing tug to the heavy lift vessel. Internal studies at Seaway Heavy Lifting have resulted in two solutions which will be compared in chapter 4.

The first method uses a tug to position the monopile perpendicular to the vessel after which a winch on the deck of the HLV pulls in the monopile until it is close enough for the rigging, which is pre-attached to the monopile, to be hooked onto the vessel crane. This method will be referred to as the 'perpendicular option'. The second method uses a tug to position the monopile alongside the vessel where it will be temporarily moored against fenders while the rigging is hooked onto the vessel crane. This method will be referred to as the 'alongside option'. The following sections describe the two proposed solutions for hooking and upending the floating monopiles in further detail.

2.4.1. Perpendicular option

The hooking and upending of the monopile are split up into various steps which are discussed separately:

- The towing of the monopile to the vessel;
- Handover of the monopile from the towing tug to the HLV;
- Hooking of the monopile rigging onto the main hook of the HLV crane
- Upending of the monopile

Towing of the monopile

The monopile is towed to the project location on the top cap that is used to seal the monopile. The tow rigging consists of two softslings attached to the top cap on one end and the towline on the other end. When the tug and monopile arrive at the project location, a second tug hooks onto the bottom cap of the monopile to aid in manoeuvring when the tug and monopile approach the HLV. Figure 2.7 gives an overview of the towing arrangement.

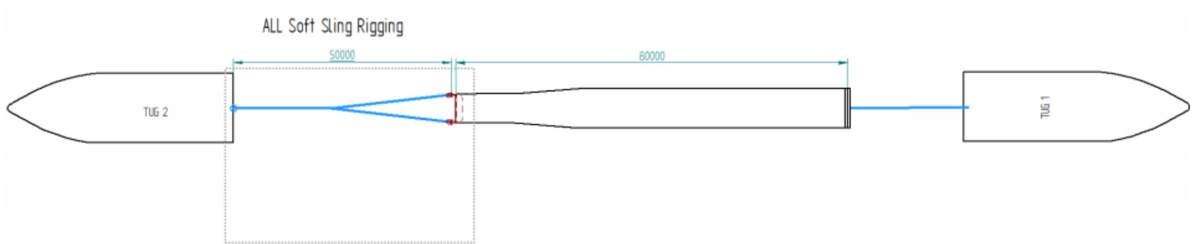

Figure 2.7: Towing arrangement

Handover to the HLV

From the towing tug, a line is handed over to the HLV. This is used as a forerunner to connect the rigging on the top cap to a winch on the deck of the HLV (Figure 2.8). After the rigging is handed over to the HLV, the towing tug can move away. The tug connected to the bottom cap is then used to keep the monopile in position (Figure 2.9). This tug has to provide enough pull force to keep constant tension on the line between the vessel and the top cap of the monopile.

Hooking to the main hook

After the handover has been successfully made, the winch on the deck of the HLV is used to pull the monopile towards the HLV (Figure 2.10). Once the rigging has been pulled onto the deck it is secured on deck and the slings are attached to the main hook (Figure 2.11). The tug pulling on the bottom cap exerts a constant force to ensure the monopile does not collide with the side of the HLV and to prevent snap loading in the line between the HLV and the monopile.

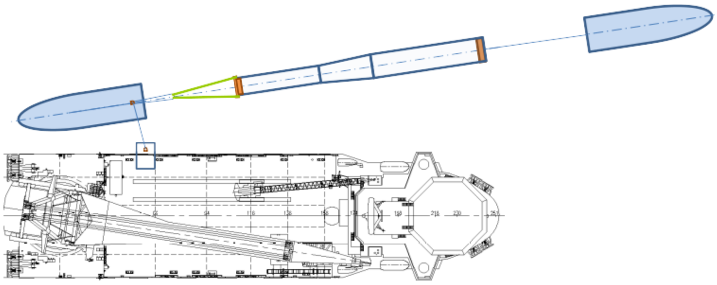

Figure 2.8: Forerunner handover

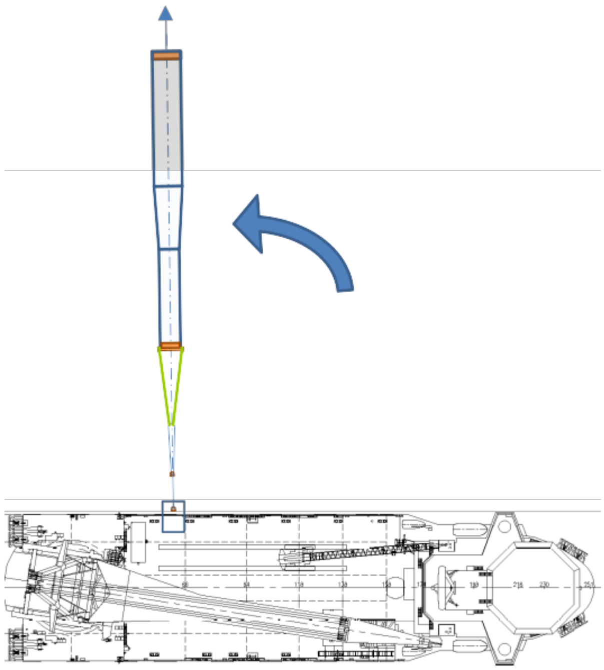

Figure 2.9: Monopile repositioning

Upending of the monopile

With the rigging secured on the main hook the upending process starts. The crane lifts the top cap of the monopile until the monopile is vertical (Figure 2.12). While outside the scope of this thesis, this will also be a critical part of the installation procedure. Large movements of the monopile during upending might cause eccentric loading of the vessel crane and the changing waterline area of the monopile during upending means the behaviour of the monopile in waves will change as more of its weight is supported by the vessel crane.

2.4.2. Alongside option

As with the perpendicular option, for the alongside option the upending of the monopile is split up into various steps which are discussed separately:

Towing of the monopile

As with the perpendicular option, the monopile is towed on the rigging that will be used for the upending of the monopile. After the monopile is towed out to the vessel it is positioned alongside the HLV (Figure 2.13). A supporting tug pushes the monopile against fenders at the sideshell of the vessel (Figure 2.14). In this way, the monopile can be restrained against the sideshell without causing damage to either the monopile or the vessel.

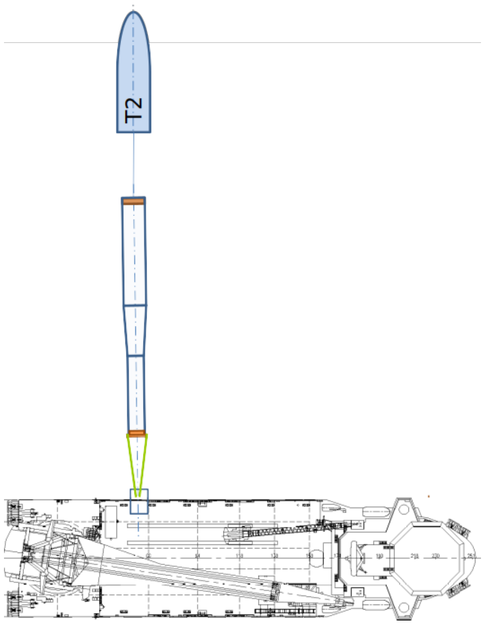

Figure 2.10: Monopile pull in

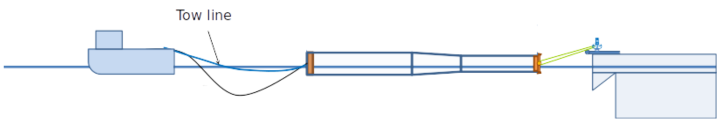

Figure 2.11: Hooking the MP onto the crane

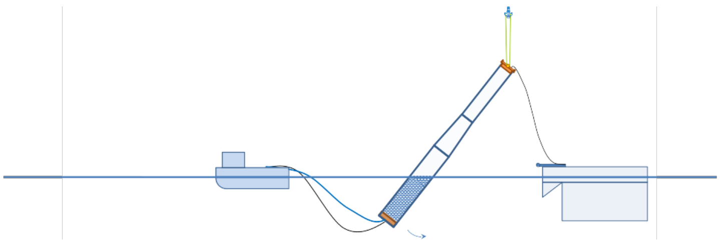

Figure 2.12: Upending of the monopile

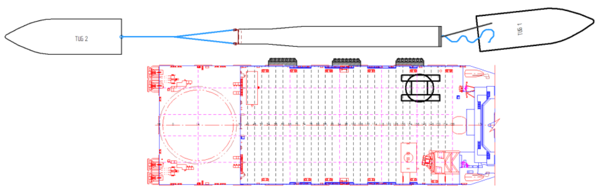

Figure 2.13: Monopile positioned alongside the HLV

Handover to the HLV

Since the monopile is now restrained against the sideshell of the HLV the rigging can be handed over using either the whip hoist of the main crane or a secondary crawler crane on deck of the HLV. Because the monopile is restrained against the sideshell there is no tension on the rigging.

Hooking onto the main hook

The rigging is then hooked onto the main hook of the vessel crane. It is essential to keep the monopile restrained to ensure there is no tension on the rigging. Tension in the rigging can endanger the riggers while they are hooking the slings onto the main hook.

