Large Floating Monopiles

Installation in Heavy Weather Conditions

J. Maliepaard

Large Floating Monopiles

Installation in Heavy Weather Conditions

by

J. Maliepaard

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Tuesday August 28, 2018 at 2.30 PM.

Student number:	1508253	
Project duration:	June 27, 2016 – August 28, 2018	
Thesis committee:	dr. ir. S.A. Miedema,	TU Delft, supervisor
	Ir. R. L. J. Helmons,	TU Delft
	Dr. Ir. H. Polinder,	TU Delft
	Ir. A. Shahbazkhani,	Seaway Heavy Lifting

This thesis is confidential and cannot be made public until August 28, 2023.

TU Delft

Abstract

The offshore wind market experiences large growth over the last decade. There is a clear trend to installation in deeper waters and to larger wind turbines, to maximize the energy output. The majority of offshore windmills use a monopile foundation, which due to the current trends are getting larger. Seaway Heavy Lifting (SHL) is a company that installs these monopile foundations, with their Heavy Lift Vessels (HLV). The largest HLV of Seaway can transport and install three monopiles at a time. However, with larger monopiles it is expected to be reduced to two monopiles or even less. In order to be competitive in the monopile installation market, SHL is looking for a method to transport the monopiles to the HLV, instead of using the HLV for transportation. A previous comparative study showed that floating transport of monopiles to the HLV is the most favorable method. However, SHL is unexperienced with this method and therefore requires a study on developing the best method to install the monopiles within the workability of the HLV. Therefore, the thesis goal is:
"Design of a method for installation of large floating monopiles in heavy weather conditions".
To design such a method, it will first be determined what steps are necessary and which options can used to fulfill these steps. With a multi criteria analysis will be determined what combination will lead to the best method. The best two methods will be subjected to a sensitivity analysis to determine its feasibility.
The method consists of five steps: floatation, towing, mooring, hook-in and lifting. A multicriteria analysis shows that using airbags is the most favorable method of making the monopile float, while using a flange clamp for towing and lifting. In order to reduce motions, the mooring can be either on the side of the vessel in a gripper frame, or by sinking the back end of the monopile to the seabed. When the monopile is in moored position the pre-rigged rigging can be taken over by the main hook of the crane.
Both methods are modelled in the simulation software package Ansys AQWA. A soil model has been made to assess the influence of the grounding on the motion behavior of the monopile. Due to the soil properties it is faster and relatively accurate to model the connection between the soil and the monopile as a hinge instead of applying the soil model. The system is subjected to different wavespectra, while varying the direction of the environmental forces, the trim of the monopile on the seabed and the orientation of the monopile to the vessel.
The installation of a grounded monopile in heavy weather is a feasible option. The simulations have shown that installation is possible up till a significant waveheigth of two meters with a peak period of 8s. The least trimmed position has the best performance over different environmental forces directions. The best option for installation is in a configuration where the vessel and the monopile are facing the environmental conditions head-on, with a 42 degrees monopile trim. However, it has to be noted that other monopile orientations with respect to the HLV are performing good as well, as long as the trim of the monopile is 42 degrees. Using other trim options is possible, but limited to specific orientations.
The installation of monopiles with a gripper attached to the vessel seems to be a viable option, but only once the soil model is improved. The simplification of the soil model by replacing it with a hinge gives uncertainties in the real force acting on the interface between the vessel and the grounded monopile. However, when considering the RMS force of 30 minute simulations without taking lateral forces into account, the results are well within the set boundaries.
Thus can be concluded that installation of a floating monopile is feasible, when using the grounding method. It is recommended to improve the soil model for both methods, to improve the accuracy of the results. To ensure a safe installation and a safe operation during its lifetime, the structural integrity of the monopile should be investigated. Small deformations can drastically reduce the fatigue life of the structure. An end-plug to lower the monopile to the seabed and reinforce the structure could be an option to ensure the structural integrity. Furthermore, it should be investigated if a gripperframe is a realistic option due to its size. The dimension could turn out impossible for catching and releasing extra large monopiles in heavy weather conditions. Lastly, it turns out that grounding a monopile is more time consuming and difficult than anticipated. Therefore it is recommended to research the installation of a free floating monopile or mooring a floating monopile alongside the HLV.

Contents

List of Figures

1 Introduction

Offshore wind energy is nowadays more popular than ever. It all started with eleven turbines installed of the coast of Denmark in 1991, producing a total power of 4,95MW. The next ten years only small projects where installed, but as development went on, the installed capacity grew exponentially from 2002. Most recent numbers state that 3018MW is installed in 2015, resulting in an overall total installed capacity of 11GW in Europe.[1]

Seaway Heavy Lifting is a contractor installing foundations and substations for the offshore wind industry. But they are not the only one, competition in the offshore wind market is fierce. The majority of installation is done from relatively cheap jack-up vessels. Due to their stability when jacked up, it can install foundations as well as a complete wind turbine. The largest drawbacks of jack-up vessels are the generally low crane capacity [2] and the transit weather window. Seaway Heavy Lifting is strong is both these points. A large crane and high workability come however with a relatively high price tag. Heavy lift vessels (HLV's) are expensive, so in order to stay competitive the time these vessels are used needs to be minimized.

There are several types of foundation that are used. Since most wind farms are installed in shallow waters (water depths not exceeding 30m) the majority of used foundations are monopiles. The strongest advantages of the monopile over the jacket foundation, are the simplicity and costs. However, the trend to installation in deeper water results in larger monopiles. This will pose future problems for transportation.

One of the most time consuming operations is the loading on board the HLV and transport of the monopiles to the installation site. The expensive HLV can currently transport three monopiles at a time. This is limited by a maximum monopile diameter of 8.5m. The expectation is that future monopiles will exceed this 8.5m, which makes each transport even less effective. To counteract this problem the transportation of monopiles has to be arranged by other means. This can be either on barges or by floating transport.

1.1. Thesis goal

Seaway Heavy Lifting has already done a comparative study and concluded that floating transport of monopiles has several advantages over transport by barges. Mainly because fewer lifting operations are needed and there is less human involvement necessary. However, the installation of floating monopiles, with the same workability as the HLV, has never been done before. This study will focus on developing such a method. The thesis goal therefore will be:

"Design of a method for installation of large floating monopiles in heavy weather conditions"

1.2. Thesis approach

To obtain such a method the following approach is taken:

In order to put everything in perspective, a brief description about Seaway Heavy Lifting is given and a closer look must be taken at the offshore wind industry. How did it emerge and what trends are there for future projects? After that, the focus will be on similar projects. What can be learned from previous floating monopile installations? With a background in mind, the boudaries of the thesis are set in the Scope of Work. It will be clear what will be done and what not. The next step will be generating possible concepts on how to install a floating monopiles. With these concepts a Multicriteria analysis has to be conducted to dermine which one is most favourable. To aid this analysis, several experts within SHL will provide counsel. The best concepts will be worked out more in-dept in chapter 6 and will be subjected to a sensitivity analysis to determine their feasibilty. In order to perform an in-depth analysis, a model has to be made in Ansys AQWA. In chapter 8 the fundamentals of these analyses will be explained. This basis gives more background for the sensity analysis results in chapter 9 and 10. This thesis will end with the general conclusions and will provide recommendations for further research into this topic.

2 Background

With the goal of the thesis in mind, it is necessary to have more background knowledge of the subject to understand further details better. This chapter is intended to provide a more detailed context for the thesis problem. The first section will contain a descripion of Seaway Heavy Lifting and what they do. Thereafter, a closer look is taken at the offshore wind market and more specifically the wind turbine foundations. The chapter is finalized with a section about similar projects.

2.1. Seaway Heavy Lifting

Seaway Heavy Lifting (SHL) is a leading offshore contractor in the global Oil & Gas and Renewables industry, offering tailored Transportation & Installation (T&I) and Engineering, Procurement, Construction and Installation (EPCI) solutions. The client portfolio includes the major operators in the offshore Oil & Gas and offshore Renewable industry. SHL operates globally focussing on the North Sea, Mediterranean, America's, Africa, Asia Pacific and Middle East. The track record is reflected in Seaway Heavy Lifting portfolio of project and client references. The goal of the company is to provide their clients with the most effective and added value solutions. This is obtained using the highest standards of safety and environmental protection, tailored solutions and modern crane vessels equipped with the latest hardware and large crane capacities.

SHL currently owns and operates two Heavy Lift Vessels (HLV), the Stanislav Yudin and the Oleg Strashnov (figure 2.1). The Stanislav Yudin was acquired in 1992 and is equipped with a 2,500 tonnes revolving crane with an operating height of 78.4m and a 500 tonnes auxiliary hook with an operating height of 100.8m. The vessel uses an eight point anchoring system and is Light Ice Class certified. The Oleg Strashnov was added to the fleet in 2011. The vessel is equipped with a fully revolving crane with a capacity of 5,000 tonnes and a lifting height of 102m. The auxiliary hooks has a capacity of 800 tonnes and can lift up to 132m. Station keeping can be accomplished by either eight point anchoring or dynamic positioning (DP3). Since 2009 SHL is active in the offshore Renewables, installing monopiles, jackets and substations. SHL owns a variety of hammers, rigging and pile handling tools.[3]

Figure 2.1: The two heavy lift vessels, the Stanislav Yudin (left) and the Oleg Strashnov (right)

2.2. Offshore wind market

From the first offshore wind turbines in 1991 to now, offshore wind has taken a flight. According to EWEA (European Wind Energy Association) the last decade the growth in capacity was more than tenfold in Europe alone. This growth will continue to due to the Paris climate conference in December 2015. which led to a legally binding global climate deal to limit global warming. To comply with this agreement, the European Union set a binding target of a 27% share of renewable power by 2030[4]. This growth in capacity comes with

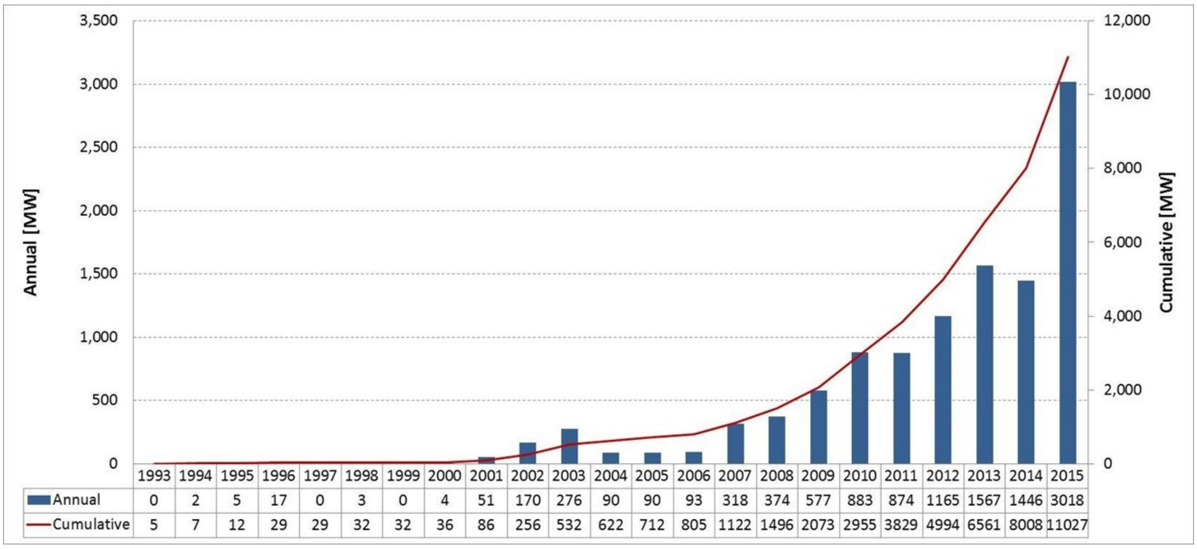

Figure 2.2: Installed offshore wind power per year within Europe

a trend of increasing wind turbine output. In 2015 the average wind turbine had an output of 4.2MW which is a 13% increase compared with 2014 [5]. This is mainly due to the installation of 5-6MW turbines. The newest models nowadays have an output of 8MW and it is expected to rise further in the future. Since the energy production is directly related to the circular area of the rotor, the wind turbines have to grow bigger in order to gain higher outputs. A larger rotor leads to a larger structure and thus the need for a larger foundation.

Besides the trend toward more powerful turbines, the installation takes place further offshore and in deeper waters. As a consequence, the wind turbine and foundation have to withstand higher environmental forces. To counteract these external forces, larger foundations are needed.

2.3. Foundations

The type of foundation that is used depends mainly on water depth. Monopiles are used to depths of 30m, gravity based structures and jackets are used for deeper waters. However, jacket structures are more complex and therefore more time consuming and expensive to create in comparison with monopiles. A comparison of currently installed foundations can be seen in figure 2.4 [6]

Currently, Seaway Heavy Lifting transports monopiles on board the HLV. A purpose build frame is placed on board for two monopiles with a maximum diameter of 8.5m. Next to the frame, a third monopile can be transported in an upend cradle. This setup leaves enough deck space to transport three transition pieces and grouting as well. An alternative method is to supply monopiles by barge by two or three at a time. The monopiles will be lifted from the barge into the upend cradle, and from there it will be upended and installed.

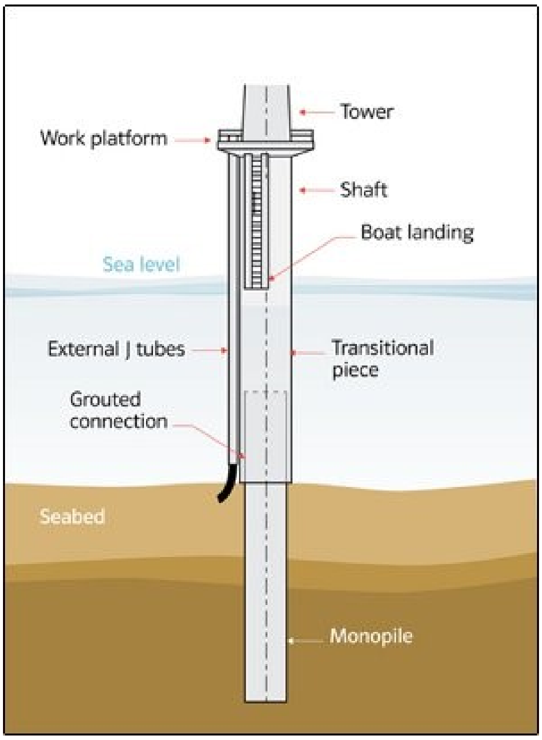

Figure 2.3: The layout of a monopile

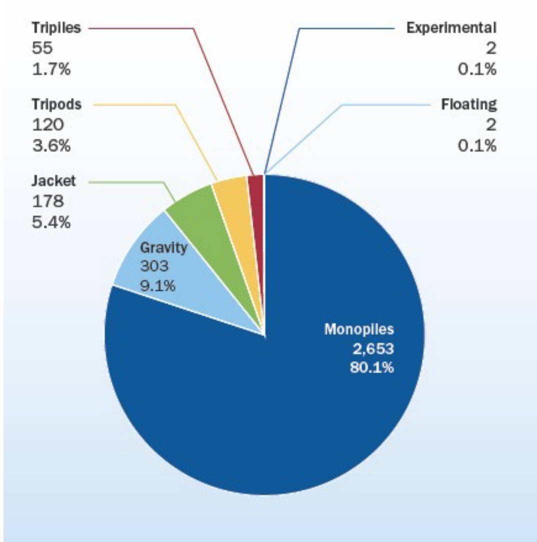

Figure 2.4: Foundation pie chart

Figure 2.5: Wind turbine foundation installation with the vessel Svanen

2.4. Reference projects

The concept of floating monopiles is not new. Since 2006 this installation method is used by Ballast Nedam, and later Van Oord, with the vessel Svanen. The monopiles are floated by means of end-caps and are towed to location. The monopile is moored to the vessel and slings are attached to the trunnions, or a lifting tool is inserted. After that the monopile is lifted completely out of the water to release the bottom cap. When the monopile is lowered vertically and resting on the seabed, the top cap is removed and the piling hammer placed on top. The monopile is then driven into the ground. Although the Svanen is doing floating monopile installations for several years now, it has its drawbacks and had failures. At the Belwind Offshore Wind farm in 2009, two monopiles sunk during transport due to top cap failure. Slamming impact damaged the hydraulic system which led to failure of the plug. Both monopiles sunk in a busy shipping route, so Belgian government suspended the installation until a proper solution was found. Besides these failures, the Svanen is also limited by weather. The vessel is basically a dual barge setup with a large crane on top, that comes with the same low workability as most barges. It was originally designed for construction of bridges. It can operate only in low sea states and has a transit speed of 7 knots.
Besides the Svanen, no other ships have installed complete projects with floating monopiles. There have been some tests with jack-up barges, but those proved insufficient to continue.

3
Scope of Work

The subject of this research is the installation of extra large floating monopiles in a safe and efficient way. The execution of this installation is consists of multiple steps, all of which can can be undertaken in multiple ways. Naturally, some steps are more critical than other steps and therefore require more attention. This chapter will narrow down what the most important parts are and where this thesis will focus on. Next to that, it will exclude parts that may be important but cannot be researched within the thesis due to limitations in time or resources.

3.1. Scope of Work

By studying the background information and getting a general picture of the installation process, a number of necessary steps The total proces of installing a floating monopile consist of different phases. A distinction can be made between the launching of the monopile, the transportation to the installation site, making te connection between the monopile and the crane, the lifting and placement of the monopile and finally the hammering into the soil. This report will focus on making the connection between the monopile and the crane. This doesn't mean that the other phases can be neglected. The goal of this installation method for SHL is a reduction in time and costs. With that in mind, one of the main objectives is to perform as few as possible operations offshore. Due to the possible onshore preparations this will have an influences on all the phases of installation.

Since the focus will be on the hook-in of the monopile, the process of installation is from here on defined as the entering of the 500m zone around the vessel until the moment the hammer is placed on top the vertical monopile. The report will go in depth on the operational workability and feasibility of this process. The other parts, e.g. structural design and time savings, will be mentioned and taken into consideration but not worked out in detail. The hammering of the pile and installation of the transition piece will be left out completely, since that isn't any different from regular monopile installation.

The installation of monopiles can be done from both SHL vessels. However, since the Oleg Strashnov is DP3 equiped we will only consider this vessel for performing the installation. Since there are no mooring lines needed, the dynamic positioning enables more movement around the vessel. However, installation of monopiles on DP is still in development. Therefore also installation on an eight point mooring system will be considered.

4

Concepts

In order to find the best solution for the problem, a careful analysis has to be made of possible solutions. A function analysis is done first to determine which components are needed. After the function analysis, the individual solutions to the different components are listed. Then final concepts can be generated by combining the best solutions for each step. However, a combination of best solutions isn't necessarily the best final concept, so the concepts will combine certain best and second best options.

4.1. Function analysis

The process of installation of a floating monopile is composed of different steps that can be analysed separately. Given the scope of work, the following steps are necessary (figure 4.1)

Figure 4.1: Required steps for floating monopile installation

4.2. Floatation

In order to tow the monopile to the location, it has to stay afloat behind the tug. The monopile will not float by itself, but the required buoyancy can be created. The following methods can be used.

4.2.1. End-caps

The system consists of two caps with a hydraulic operated sealing for water tightness. The top cap is suitable for sealing, towing and lifting. The bottomcap can only function as a seal. See picture4.2. Attention should be paid to a possible J-tube hole that needs to be covered as well. It is preferable to combine this method with an internal floating device for redundancy. Similar methods used in the past have caused sinking monopiles and delays because of end-cap failure.

4.2.2. Internal floating devices

The required buoyancy can also be achieved by filling the monopile with inflatable air bags. An advantage of this system is the redundancy, since multiple bags are used, and more controllable buoyancy. The depth of the monopile can be adjusted by the amount of air in the bags. The system could be equipped with tanks of compressed air to (re-)inflate the air bags during the installation if necessary. The bags need to be connected with an elastic link to compress the package when deflated.

4.2.3. External floating devices

The monopile floats by means of inflatable air bags attached to the outside of the monopile. It has the same advantages as internal air bags, but offers a more straight forward release of the bags.

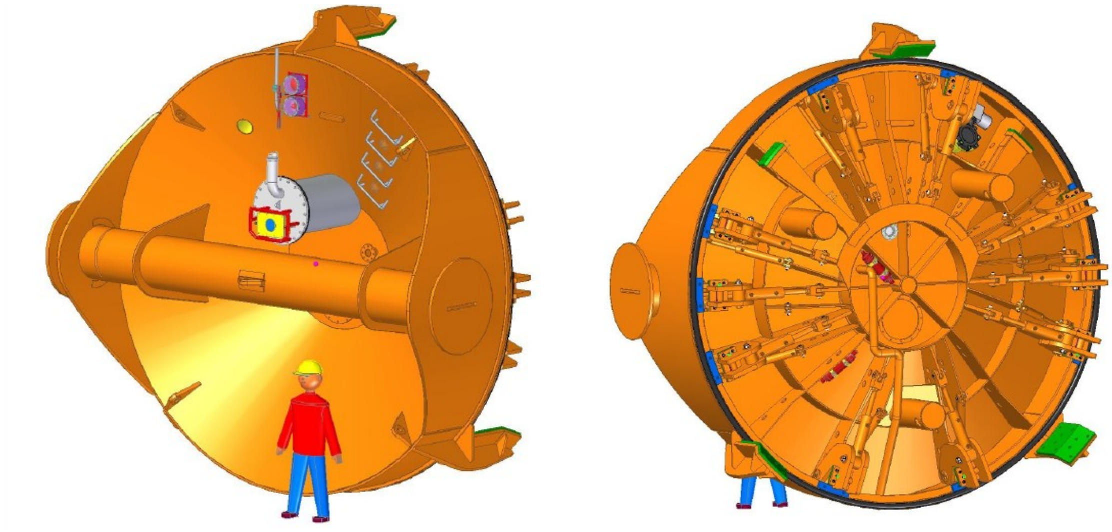

Figure 4.2: Endcaps for a monopile

4.3. Towing

The floating monopile is towed to the HLV by one or more tugs. The removal of the towing end point and placement of the lifting tool is time consuming, so it is preferable to lift the monopile on the same device as it will be towed on.

4.3.1. End-caps

The end-caps as displayed in figure 4.2 can also suitable for towing. The towing bridle has to be placed alongside the lift rigging.

