

Feasibility Assessment of the Transport and Installation Frame for Bottom-fixed Wind

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by

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Cover: Initial TIF design of Bluewater Energy Services

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Abstract

Limiting global warming to 1.5°C is urgent, as highlighted by IPCC and IEA reports aiming for net zero emissions by 2050. Wind energy, particularly offshore, offers significant potential for renewable energy capacity expansion. Although offshore installations are limited to shallow waters using monopiles, deeper waters with higher wind speeds require larger turbines. This transition to deeper waters and larger turbines is challenging and requires continuous development and innovation. Floating wind turbines show promise for overcoming these challenges, but further improvements are needed to scale up floating wind farms and reduce installation costs for profitability. Bluewater Energy Services is a company actively exploring solutions to improve the installation method of floating wind turbines with the Transport and Installation Frame. In addition to the market gap for the installation of floating wind turbines, there are also opportunities in the development of bottom-fixed wind for larger wind turbines and greater water depths. Therefore, the goal of Bluewater is to design a frame for the transport and installation of both bottom-fixed and floating wind to increase profitability.

The aim of this research project is to assess the feasibility of the Transport and Installation Frame for bottom-fixed wind. The research question has been answered using a systematic design methodology. Initially, information was collected, research questions were formulated and starting points were established through a literature study. The first phase, system analysis, outlined the transport and installation methodology and defined the design criteria. Subsequently, the design of the bottom-fixed structure, which could be installed using the frame was explored. Finally, the limitations of the transport and installation methodology were examined, particularly focusing on the maximum angle of heel, natural period, and the weather window.

Towards the conclusion of the thesis, an evaluation is presented regarding the feasibility of the frame for bottom-fixed wind. This includes an initial design for the bottom-fixed structure and the transport and installation methodology, based on the integrated installation method for a 15 MW wind turbine. The transport and installation methodology in this thesis focuses on the compression principle. In which the Transport and Installation Frame remains at the waterline and the bottom-fixed structure is lowered to the seabed at 80 meters by pushing it with spud piles down. This study identifies critical stages and associated issues related to static stability, maximum heeling angles, deck or edge immersion, spud pile strength, seabed placement, and the natural periods in heave and pitch.

The results of the design research indicate that, within the identified limitations, there are no significant unresolved issues affecting the feasibility of the transport and installation frame for bottom-fixed wind. This conclusion is based on analyses focused on static and strength analysis. To assess the technical feasibility, it is recommended that the specifications of the weather window be refined, static optimisation be performed, and critical issues related to dynamic behavior be addressed, specifically during seabed placement and dynamic responses to external forces. To further develop this project and explore the profitability, it is recommended to obtain an overview of the specific location, costs, and installation time.

Preface

This master's thesis is submitted to fulfil the requirements for obtaining the master's degree in Civil Engineering at the Delft University of Technology. This master's thesis has been completed in cooperation with the company Bluewater Energy Services.

I am especially thankful to my supervisors for their guidance throughout my thesis. Their assistance has been helping me find direction in my work and providing the theoretical background necessary and experience in the field to do the research and to make the design choices.

Frank Lange, I am grateful for your enthusiasm and interest in floating wind structures, it has been inspiring. Our conversations and brainstorming sessions about the various possibilities for this project have been valuable. Thank you for sharing your experience in the offshore industry, opening the opportunity to collaborate with Bluewater, and for your guidance over the past months.

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Reflecting on my experience, I have not only learned a lot about doing research, but I have also gained insight into Bluewater and their operations. I have worked with experienced professionals from whom I gained valuable knowledge and I am grateful for the opportunity to do this research in cooperation with Bluewater. Furthermore, this project has broadened my horizons by expanding my background in civil engineering and allowing me to gain knowledge in the offshore sector. Thank you for the insightful discussions and knowledge shared during this project.

Enjoy reading!

*Jasmijn van Veen
Delft, July 2024*

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Introduction

1.1. Design Context

The need to limit global warming to 1.5 ° C has become more pressing in recent years, and is highlighted by the Intergovernmental Panel on Climate Change (IPCC) and stated in the report of the International Energy Agency (IEA), which aims to achieve net zero emissions by 2050. This goal emphasizes how urgently patterns of energy production and consumption have to shift [22, 32].

One of the biggest opportunities for increasing energy production by the expansion of renewable capacity is wind [25]. Most of the wind energy in the world today is provided by offshore wind [24]. There is a lot of opportunity for expansion in the offshore wind sector. The need for a significant increase in offshore wind installations arises from the goals that national governments have set for offshore wind. A scenario is presented in which it is anticipated that installation rates will increase over the following years. Offshore wind installations would have to increase annually from approximately 1.2 GW in 2022 to more than 20 GW in 2030 to meet the requirements of the REPowerEU scenario [4, 7].