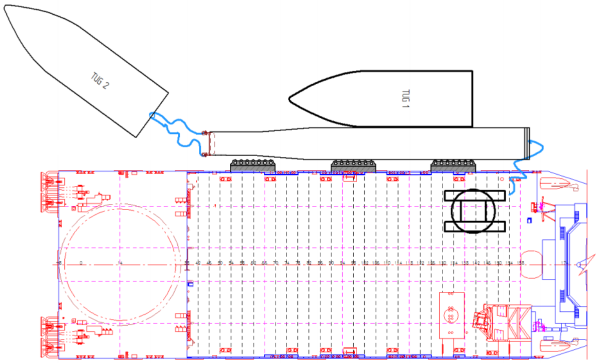

Figure 2.14: Monopile restrained against the sideshell of the HLV by supporting tug

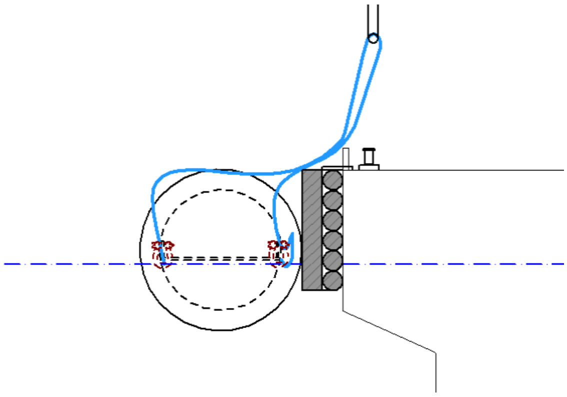

Figure 2.15: Rigging handover to the HLV using the whip hoist

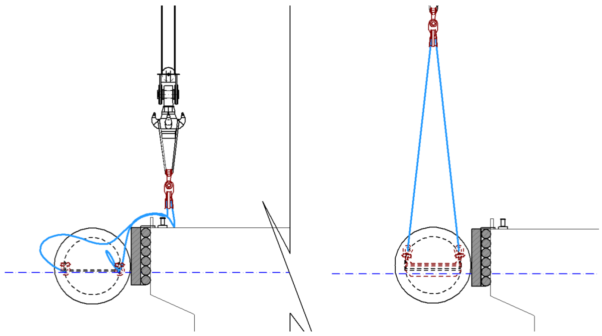

Figure 2.16: Monopile hook on

Upending of the monopile

After the rigging is hooked onto the main hook the upending of the monopile begins. As with the perpendicular option, care must be taken while upending the monopile because at this point in the installation procedure the only restraints on the monopile are the main rigging and the supporting tug. This may lead to unexpected motions of the monopile. This behaviour falls outside of the scope of this thesis but it is advised to model the behaviour of the monopile during upending in future work to ensure this part of the operation can be safely executed.

3
The model

To compare the two proposed solutions, a numerical study has been carried out. The goal of this numerical study has been twofold. In chapter 4 the two proposed installation methods will be studied to compare the motions of the vessel and monopile in both situations. In chapter 5 the resultant forces on the monopile-vessel connection will be studied in more detail. This chapter describes the numerical methods used and describes the boundary conditions and assumptions used in the model.

3.1. Modelling approach

For this study, two different modelling approaches are used: Frequency domain analysis and time domain analysis.

3.1.1. Frequency domain analysis

In chapter 4 a parametric variation study is performed for the two proposed solutions. Calculating the motions of the monopile and vessel is a computationally intensive task, due to both system nonlinearities and possible position-dependent environmental loads. By linearizing these computations in a frequency domain analysis, these calculations can be solved faster. This fast calculation makes frequency domain analysis a more suitable analysis for a parametric variation study.

3.1.2. Time domain analysis

In chapter 5 a time domain analysis is performed for the solution determined in chapter 4. In contrast to frequency domain analysis, time domain analysis does include non-linearities. Time domain analysis is more computationally intensive than frequency domain analysis, however by calculating the real-time motion of the vessel and monopile in irregular waves this method can give a deeper understanding of the behaviour of the coupled system. Time domain analysis is used in chapter 5 to determine the loading in the slings connecting the monopile to the vessel and to determine the workability of the chosen solution.

3.2. Reference systems

Three different reference systems are used to describe the behaviour of the system:

- A global earth-bound reference system in which the (x,y) plane lies on the still water surface with the positive z-axis pointing upwards.
- Two local moving reference systems, one for the vessel and one for the monopile. These axis systems have their origins in the centre of gravity of their respective structure, the (x,y) plane parallel to the still water surface, the x-axis pointing to the bow of the structure and the z-axis pointing upward.

All motions of the vessel and monopile like surge, sway, pitch etc. are given in the local fixed axis system unless otherwise specified. All relative motions between vessel and MP are given in the global fixed reference system unless otherwise specified.

Wave direction is defined as the angle from the positive global x-axis to the direction in which the wave is travelling, measured anti-clockwise when seen from above. Therefore waves travelling in the positive X-direction have a 0-degree wave direction, while waves travelling in the positive Y-direction have a 90-degree wave direction.

3.3. Monopile model

For this study, a design monopile with a length of 80 meters has been used. This monopile weighs 1200 tonnes and has a diameter varying from 6.25m at the top to 9.0m at the bottom of the monopile. Table 3.1 gives the main properties of the monopile. The top and bottom caps have been estimated as weighing 20 tonnes each. Figure 3.1 gives an overview of the main dimensions of the monopile.

In Ansys AQWA the moment of inertia is defined at the centre of gravity of a structure and around the global rotational axes. From this, it follows that for the monopile at 90 degrees the inertia around the x-axis and y-axis should be flipped. For different angles this approach does not hold. Using the inertia tensor the inertia matrix for an arbitrary angle can be calculated.

The inertia around an arbitrary axis can then be calculated using $I_i = \mathbf{n} \cdot \mathbf{I} \cdot \mathbf{n}$, in which $\mathbf{n}$ is the unity vector along the axis.

LOA	80.00	m
Diameter top	6.50	m
Diameter bottom	9.00	m
Weight	1200.00	tonne
Max. draught	3.3	m
CoG	40.53	m

Table 3.1: Main dimensions design monopile

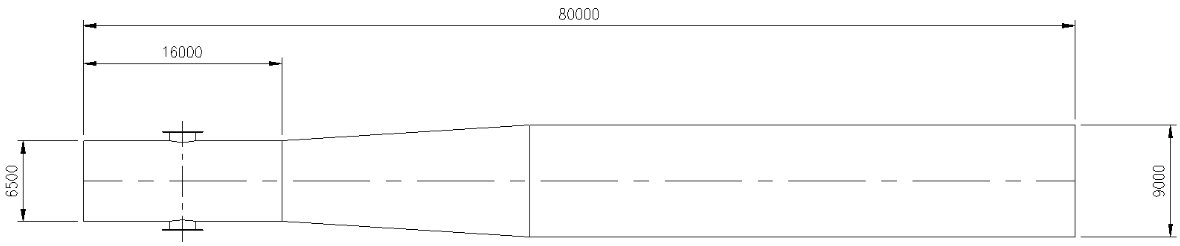

Figure 3.1: Monopile main dimensions

3.3.1. Monopile mesh

The mesh for the monopile was made using the mesh function provided by Ansys AQWA. The influence of the panel size on the hydrodynamic coefficients was verified with a sensitivity analysis (Figure 3.3). The starting point for the panel size was based on the wavelength of the shortest waves in the assumed spectrum. The cutoff point for the spectrum (subsection 3.5.1) is 1.7rad/s or a 3.7 second wave period. For the design water depth of 35 meters, this wave has a length of 21 meters. As a guideline [2], panel size should to be smaller than $\frac{1}{8}$ of the wave length. For the sea state to be studied, this amounts to a maximum panel size of 2.6 meters. To verify the panel size for the monopile ANSYS AQWA was used to determine the RAOs of the monopile for panel sizes between 2.5 meters and 0.5 meters, with intervals of 0.5 meters. When the panel size decreases, the RAOs converge to a constant value (Figure 3.2) Starting at a panel size of 1.5m the difference is smaller than 1% which is deemed acceptable at this design stage. Further analysis will therefore use a maximum panel size of 1.5 meters for the monopile.

3.4. Oleg Strashnov Model

The model for the Oleg Strashnov used in this study was built in-house by Seaway Heavy Lifting (Figure 3.4). Based on the experience Seaway Heavy Lifting has operating the Oleg Strashnov, parameters