4.3.2. Flange clamp

Some monopiles are equipped with a flange on the top, used for attaching the transition piece on which the windturbine will be installed. Since it has to bear the weight and forces of a wind turbine it is also strong enough for towing and lifting. A tool that clamps behind the flange can be used, proving a stronger connection than a hydraulic pressed seal as used in the end caps, see figure 4.3. An extra grating on the clamp will provide protection from inflow and can be used to reduce drag resistance.

Figure 4.3: Flange clamp

4.3.3. Monopile clamp
A monopile clamp can function for both towing and lifting. Since the placement is not restricted to the ends, it can be placed in most favourable position if needed. The clamp can be equiped with trunnions or other hooking points for attaching the lifting- and towing gear.

4.3.4. Directly attached to tug
If the monopile is directly attached to the side of the tug it is more controllable than floating behind the tug. This is not an issue during transport but can prove handy when mooring the monopile to or near the vessel.

4.4. Mooring and ballasting
In order to perform a safe and fast hook-in, the relative motions between the monopile and the HLV need to be minimized. Therefore, the monopile can be moored against, or near, the HLV. Below mooring methods can be combined with (partially) ballasting for improved performance.

4.4.1. Away from ship
The monopile can be stored floating near the vessel, within the reach of the main crane. Bypassing the mooring to the vessel can possibly save time and reduces the risk of collision between the monopile and the vessel.

4.4.2. Against fenders
Mooring against fenders is a proven concept that is used widely in the maritime industry. Either from ship-to-shore or from ship-to-ship it is a reliable and cheap way to deal with impact forces between the two objects. Because of the round shape of the monopile, attention should be paid to possible misallignment of the fenders.

4.4.3. In gripping frame
Berthing the floating monopile in a purpose build gripper frame can help stabilise the monopile and simplify the hook-in procedure. One or two arms can be used to grab the monopile when it's near the vessel. The arm can be attached to a sliding bollard like structure to eliminate heave forces from the monopile acting on the vessel. The addition of an active heave compensation system could further improve the accesability of the monopile once it's gripped.

4.4.4. Ballasted
To improve motions, the depth of the monopile can be varied. From naturally buoyant to deeper in the water. Also variations in trim should be considered for perfomance optimization.

4.4.5. Grounded
By ballasting the monopile in such a way that the bottom end will lower to the seabed, the monopile is in a possibly more stable position. Bottom of the monopile can be equipped with a rotating mud mat to prevent sinking in the seabed during upending.

4.4.6. Wet stored
By sinking the monopile completely to the seabed, it is less influenced by environmental conditions. However, this comes with challenges for hook-in since visibility and access are less.

4.4.7. Vertical floating
Using the right combination of floatation devices and ballasting, the monopile can be floated vertically. Bringing the monopile upright saves lifting time of the crane, but makes hook-in probably more difficult.

4.5. Hook-in
The main bottleneck of the whole process is the hook-in procedure. Attaching the monopile to the crane hook in a safe way is a challenge. Below methods can be used to make a connection between the rigging and the main hook.

4.5.1. Pre-rigged sling hook-in on tug

Picking up the rigging from the tug has the advantage that no personnel transfer is needed since there is already personnel present on the tug. The rigging that is used to tow can be handed over to the hook, or a second, pre-installed rigging, can be attached and handed over. It has to be noted that a towing bridle is much longer than a regular lift rigging. This can have consequences because of the maximum lifting height of the crane.

4.5.2. Pick up (forerunner) with magnetic device

A quick and automatic connection can be made between the rigging and the ship if it is picked up with a magnetic device. It can be either picked up from the water or from the deck of the tug. Since a magnet can't be used to lift heavy objects it has to be determined if the rigging can be picked up or a lighter forerunner is needed. Once the rigging is onboard the HLV, it can be connected to the main hook. For this operation the main crane or the small deck crane can be used.

4.5.3. Stab ILT/ELT/Vibrohammer/Ball gripper

In case the towing devices cannot be used for lifting, the monopile can be picked up with a lifting tool such as an Internal Lifting Tool (ILT), External Lifting Tool (ELT), vibrohammer or ball gripper.

4.6. Lifting

The main possibilities for lifting the floating monopile are already discussed in above paragraphs. The main options for lifting are: Trunnions, on end-cap, on a flange clamp, with an ILT or ELT, of with a ballgripper.

4.7. Concept generation

Since there are a lot of different possibilities for each step, generating concepts from all combinations would result in too many options. Therefore a different approach is taken. A comparison study is conducted with several experts within SHL to highlight the best options per category. There are no restrictions set in this comparison, in order to get the best outlook on the ideal situation. After that, the best results are combined into several concepts. There are multiple concepts since a combination of the best results doesn't necessarily have to result in the best concept. Internal floating devices proved favorable for keeping the monopile afloat. Although the difference with regards to end-caps and external floating devices is not big, the internal option is regarded more safe. For transportation, towing on trunnions is liked best. Although trunnions are excluded in this research, it is indeed an accessible and easy method. Towing on the lifting tool was listed as second best option due to reduction in installation time since the towing tool doesn't need to be swapped for a lifting tool. Mooring the monopile away from the HLV is perceived slightly safer than mooring the monopile in a gripper frame, but both options scored well. The connection between the monopile and the vessel can be made by fishing a mooring line out of the water or a monkeyfist shoot over between the tug and the vessel. Once the initial connection is made the HLV can move to the monopile and pick it up with the main crane.

4.8. Concept 1: End-caps

This concept is most straightforward and is similar to the currently used method by the vessel Svanen. The monopile floats by means of end-caps, with an airbag inside for redundancy. The tow and lifting can be performed on the top cap. The tugboat brings the monopile alongside the HLV, where it is moored against fenders to prevent impact damage. The rigging is taken over by the main crane and the monopile can be lifted and placed in the outrigger.

Drawbacks:

- Monopile needs to be lifted completely out of the water for bottom cap release
- Bottom section of monopile not uniform, in need of multiple plug dimensions

4.9. Concept 2: Flange clamp

The monopile floats by means of internal floating devices and is towed and lifted on a flange clamp. The pile is stored near the HLV, either (ballasted) floating or grounded. The grounding can be controlled by deflating the internal air bags one by one. A forerunner attached to the rigging is picked up (magnetically) by the crane, so the rigging can be pulled in on board where it will be attached to the main hook. The monopile can be lifted

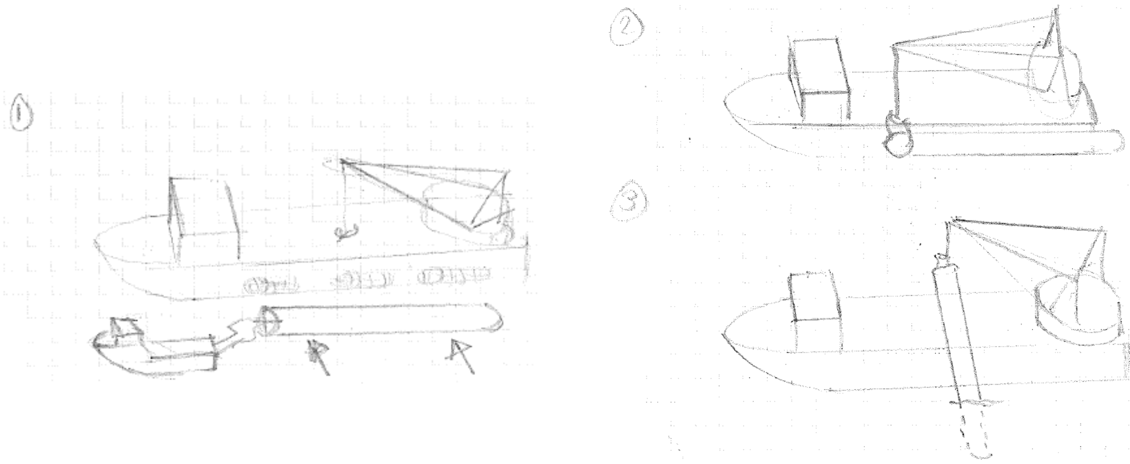

Figure 4.4: Concept 1

and placed in the outrigger. The internal air bags will be attached to the clamp so it can be removed together before the driving hammer is placed.
Drawbacks:
- Monopile needs to be flanged
- Soil need to be suited for monopile grounding

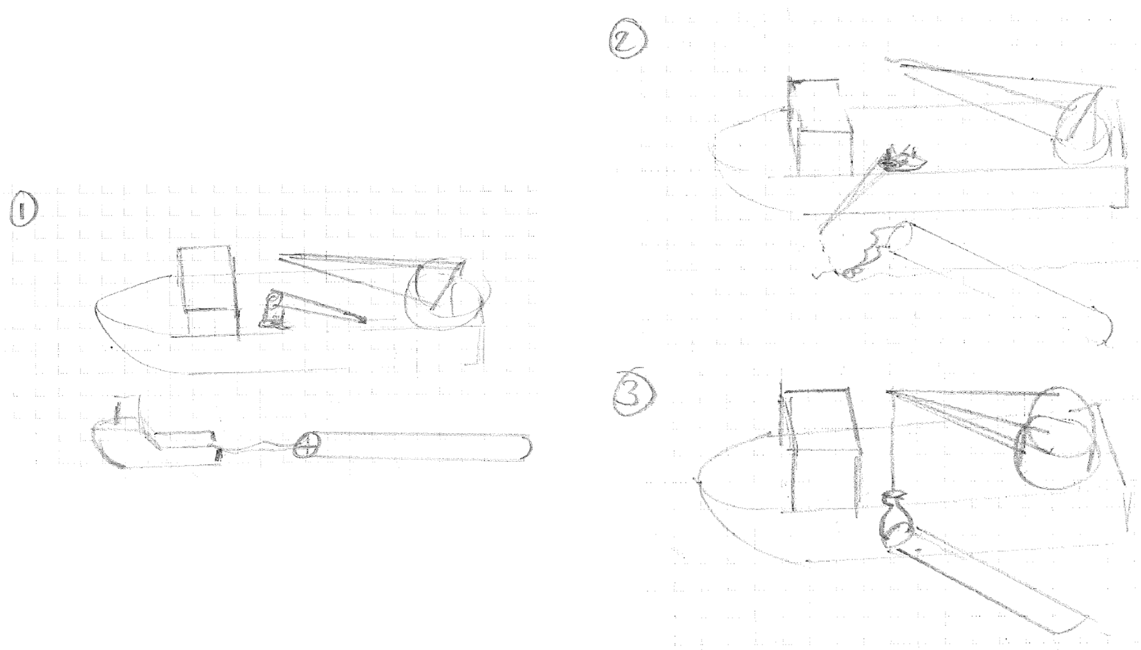

Figure 4.5: Concept 2

4.10. Concept 3: Monogripper

The monopile is floated by means of internal floating devices and can be towed and lifted on a flange clamp. The monopile will be pushed into a gripper frame attached to the HLV. The frame consists of one clamp, which can allow free heave and pitch motion of the monopile. Once the monopile is positioned in the gripper the bottom end will be ballasted in order to lower it to the seabed. The frame can be locked or motion compensated in such a wat that the top of the monopile has the same motion as the HLV. Now hook-in can be performed on deck of the HLV. Once the monopile is hooked in, the clamp can be opened and the monopile can be lifted an placed in the outrigger. The internal air bags will be attached to the clamp so it can be re-

moved together before the driving hammer is placed. An additional option is to transform the gripper into an outrigger to perfrom installation even faster.
Drawbacks:
- Capacity limits on motion compensated frame
- Soil need to be suited for monopile grounding

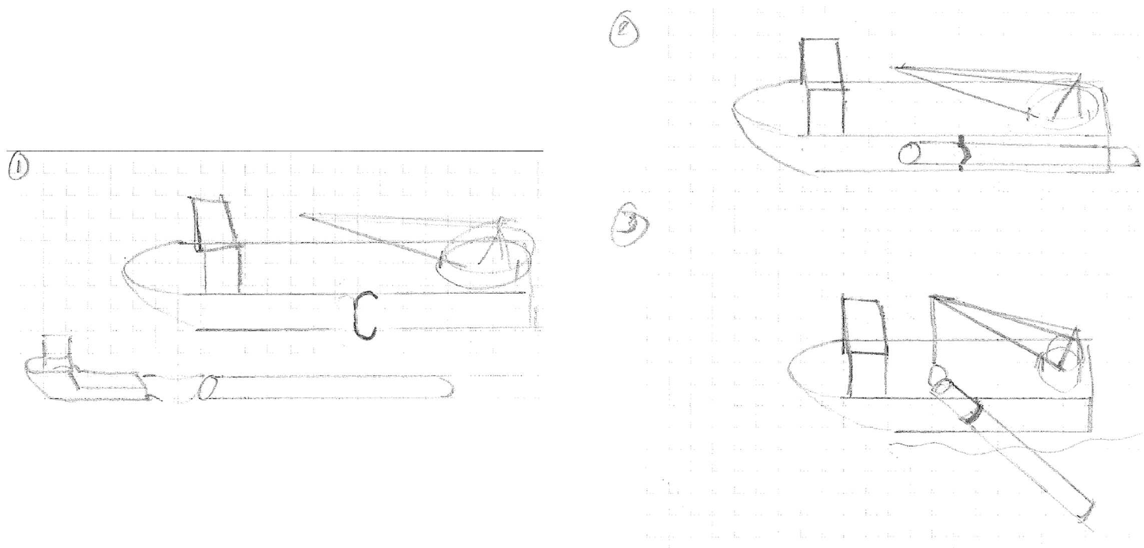

Figure 4.6: Concept 3

4.11. Concept 4: Gripper frame

The monopile is floated by means of internal floating devices and can be towed and lifted on a flange clamp. The monopile will be pushed into a gripper frame attached to the HLV. The frame consists of two clamps that can move independently, but will keep the same path as the wave height in order to limit forces on the HLV. The floating devices will be partially deflated to the point that the monopile will rest in the frame, preferably below the waterline. Now rigging can be picked up. Once the monopile is hooked in, the clamps can be released and the monopile can be lifted. An additional option is to transform one of the grippers into an outrigger, or to position one of the grippers below the outrigger so that it can be upended directly into the outrigger.
Drawbacks:
- Frame is possibly heavy and expensive
- Location outrigger and frame possibly coincide

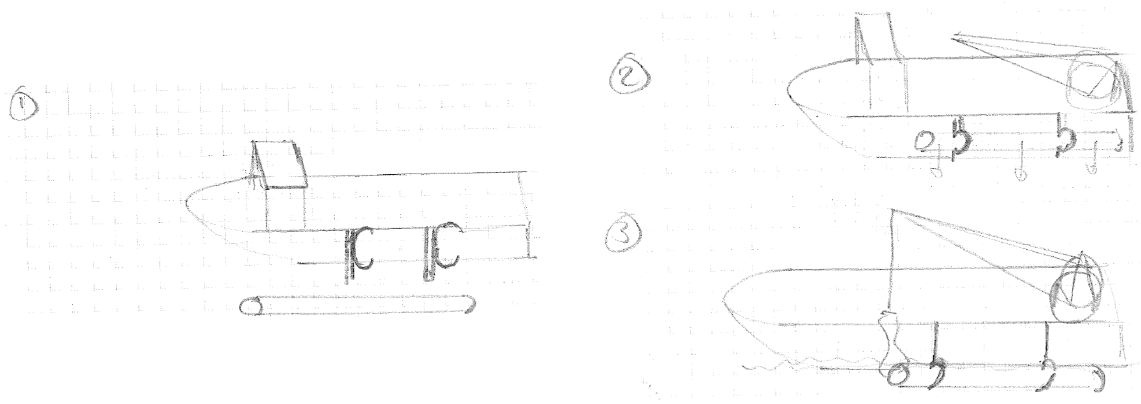

Figure 4.7: Concept 4

5
Concept selection

The final concepts have been discussed with several operational experts within SHL and are subjected to a MCA analysis. The following criteria were rated with the relative impartance between brackets.
Safety (4)
Like all companies operating offshore, safety is a very important matter for Seaway Heavy Lifting. The company states this in its Incident and Injury Free policy, the operation shall be undertaken in such a way that maximizes safety and environmental protection. A method becomes less safe if more human involvement is needed or if certain operations bring more risk.
Estimated costs (2)
Since SHL is a company with shareholders, a solution that is financially attractive is preferred over an expensive solution. However, this is not a leading criterion.
Installation time (4)
One of the main drivers behind the concept of floating monopiles is the advantage of a faster installation and therefore lower installation costs. This makes the estimated duration a very important aspect.
Impact on current setup (1)
The design and build of new equipment is time consuming and costly. Therefore the same applies as for the estimated costs.
Workability (5)
An important aspect of this thesis is the ability to install the monopile within the operational limits of the HLV. Hence, the workability needs to be as high as possible but at least at the maximum workability of the HLV.
Durability (1)
The lifetime of the equipment is something to take into consideration. Besides the safety aspect of failure, it is preferable to have a lasting solution.
Exchangeable with other projects (2)
A solution that can be used for multiple projects in a row is preferable over a solution that needs to be tailor made for one project. In practice this means that a solution should be applicable to different diameters and lengths of monopiles.
Feasibility (5)
The operational feasibility is the most important aspect of the MCA. Given the demanding circumstances for the installation, the feasibility should be as high as possible.

5.1. Concept scores

Because not all points are equally important, a weighing factor is applied. Given the aim of the research is to perform installation in heavy weather conditions, the focus will be on the safety, workability and feasibility. The averaged results of the MCA are shown in table.

	Concept 1	Concept 2	Concept 3	Concept 4
Safety	2.25	3.5	3	2.5
Costs	3.25	2.5	1.75	1.25
Installation time	2.25	2.5	3.5	3.5
Impact on current setup	4.5	4.25	2	1.75
Workability	2.25	2.5	3.5	2.75
Durability	3.25	3.5	2.5	2.25
Exchangeable with other projects	3	3.25	3	3
Feasibility	3.75	3.75	3.5	3
Total score	2.84	3.19	3.13	2.72

From the score table it is clear that the Flange Clamp concept is preferable and the Monogripper scores close. The other two concepts fall behind on perceived less safety and workability. Because the Monogripper scores high on both installation time and workability, this is also worth investigating. Besides these two strong points, the two concepts are based on the same method of towing, floatation and have similar mooring options. Considering these points, the research will continue with both concepts for a sensitivity analysis.

6
Concept detailing

The chosen approach is a combination of two beforementioned concepts which have an overlap. This chapter will clarify and detail how the concepts work, and highlight the important parts.

6.1. General procedure

The main setup of the concepts will still be applicable. The monopile is prepared onshore with internal air bags, a flange clamp, and rigging for lifting. After the launch in the harbour, the floating monopile will be connected to a suitable tug with a towing bridle. The tug will transport the monopile to the location of installation where the monopile will be handed over to the HLV. At this point the two chosen concepts differ from each other, so a distinction between two cases is made. The first option is to handover rigging directly to the crane from the tug. The second options is to catch the monopile in a gripping frame attached to the HLV. After the monopile is hooked in the crane, it will be lifted vertical and placed in the outrigger. Then the piling hammer will be placed on top and the monopile can be hammered into the seabed. The lifting and piling is applicable to both concepts.

6.2. Airbag system

The monopile will stay afloat by airbags deployed inside the monopile. This will be a series of inflatable balloons over the entire length of the monopile. To ensure that the monopile will stay afloat the airbags will consist of several inflatable cylinders (figure 6.1). If one of the cylinders will deflate uncontrollable, the other cylinders can expand and compensate the loss of buoyancy. Each cluster of inflatable cylinders will have a length between 5 and 10 meters. To control the trim and grounding each cluster can be deflated separately. The airbags will form one chain inside the monopile and the chain will be connected to the flange clamp on top. This enables a swift removal once all the airbags are deflated. Before the hammer is placed on top the flange clamp can be lifted of together with the chain of air bags. To speed up this process, the airbags will be interconnected by means of an elastic rope. This compresses the airbags and results in a reduced length of the removal lift.

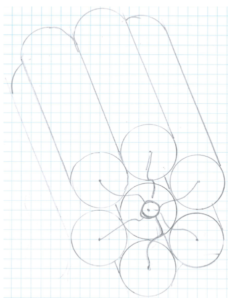

Figure 6.1: Internal floater cluster

6.3. Flange connection

The monopile is supposed to be equipped with a flange for the connection to the Transition Piece (TP) as can be seen in figure 6.2. Since all forces from the wind turbine are passed through this flange to the foundation, the flange has to be very strong. It is assumed that this is strong enough to tow and lift as well. The flange clamp will provide the connection between the monopile and the towing bridle as well as the lifting gear. By grasping behind the flange it proves a stronger and easier then more traditional friction based clamps. However, a point of attention is the critical margin to which the flange is allowed to deform.