Common offshore wind installations are fixed to the seabed, restricting deployment to shallow waters. These wind turbines are predominantly monopiles, which have limitations in terms of turbine size and water depth. To meet energy goals, larger wind turbines are required. The solution for efficient wind energy production lies further offshore, where wind turbines can capture more consistent and higher wind speeds [27].

1.1.1. Design Problem

With continuous development, the shift to offshore wind is currently occurring in deeper waters and for larger wind turbines. Technology that allows for floating wind is one possible way to tackle this challenge. Although floating wind turbines have shown feasibility, considerable improvements are still needed to scale them up for the development of floating wind farms. Specifically, the high costs of installing floating wind, makes it unprofitable to invest in. Consequently, it is necessary to explore improved installation techniques [23].

Bluewater Energy Services (BES) is a company that actively explores solutions to address floating wind installation methods. Efforts are being made to design a Transport and Installation Frame (TIF). This frame should make the transport and installation of floating wind cheaper and more efficient, by using an integrated installation method. This method of installation reduces the time required for offshore operations, as the floating platform and wind turbine are towed offshore together.

Besides reduction of the installation costs for the floating wind installation method as described above, the TIF provides also a market opportunity for the bottom-fixed wind sector for larger wind turbines and greater water depths. As wind turbines grow in size and the water depths for installation become greater, the forces and moments exerted on the bottom-fixed structure also increase. Consequently, alternative solutions need to be considered beyond the current monopile design to better withstand these increased forces.

1.2. Research Objective

The aim of this research is to increase the attractiveness of the frame for the offshore wind market by ensuring its multi-functionality, for both floating and bottom-fixed wind installations. This leads to the following research aim:

The objective of this research project is to evaluate the feasibility of the Transport and Installation Frame for both floating wind (TLP) and bottom fixed wind.

1.2.1. Research Questions

To address a segment of the research objective, this research will focus on the feasibility of bottom-fixed wind installations and examine the following research question:

The aim of this research project is to assess the feasibility of the Transport and Installation Frame for bottom-fixed wind.

To address the research question, it is necessary to address several sub-questions.

1. What is the transport and installation methodology with the TIF?
2. What is the design of the bottom-fixed structure?
3. At what loading does transport and installation remain feasible?
4. Which additional issues must be addressed to demonstrate feasibility?

To effectively address the question, it is essential to define the concept of feasibility within the context of this design research. With regard to the first three sub-questions, the focus will be on technical feasibility. First, the transport and installation methodology will be examined, followed by an analysis to identify critical issues on a technical level. With regard to the last sub-question, the remaining feasibility aspects will be addressed.

By examining these points, the first part of the feasibility study of this transport and installation method within the scope of this study will be demonstrated.

1.3. Research Methodology

The following is an outline of the design methodology and the steps necessary to address the research question. A methodical design phase plan was developed to explain the steps necessary to obtain answers to the research questions, as shown in Figure 1.1.

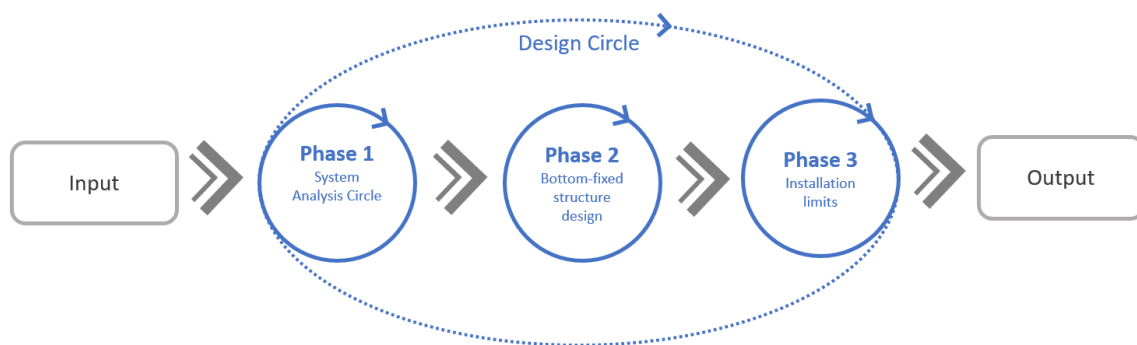


Figure 1.1: Design Circle

The first step involves gathering all available information, formulating research questions, and establishing starting points through a literature study. These input parameters are set values that define the scope. Once the input values are known, the process proceeds to the design circle. The design cycle is a process that includes analysis, synthesis, simulation, evaluation, and decision making. By going through each phase, the previous phase is reevaluated to ensure all steps are thoroughly reviewed.