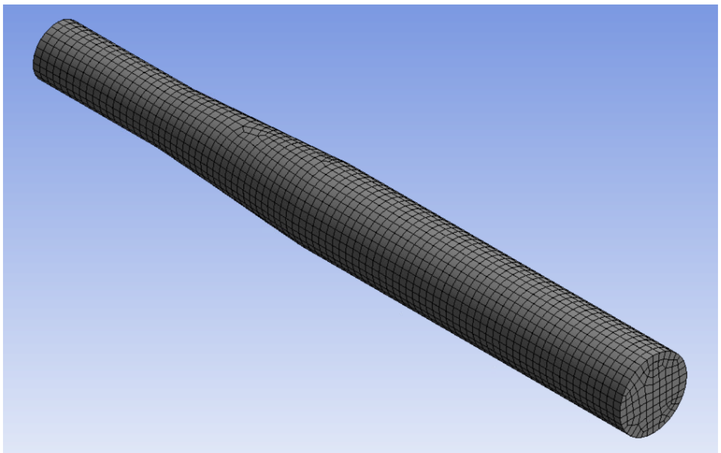

Figure 3.2: Monopile mesh

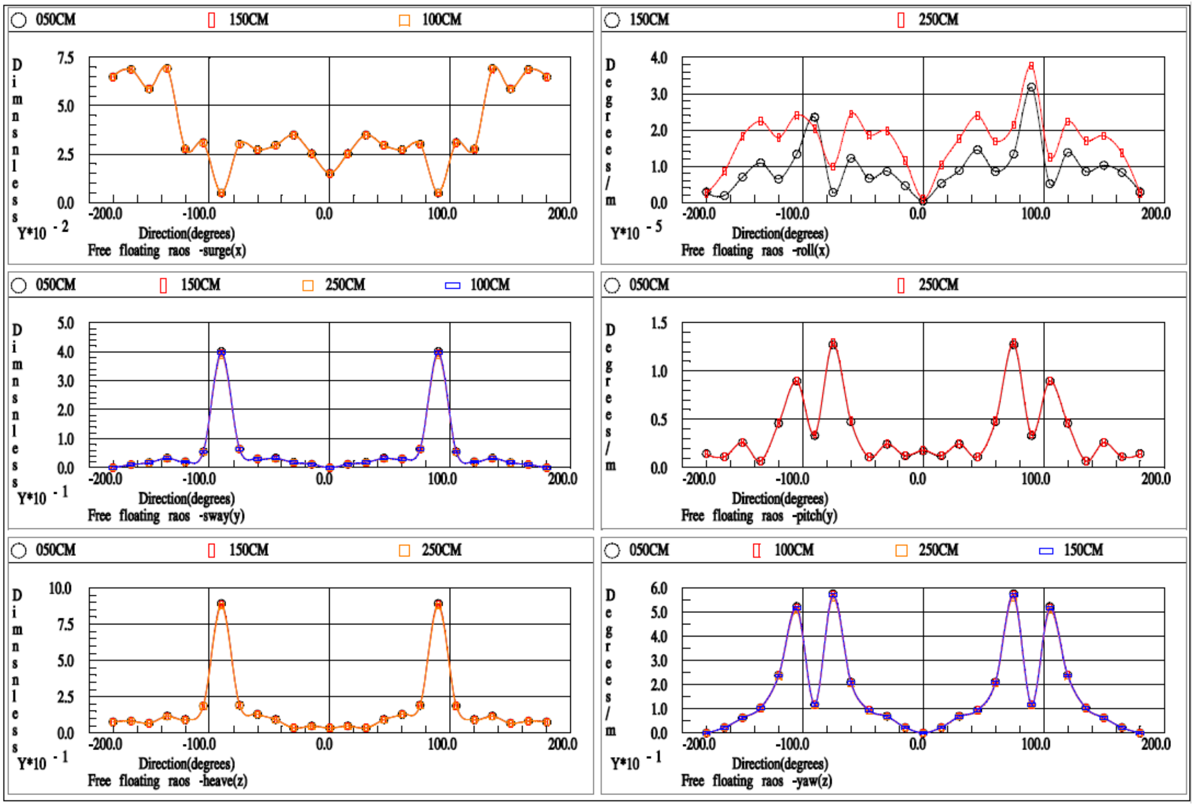

Figure 3.3: Convergence of mesh sizing

for the roll damping and metacentric height of the vessel have been tuned. As this model tuning is proprietary the values for the tuning are not provided.

3.5. External forces

Various external forces act on the system and influence its behaviour. Some of these forces will be either simplified or neglected in the model.

3.5.1. Wave loading

For the wave loading on the system, various assumptions were made.

Pierson Moskovitz wave spectrum As this is a generalized study without a defined installation lo-

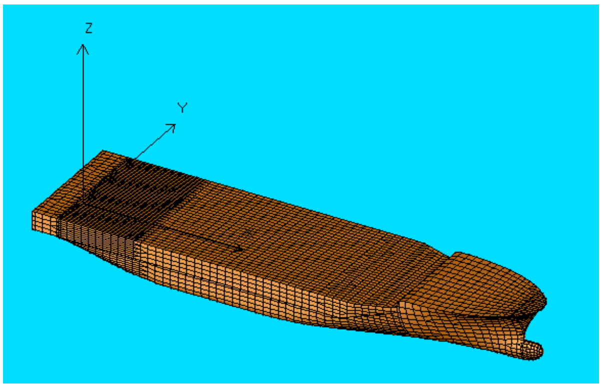

Figure 3.4: Oleg strashnov mesh

cation a Pierson Moskovitz wave spectrum is used for the calculations. This assumes a fully developed sea state.

Wave height Significant wave height between 1.0 and 1.5 meters

Wave period Peak period between 5.0 and 7.5 seconds

Waterdepth the water depth is assumed to be 35 meters following the design depth of the reference monopile.

To ensure that the wave conditions would be in the range which can be simulated by AQWA the wave conditions were classed in a wave theory per the division as stated in Méhauté [10] (see Figure 3.5). For the design water depth of 35 meter, all combinations of the wave height and the wave period fall within the area of the Stokes 2nd order theory. AQWA, by default, uses Stokes 2nd order theory to model the system.

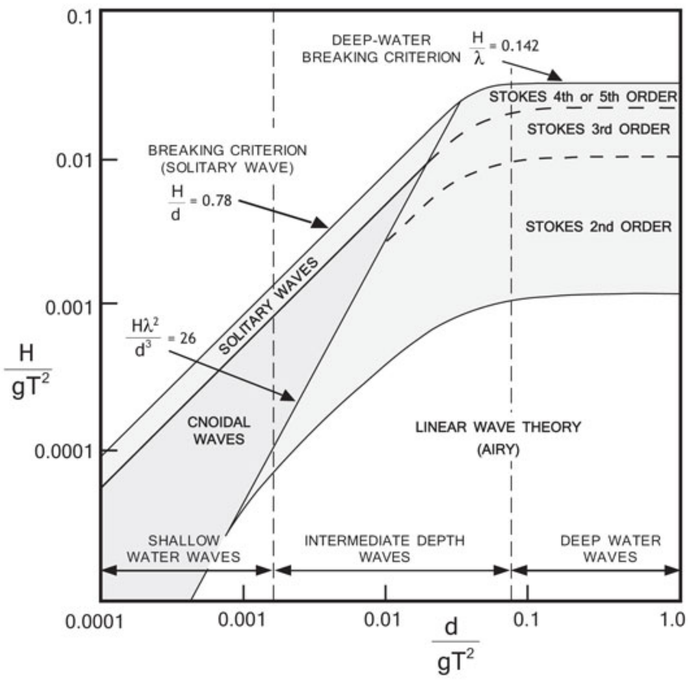

Figure 3.5: Validity of wave theories [10]

Use of the AQWA Naut module for time domain analysis means second-order wave drift forces were not included in the analysis. The HLV will either be on pre-tensioned anchors which will limit the movement of the HLV due to second-order wave drift force, or the HLV will be on dynamic positioning, in which case the thrusters compensate for the second-order wave drift forces. The monopile will be influenced by second-order forces due to the low damping in surge and sway direction but because these motions have large periods they can be counteracted by repositioning the supporting tug, thereby limiting the large motions that are usually associated with second-order wave drift forces.

3.5.2. Wind and current loading

Both wind and current loading are not included in the model. Current loading on the system will be an almost constant force on both floating structures. As this force does not vary in time it will be counteracted by the mooring of the vessel and will have a negligible influence on the dynamic motions of the system. Wind loading is variable but its effect on the motions of the vessel will be small compared to the wave loading due to the pretension in the anchor lines while the vessel is moored. The wind loading on the monopile itself is also estimated to be small since the monopile has a small wind catching surface which is located near the sea surface, where the wind speeds are lower than at higher elevations above the sea surface.

3.5.3. Hydromechanical coupling

As the HLV and monopile are close to each other they will affect each other's motions. Assuming the monopile is positioned downwind from the HLV the vessel will shield the monopile from shorter waves, thereby reducing the wave loads on the monopile. This hydromechanical coupling is accounted for in the AQWA model. The wave damping effect of the vessel is further explored in chapter 4.

3.5.4. Mooring and mechanical coupling

The HLV and the monopile are restrained by three mechanical couplings:

Mooring lines Oleg Strashnov Pre-tensioned mooring using a mooring pattern provided by Seaway Heavy Lifting

Monopile - vessel connection The soft slings on which the monopile is towed are modelled as two lines from the tip of the monopile to the sideshell of the vessel. Here they will be connected to a line coming from a winch on the deck of the vessel. Modelling this system resulted in convergence problems due to the lack of restraints on the connection between the winch line and soft slings. Therefore only the two softslings are modelled which are connected to a fixed point on deck. The presence of the winch wire has been accounted for by using the combined stiffness of the softsling and winch wire as the stiffness for the modelled slings.

Supporting tug The force exerted on the system by the supporting tug in the perpendicular option is modelled as a constant tension winch set to a pull force of 10 tonnes.

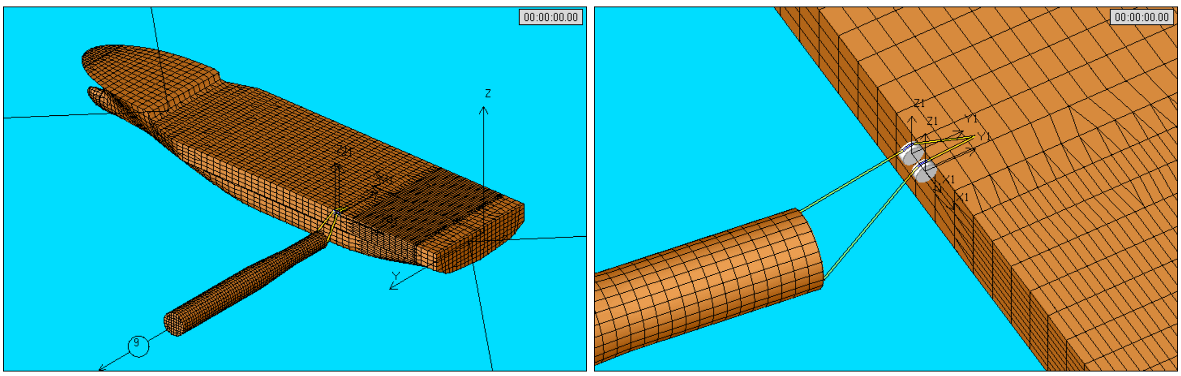

Figure 3.6: Overview of the simulated model in equilibrium position

3.6. Vessel Shielding

Vessel shielding has a large effect on the motions of the monopile. To estimate the vessel shielding effect AQWA was used to estimate the wave field surrounding the vessel for various incoming wave headings and wave periods. The wave period was varied from four seconds to ten seconds with one-second intervals. Two incoming wave angles were studied: 135 degrees (bow sea) and 90 degrees (beam sea).

Figure 3.7 shows the vessel shielding effect for the Oleg Strashnov and monopile system for short (5s period) regular waves.