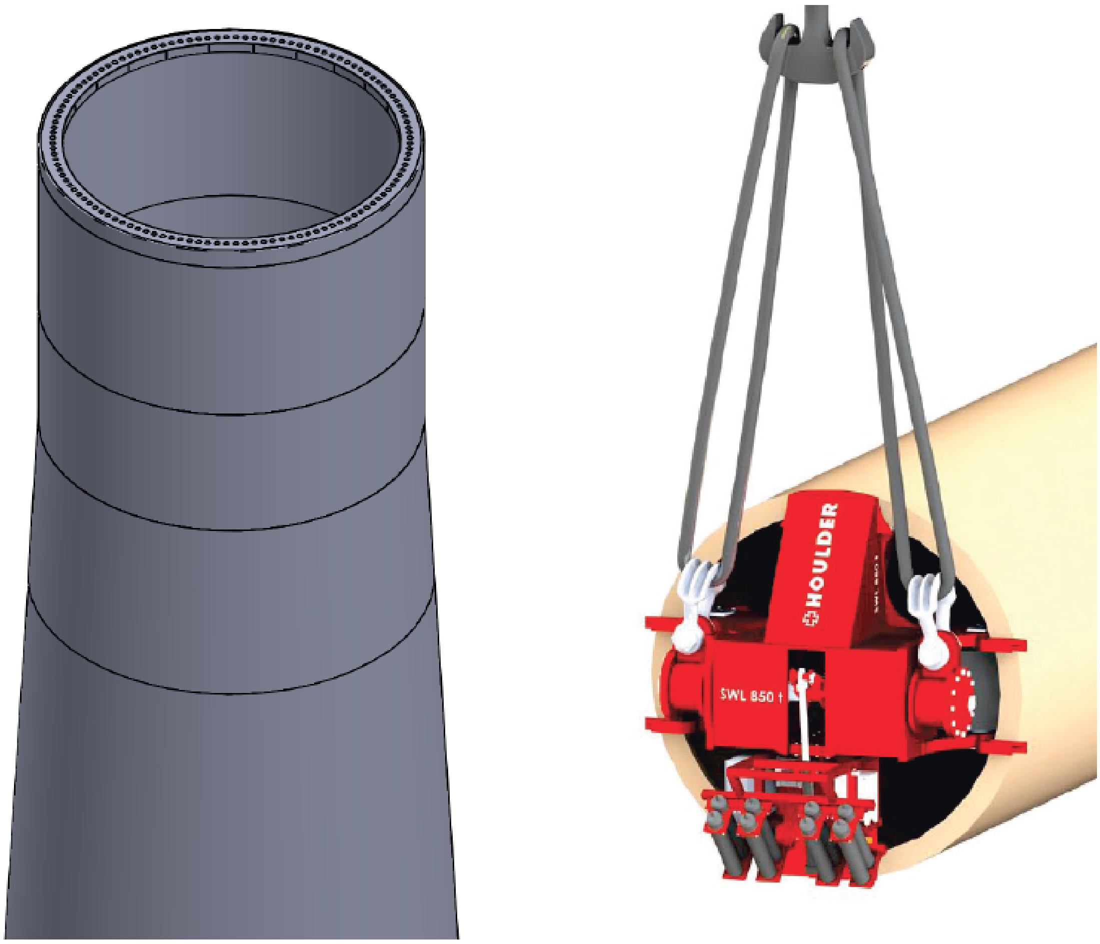

Figure 6.2: Flanged monopile head and flange clamp

6.4. Grounding procedure

The motions of the monopile are assumed to be less if one side is resting on the seabed. The waterplane area is strongly reduced and the HLV can provide shielding from the smaller waves. By deflating the airbags inside from back to front the monopile will incline and at a certain moment lose stability and sink to the seabed. This process of sinking has to be analysed in order to make an estimate of the forces during landing. The structural integrity of the monopile has to be maintained. In case the monopile isn't strong enought to support its own weight, it can be reinforced with a plug. An additional benefit of this plug is an extra connection point which can be used to control the grounding process. The backside of the monopile can be lowered down with a winch onboard a tug or the HLV.

6.5. Lifting

Once the monopile is grounded the main hook of the crane can be brought to the monopile head, when the relative motion between the monopile head and the hook are low enough the rigging can be attached to the hook. When the rigging is attached the monopile can be upended and placed in the outrigger for installation.

7

Grounding procedure

The first step of the installation is the lowering of the bottom of the monopile to the seabed. This will happen by deflating the internal buoyancy bags until the stability is lost and the monopile will sink. The important aspects of this procedure are the initial position of the monopile, the deflating process, and the impact on the seabed.

7.1. Initial position

The initial position during the tow of the monopile is assumed to be with the buoyancy bags fully inflated to minimize the draft. To determine this initial position the hydrostatic analysis software Ansys Aqwa Librium is used. The program works iteratively to a static equilibrium between the buoyancy and hydrostatic forces. In this analysis environmental forces are excluded.

7.2. Trim during tow

As seen in figure [xx] the floating monopile under full inflated conditions is under a trim angle of 1.3°. During tow it might be favourable to trim the monopile horizontally to reduce drag forces. This position can be realized by deflating of the last buoyancy bag, or reducing the buoyancy bag in size.

7.2.1. Weather restrictions

While installation is limited to certain wheater conditions, the transportation of the floating monopile to the installation location is less so. The added equipment to the monopile is mainly inside, except for the flange clamp where it will be towed. This flange clamp will be govering for the tow process as wave impact can damage the equipment. The exact restrictions will depend on the type of equipment that is installed, but will likely be much higher than the installaton weather conditions.

7.3. Grounding

7.3.1. Deflating procedure

The grounding of the monopile is realized by deflating the internal buoyancy bags from back to end. This process can be divided into two parts. First, the buoyancy bags are deflated until the monopile starts to sink to the seabed. Second, once the monopile is grounded, the deflation of the other buoyancy bags start to determine the final trim of the monopile on the seabed. This trim likely influences the motions of the monopile, which will be investigated in the sensitivity analysis.

7.3.2. Impact on seabed

The most critical part for the monopile is the impact on the seabed. . Therefore, an assessment of the impact has to be made. The monopile is modelled in Ansys Aqwa Drift to take the motion into account. Again, no environmental forces are acting on the monopile. The monopile is assessed from the point where it starts to sink to seabed until the moment before impact. According to the simulation software the following speeds of the centre of gravity of the monopile are registered just before reaching the seabed:

V_v = -1.70 m/s
V_h= -3.167 m/s
Rotational speed = 4.85 $\circ$/s
Converted to the motions at the bottom of the pile:
V_v = -4.71 m/s
V_h= 0.63 m/s
V_{tot} = 4.75 m/s
As can be seen the impact on the seabed is severe and will most likely damage the bottom of the monopile. It is therefore necessary to equip the monopile with a bottom plug with a cable attached, so the monopile can be grounded in a controllable manner. In a scenario where the seabed is rocky or may contain boulders, the damage of impact can be destructive even at lower speeds. It is therefor advised to check the soil in the installation area beforehand.

8
Fundamentals

With the concepts known, it must be studied if these concept can be feasible in real operations. To do so, both situations need te be modelled in simulation software. This chapter will deal with the fundamentals of the simulations. Since both scenario's require the monopile to be grounded, the simulation need to take care of the coupling with te seabed. The soil model will be explained in detail. Furthermore, an introduction to the basics of the simulation software, Ansys AQWA will be given. It will provide a background for the coming chapters dealing with the simulations itself.

8.1. Soil conditions

When the monopile is lowered to the seabed, it will sink into the seabed and remain in contact with the seabed during the whole operation. This contact will possibly influence the motions of the monopile at the seasurface. To assess the magnitude of this influence, research has to be conducted about the behaviour of the soil. Since offshore wind farms are mainly installed in Europe, in the North Sea and Baltic Sea, the soil conditions have to be representative for these areas. To capture a wide scope, three different soil conditions will be tested.

1. Loose sand
    - $\gamma = 10kN/m^3$
    - $\nu = 0.2$
    - G = 150 MPa
    - $\phi = 20°$
2. Hard sand
    - $\gamma = 10kN/m^3$
    - $\nu = 0.3$
    - G = 300MPa
    - $\phi = 25°$
3. Clay
    - c = 20kPa
    - $\gamma = 18kN/m^3$
    - G = 300 MPa

- $\nu = 0.45$

The depth the monopile will sink in the seabed depends on the contact area of the pile with the seabed and the soil properties. The monopile with a certain depth in the seabed will be regarded as a shallow foundation. Recommended practice is to assume undrained soil conditions, which state the following bearing capacity by Terzaghi. The formula is adapted by the API with correction factors to accommodate a better solution.

$$Q = (cN_cK_c + \gamma D)A \tag{8.1}$$

Where:
Q = vertical load
C = undrained shear strength of soil
N_c = Dimensionless constant, 5.14
ϕ = undrained friction angle 0°.
γ = Unit weight of soil
D = depth of the sinking
A = effective area foundation

Similarly, for the sandy soil cases, the bearing capacity for drained soils is found:

$$Q = (c'N_cK_c + qN_qK_q + \frac{1}{2}\gamma BN_\gamma K_\gamma)A \tag{8.2}$$

Within additional factors:
B = Minimum lateral foundation dimension
q = γD, where D is the depth of the foundation
For both equations, the N_c, N_q and N_γ are dependend on ϕ, and are found by the following formula's:

$$N_q = \frac{1+sin(\phi)}{1-sin(\phi)}\exp(\pi tan(\phi)) \tag{8.3}$$

$$N_c = (N_q - 1)cot(\phi) \tag{8.4}$$

$$N_\gamma = \frac{3}{2}(N_q - 1)tan(\phi) \tag{8.5}$$

The vertical loads are determined by finding the equilibrium position with the use of Aqwa Librium. Each trim position has a different distribution of buoyancy and weight on the seabed. As can bee seen in 8.1. The

Parameters								
Soil	Inverse	Z force (MN)	Depth (m)	R (m)	G (Mpa)	Poisson	k_H (N/m)	k_rotatie N/rad
Clay29	29,25	6,436	1,43	3,07	300	0,45	4,77E+09	4,63E+10
Clay35	34,7555	5,105	1,48	2,59	300	0,45	4,02E+09	2,78E+10
Clay41	41,2115	3,529	1,37	2,459	300	0,45	3,82E+09	2,38E+10
Clay50	49,972	1,33	0,88	1,595	300	0,45	2,48E+09	6,49E+09
Sand1_29	29,25	6,436	0,63	1,61	300	0,3	2,35E+09	6,68E+09
Sand1_35	34,7555	5,105	0,5	1,05	300	0,3	1,53E+09	1,85E+09
Sand1_41	41,2115	3,529	0,42	1,05	300	0,3	1,53E+09	1,85E+09
Sand1_50	49,972	1,33	0,5	0,98	300	0,3	1,43E+09	1,51E+09
Sand2_29	29,25	6,436	0,42	1,27	200	0,2	1,20E+09	2,18E+09
Sand2_35	34,7555	5,105	0,43	1,17	200	0,2	1,11E+09	1,71E+09
Sand2_41	41,2115	3,529	0,56	1,3	200	0,2	1,23E+09	2,34E+09
Sand2_50	49,972	1,33	0,34	0,8	200	0,2	7,59E+08	5,46E+08

Figure 8.1: Soil stiffness

resulting stiffnesses are found by applying the following formula's [7]. These are applicable for foundation materials which are assumed isotropic and homogeneous and for a structure base that is circular, rigid and rests on the soil surface. Because the resting part of the monopile is not circular, the radius is assumed to be the same as a radius of a circle with the same area.

Horizontal plane stiffness:

$$u_H = (\frac{7-8\nu}{32(1-\nu)GR})H \tag{8.6}$$

Torsional stiffness:

$$\theta_t = (\frac{3}{16GR^3})T \tag{8.7}$$

Where:
u_H = Horizontal displacement
H = Horizontal load
θ_t = Torsional rotation
T = Torsional moment
G = elastic shear modulus of the soil
ν = poisson's ratio of the soil
R = radius of the base

8.2. Hydrodynamic model

The monopile and vessel are subjected to different environmental forces, namely waves and current. This chapter will provide background information about the calculation of the body motions. First, a closer look will be given to the environmental conditions. Second, there will be more details of how these environmental forces interact with the body.

8.2.1. Axis convention

Throughout the following chapters the following axes systems are used by Ansys AQWA, the Local Reference Axis (LRA) and the Local System Axis (LSA), both can be seen in figure 8.2. The LRA has its origin on the mean water surface with Z-axis pointing upwards, X and Y on the mean water surface. The mean water surface is at Z=0. This axis system will not move. The LSA has its origin at the CoG of the structure, with X, Y and Z axes parallel to the FRA when the vessel is in its initial definition position. As is customary, X is along the length of the vessel, Y along the beam to port, and Z in the direction of the cross product of X and Y. This axis system moves with the vessel.

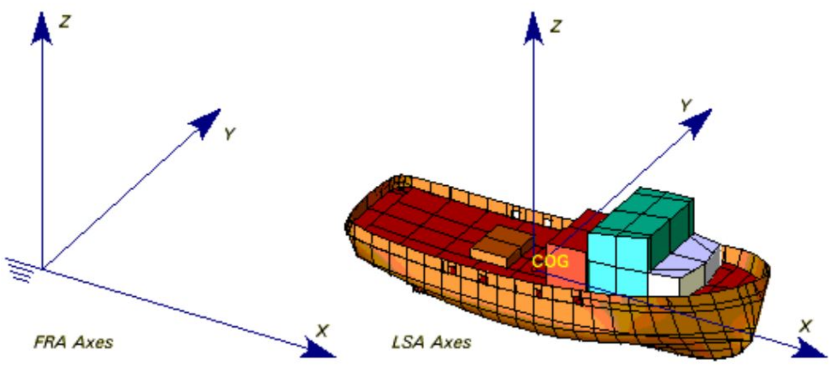

Figure 8.2: Local Reference Axis and Local System Axis

8.2.2. Rigid body motions

The six motions around the structure Centre of Gravity are defined by three translations and three rotations:
x = surge in the longitudinal x-direction, positive forwards.
y = Sway in the lateral y-direction, positive to starboard.
z = Heave in the vertical z-direction, positive upwards.
θ = Roll about the x-axis, positive right turning
ϕ = Pitch about the y-axis, positive right turning

ψ = Yaw about the z-axis, positive right turning

The motions about the axis are shown in figure 8.3

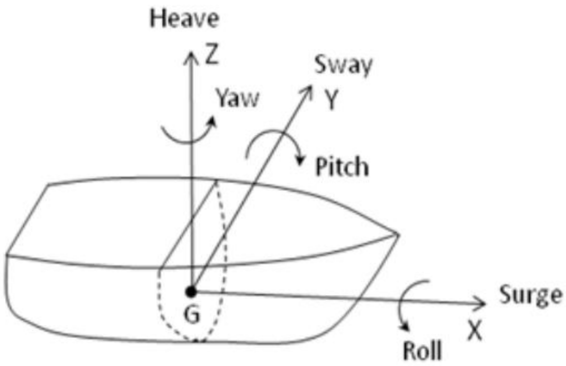

Figure 8.3: Motions around the axis system

Transformation from one axis system to another can be achieved with Euler rotation matrices.

$$R = R_x * R_y * R_z \tag{8.8}$$

Where:

$$R_x(\theta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta) & -\sin(\theta) \\ 0 & \sin(\theta) & \cos(\theta) \end{bmatrix} \tag{8.9}$$

$$R_y(\phi) = \begin{bmatrix} \cos(\phi) & 0 & \sin(\phi) \\ 0 & 1 & 0 \\ -\sin(\phi) & 0 & \cos(\phi) \end{bmatrix} \tag{8.10}$$

$$R_z(\psi) = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{8.11}$$

These equations are used later on to determine the Inertia matrices for the monopile after rotations.

8.2.3. Potential wave theory

The sofware program Aqwa uses potential wave theory for the calculation of forces acting on the body. This section will explain the fundamentals of potential wave theory. In potential wave theory the water is assumed to be an ideal fluid with only the earth's gravitation inducing the forces that control the motions of the water particles. An ideal fluid is asssumed to be incompressible, to have a constant density and to have no viscosity. The incompressibility can be assumed realistic since the forces acting on the particles are very small. The density of seawater depends on temperature and salinity and is therefore not everywhere the same, however, over a distance of a few wavelength these can be considered constant.
The velocity potential is defined as a function of which the spatial derivatives are equal to the velocities of the water particles. So $u_x = \frac{\partial \phi}{\partial x}$, $u_y = \frac{\partial \phi}{\partial y}$, $u_z = \frac{\partial \phi}{\partial z}$. This potential function for the harmonic wave has to fullfil four requirements:

1. Continuity condition or Laplace equation

2. Seabed boundary condition

3. Free surface dynamic boundary condition

4. Free surface kinematic boundary condition

Since the fluid is homogeneous and incompressible, the continuity equation becomes

$$\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} + \frac{\partial u}{\partial z} = 0 \tag{8.12}$$

The seabed is assumed watertight, so the vertical velocity of the water particles at the seabed $(z = -d)$ is zero:

$$\frac{\partial \Phi_w}{\partial z} = 0 \tag{8.13}$$

At the free surface $z = \eta$, the kinematic and dynamic boundary condition apply:

$$\frac{\partial \Phi}{\partial z} = \frac{\partial \eta}{\partial t} \tag{8.14}$$

$$\frac{\partial \Phi}{\partial t} + g\eta = 0 \tag{8.15}$$

Then, from the momementum balance follows the Bernouilli equation:

$$\frac{\partial \Phi}{\partial t} + \frac{p}{\rho} + gz = 0 \tag{8.16}$$

With the pressure known, the forces and moments follow from an integration over the submerged surface of the body.

$$F = \int_S (p \cdot n) dS \tag{8.17}$$

$$M = \int_S p(r \times n) dS \tag{8.18}$$

Where S is the wet surface of the body, n is the normal vector and r is the position vector of surface dS in the global coordinate system.

8.2.4. Irregular waves

The first order waves influence the body directly with the wave frequency, the forces are linearly related to the waveheight. Mathematically the waves are describes by the following sinusoidal formula:

$$\zeta(t) = \zeta_a cos(kx - \omega t) \tag{8.19}$$

Where ζ_a is the wave amplitude, k the wavenumber and ω the wavefrequency.
However, in reality a wave with a single waveheight and frequency doesn't occur. Waves are a summation of different regular waves with each a different frequency as can be seen in figure 8.4. Mathematically, this superposition of regular waves can be described by:

$$\zeta(t) = \sum_{n=1}^{n} \zeta a_n cos(k_n x - \omega_n t + \epsilon_n) \tag{8.20}$$

Where n is the number of stacked waves and ϵ is the phase angle.

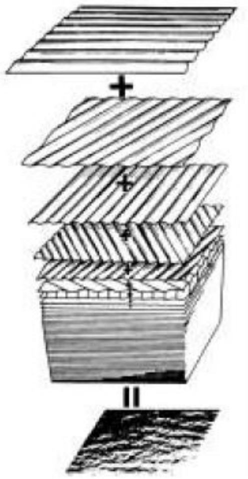

Figure 8.4: Stack of regular waves

To describe the irregular wave in the frequency domain, the Fourier analysis can be applied. The spreading of the wave frequency of a certain seastae of irregular waves is described by the wave energy density spectrum. The transformation from the sum of independent regular waves (with their own frequency, amplitude and phase in the frequency domain) to the wave spectrum is shown in figure 8.5. A common wave energy density spectrum is the Joint North Sea Wave Project (JONSWAP) and was established by extensive measurements carried out in the North Sea (equation 8.21). The transformation to the frequency domain is applied since wave data from Ansys AQWA in the frequency domain is used in this thesis (see figure 8.5. Since another model in this thesis is eventually made in the time domain, another transformation from the frequency to time domain should be performed.

$$S_{\zeta}(\omega) = \frac{320 * H_{1/3}^2}{T_p^4} * \omega^{-5} * exp(\frac{-1950}{T_p^4} * \omega^{-4}) * \gamma^4 \tag{8.21}$$

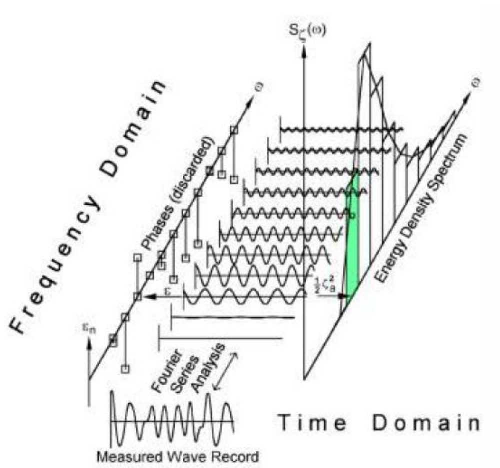

Figure 8.5: Stacked waves to wavespectrum

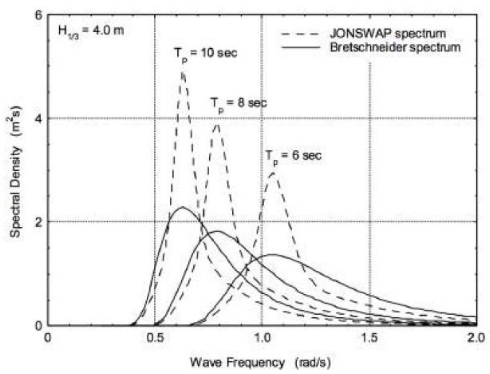

Figure 8.6: JONSWAP spectrum with different wave peak periods

8.2.5. Time domain simulations

Time domain analysis is used to simulate the real-time motion of a floating body while operating in irregular waves. Wave-frequency motions and low period oscillatory drift motions may be considered. Current loading is also applied. The difference frequency and sum frequency second order forces are calculated at each time step in the simulation, together with the first order wave frequency forces and instantaneous values of all other forces. These are applied to the structures and the resulting accelerations are calculated, from which the structure positions and velocities are determined at the subsequent time step. The system properties at the end of one time step are then the starting conditions for the next, and so a time history of the motion of each structure is constructed.[8]

8.2.6. Frequency domain simulations

The determination of the motions of a moored floating structure system in response to environmental forces is a complex procedure, which may include system nonlinearities and position-dependent environmental loads. By means of linearization, these calculations can be solved faster. This fast calculation makes frequency domain analysis a more suitable analysis for a parametric variation study.
In Ansys Aqwa it is assumed that the frequency domain simulation is carried out from a previoulsy determined position of equilibrium. Mooring line stiffness, hydrostatic stiffness and the stiffness due to reaction forces at articulations are re-estimated at this equilibrium location.

9

Motion analysis grounded monopile

With the fundamental knowledge about Ansys AQWA and the soil model, the first case can be put into a model. This chapter will deal with the sensitivty analysis of the grounded monopile next to the vessel. Firstly, the making of the model will be discussed, followed by the differend load cases the model will be subjected to. After these basics are known, the results of the analysis are discussed.

9.1. Preparations

The goal of these simulations is to know under which circumstances the monopile can be installed with the HLV. There are a number of parameters to be varied. Firstly, the environmental conditions like significant waveheight, wave peak period and the direction of the waves are systematically varied. The orientation of the grounded monopile is also taken into consideration, the monopile will be placed in different headings with respect to the HLV. Lastly, the trim of the monopile on the seabed will be varied to see the influence of different waterplane areas and different bouyancy scenarios.
To accurately predict the motions of the system, the following elements need te be present in the input for AQWA:
1. A model of the vessel, with parameters garantueeing realistic behaviour
2. A model of the monopile, with parameters garantueeing realistic behaviour
3. Environmental conditions

9.1.1. Vessel model

Ansys Aqwa is finite element modelling software, which means that models are build using elements with different properties. Case of the vessel and monopile, a geometric shape is converted into a surface body which is meshed to create diffracting elements. The geometric shape of the vessel is based in the design for the actual vessel, which the Naval Architecture department of SHL converted to a Ansys AQWA model. To ensure natural behaviour of the whole structure, the properties like Centre of Bouyancy, Centre of Gravity, Inertia etc. are defined as well. Figure 9.1 shows the vessel model. To simulate the anchoring of the vessel, mooring lines are used in AQWA. The four anchorlines are attached at the centreline of the vessel to enable roll motion. While the length of the lines enables the other motions as well, while maintaining the position of the vessel.

9.1.2. Monopile model

The monopile is build from TUBE elements, with closed tubes to create watertight compartments, to mimic the bouyancy bags inside. All the forces on the TUBE elements are calculated via Morrison's equation. The Centre of Bouyancy and the Centre of Gravity follow directly from the geometrical shape. The Moment of Inertia however are different for each orientation of the monopile. These moments are computed by adjusting the Moments of Inertia in the standard orientation with the Euler rotation matrix as explained in chapter 8

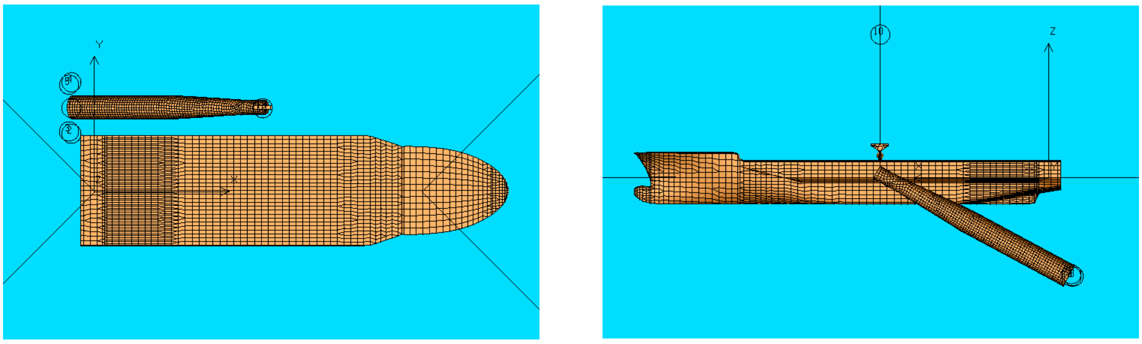

Figure 9.1: Vessel and monopile model in Ansys AQWA

9.2. Load cases

Determination of sensitivities is a key issue in measuring the performance of the grounded monopile. To capture these sensitivities, a variety of circumstances has to be simulated. A number of key factors is being systematically varied to assess their effect on the final outcome, namely:

- Wave height
- Wave peak period
- Environmental direction
- Orientation with respect to vessel
- Trim monopile on seabed

The main component of the environmental forces is the wave force. By exciting the monopile, the waves are the main contributor of energy to the system. The waves consist of two components, the wave height and the peak period. Together they define a wavespectrum as explained in paragraph 8.2.4. The direction of environmental forces will affect the motions of the monopile, but more important, it will affect the motions of the vessel. Vessel performance is usually better in head waves than in beam waves. The shielding of the vessel also influences the magnitude of the environmental forces on the monopile.
The monopile will be installed over the starboard side of the vessel. On that side the orientation of the monopile is varied over 180°.
The monopile will have different trim angles on the seabed. This is achieved by reducing the buoyancy of the monopile. The buoyancy influences the weight on seabed as well as the trim position. A more upright position will result in a smaller waterplane area, a fully trimmed position results in a higher wet surface area. Both have an effect on the motions, so an optimum has to be found here.
This makes for the following variations in load cases:

Parameter	Range	Step size
Wave height	0-2.5m	0.25m
Wave peak period	3-12s	1s
Direction environmental forces	360°	30°
Orientation monopile	$0-180°$	15°
Trim monopile	$29-42°$	6.5°

9.3. Results

After running the simulations and collecting all the data, we can compare the outcome with the set criteria in $H_s - T_p$ diagrams. These diagrams show at which significant wave height and wave period the installation limiters are met. Since a parametric study generates a lot of data, only the most important findings are discussed.

9.3.1. Optimal heading and monopile orientation

Vessels are designed to perform best when sailing straight, so to take the environmental forces head-on. The same is seen in this parametric study, the configurations where the vessel is heading into the environmental forces produces the best results. An example is given with the figure below, where the monopile is heading 180° to the vessel. There is a clear shift in performance when the environmental forces are coming from portside and from behind compared to taking it head-on.

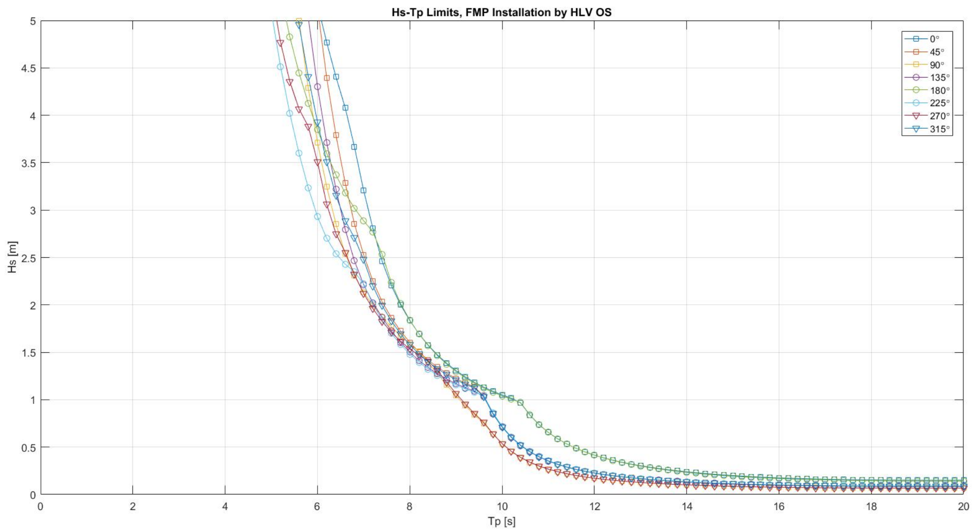

Figure 9.2: Monopile heading 0° $H_s - T_p$ plot Trim 42°

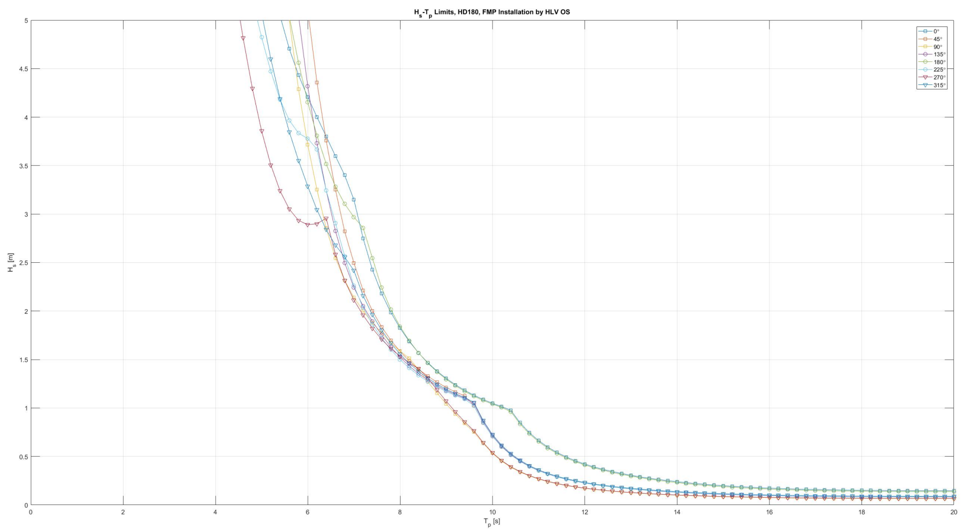

Figure 9.3: Monopile heading 180° $H_s - T_p$ plot Trim 42°

As can be seen in figure 9.2 the monopile peforms close to the set criteria of $H_s = 2m$ and $T_p = 8s$ when the environmental forces are coming head-on. The same applies to the configuration where the monopile is oriented at 180° as can bet seen in figure 9.3. Both configurations are here shown with a monopile trim of 42° to the seabed.

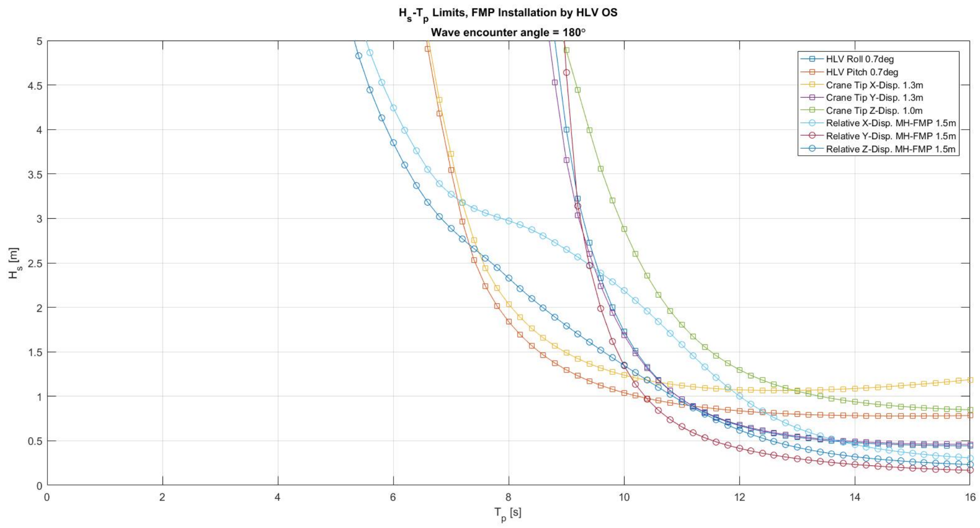

Figure 9.4: Monopile heading 0° $H_s - T_p$ plot, Environmental direction 180°, Trim 42°

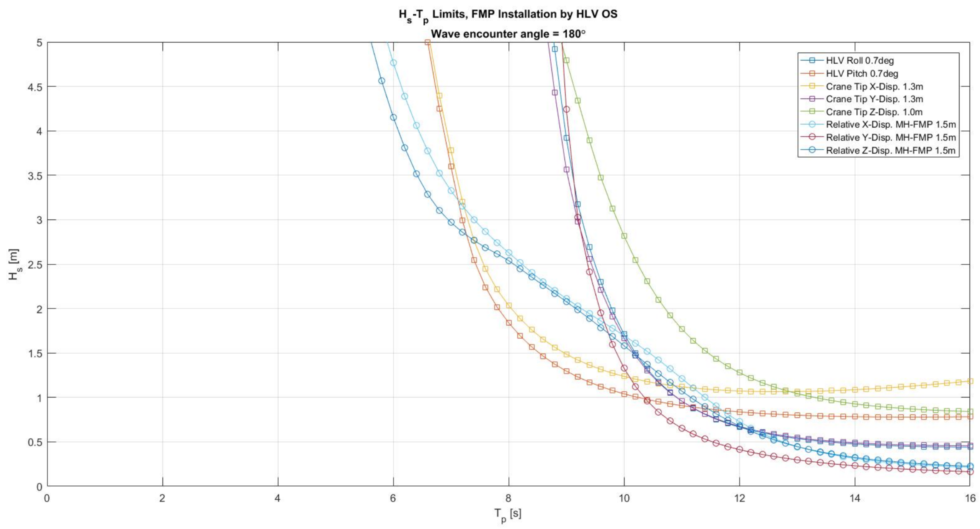

Figure 9.5: Monopile heading 180° $H_s - T_p$ plot, Environmental direction 180°, Trim 42°

To understand the behaviour of the monopile better, a closer look can be taken at the individual components that make up the $H_s - T_p$ diagram. Figure 9.4 shows where the limitations are exceeded in the monopile orientation , Environmental direction 000°, with environmental forces head-on configuration. It can be seen that the performance is mainly limited by the vessel pitch, it also can be seen that in waves with $T_p > 10s$ the difference in y-direction between the crane hook and the monopile head is too large. Whereas for higher but shorter waves the gap between hook and monopile in vertical direction the limiting factor is. The same can be seen for the monopile orientation of 180° in figure 9.5, where the exact same criteria are the limiting factors. It is interesting to note that the relative z-displacement is more noticable when the waves are in opposite direction of the monopile.

9.3.2. Optimal trim

The other parameter that is varied is the monopile trim. To recap, a deeper trimmed monopile has less bouyancy en a larger waterplane area, a higher trimmed monopile has more bouyancy and a smaller waterplane area. It's mostly interesting to look at the behaviour around the installation limits of the vessel, the $H_s = 2m$ and $T_p = 8s$. But performance overall is taken into account as well. When comparing monopile orientation 180° in figure 9.6, 9.7 and 9.3, it can be seen that performce is drastically reduced for the starboard incoming environmental forces for lower trims. The performance in the 0° and 180° incoming waves are still similar and within the acceptable range. The monopile orientation of 000° shows similar results, although the 35° has less perfomnce reduction from starboard. While performance differences between 000° and 180° monopile orientation at 42° trim are small, it makes a larger difference at 29° and 35°, especially for the starboard incoming environmental forces.

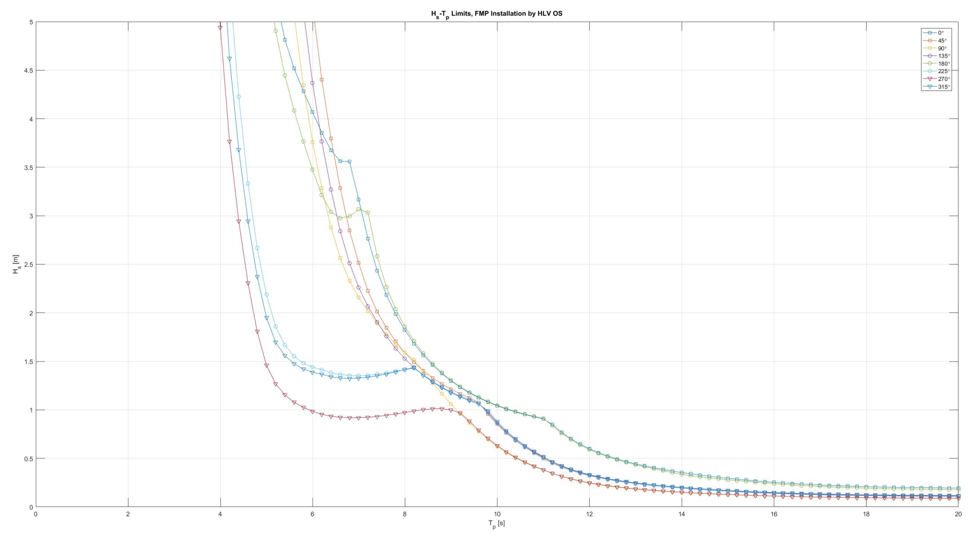

Figure 9.6: Monopile heading 180° $H_s - T_p$ plot Trim 29°

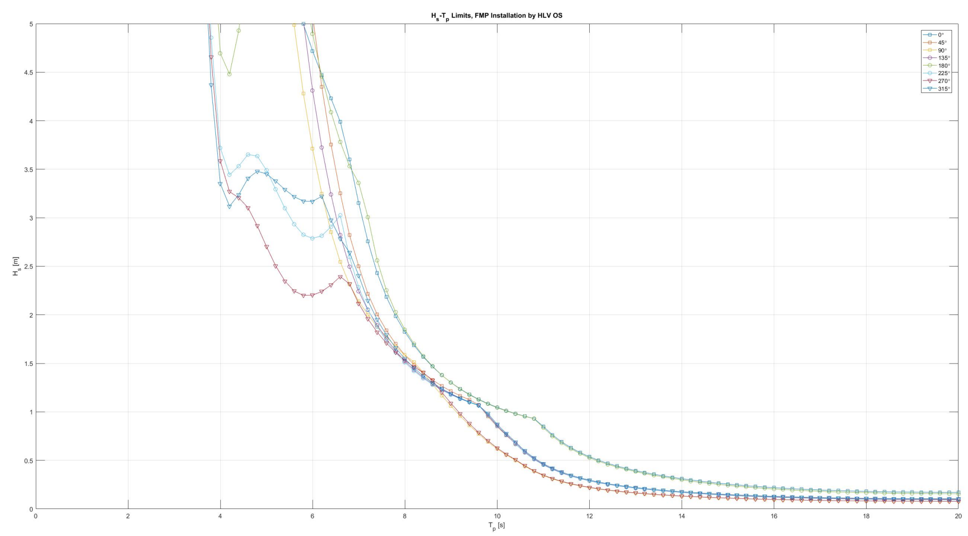

Figure 9.7: Monopile heading 180° $H_s - T_p$ plot Trim 35°

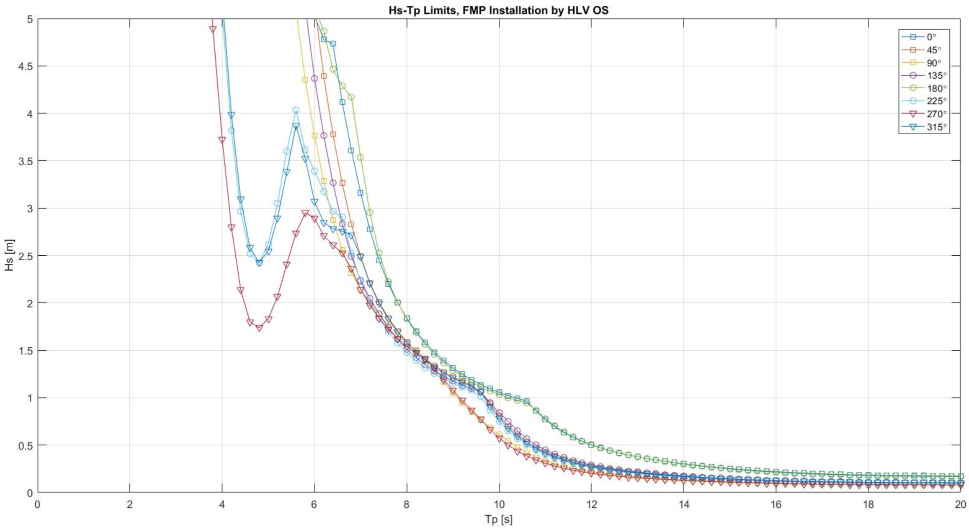

Figure 9.8: Monopile heading 000° $H_s - T_p$ plot Trim 29°

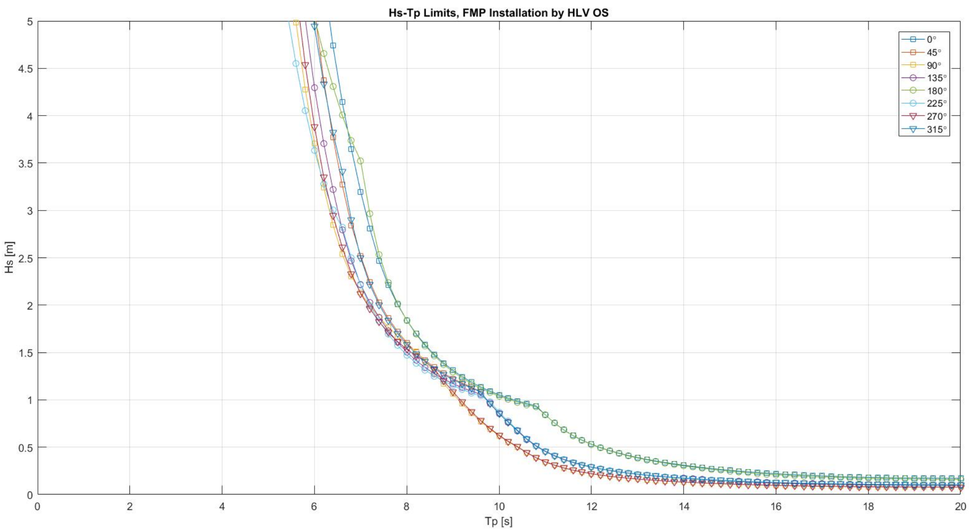

Figure 9.9: Monopile heading 000° $H_s - T_p$ plot Trim 35°

To illustrate the difference monopile heading can make, a closer look will be taken at 120°/29° orientation in figure 9.10. Here the 0° and 180° wavedirection perform worse than 45° and 90°. At 35° trim, this direction performs particularly bad at wave peak periods around 5s.