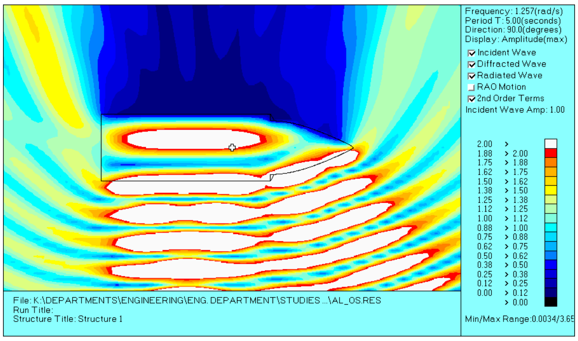

Figure 3.7: Vessel shielding 5s

Figure 3.8 shows the same configuration with slightly longer regular waves (7s period). It can be seen that for short waves the shielding effect is more pronounced and will thus result in smaller wave loading on the monopile compared to longer waves.

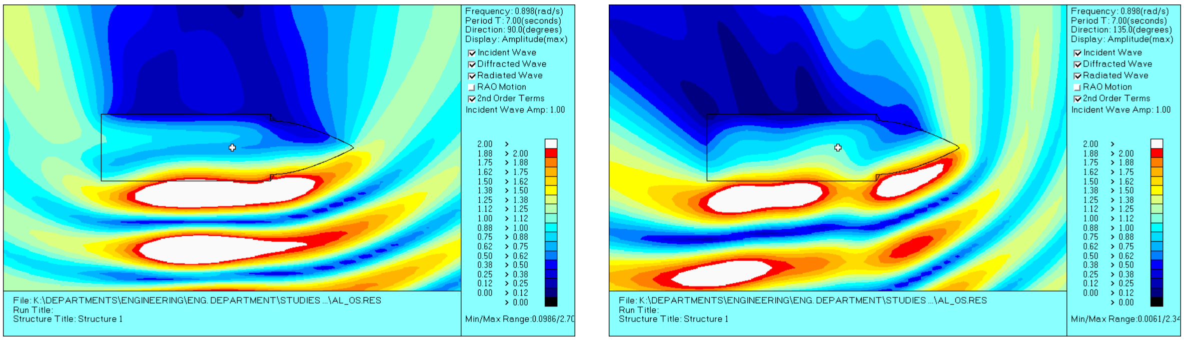

Figure 3.8: Vessel shielding 7s

Lastly in Figure 3.9 the system is faced with longer period waves (9s period). Here the shielding effect of the vessel almost completely disappears. It is expected that in these conditions the motions of the monopile will become unacceptably large since the motions are no longer dampened by the shielding of the vessel.

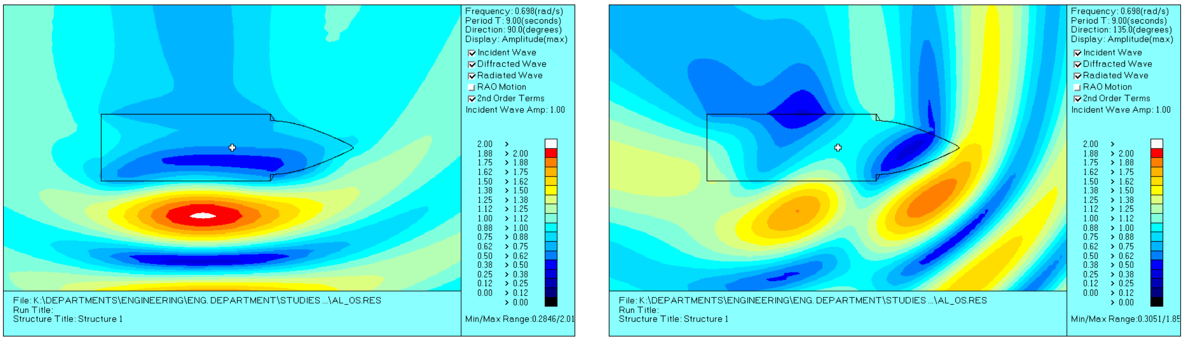

Figure 3.9: Vessel shielding 9s

3.7. Model validation

3.7.1. Vessel shielding

In order to validate the model, the wave shielding calculated using ANSYS AQWA will be compared with a hand calculation. An estimation of the wave field behind the vessel can be made by treating the vessel as a breakwater. This is not valid for all cases, since for long waves the heave RAO of the vessel will approach 1, meaning the vessel will follow the motion of the waves. For short wave the heave RAO will approach 0, meaning the vessel will remain at rest in waves. Because the motions of the vessel in unidirectional short waves are small, the amount of wave energy transferred by the vessel will be low. Therefore we can use existing literature [3] to estimate the wave height behind the vessel by comparing it to the wave field behind a static breakwater.

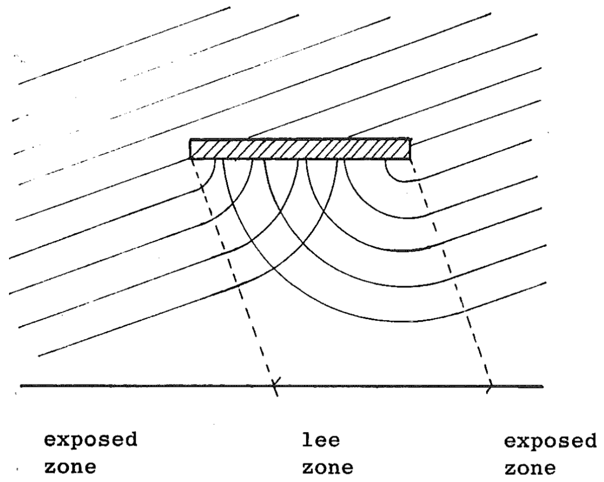

Figure 3.10: Wave propagation around breakwater [3]

Figure 3.10 gives a visual representation of wave diffraction around a fixed breakwater. Since according to Battjes [3] the wave height behind the breakwater caused by the reflected wave is an order of magnitude smaller then the diffracted incident wave, for this estimation wave reflection will not be considered.

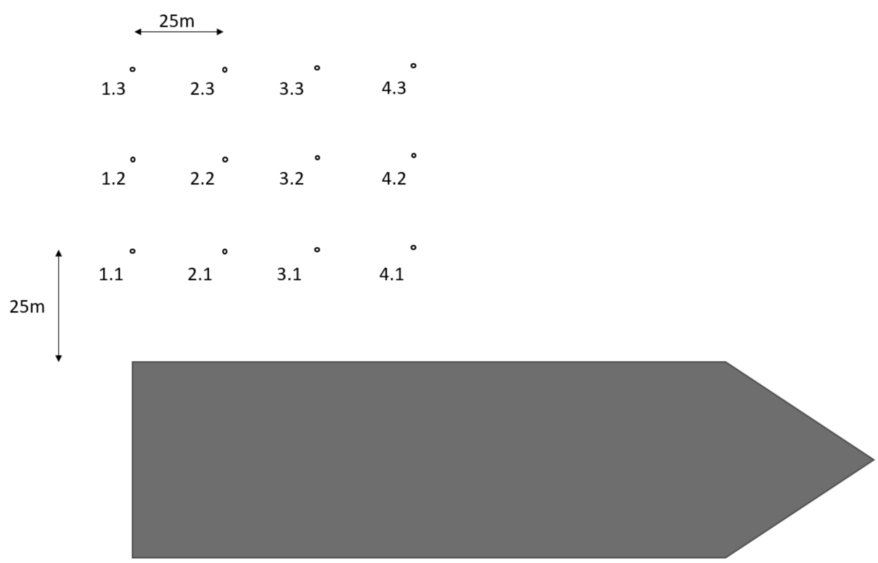

Figure 3.11: Wave height calculation points

Tthe diffracted wave height was calculated at various locations behind the vessel, according to the

Description	Unit	Value
Water depth	m	35
Length vessel overall	m	183
Beam vessel	m	47
Incident wave height	m	1.0
Incident wave period	s	4.0
Incident wave angle	deg	90
Incident wave length	m	24.97

Table 3.2: Wave sheilding validation parameters

Grid points	1	2	3	5	6
1	1.00m	0.34m	0.20m	0.16m	0.12m
2	1.00m	0.42m	0.24m	0.18m	0.15m
3	1.00m	0.48m	0.28m	0.20m	0.16m

Table 3.3: Wave height using Battjes [3] at grid points defined in Figure 3.12

grid shown in Figure 3.11. The grid points are 25 meters apart in both x-direction and y-direction.

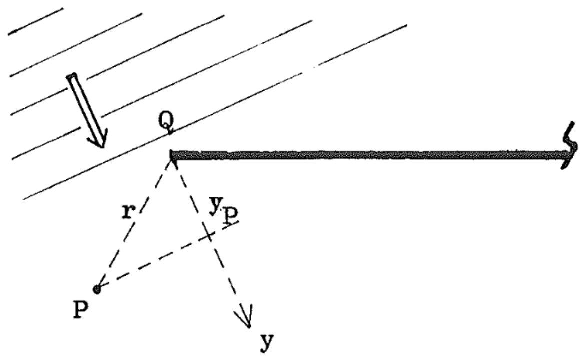

Figure 3.12: Wave field around static breakwater [3]

For the calculation the paramters given in Table 3.2 were used. Using these and the formulas from Battjes [3] the wave height at the grid points was calculated, shown in Table 3.3

The wave height as calculated using ANSYS AQA is shown in Figure 3.13. Comparing the results with the hand calculation shown in Table 3.3, we can conclude that the hand calculation matches the pattern from the simulation. The values for the wave height are in the same order of magnitude.

3.7.2. RAO validation

To check the validity of the model an analytical estimation was made to determine the heave RAO of the free floating monopile. This was then compared to the output of the ANSYS AQWA model.

The heave RAO can determined analytically using Equation 3.1 [6]. This formula is derived directly from the equation of motion and the hydrostatic pressure acting on the structure by the waves. It is therefore only valid for the these conditions:

- structure length small compared to wavelength
- uniform draft for the entire structure

If both these conditions are met the hydrostatic pressure acting on the bottom of the object can be assumed uniform. Since the object length should be small compared to the wavelength, waves facing the long side of the monopile were studied (beam waves).