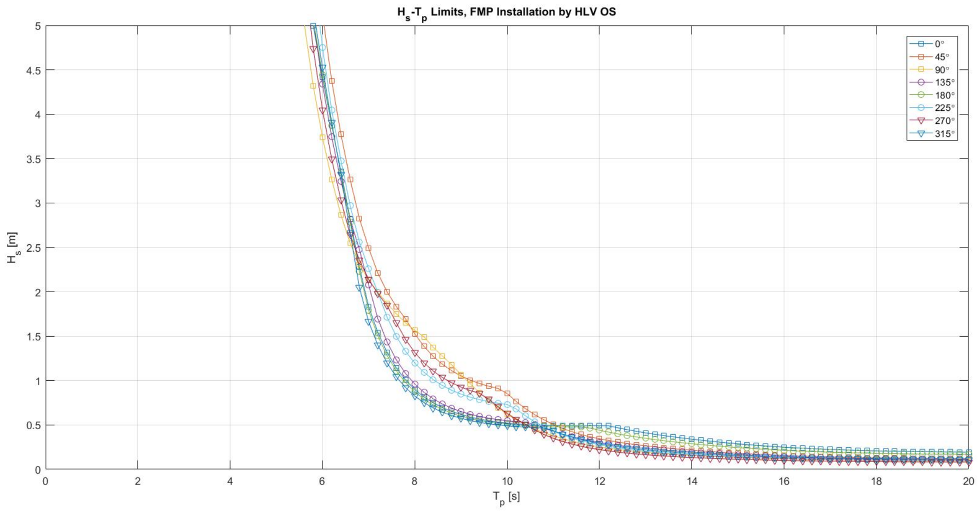

Figure 9.10: Monopile heading 120° $H_s - T_p$ plot Trim 29°

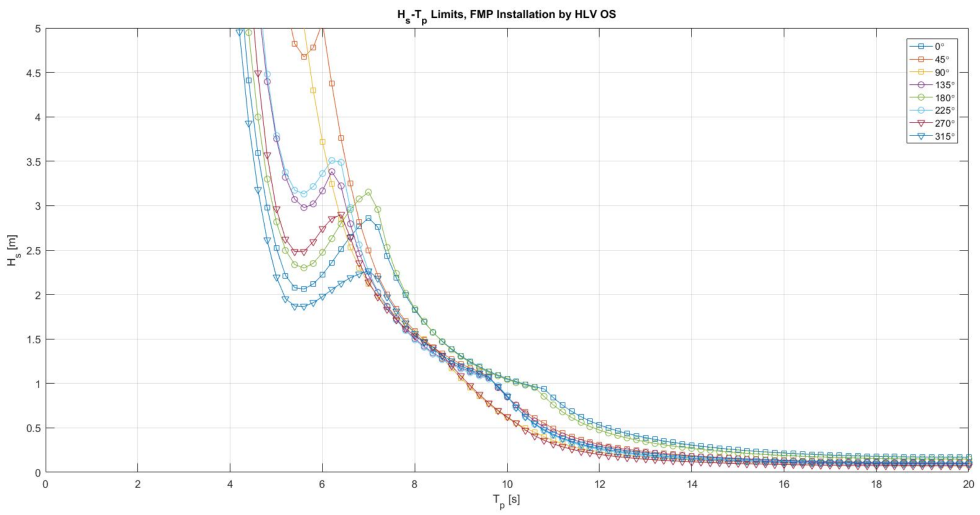

Figure 9.11: Monopile heading 120° $H_s - T_p$ plot Trim 35°

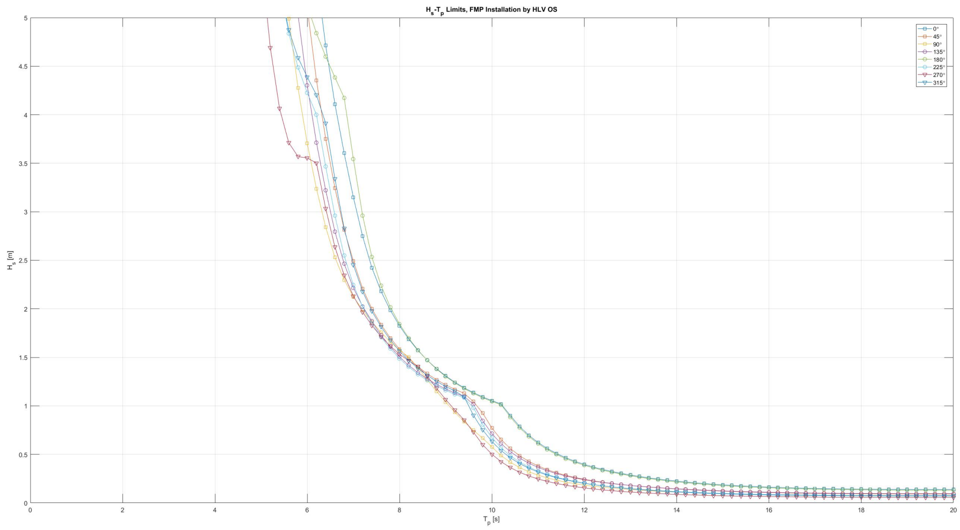

Figure 9.12: Monopile heading 90° $H_s - T_p$ plot Trim 42°

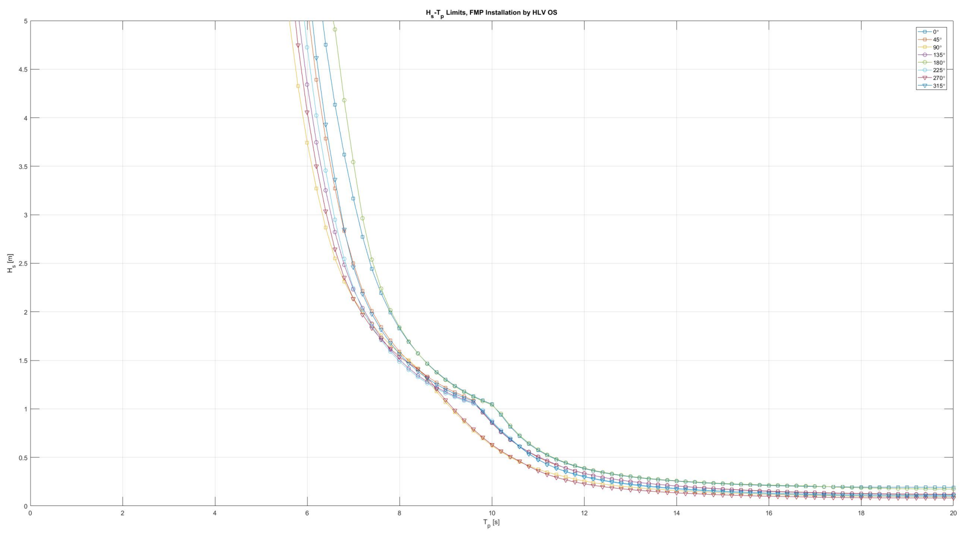

Figure 9.13: Monopile heading 90° $H_s - T_p$ plot Trim 29°

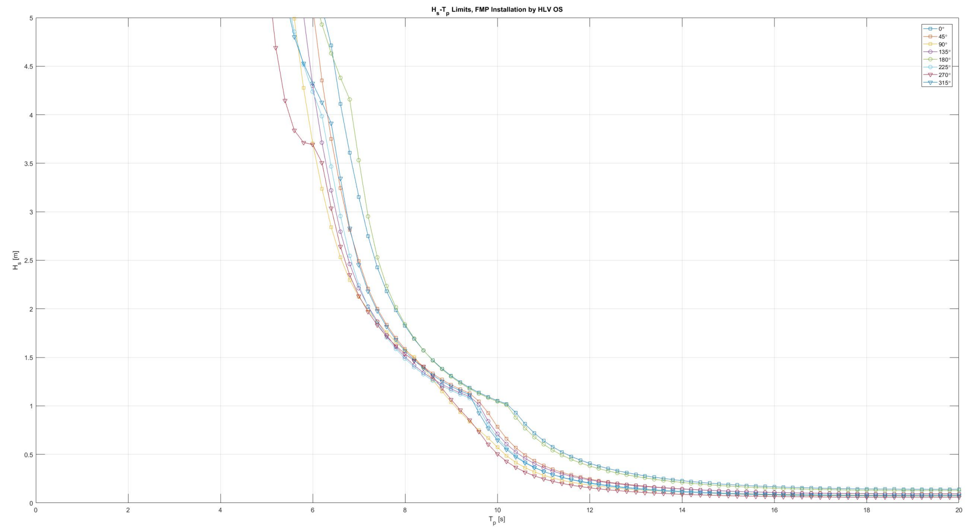

Figure 9.14: Monopile heading 105° $H_s - T_p$ plot Trim 42°

9.4. Conclusion

The installation of a grounded monopile in heavy weather is a feasible option. As simululations have shown, there are configurations in which installation up till a significant waveheigth of two meters with a peak period of 8s is possible. The performance in the least trimmed position has the best performance over different environmental forces angles. The best option for installation is in a configuration where the vessel and the monopile are facing the environmental conditions head-on, with a 42° monopile trim. However, it has to be noted that other monopile orientations with respect to the HLV are performing good as well, as long as the trim of the monopile is 42°. Using other trim options is possible, but limited to specific orientations.

9.5. Recommendations

The simplification of the soil model to a hinge is something that could be improved to get a better understanding of the problem. A critical look has to be taken at the soilmodel, because the found stiffnesses are unusually high. If the soil would be less stiff, a time domain simulation could be viable because less computational time is needed.
Furthermore, the assumption in this simulation is that the monopile is infinitely stiff and keeps its structural integrity. Because monopiles are used as a foundation, they are build to last at least 25 years. This means that they are strong and stiff, but nonetheless they aren't made for these kind of loads. Next to that, deformation tolerances for the flange are small, which could be compromised in this installation proces. It is necessary to study the impact of this installation method on the structural integrity of the monopile.

10

Monopile in gripper

The second option for stabilizing the monopile, following from the multicriteria analysis, is receiving it alongside the vessel and grabbing it with the gripper. While the monopile is resting in the cradle, the bottom is lowered to the seabed. By having two rigid connections, on the seabed and to the vessel, the monopile is supposed to be in a stable enough position to hook on to the crane. Crucial for this position are the forces on the interface between the vessel and the monopile, since the hull of the vessel is not infinitely strong. Therefore a model has to made to simulate the motions of the vessel together with the monopile under different environmental conditions.

Firstly, the general procedure will be explained. Then it continues with the approach on how to model that accurately. This model will be subjected to a sensitivity analysis, from which conclusions can be drawn about the feasibility of this procedure.

10.1. Receiving monopile in gripper

As explained in chapter 6, the monopile is equiped with bouyancy bags to provide floatation and a flange clamp for lifting and towing. The monopile is to be brought alongside the vessel by tugs, while the gripper is in an open position. The FMP will rest against the hull of the vessel, while fenders will prevent impact damage to either the hull or the monopile. The gripper will need to be sufficiently large to accomodate the height of the monopile as well as an extra clearance for vertical motions (heave and pitch) during the reception. Once the gripper is closed around the monopile, the bouyancybags inside can be deflated, so the bottom lowers to the seabed. Once the monopile is on the seabed, the hook in procedure can start. During the hook in of the monopile to the crane, the monopile and the vessel form a system together. Where the monopile is connected to both the seafloor and the vessel, thus influencing the vessel motions.

10.2. Modelling

To assess the hydromechanical behaviour of the monopile and the vessel, a model is made. The model aims to make a realistic representation of the force interacting on the interface between the hull of the vessel and the (head of) the monopile. Since te monopile rests on a seabed with a high soil stiffness, the connection is assumed to be a hinge, allowing free rotation in the XZ-plane. There is no additional spring stiffness limiting the rocking motion of the monopile, because there are no physical restrictions preventing that particular motion. It has to be noted that due to the modelling of the seabed - monopile connection as a hinge, the monopile will act as an anchor point for the vessel since the hinge is a highly stiff connection. This is realisticly seen not true, the vessel will be kept in place by either dynamic positioning or anchor lines. And thereby reducing the forces on the hinge and monopile-hull interface.
The environmental forces on the system will be provided bij JONSWAP spectra (see paragraph 8.2.4) with waveheights ranging from 1m to 2m and peak wave periods ranging from 4s to 10s. Additionally a current is introduced in the same direction as the waves, varying from 0 m/s to 1 m/s. A timeframe of 30min per simulation is chosen in order to reach a fair indication of the maximum force without taking too much computation time. The simulations are run in time domain to capture as much detail as possible.

10.2.1. Assumptions

Like the previous simulation, the vessel is moored with anchorlines in four directions to maintain position while operating. The attachment point are at the centreline of the HLV, thus allowing for roll motion.

- Vessel moored with anchor lines
- Monopile connection with seabed is a hinge
- Vessel to monopile connection is a ball joint
- Only environmental impact from 180°, 225° and 270°.
- Vesseland monopile infinitely stiff

10.3. Results

The performed simulations result in plots where the force is shown against environmental characteristics. As expected, the performance while taking the environmental forces head-on is best. Through all plots it appears lower than the other directions. As can be seen in below plots, the resulting forces are relatively high. The forces are a summation of three force vectors in X-, Y-, and Z-direction. Distinction is made between the maximum and RMS value of the force over a 30 minute simulation. The RMS value will be the leading value since that gives the best representation of forces acting at the same time. The maximum value is used to put the RMS in perspective. It is assumed that the maximum forces in X-, Y-, and Z-direction don't occur at the same time.

$$F_{res} = \sqrt{F_x^2 + F_y^2 + F_z^2} \tag{10.1}$$

10.3.1. RMS XYZ force

The RMS value of the force on the hull gives the best representation of the actual force at a point in time. Three cases shown with currents of 0, 0.5 and 1 m/s. It is clear from the figures that the treshold of 4MN is rapidly surpassed as the wave peak period becomes higher. Only a seastate without current and a $H_s = 1m$ and coming from head-on is not exceeding the limitations. An incease in waveheight still allows for lower wave peak periods, which is within the installation goal. A higher current is causing forces mostly too large. A change in direction of the environmental direction is in all cases not possible, even at the lowest seastates, the force limitations are surpassed.

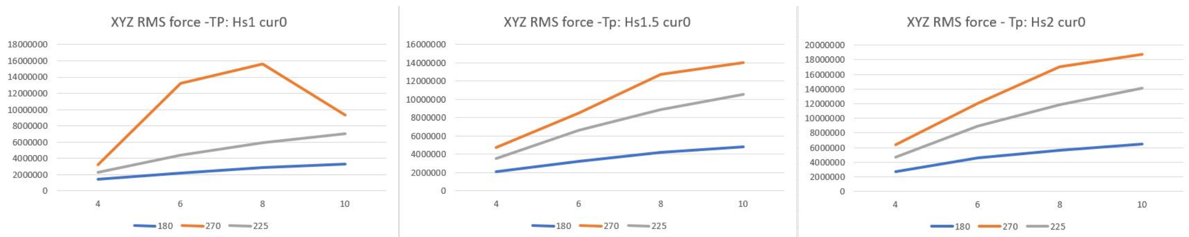

Figure 10.1: XYZ RMS force with current = 0 m/s

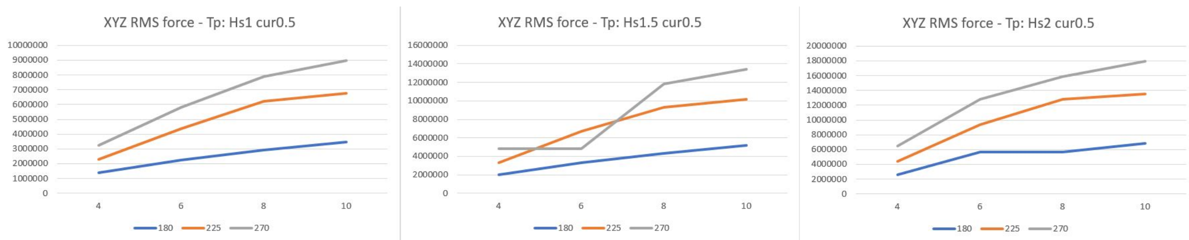

Figure 10.2: XYZ RMS force with current = 0.5 m/s

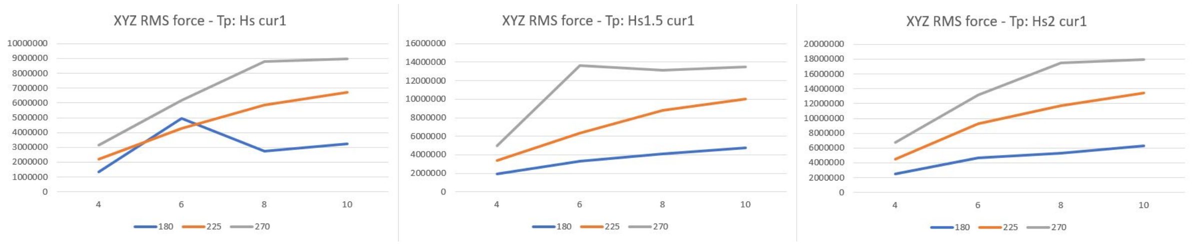

Figure 10.3: XYZ RMS force with current = 1 m/s

10.3.2. Maximum XYZ-force

To get a better understanding of the forces acting on the hull, a closer look has to be taken at the acting maximum forces. Despite the probability that all maximum forces are acting at the same time, it gives an indication of how large these forces can be. After all, it's the maximum force that is ultimately governing for the hull integrity. As can be seen below in figure 10.4, the forces are significantly larger than the RMS value in the same situation. The value of 4MN is exceeded by a $T_p = 6s$, which is below the desired value of $T_p = 8s$. When operating in waveheigths larger than 1m, the forces become larger than 5MN with extremes of 30MN at $H_s = 2m$ and $T_p = 10s$ in figure 10.6. These values are nowhere near the hull strenght limits.

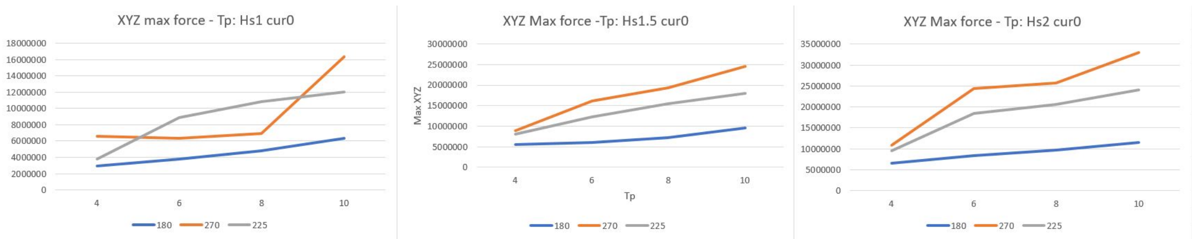

Figure 10.4: XYZ maximum force with current = 0 m/s

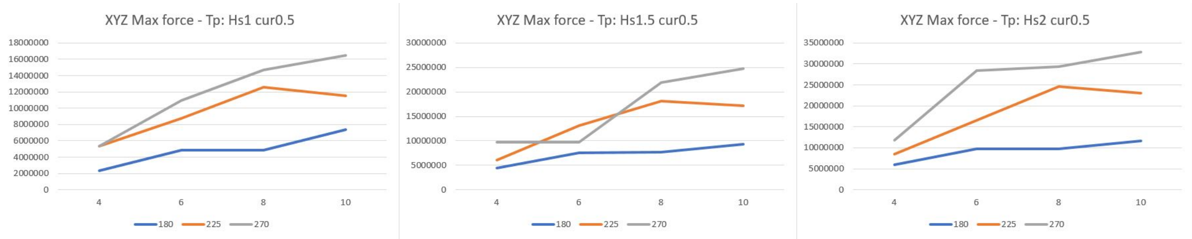

Figure 10.5: XYZ maximum force with current = 0.5 m/s

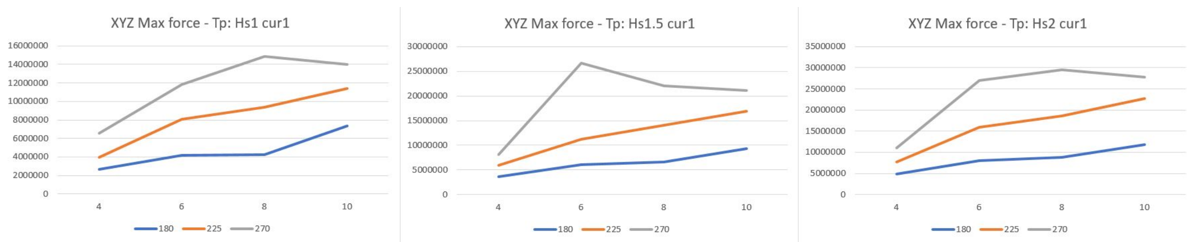

Figure 10.6: XYZ maximum force with current = 1 m/s

From analysis of data is becomes clear that the force in Y-direction is the largest contributing forces in most cases. This could be a consequence of how the model is set-up. The connection with the seabed is assumed as a hinge, which means that all lateral movements along the Y-axis are restricted. Since the monopile is an infinitely stiff structure, the vessel is also restricted in lateral movement. This causes all the lateral forces that are acting on the vessel will be present in the joint connection between the hull and the monopile. The heave and surge motion are similarly restricted, but can compensate for eachother because they act in the same plane. A surge forward results in a negative heave motion and vice versa.

10.3.3. Maximum XZ-force

To see the influence of the lateral force on the hinge, a closer look can be taken at the X- and Z-force only. In figure 10.7 can be seen that the forces are considerably lower when the lateral force is left out. The installation criteria are met, even when considering the maximum forces.

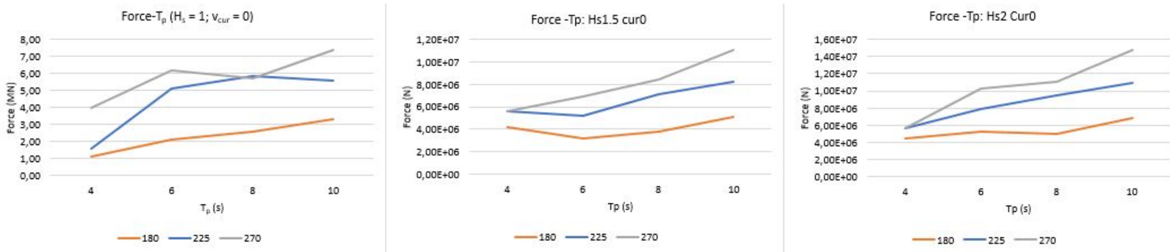

Figure 10.7: XZ maximum force with current = 0 m/s

As can be seen from the plots, performance is still under 5MN for a significant wave heigth of 1.5m at a peak period of 8s. This only applies for the conditions without a current present. Adding a current brings the peformance up to a H_s of 2m. Possibly due to a stabilizing effect on the vessel. Performance from 225° or 270° is decreasing compared to the head-on situation.

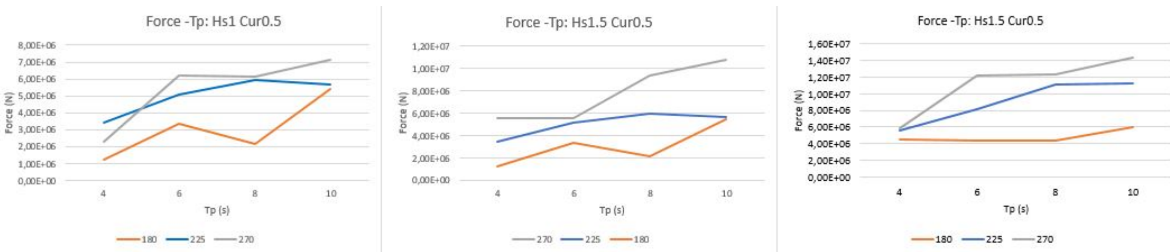

Figure 10.8: XZ maximum force with current = 0.5 m/s

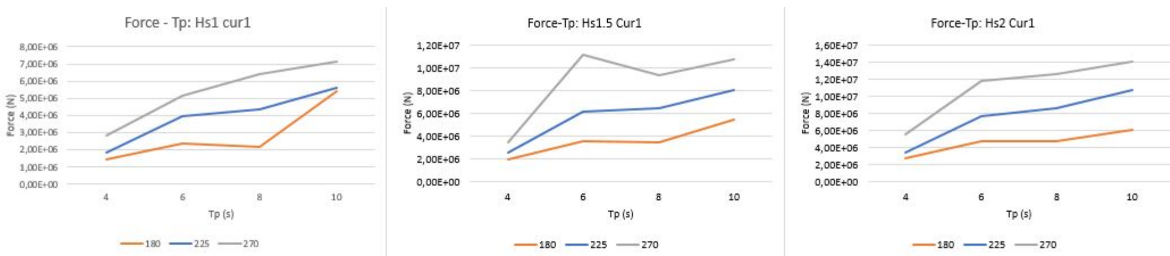

Figure 10.9: XZ maximum force with current = 1 m/s

10.3.4. RMS XZ-force

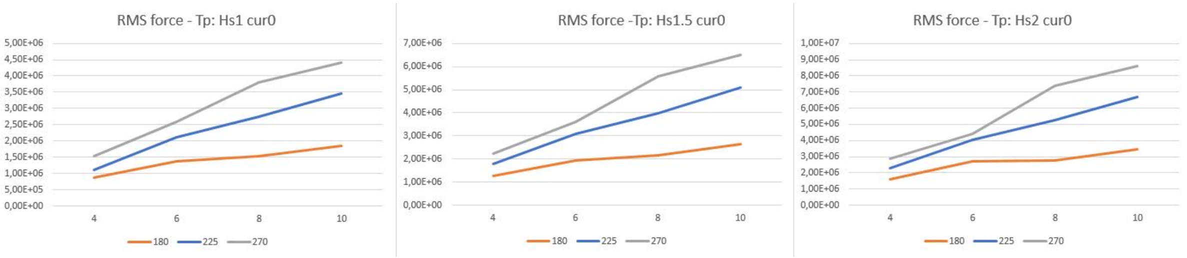

Figure 10.10: XZ RMS force with current = 0 m/s

When comparing the RMS value of the force instead of the maximum values, performance is a lot better. Without current velocity, even at a significant waveheigth of 2m, the maximum allowable force isn't exceeded.

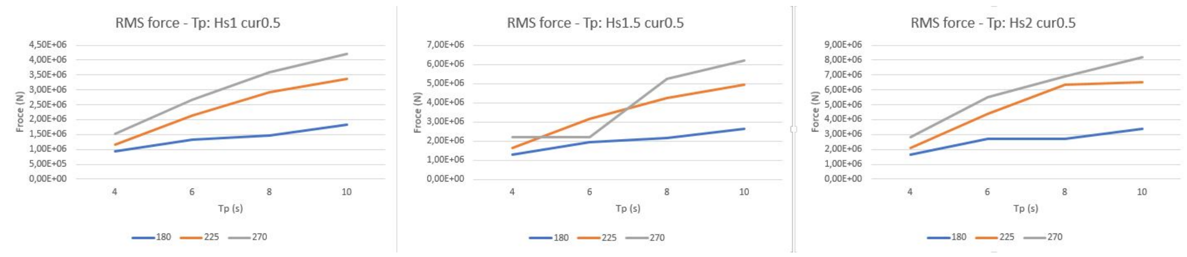

Figure 10.11: XZ RMS force with current = 0.5 m/s

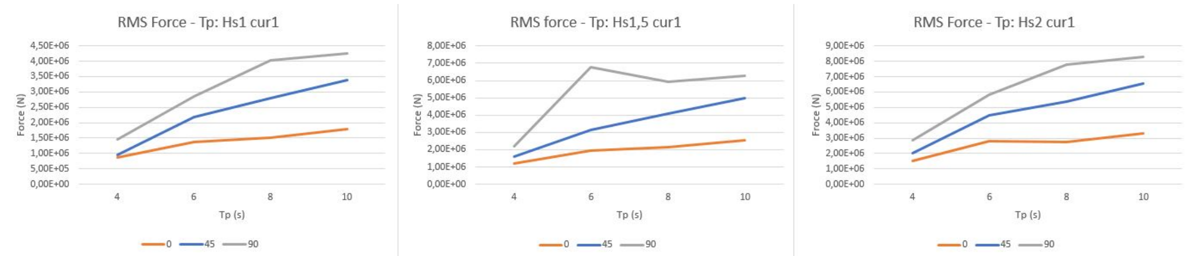

Figure 10.12: XZ RMS force with current = 1 m/s

10.4. Conclusion

The method of attaching a gripper to the vessel to hold the monopile is only possible at lower waveheights and during shorter waves. The required installation criteria are only met when considering the RMS force at the interface of the hull and monopile. This indicates that it can be a viable option for floating monopile installation, but furher research has to be done.

10.5. Recommendations

The concept of a gripperframe attached to the hull of the vessel, to stabilize a monopile seem a feasible option. However, due to time constraints in this theses, only an indication of the forces is presented in this chapter. A more detailed comparison could be achieved by computing the resulting maximum force vector during each timestep in the simulation. This results in an actual maximum force per timestep instead of a summation of the maximum forces during a 30 minute simulation.
To get a more realistic view of the forces acting on the interface between the vessel and monopile, further research can be done on the soil model. In the current situation, the soil model is replaced by a hinge, which results in forces that are probably too large as explained in subsection 10.3.2.
Furthermore, due to time constraints, only three different directions are taken into account. With more computational power or time, one could make a more complete study by taking into account different angles. In

this study it is assumed that all environmental forces are collineair. This is a conservative approach that not always reflects on a real situation. Leaving collineairity out could give insight in how the different environmental forces are contributing.
Lastly, system is designed for very large monopiles with a top diameter of 6m and a weight of 1600 tons. The gripper that has to contain such a structure is going to be quite large and heavy, which may not be very practical during operations. During a catch or release of the monopile, the gripper has to open far enough to clear the monopile. The motion of the heavy monopile in the waves could damage the gripper frame during such operations.

11

Conclusions

Over the last years, the offshore wind market keeps on growing. There is a clear trend to deeper waters and larger windturbines, to maximize the captured wind energy. With these larger windturbines comes a larger foundation, which is posing problems for future installation. Seaway Heavy Lifting (SHL) is a company that installs these foundations, so called monopiles, with their Heavy Lift Vessels (HLV). Nowadays, the largest HLV of Seaway can transport and install three monopiles at a time. However, with larger monopile it is expected to be reduced to two monopiles or even less. In order to be competitive in the monopile installation market, SHL is looking for a method to transport the monopiles to the HLV, instead of using the HLV for transportation. A previous comparative study showed that floating transport of monopiles to the HLV is the most favorable method. However, SHL is unexperienced with this method and therefore requires a study on developing the best method to install the monopiles within the workability of the HLV. Therefore, the thesis goal is: 1"Design of a method for installation of large floating monopiles in heavy weather conditions"

The concepts of how such an installation could work constist of five steps: floatation, towing, mooring, hook-in and lifting. A multicriteria analysis shows that using airbags is the most favorable method of making the monopile float, while using a flange clamp for towing and lifting. In order to reduce motions, the mooring can be either on the side of the vessel in a gripper frame, or by sinking one end of the monopile to the seabed. When the monopile is in moored position the pre-rigged rigging can be taken over by the main hook of the crane.

To assess whether or not these method can be applied in real operations, a feasibility study is conducted. Both methods are modelled in the simulation software package Ansys AQWA. A soil model has been made to assess the influence of the grounding on the motion behaviour of the monopile. Due to the stiffness of the soil, it is more time efficient to model the connection between the soil and the monopile as a hinge.

The installation of a grounded monopile in heavy weather is a feasible option. As simululations have shown, there are configurations in which installation up till a significant waveheigth of two meters with a peak period of 8s is possible. The least trimmed position has the best performance over different environmental forces angles. The best option for installation is in a configuration where the vessel and the monopile are facing the environmental conditions head-on, with a 42° monopile trim. However, it has to be noted that other monopile orientations with respect to the HLV are performing good as well, as long as the trim of the monopile is 42°. Using other trim options for whatever reason is possible, but limited to specific orientations.

The installation of monopiles with a gripper attached to the vessel seems to be a viable option, but only once the soil model is improved. The simplification of the soil model by replacing it with a hinge gives uncertainties in the real force actin on the interface between the vessel and the grounded monopile. However, when look at the RMS force of 30 minute simulations without taking lateral forces into account, the results are well within the set boundaries.

12 Recommendations

In this report, various issues have been recognised that could improve the results of the thesis. The following subjects need further investigation:
Firstly, the structural integrity of the monopile should be investigated. Due to the cyclic loading by the windturbine, deformations can lead to fatigue problems on the long term and hence deformation margins are small. It is therefore vital that the monopile isn't deformed. Deformation can occur during the tow and lift on the monopile flange or on the bottom during the grounding on the monopile. As shown in chapter 7, uncontrolled grounding probably causes impact damage. A temporal reinforcement in the form of a plug could prevent such deformation at the bottom. This plug could also be used to control the grounding proces with a crane.
Furtermore, Although it's only an indication that a gripper frame might work, a decent estimate about gripper proportions should be made. The dimensions and weight of the large monopiles could cause an excessive large frame. Besides the size, the placement could coincide with the currently installed outrigger frame. It's likeley that the two structures cannot be installed at the same time. However, it is an option to make the gripper frame rotatable so that it can take over the outrigger activities.
Due to time constraints in the simulation phase, it is chosen to replace the soil model with a simplistic hinge connection. Although this gives a proper first estimate, the simulations could be more accurate by implementing the soil model. The stiffness of the soil as computed in this thesis should be re-evaluated because it's higher than expected. A less stiff soil enables a larger step-size in the timedomain simulations, which would drastically reduce the overal simulation time.
From the Multi Criteria Analysis follows that grounding is a feasible option. However, due to above proposed recommendations, it becomes a more equipment depending operation and the grounding procedure is possibly compromising the structural integrity. Not grounding the monopile could be less expensive and less critical for the structural integrity. Further investigation is needed in the relative motions between vessel and monopile which can be compared to this study.

A

References

(1) https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Offshore-Statistics-2017.pdf. Accessed: 17-7-2018.

(2) Offshorewindpower.com, 2014. Accessed: 26-7-2016

(3) www.seawayheavylifting.com/cy/profile 27-07-2015. Accessed 24-7-2016

(4) https://ec.europa.eu/clima/policies/strategies/2030/index$_e$*n.htm.Accessed*24 – 7 – 2016

(5)*EWEAEuropeanOffshoreStatistics*2015.

(6)*http://www.windpower–international.com/features/featuregood–foundations–the–pros–and – cons – of – monopiles* – 4158694.*Accessed*26 – 7 – 2016

(7)*APIRECOMMENDEDPRACTICE*2*A – WSD*

(8)*AnsysAqwamanual*

B

Oleg Strashnov Factsheet

Name	Oleg Strashnov		
Operator	Seaway Heavy Lifting		
Flag state	Cyprus		
Classification	1A1 Crane Vessel clean DK (+) HELDK-SH DYNPOS AUTRO-(A) EO BIS		
Accommodation	220 persons		
Helicopter deck	Equipped for S-61 and S-92		
Dimensions	Length overall	m	183.0
	Breadth	m	47.0
	Depth from deck	m	18.2
	Draught	m	8.5 - 13.8
Propulsion/ Power	Main engines (six)	kW	4,500
	Main thrusters (two)	kW	5,500, fixed pitch, 360°
	Bow thrusters (two)	kW	1,145 tunnel
	DP thrusters (two)	kW	3,500, 360°
	Maximum Transit speed	knot	12
Ballast system	Ballasting tanks	m^3	35,156
	Anti-heeling tanks	m^3	15,287
	Ballast pumps (two)	m^3/h	700
	Anti-heeling pumps (eight)	m^3/h	2,500
Positioning system	DP3 positioning system		
	Eight-point mooring System		
	Anchors	t	15
	Maximum Pull Winches	kN	2,430
	Brake holding capacity	kN	3,800
Crane	Make	Gusto	
	Main hoist		
	- Maximum revolving capacity	Mt	5,000 @ 32 m
	- Maximum lift height above water level	m	98.7
	Auxiliary hoist I		
	- Maximum capacity	Mt	800 @ 72 m
	- Maximum lift height above water level	m	130.2
	Auxiliary hoist II		
	- Maximum capacity	Mt	200
	- Maximum lift height above water level	m	109.5