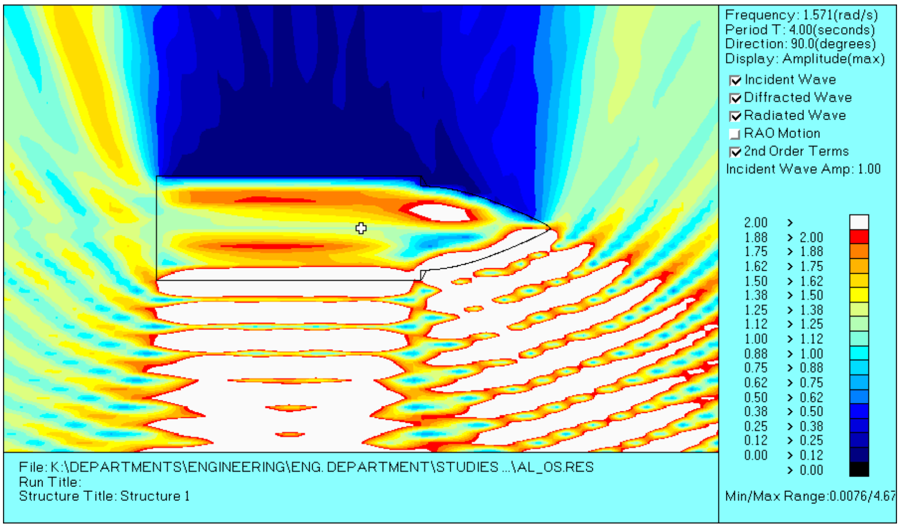

Figure 3.13: Wave shielding Oleg Strashnov

$$\frac{z_a}{\zeta_a} = e^{-kT}\sqrt{\frac{\{c - a\omega^2\}^2 + \{b\omega\}^2}{\{c - (m+a)\omega^2\}^2 + \{b\omega\}^2}} \tag{3.1}$$

In which:
a: added mass
b: damping
c: spring coefficient
m: mass
k: wave number
T: draft

After substituting the known values for c, m, k and T, we are left with the unknowns for added mass and damping. Using Figure 6.10 from Journée et al. [6] the added mass is estimated at 40% of the mass of the monopile. A damping of 70% of critical damping was assumed. The resulting RAO for heave is shown in Figure 3.14.

The following observations can be made from Figure 3.14:

- In both results the natural frequency of the system is similar. 1.4 rad/s for the ANSYS AQWA calculation and 1.5 rad/s for the calculation using Journée et al. [6]
- For both results the curves have a roughly similar shape.
- For very long waves the heave RAO trends to 1.0 as the monopile follows the motion of the waves.
- Both curves peaks near the natural heave frequency of the monopile.
- For wave shorter than the natural frequency both curves trend to 0.0 on a logarithmic curve.

There are several reasons for the differences between the results from the ANSYS AQWA simulation and the calculation using Journée et al. [6]: Firstly, the values for added mass and damping were estimated and assumed the same for all wave frequencies. In reality both will vary with the wave frequencies.

Secondly the draft of the monopile was assumed to be uniform. In reality the submerged part of the monopile has the shape of a bisected cylinder, and therefore not a constant draft.

Furthermore, the wave length was assumed to be very long compared to the width of the monopile so that the hydrostatic pressure on the submerged part of the monopile could be considered constant. For the lower wave frequencies this is true, but the higher the wave frequency the less valid this assumption becomes. This also explains why for higher wave frequencies the results from the simulations and the calculation start to diverge. As the wave frequency becomes higher the wave length becomes smaller and the pressure variation over the width of the monopile increases. The pressure variation cause the RAO to decrease faster in the simulations then in the calculations using Journée et al. [6].

From this it shows that the ANSYS AQWA simulation results match the expectations from wave theory, and are a valid tool to use for further study of the motions of this system.

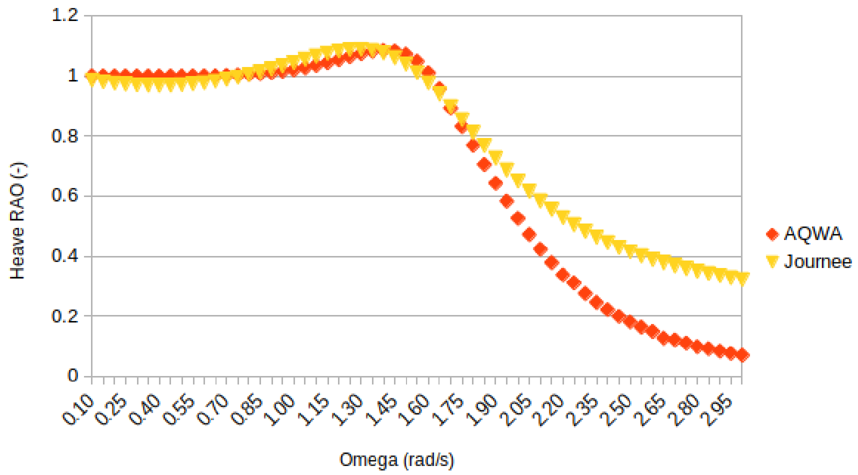

Figure 3.14: Heave RAO comparison

4

Frequency Domain Analysis

As described in chapter 2, two different methods are proposed for the hooking of the monopile onto the vessel crane. This chapter presents first a comparison between these two options, so as to determine the option that will be considered for further study. Secondly, this chapter presents a variation study where the location of the monopile with respect to the installation vessel is varied. Using this study a single configuration is selected that will be further studied in chapter 5.

4.1. Method selection

To select one of the two configurations a frequency domain analysis has been performed. Using the parameters described in chapter 3. As described in chapter 2, a large risk during the installation is the endangerment of the riggers, who have to transfer the slings that are used to tow the monopile during transport to the vessel and hook the slings to the vessel crane. For this reason, the safety of the riggers is used as the most important selection criterium and will be the only selection criterium considered. For this initial screening, three configurations were considered, shown in Figure 4.1. A high risk for accidents occurs when there are large relative motions between the tip of the monopile and the side-shell of the vessel, where the riggers are working. To quantify the safety of the riggers the RAO for the relative vertical motion between the monopile tip and the vessel side-shell nearest to the monopile tip is used. The resulting relative vertical motion for various incoming wave angles is plotted in Figure 4.2.

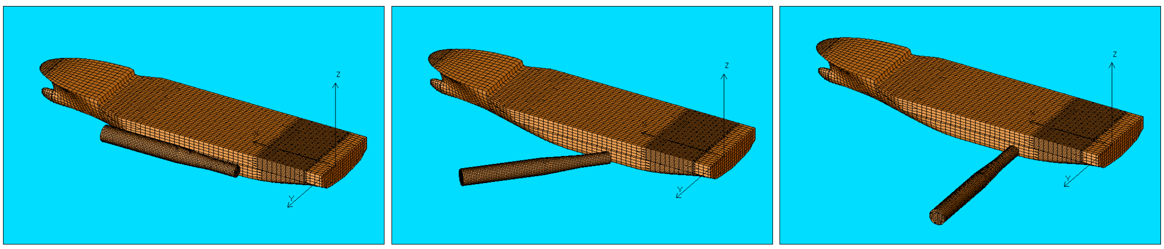

Figure 4.1: Monopile at a 0 degree, 45 degree and 90 degree angle with respect to the vessel

Figure 4.2 shows that the differences in relative vertical motion between the monopile tip and the side-shell vary with the incoming wave angle. With the monopile parallel to the vessel, the largest relative motion occurs for waves at a 90-degree angle to the vessel. In this situation, the monopile motions are minimal due to the shielding effect of the vessel, and the large relative motions are driven by the roll motion of the vessel. With the monopile at a 45-degree or 90-degree angle to the vessel, the largest motions occur in bow waves. With this wave angle, the monopile is not fully in the shadow of the vessel causing larger motions of the monopile.

Based on the results in Figure 4.2 the maximum relative vertical motion is the largest for the configuration where the monopile is parallel to the vessel. Aside from this the other 45-degree and 90-degree configurations are also more adaptable. In changing weather conditions the monopile could be repositioned to make optimal use of the shielding of the vessel without having to reposition the anchor spread

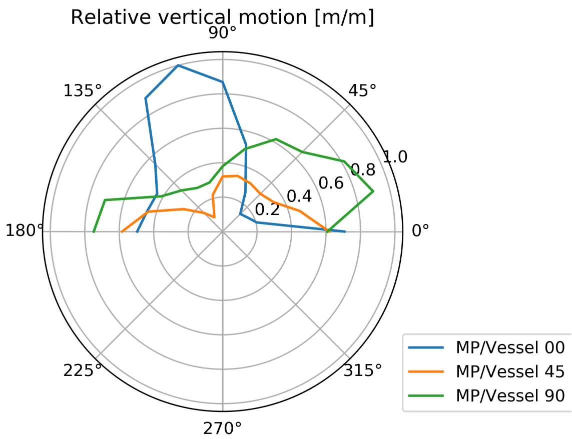

Figure 4.2: Option comparison

of the vessel. Because of these advantages from here on the perpendicular option will be considered in more detail.

4.2. Variation study monopile orientation

To find the optimal vessel/monopile configuration several parameters have been considered. Using these parameters and the model presented in chapter 3, a frequency domain analysis has been performed to compare the various configurations.

Two parameters were considered: The location of the monopile tip with respect to the side-shell of the vessel and the angle between the vessel and the monopile. To score the various configurations two values were studied, the relative vertical motion between the tip of the monopile and the side-shell of the vessel, and the tension in the slings that will connect the vessel to the monopile.

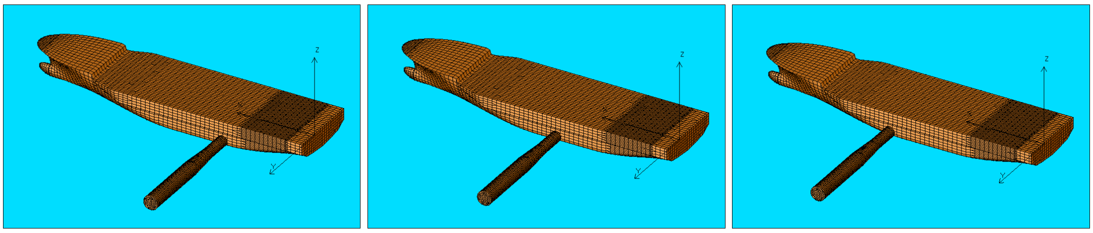

Figure 4.3: Monopile at 40, 60 and 80 meters from the stern

Figure 4.3 shows the monopile at various locations with respect to the vessel. Four configurations were considered, with the distance between the stern of the vessel and the monopile varying from 40 meters to 80 meters.

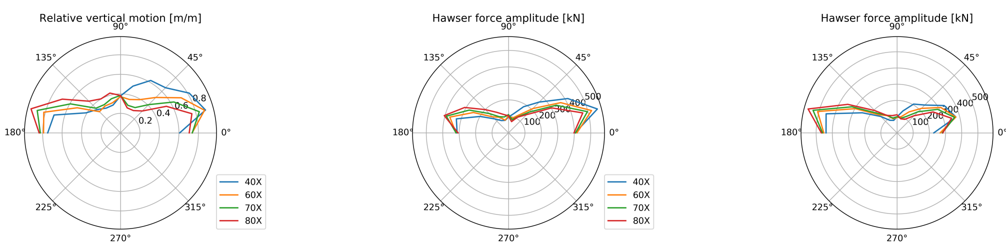

Figure 4.4: Relative vertical motion and hawser force for location variation

The results of the analysis are shown in Figure 4.4. Varying the location of the monopile has the strongest effect on the tensions in the slings and the relative motions for wave angles near 0 degrees and 180 degrees. From the results, we can see again the strong effect of wave shielding by the vessel. From the results, no optimal monopile location can be selected, because the location that has the lowest relative motions for wave angles between 0 and 90 degrees, has the highest relative motions for wave angles between 90 and 180 degrees. Based on the results all locations are equally viable.

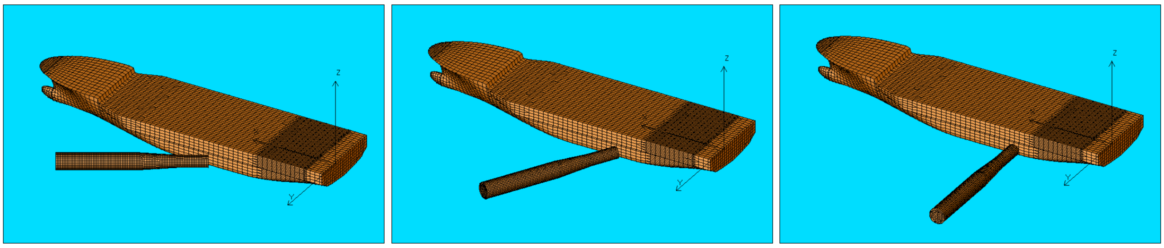

Figure 4.5: Monopile at 30, 45, 90 degrees with respect to the vessel

Figure 4.5 shows the monopile at various angles with respect to the vessel. Five configurations, with vessel-monopile angles between 30 degrees and 90 degrees, were considered.

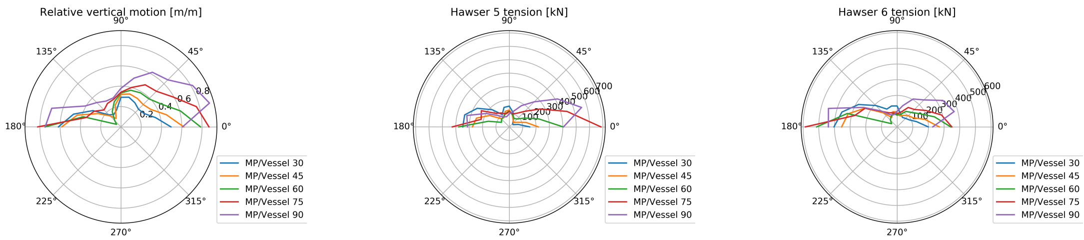

Figure 4.6: Relative vertical motion and hawser force for angle variation

Varying the angle between the vessel has a large effect on the tensions in the slings for wave angles between 0 degrees and 45 degrees. From these wave angles, the configurations with a smaller angle between the vessel and monopile benefit more from the shielding by the vessel.

4.3. Results

The analysis done in this chapter has studied the behaviour of the monopile and vessel in various configurations. First, the differences between the two installation methods presented in chapter 2 were studied. The relative motions for the installation method where the monopile is perpendicular to the installation vessel were lower than for the parallel installation method. Therefore the perpendicular method was selected for further study. The presented variation study has shown that the location of the monopile with respect to the stern of the vessel does not have a large impact on the relative motions or on the slings that will connect the monopile and the vessel. The angle between the vessel and monopile has a strong effect on the relative motions only for certain incoming wave angles. This is the case for stern waves, head waves, and bow waves. For these wave angles, the wave shielding effect on the monopile is minimal resulting in large motions and sling tensions. It should be considered however, that in operation the vessel is free to orient itself in an optimal configuration with respect to the incoming waves. Therefore, in most cases there will be no situation where the vessel subjected to the unfavourable wave directions.

While the location and orientation of the monopile with respect to the vessel do affect the relative motions between the two and the tensions in the slings, the effect is small enough that the location for further study will be based on ease of operation. The winches used to pull in the monopile will take up deck space and restrict movement on the deck for personnel and the on-deck crawler crane. Therefore the configuration where the winches are the least in the way is chosen for further study. This is with the tip of the monopile near the base of the vessel crane, 40 meters from the stern and with the monopile at a 90-degree angle with respect to the vessel.

5
Time Domain Analysis

Now that a single configuration has been selected in chapter 4, this chapter will give an estimation for the workability of the selected configuration.

5.1. Sling behaviour over 100 seconds simulation time

To get familiarised with the behaviour of the system over short timespans multiple simulations were performed with the following parameters:

- Three wave attack angles, 90 degrees, 135 degrees and 180 degrees (i.e. beam waves, bow waves and head waves)
- Total duration of the simulation of 100 seconds, in 0.01-second timesteps
- Significant wave height of 1.0 meter
- Peak period of wave spectrum of 5.0 seconds

The resulting load over time in the two slings connecting the monopile to the vessel is shown in Figure 5.1.

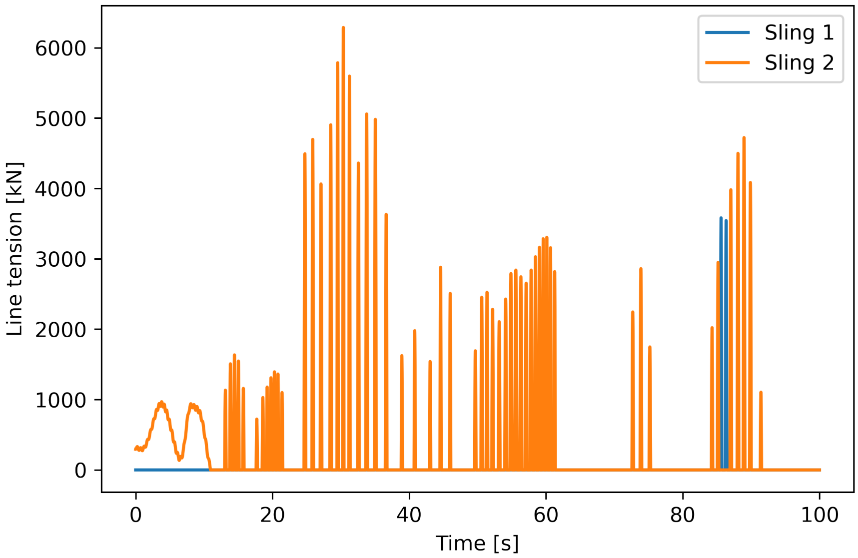

Figure 5.1: Snap loading of softslings

From this figure the following observations can be made:

- The slings connecting the monopile to the vessel are slack for the majority of the time, the force applied by the supporting tug is not high enough to keep the soft slings under constant tension
- The slings are under tension for short durations of around 0.2 seconds at a time.
- Due to this short snap loading, the maximum tensions in the slings are as high as 6000kN

The high tensions in the soft slings are caused by the high stiffness of these slings. The possibility exists that this effect is caused by numerical errors in the simulation, there are however multiple reasons to assume that the simulation is correct: The tension spikes take place over around 20 timesteps in the simulation, and the tension spikes scale fairly linearly with the sling stiffness (Figure 5.2).

The maximum loads of 6000kN are too high to be safely absorbed by the winches that are holding the monopile close to the vessel. Therefore, various methods were considered to lower the maximum tension loads to more acceptable levels. The most viable option to lower the snap loads is to reduce the stiffness of the connection between the monopile and the vessel. This is done by adding stretchers between the winchline pulling in the monopile and the softslings connected to the top of the monopile.

Lowering the combined stiffness of the system leads to a reduction in the tension in the slings, as can be seen in Figure 5.2. In this case, the combined tension of the monopile-vessel connection has been lowered in steps from the original $1 \cdot 10^8 N/m$ to a combined sling stiffness of $5 \cdot 10^5 N/m$.