C

$H_s - T_p$ diagrams

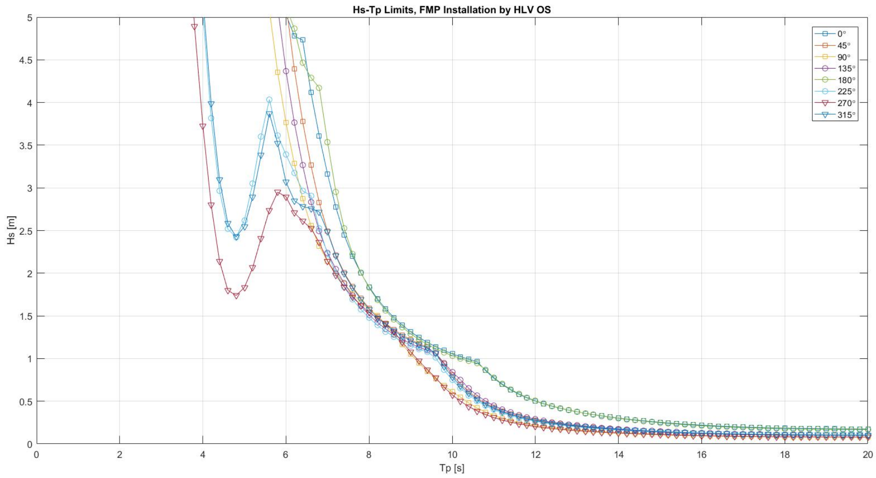

Figure C.1: $H_s - T_P$ diagram FMP heading 000° trim 29°

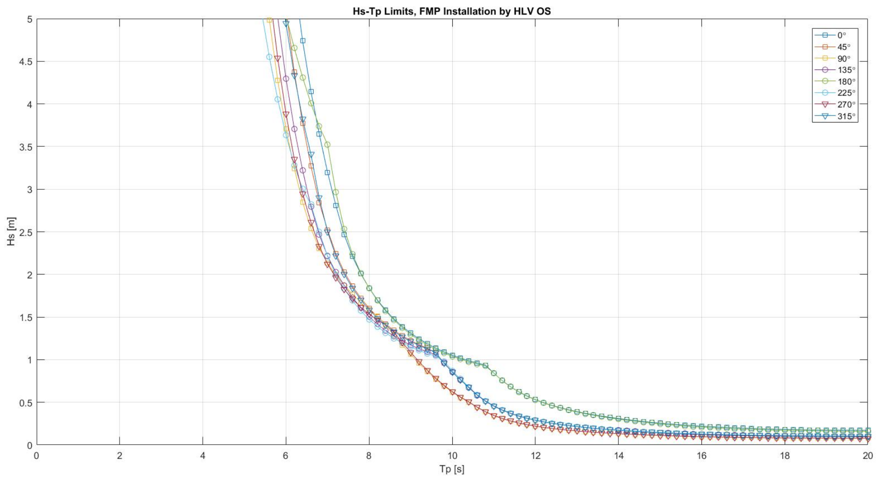

Figure C.2: $H_s - T_P$ diagram FMP heading 000° trim 35°

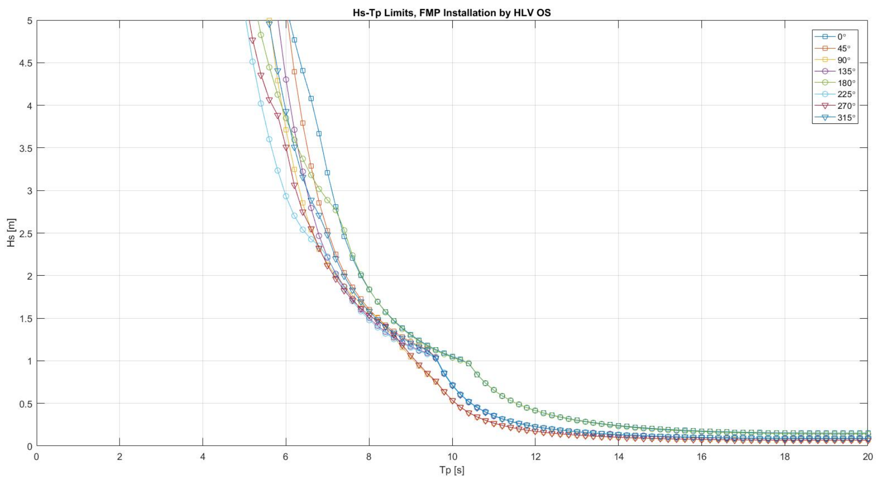

Figure C.3: $H_s - T_P$ diagram FMP heading 000° trim 42°

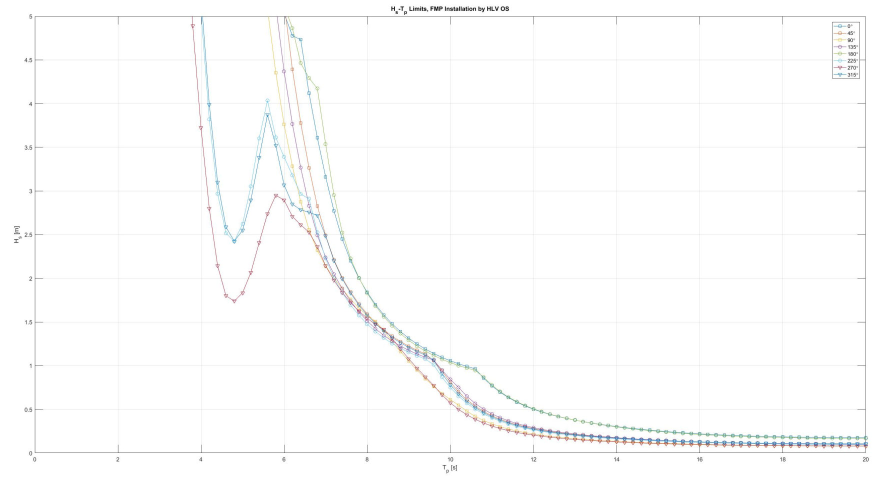

Figure C.4: $H_s - T_P$ diagram FMP heading 015° trim 29°

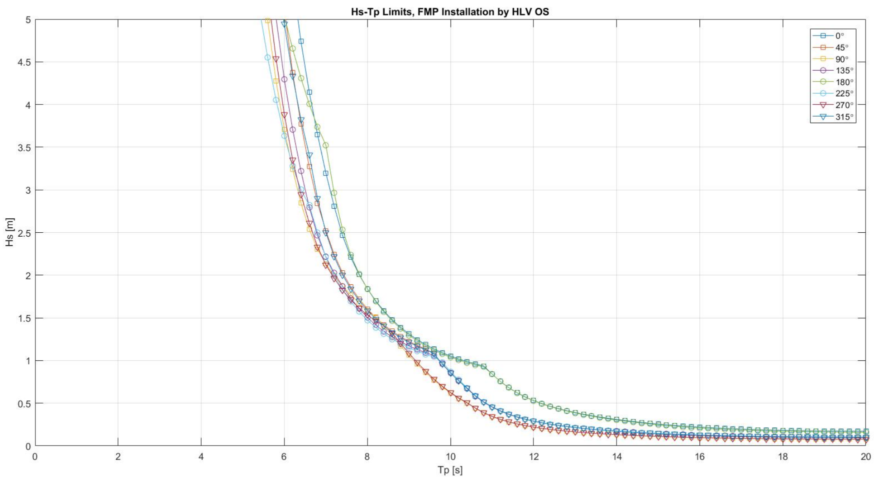

Figure C.5: $H_s - T_P$ diagram FMP heading 015° trim 35°

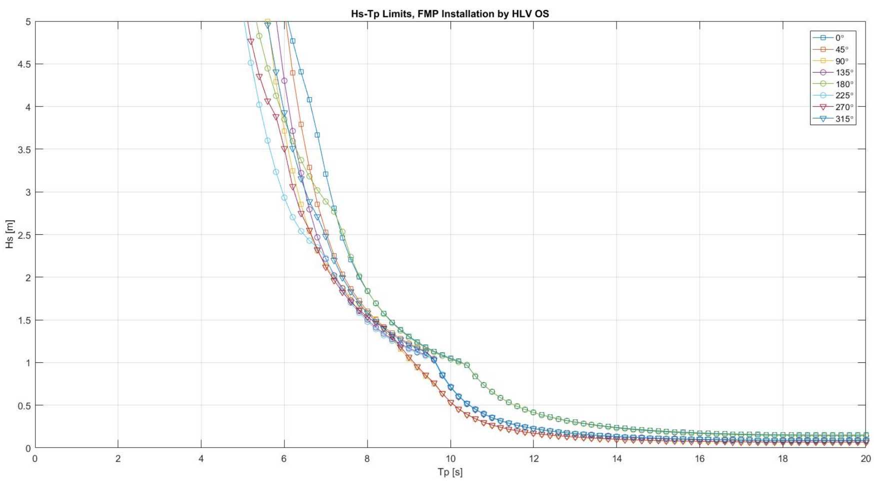

Figure C.6: $H_s - T_P$ diagram FMP heading 015° trim 42°

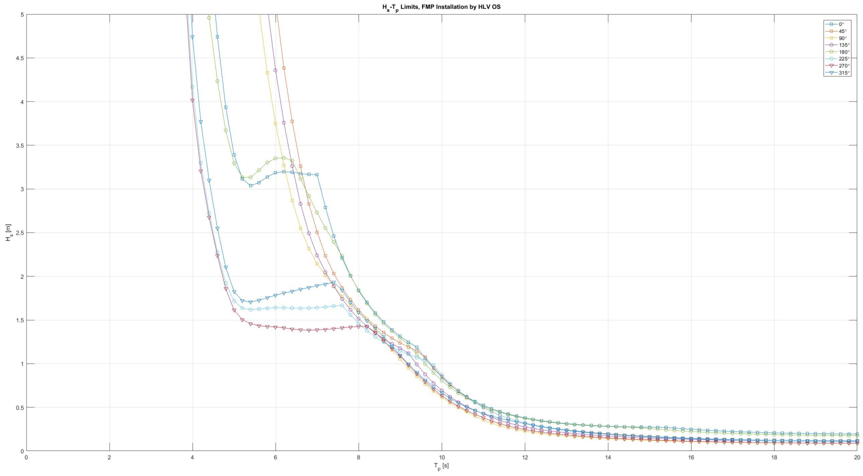

Figure C.7: $H_S - T_P$ diagram FMP heading 030° trim 29°

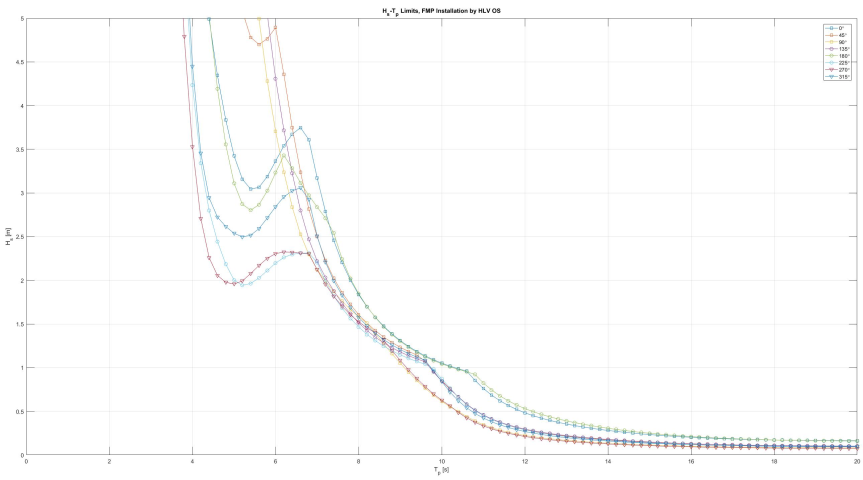

Figure C.8: $H_S - T_P$ diagram FMP heading 030° trim 35°

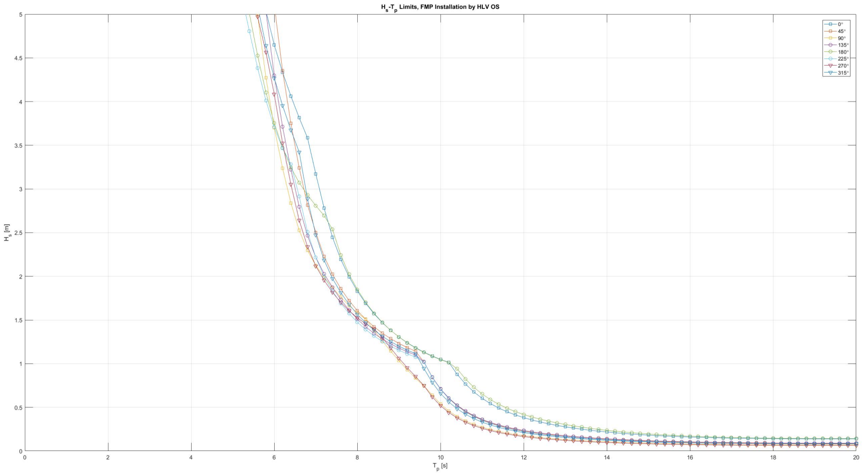

Figure C.9: $H_s - T_P$ diagram FMP heading 030° trim 42°

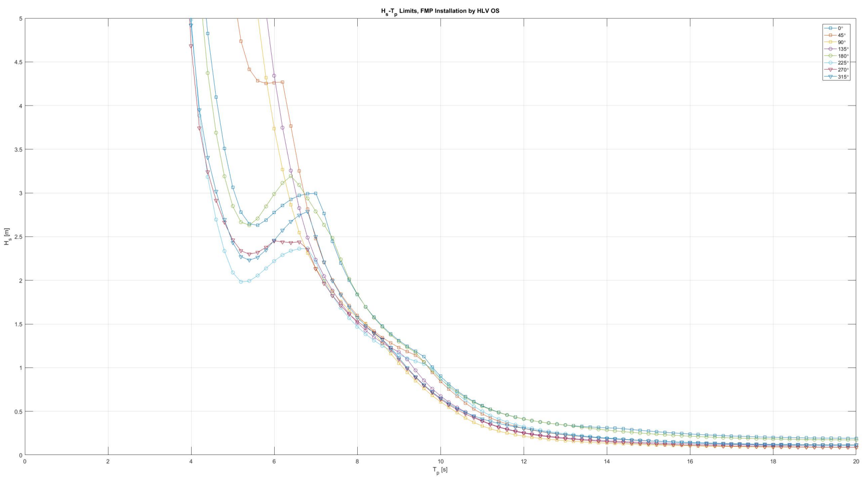

Figure C.10: $H_s - T_P$ diagram FMP heading 045° trim 29°

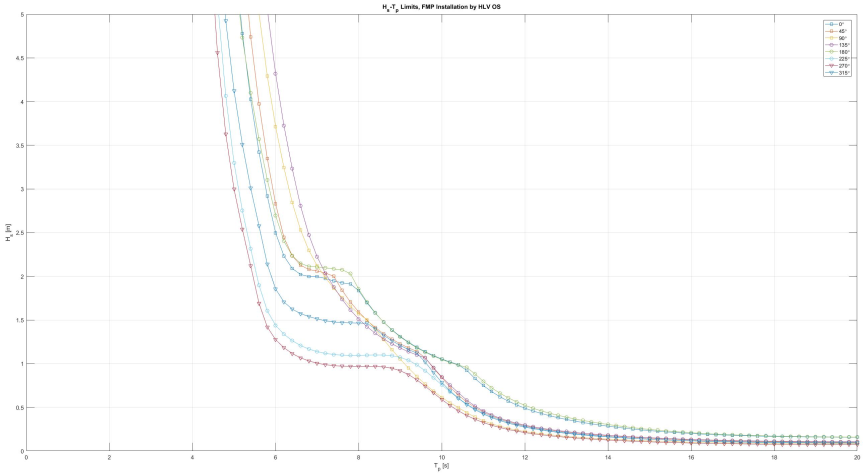

Figure C.11: $H_s - T_P$ diagram FMP heading 045° trim 35°

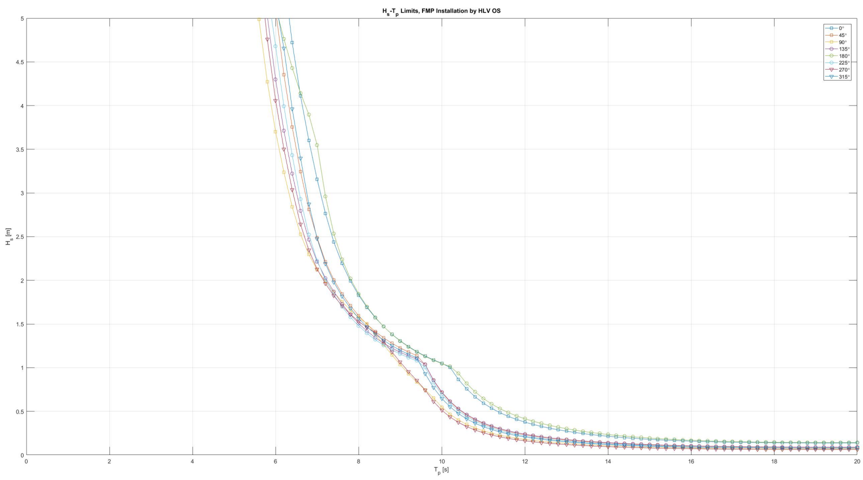

Figure C.12: $H_s - T_P$ diagram FMP heading 045° trim 42°

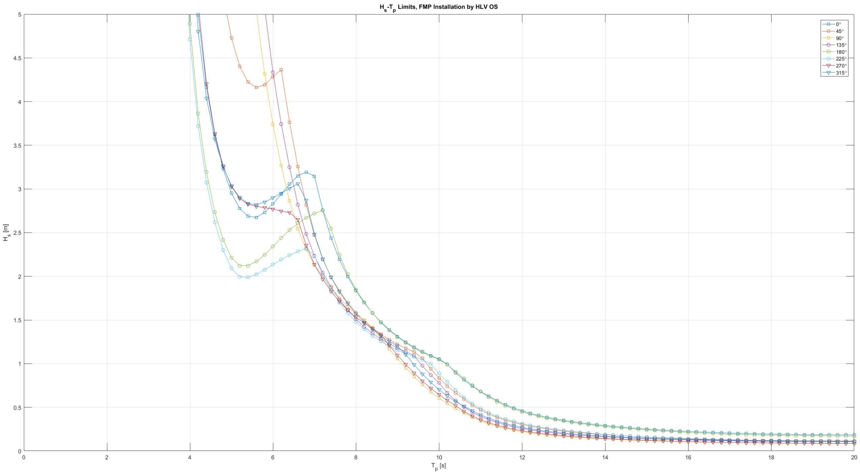

Figure C.13: $H_S - T_P$ diagram FMP heading 060° trim 29°

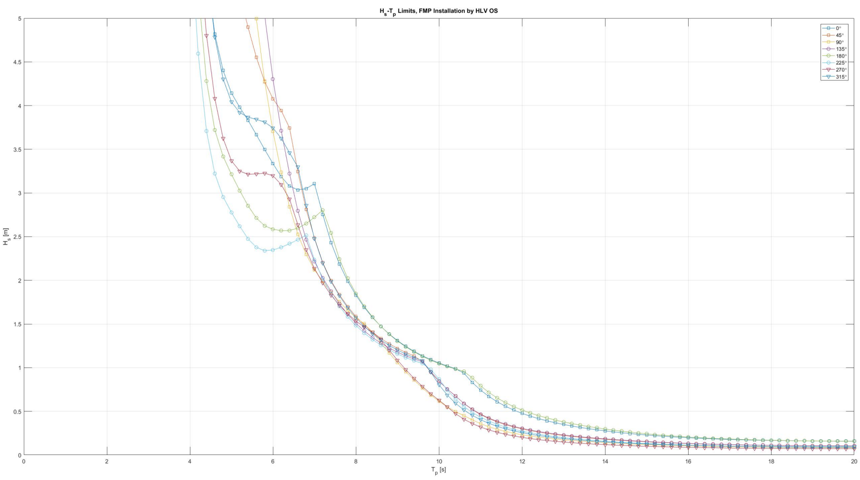

Figure C.14: $H_S - T_P$ diagram FMP heading 060° trim 35°

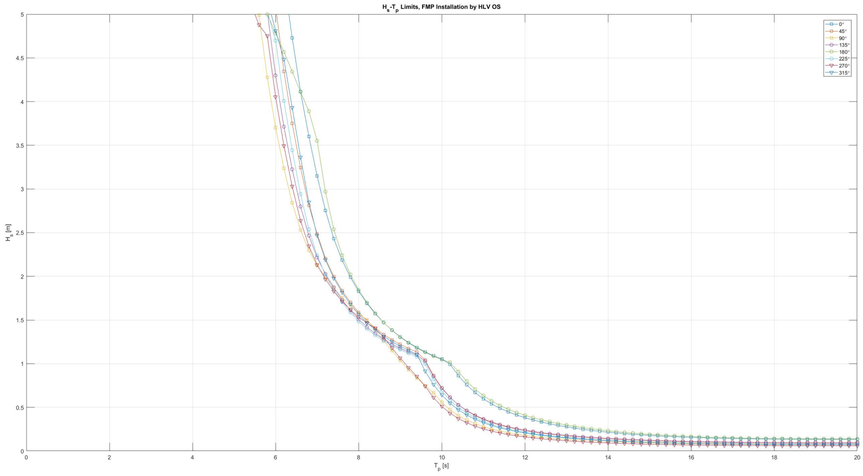

Figure C.15: $H_S - T_P$ diagram FMP heading 060° trim 42°

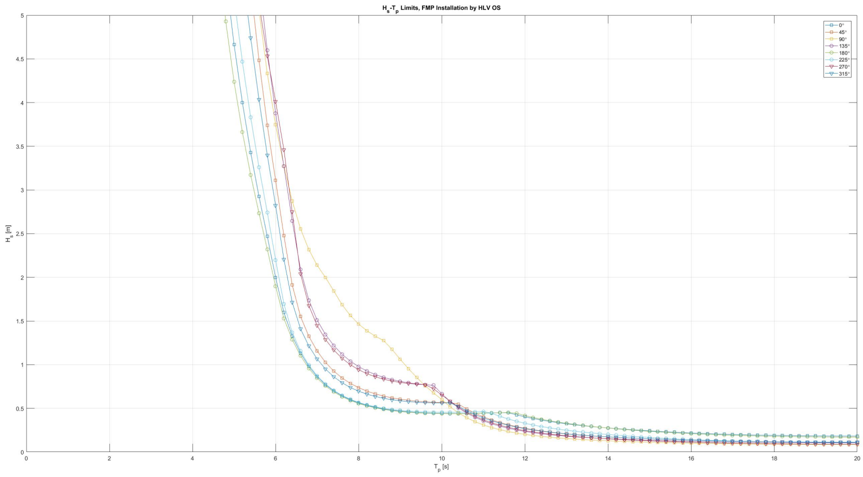

Figure C.16: $H_S - T_P$ diagram FMP heading 075° trim 29°

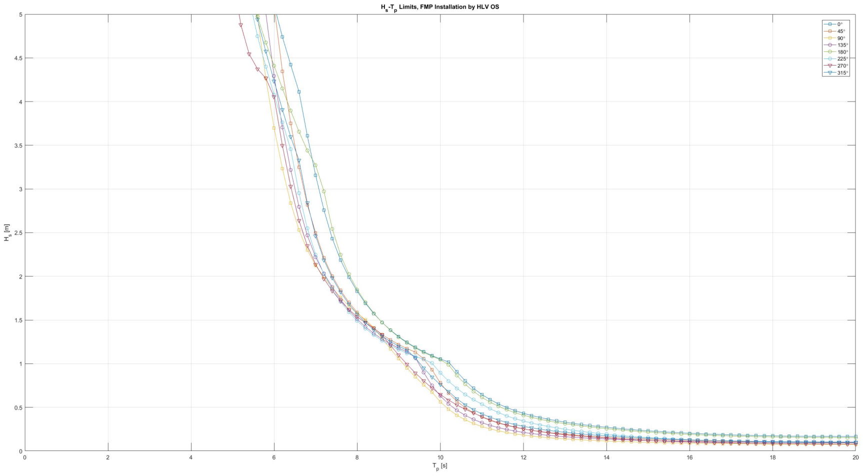

Figure C.17: $H_S - T_P$ diagram FMP heading 075° trim 35°

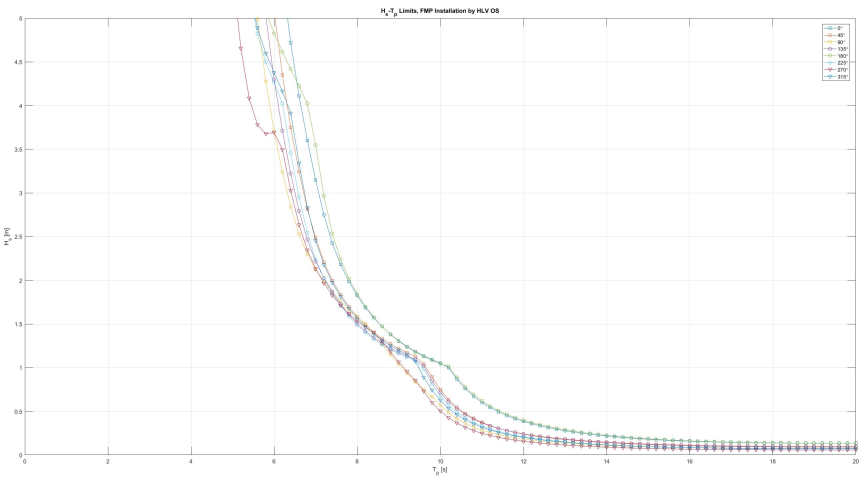

Figure C.18: $H_S - T_P$ diagram FMP heading 075° trim 42°

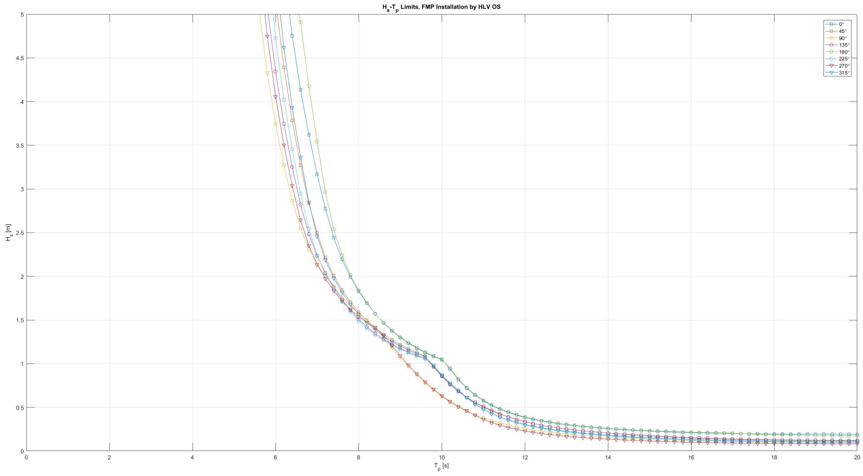

Figure C.19: $H_S - T_P$ diagram FMP heading 090° trim 29°

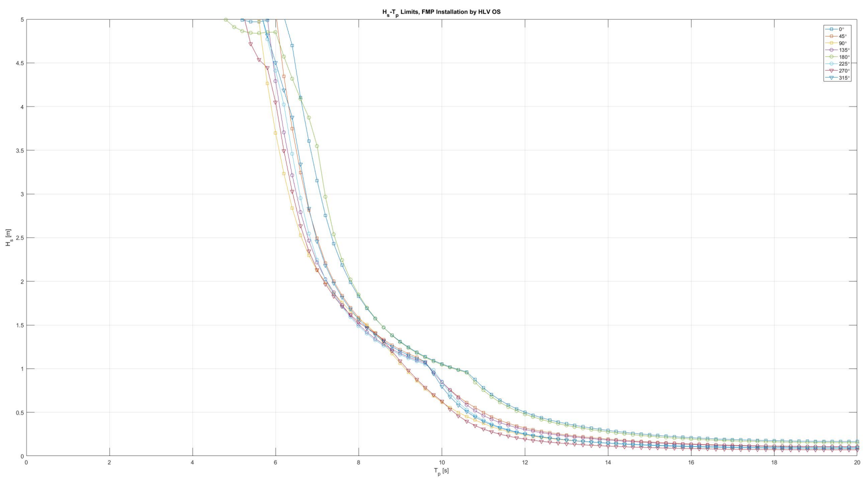