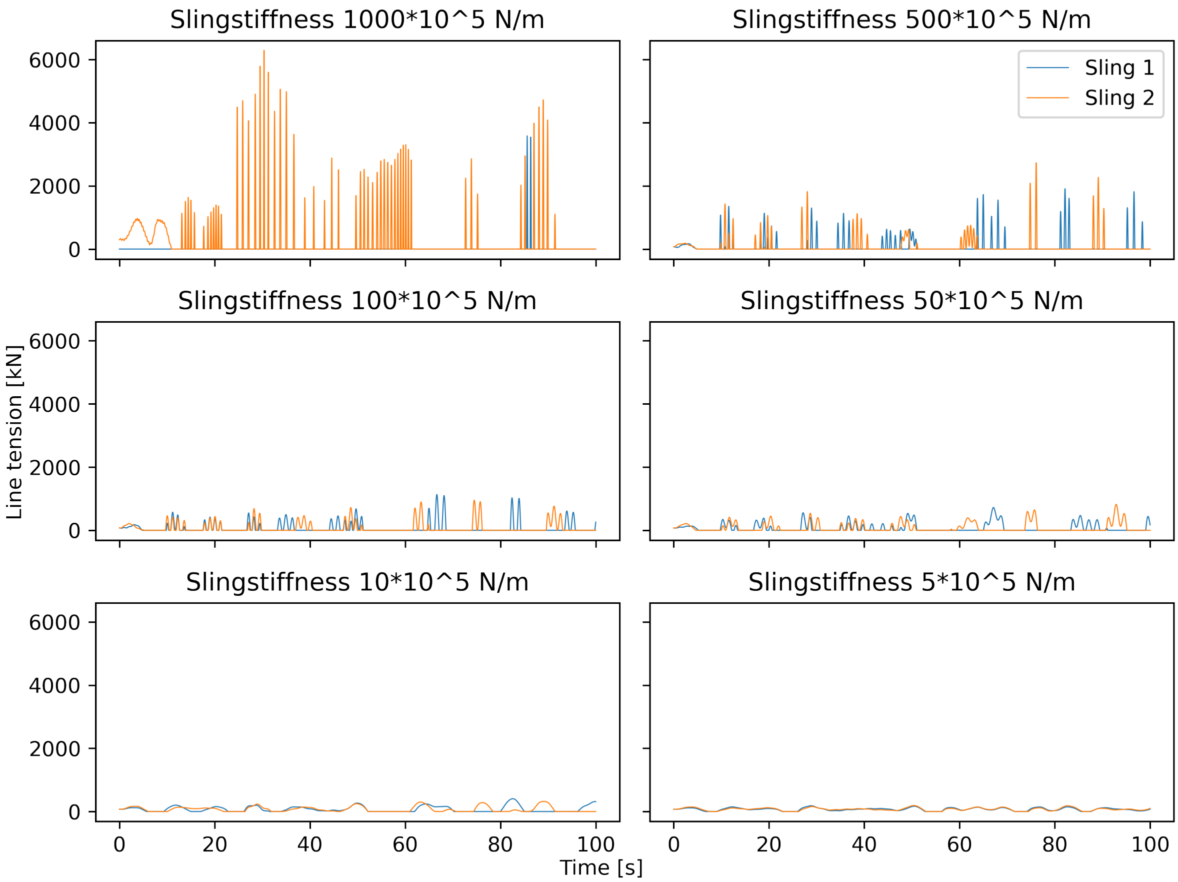

Figure 5.2: Reducing snap loading through lower sling stiffness

This shows the large effect that adding stretchers has on the behaviour of the system. Further simulations will include a combined sling stiffness of $5 \cdot 10^5 N/m$ to reduce snap loading of the slings.

5.2. Workability

To determine in what sea states the operation can safely be performed longer duration simulations were performed. A weather window of three hours was chosen as over this period it is expected that the operation can be executed.

To determine the workability of the chosen solution, the following cases were considered

Wave direction As in the previous runs, three wave directions were studied: 90, 135 and 180 degrees

Wave period The peak wave period was varied from 5.0 seconds to 7.5 seconds in steps of .5 seconds.

Simulation duration Total duration of the simulation of three hours

Wave height Significant wave height of 1.0 meter and 1.5 meters

Two limit states were considered to determine the workability of the operation:

Monopile vessel Collision To safely perform the operation and avoid damage the monopile must not collide with the side of the vessel (sideshell) during operation.

Relative vertical motion In order to ensure the safety for the personell on deck the relative vertical motion between the monopile tip and the sideshell should be limited. As an estimate for the allowable relative vertical motion, a limit of 1.8 meters has been used. This limit was used since for this value the average person will be able to safely reach up and down and will therefore be able to safely work with the slings.

5.2.1. Collision

The distance between the tip of the monopile and the vessel sideshell is shown for the three hour simulation time in Figure 5.3 for beam waves with a Hs of 1.0 meter and a Tp of 5.0 seconds. The minimum distance in this sea state is 8.6 meters, so no collision occurs.

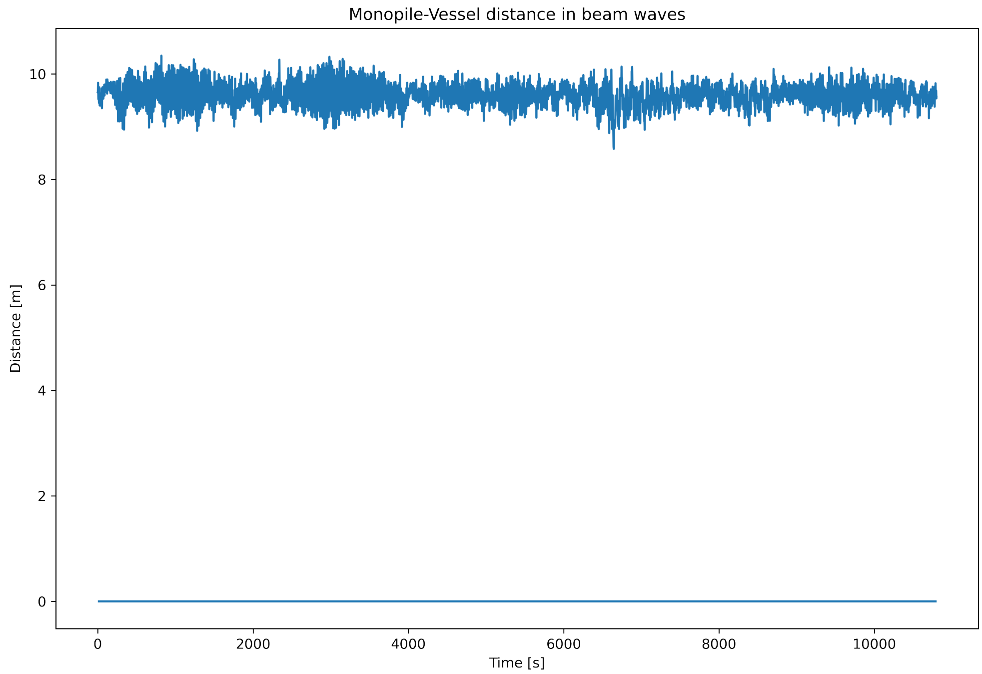

Figure 5.3: Distance between sideshell and monopile in beam waves Hs 1.0m Tp 5.0s

Figure 5.4 shows the same plot for bow waves with a Hs of 1.0 meter and a Tp of 6.0 seconds. For this sea state it can be seen from the plot that the monopile and vessel do collide, therefore this is not a workable sea state.

The results for other sea states are shown in Table 5.1 for a Hs of 1.0 meter and Table 5.2 for a Hs of 1.5 meters. If a collision occurs within a simulation, no result is shown in the tables. Both tables show that there are no workable seastes when working in head waves. This illustrates the importance of utilising the vessel shielding effect to perform the hooking operation.

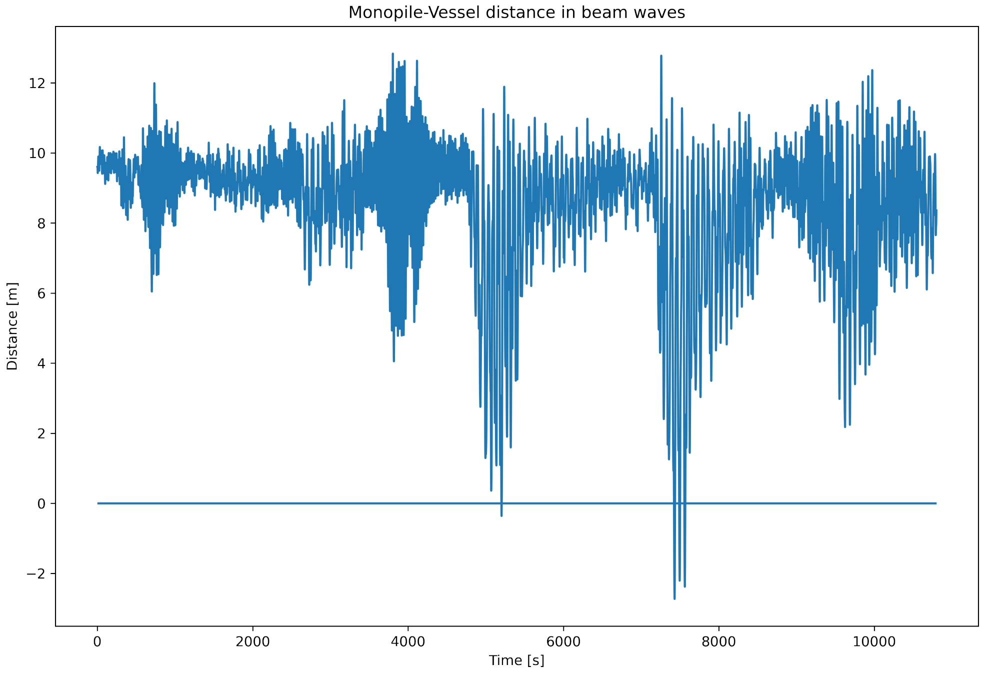

Figure 5.4: Distance between sideshell and monopile in bow waves Hs 1.0m Tp 6.0s

Wave angle / Tp	5.0s	5.5s	6.0s	6.5s	7.0s
090d	8.6m	8.3m	5.6m	2.5m	-
135d	3.1m	3.6m	-	3.8m	-
180d	-	-	-	-	-

Table 5.1: Minimum monopile sideshell distance in Hs 1.0 meter

Wave angle / Tp	5.0s	5.5s	6.0s	6.5s	7.0s
090d	6.5m	1.3m	-	1.6m	-
135d	-	-	-	-	-
180d	-	-	-	-	-

Table 5.2: Minimum monopile sideshell distance in Hs 1.5 meters

5.2.2. Relative motions

The relative vertical motion between the tip of the monopile and the vessel sideshell is shown for the three hour simulation time in Figure 5.5 for beam waves with a Hs of 1.0 meter and a Tp of 5.0 seconds. Maximum relative vertical motion for this seastate is 0.64 meter, which is below the 1.8 meter limit and makes this a workable sea state. The results for other sea states are shown in Table 5.3 for a Hs of 1.0 meter and Table 5.4 for a Hs of 1.5 meters. When the relative vertical motions are larger than the allowable 1.8 meters, no result is shown in the tables.

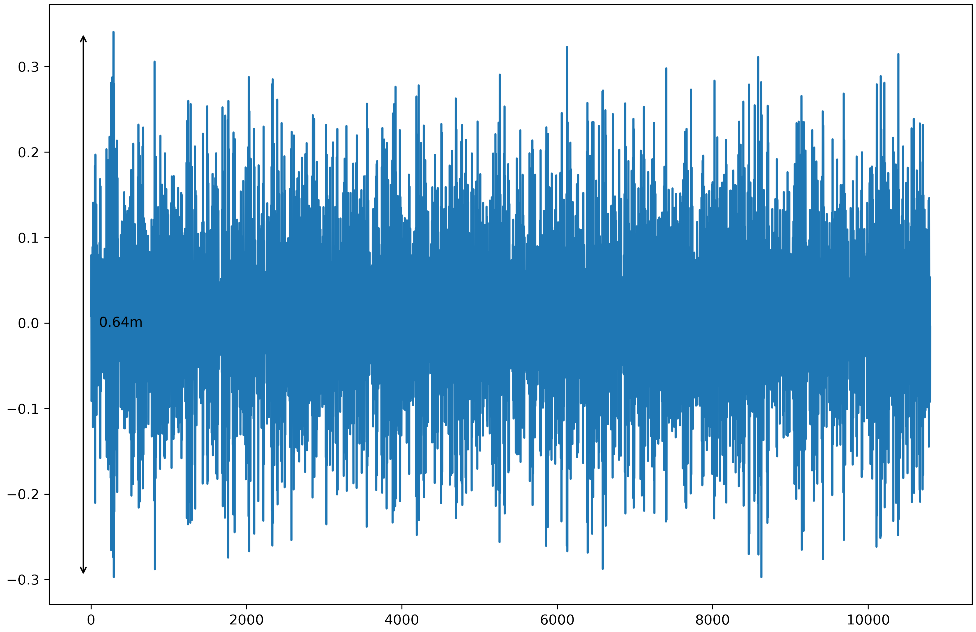

Figure 5.5: Relative vertical distance sideshell and monopile in beam waves Hs 1.0m Tp 5.0s

Wave angle / Tp	5.0s	5.5s	6.0s	6.5s	7.0s
090d	0.6m	0.8m	1.0m	1.2m	1.4m
135d	0.6m	0.8m	0.9m	1.0m	-
180d	1.7m	-	1.8m	-	-

Table 5.3: Maximum relative vertical distance in Hs 1.0 meter

Wave angle / Tp	5.0s	5.5s	6.0s	6.5s	7.0s
090d	1.0m	1.3m	1.5m	1.8m	-
135d	1.5m	1.8m	1.7m	-	-
180d	-	-	-	-	-

Table 5.4: Maximum relative vertical distance in Hs 1.5 meters

5.3. Conclusion

Based on the results presented it is estimated that this operation can be performed in a limited number of seastates. Combining the results for both limit states gives the following allowable seastates for the the hooking operation: From this, it is also shown that the collision between monopile and vessel sideshell is the limiting factor for this operation. In the considered combinations there exists no seastate where there are no collisions with the sideshell, and the workability is instead limited by the relative vertical motion.

Wave angle / Tp	5.0s	5.5s	6.0s	6.5s	7.0s
090d	Ok	Ok	Ok	Ok	-
135d	Ok	Ok	-	Ok	-
180d	-	-	-	-	-

Table 5.5: Allowable seastates Hs 1.0m

Wave angle / Tp	5.0s	5.5s	6.0s	6.5s	7.0s
090d	Ok	Ok	-	Ok	-
135d	-	-	-	-	-
180d	-	-	-	-	-

Table 5.6: Allowable seasates Hs 1.5m

6 Conclusions and recommendations

The goal of this thesis has been to formulate a method for the hooking of a floating monopile to the crane of HLV Oleg Strashnov and to model the hooking operation to determine a maximum allowable sea state for this operation.

6.1. Conclusions

The first part of this thesis has focused on the selection of a method for hooking floating monopiles onto the crane of the HLV Oleg Strashnov. Based on the model as stated in chapter 3 and the results as presented in chapter 4 these results can be summarized as follows: The relative motions between the monopile and vessel vary with wave direction and hooking method used. The quantative difference between the hooking methods is small enough that it is warranted to decide between the options based a qualative measure: Ease of handling and expected safety during the operation. Based on this the perpendicular option is selected as the most promising option for further study.

Subsequently, the perpendicular method was studied in more detail. Using the assumptions laid out in chapter 3 and the analysis in chapter 5 the following can be concluded: The relative motions between the vessel and monopile and the maximum loads in the connection between vessel and monopile are strongly dependent on the stiffness of the connection between the two structures. Longer waves reduce the shielding effect of the vessel resulting in large relative motions. For longer waves the large relative motions between the vessel and MP are a limiting factor for the safety of the operation.

Under these assumptions the chosen solution is estimated to be a workable solution in the sea states shown in Table 6.1 and Table 6.2.

Wave angle / Tp	5.0s	5.5s	6.0s	6.5s	7.0s
090d	Ok	Ok	Ok	Ok	-
135d	Ok	Ok	-	Ok	-
180d	-	-	-	-	-

Table 6.1: Allowable seastates Hs 1.0m

Wave angle / Tp	5.0s	5.5s	6.0s	6.5s	7.0s
090d	Ok	Ok	-	Ok	-
135d	-	-	-	-	-
180d	-	-	-	-	-

Table 6.2: Allowable seasates Hs 1.5m

6.2. Recommendations for further study

Various recommendations are made based on the presented results:

- Workability can be improved if the yaw motion of the monopile is reduced. Large yaw motions caused by low damping can be counteracted by repositioning of the supporting tug, which isn't included in the model. Including the effect would provide further detailing of the workability of the hooking operation.
- Wind and current loading have not been modelled for this study. It can be expected that especially when these are not loading in the same direction, this will influence the workability of the operation. Modelling this would give further insight into the total workability of the system.

Bibliography

[1] Wilson Guachamin Acero, Zhen Gao, and Torgeir Moan. Assessment of the Dynamic Responses and Allowable Sea States for a Novel Offshore Wind Turbine Installation Concept Based on the Inverted Pendulum Principle. *Energy Procedia*, 94:61–71, September 2016. ISSN 18766102. doi: 10.1016/j.egypro.2016.09.198. URL http://linkinghub.elsevier.com/retrieve/pii/S1876610216308669.

[2] Ansys Aqwa. *AQWA Reference manual 14.5*, 2013.

[3] J.A. Battjes. Short waves, 1975. URL http://resolver.tudelft.nl/uuid:4796d8a6-471c-4ca8-8e83-82143bc73978.

[4] Fride Midtbø Birkeland. Numerical Simulation of Installation of XL Monopile for Offshore Wind Turbines. 2016. URL https://brage.bibsys.no/xmlui/handle/11250/2409548.

[5] John Conti. International Energy Outlook 2016. Technical report, U.S. Energy Information Administration, Washington D.C., May 2016. URL www.eia.gov/forecasts/ieo.

[6] J.M.J. Journée, W.W. Massie, and R.M.H. Huijsmans. *Offshore Hydromechanics, third edition*. 2015.

[7] Ioannis Lessis, Francisco Javier López Maldonado, Christos Vlachos, Angelo Marino, and Agnieszka Kiełkiewicz. The practicality and challenges of using xl monopiles for offshore wind turbine substructures. http://www.esru.strath.ac.uk/EandE/Web_sites/14-15/XL_Monopiles/index.html, 2019. Accessed: 2019-09-30.

[8] Lin Li, Zhen Gao, Torgeir Moan, and Harald Ormberg. Analysis of lifting operation of a monopile for an offshore wind turbine considering vessel shielding effects. *Marine Structures*, 39:287–314, December 2014. ISSN 09518339. doi: 10.1016/j.marstruc.2014.07.009. URL http://linkinghub.elsevier.com/retrieve/pii/S0951833914000653.

[9] J Maliepaard. Installation of large floating monopiles in heavy weather conditions. Master's thesis, Delft University of Technology, August 2018.

[10] B. Le Méhauté. *An introduction to hydrodynamics and water waves*. Springer, 1976.

[11] United Nations. World Population prospects: The 2017 revision, Key Findings and Advance Tables. Technical Report ESA/P/WP/248, United nations, Department of Economic and Social Affairs, Population Division, New York, 2017.

[12] Trevor J. Price. James blyth, 09 2017. URL https://doi.org/10.1093/ref:odnb/100957.

[13] Michael Siems Rüdiger Scharff. Monopile foundations for offshore wind turbines - solutions for greater water depths. *Steel Construction*, 6(1):47–53, February 2013. ISSN 18670520. doi: 10.1002/stco.201300010.

[14] Arunjyoti Sarkar and Ove T. Gudmestad. Study on a new method for installing a monopile and a fully integrated offshore wind turbine structure. *Marine Structures*, 33:160–187, October 2013. ISSN 0951-8339. doi: 10.1016/j.marstruc.2013.06.001. URL http://www.sciencedirect.com/science/article/pii/S0951833913000440.

[15] Seaway Heavy Lifting. Oleg strashnov, 2018.

[16] Wind Europe. Offshore wind in europe - Key trends and statistics 2017. Technical report, Wind Europe, January 2017.