Figure C.20: $H_S - T_P$ diagram FMP heading 090° trim 35°

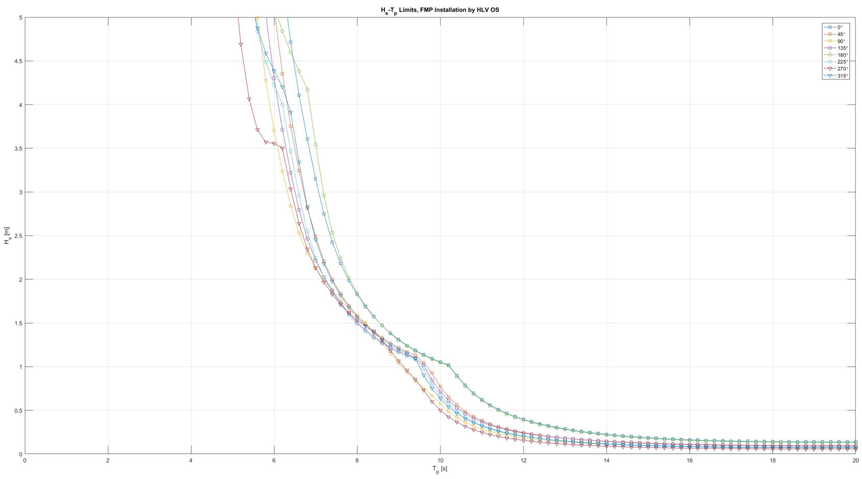

Figure C.21: $H_S - T_P$ diagram FMP heading 090° trim 42°

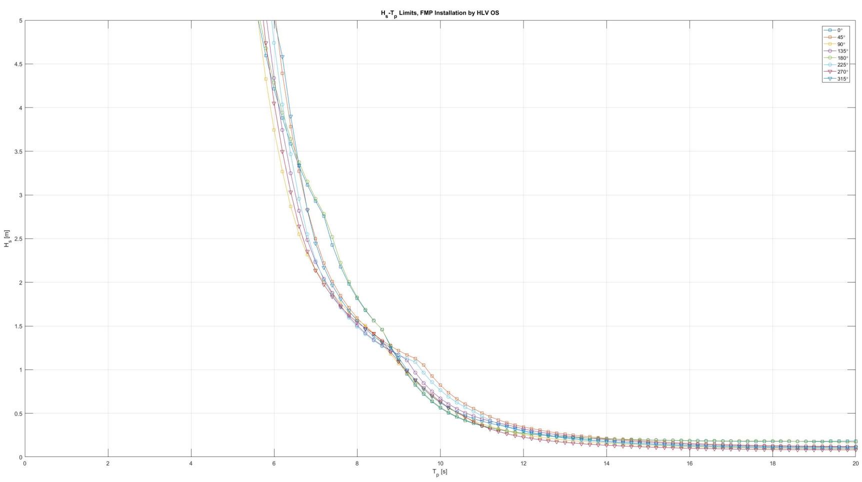

Figure C.22: $H_S - T_P$ diagram FMP heading 105° trim 29°

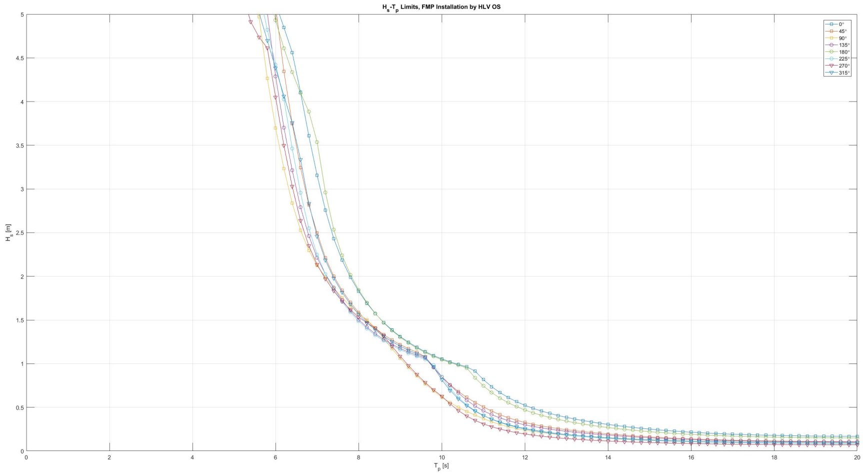

Figure C.23: $H_S - T_P$ diagram FMP heading 105° trim 35°

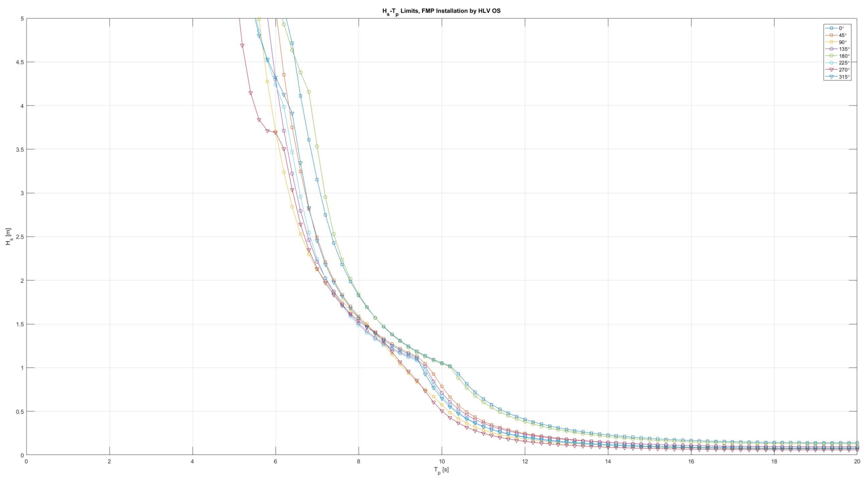

Figure C.24: $H_S - T_P$ diagram FMP heading 105° trim 42°

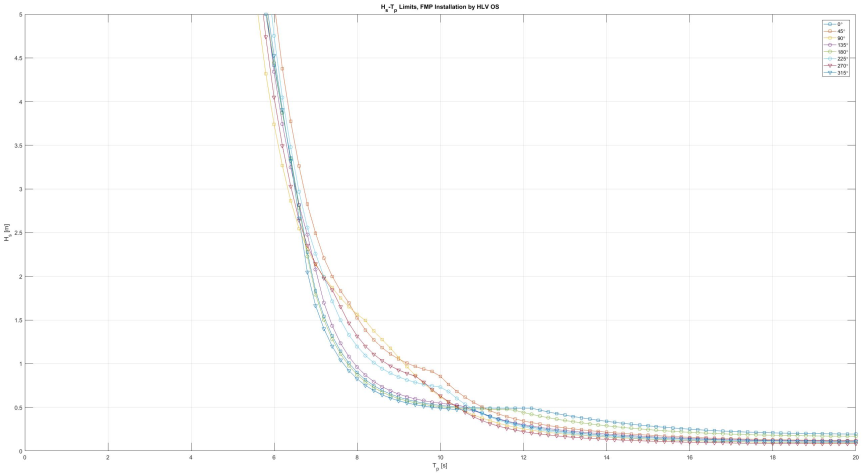

Figure C.25: $H_S - T_P$ diagram FMP heading 120° trim 29°

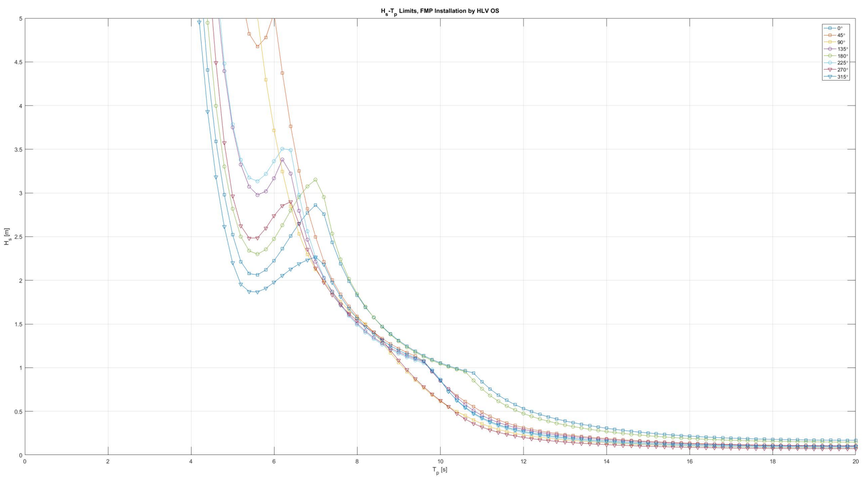

Figure C.26: $H_S - T_P$ diagram FMP heading 120° trim 35°

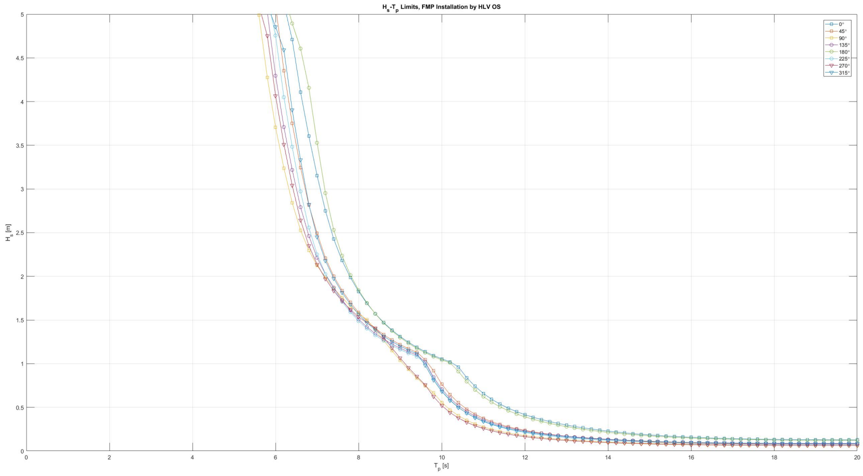

Figure C.27: $H_S - T_P$ diagram FMP heading 120° trim 42°

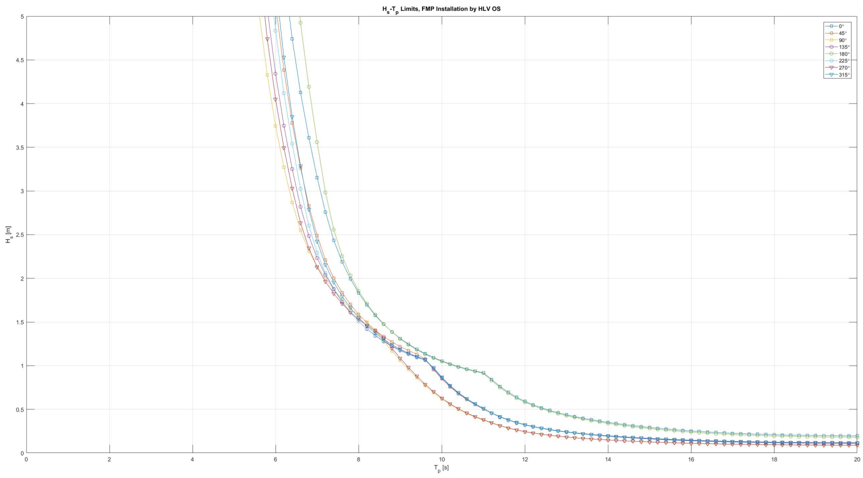

Figure C.28: $H_S - T_P$ diagram FMP heading 135° trim 29°

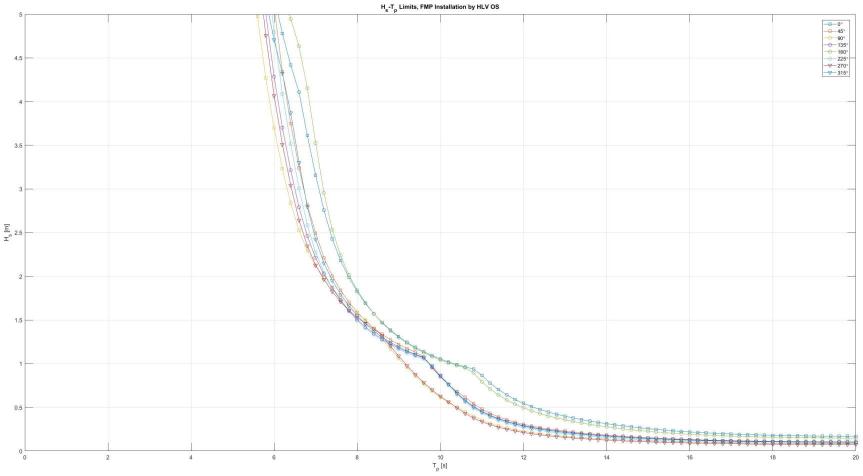

Figure C.29: $H_S - T_P$ diagram FMP heading 135° trim 35°

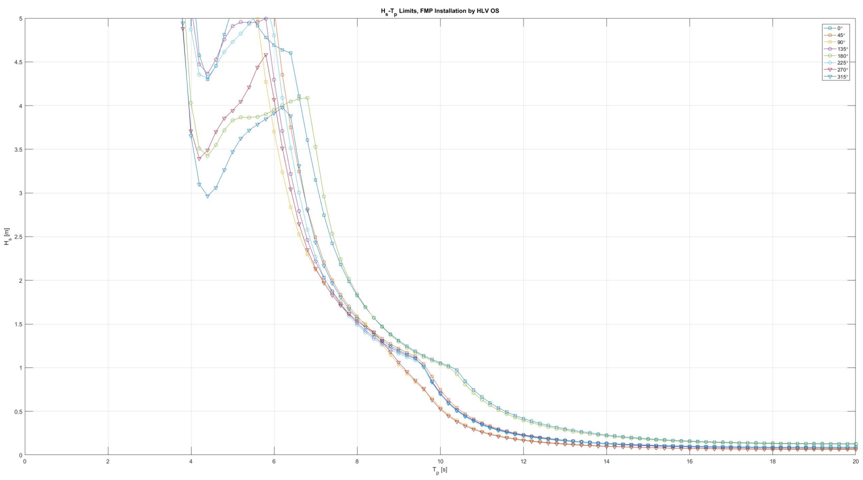

Figure C.30: $H_S - T_P$ diagram FMP heading 135° trim 42°

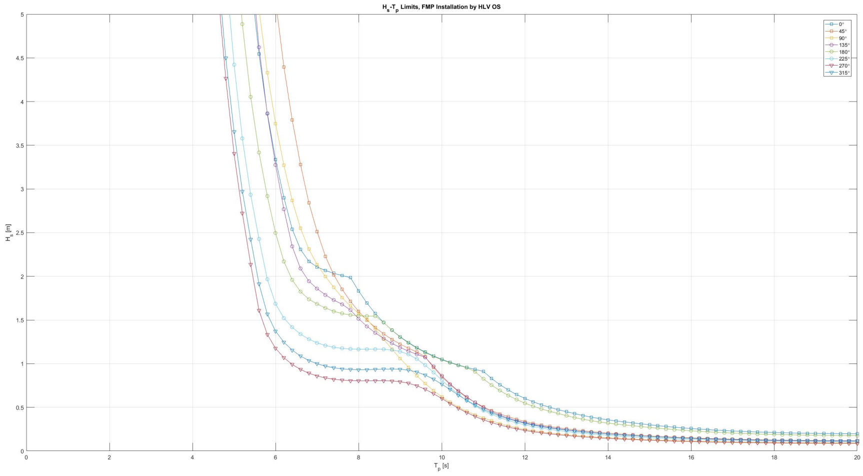

Figure C.31: $H_S - T_P$ diagram FMP heading 150° trim 29°

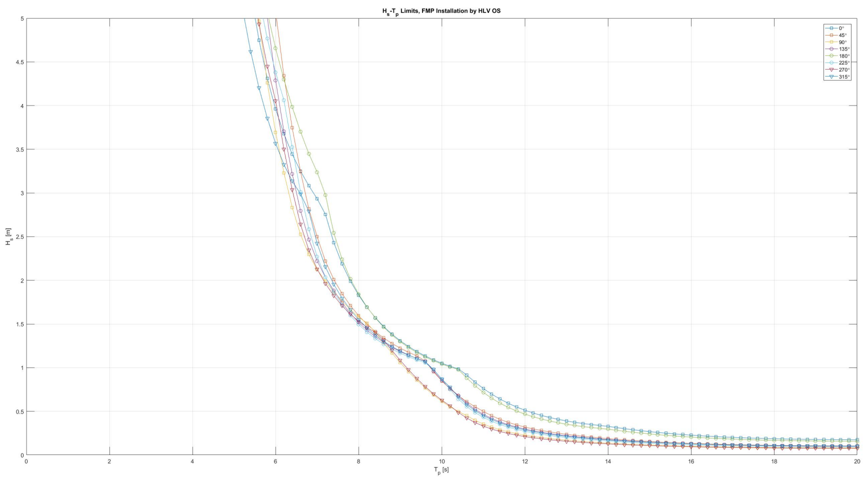

Figure C.32: $H_S - T_P$ diagram FMP heading 150° trim 35°

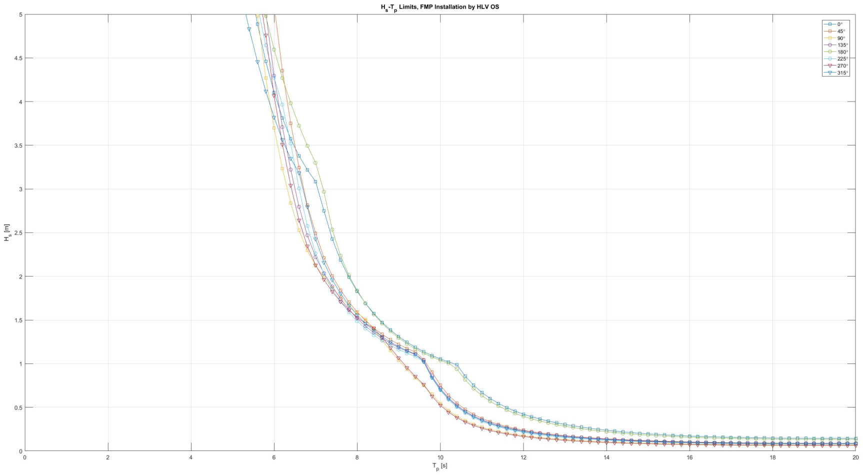

Figure C.33: $H_S - T_P$ diagram FMP heading 150° trim 42°

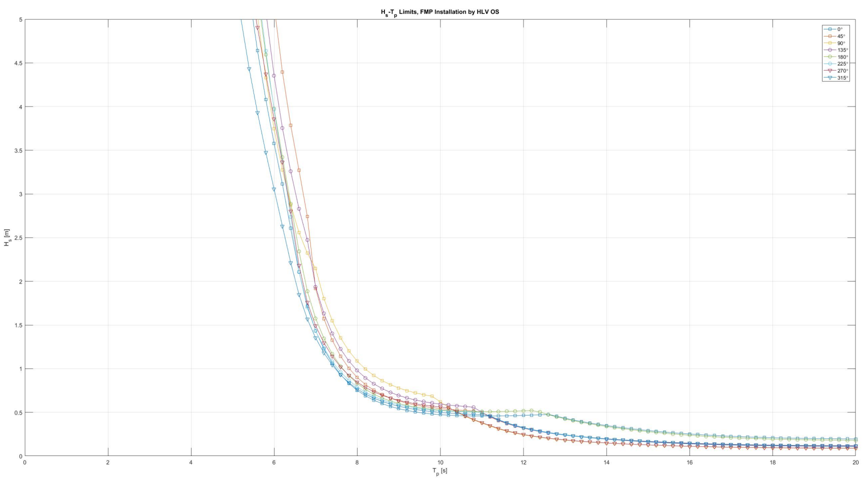

Figure C.34: $H_S - T_P$ diagram FMP heading 165° trim 29°

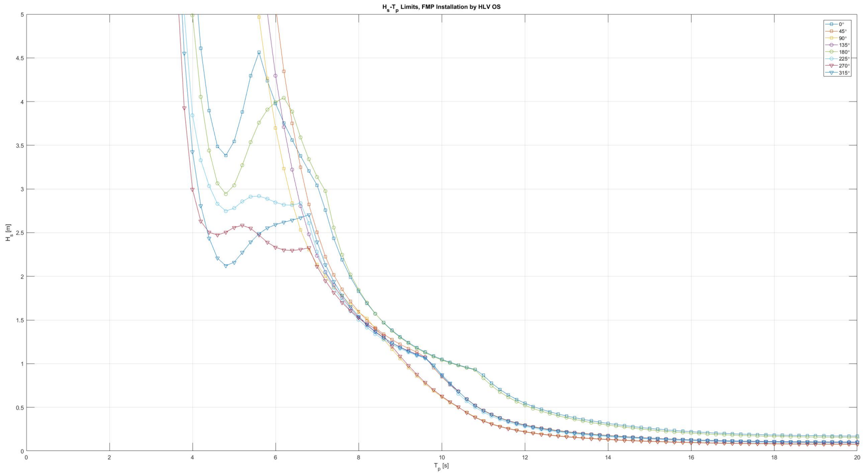

Figure C.35: $H_S - T_P$ diagram FMP heading 165° trim 35°

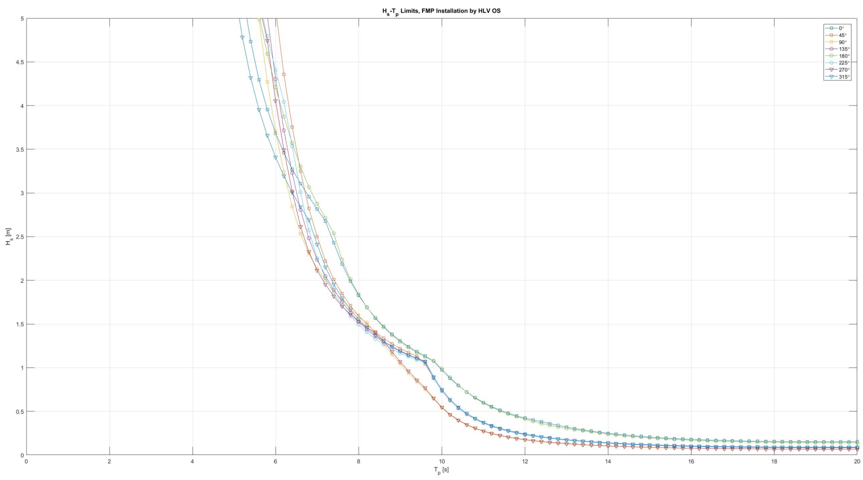

Figure C.36: $H_S - T_P$ diagram FMP heading 165° trim 42°

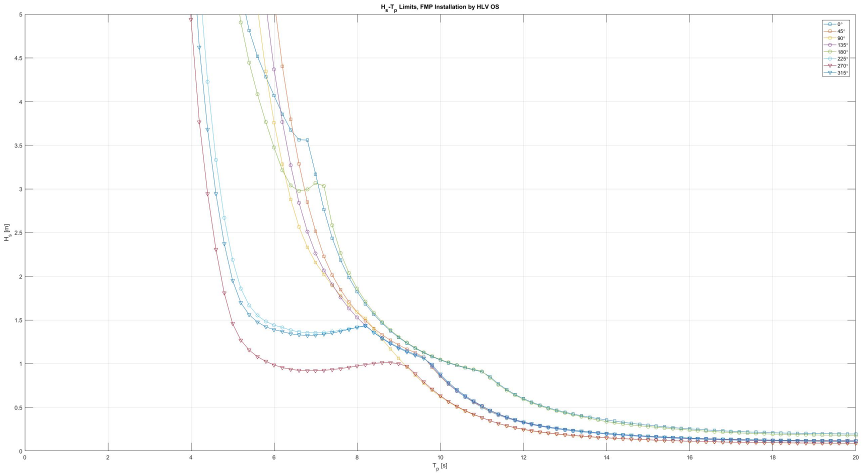

Figure C.37: $H_S - T_P$ diagram FMP heading 180° trim 29°

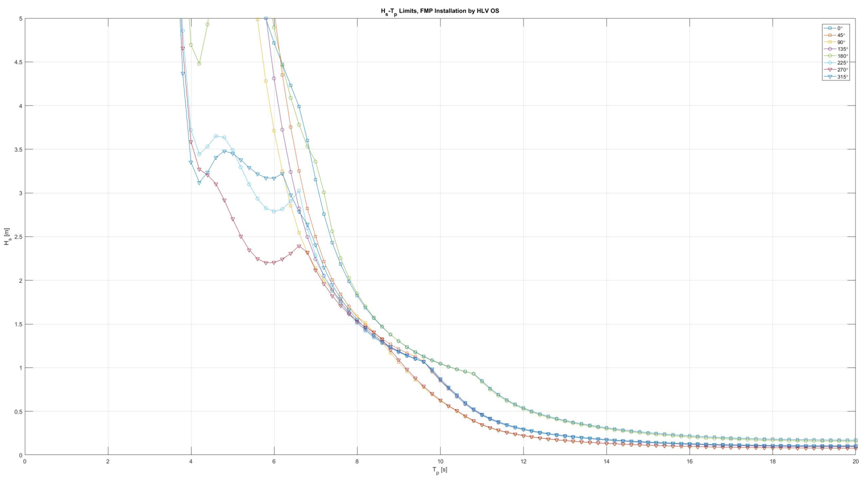

Figure C.38: $H_S - T_P$ diagram FMP heading 180° trim 35°

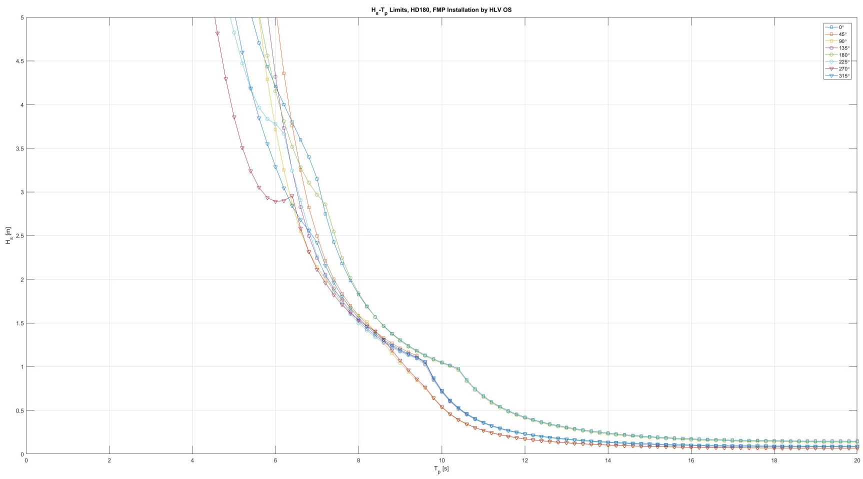

Figure C.39: $H_s - T_P$ diagram FMP heading 180° trim 42°