The System Analysis Circle is the first phase to be completed. This phase gives an overview of the entire design process, outlining the transport and installation methodology on a high level, as well as establishing the design criteria.

The second phase represents the initial design phase and is characterized by a circular approach. In this phase, the design of the bottom-fixed structure is completed, including static stability and strength analysis. It is crucial that in phase two, each choice undergoes the decision cycles of phase one again. The iterative process delves deeper into the loop with each phase, exploring increasingly levels of detail.

The third phase also represents a design phase that follows a circular process. In this phase, the critical points are examined and the limitations of the transport and installation method for different installation stages are identified. These three design phases are interconnected and collectively form the design loop. Each phase contributes answers to various research questions.

1.4. Assumptions and Delineations

To effectively narrow the broad spectrum of variables to this design problem, certain assumptions and delineations must be established. Through a series of iterative design cycles, the scope of the research will be narrowed. Key selections will be done by a preliminary analysis of market opportunities and the needs of the offshore market. This design study represents an initial feasibility study of this transport and installation method. This requires making assumptions through simplification of the problem and identifying the primary determinants that are crucial for assessing the feasibility. The precise pre-defined values for this design are explained in the Appendices, along with chosen assumptions and the simplification of the calculations.

- Appendix B: Environmental Forces
- Appendix C: Strength Analysis Bottom-fixed Structure
- Appendix D: Buoyancy and Gravitational Forces
- Appendix E: Stability Analysis
- Appendix F: Seabed Placement Analysis
- Appendix G: Eigen Period Analysis

Furthermore, the delineations of the scope are presented below, along with an explanation of the reasoning behind the scope definitions.

Wind Turbine

The first step in this design research is to select the wind turbine to be used for the design. It is crucial to anticipate future developments in this context. Considering the current rate of development, a 22 MW wind turbine would be the most suitable option. However, considering the ongoing design process on the TIF for a 15 MW wind turbine, it is reasonable to align the development of the bottom-fixed structure with the specifications for a 15 MW wind turbine as well. To ensure that the installation method is suitable for the same wind turbine, the bottom-fixed structure will also be designed for the 15 MW wind turbine.

Offshore Site Conditions

The selection of an offshore location for the bottom-fixed structure is not predetermined. A design for the bottom-fixed structure will be done considering the design parameters of the TIF. Following this, an evaluation will be done to assess the forces and environmental conditions that the methodology can withstand. The objective of this analysis is not to confirm the feasibility of installation at a specific location. Rather, it is intended to provide a more comprehensive understanding of the methodology.

During the investigation of the installation stages (refer to Chapter 4), the possibilities for the installation of the bottom-fixed structure with the TIF were evaluated. An analysis was performed to identify feasible water depths for installation. Installation at water depths of up to 40 meters was defined as feasible without the need for an additional lowering mechanism to get the bottom-fixed structure on the seabed. To provide insights into the feasibility of the TIF for a bottom-fixed structure across a broader range of water depths, it is essential to demonstrate the installation's possibility for deeper water depths than 40 meters.

The feasible water depths for the bottom-fixed structures extend up to approximately 80 meters. Given that this value also marks the difficulty level for the installation of monopiles (the most commonly used foundation type for offshore wind), at this depth there is a market opportunity in the current offshore wind market [8, 34]. This research aims to address this gap by focusing on demonstrating the feasibility of the transport and installation method for depths up to 80 meters. This study will specifically assess the feasibility of a water depth of 80 meters. If feasibility can be demonstrated for a water depth of 80 meters, it suggests potential feasibility for the 40-80 meter range in later stages, with fewer significant obstacles due to the lower mass and height of the bottom-fixed structure.

1.5. Report Outline

This report will present the design basis, theoretical background, design choices, limitations, and implementations of this design.

Starting with Chapter 2, a design basis will be provided, including the design requirements and characteristics of the transport and installation frame, the wind turbine, and environmental forces. Chapter 3 will cover the design of the bottom-fixed structure, including the design choices, strength analysis, and dimensions. This chapter will address research question 2. Chapter 4 will provide an overview of the transport and installation method, listing masses and buoyancy forces, and explaining the chosen transport and installation principle, thus providing information relevant for research question 1. Chapter 5 will identify all the critical issues found in Chapter 4. These issues will be identified, further investigated, and possibly resolved. This will include initial static stability, maximum angle of heel, seabed placement, natural period, and the weather window, thereby defining the limits to answer research question 3. Following this, Chapter 6 will provide an overview of all transport and installation stages, practically outlining all points for the various stages, and also contributing to answering research question 1. Subsequently, Chapter 7 will address the final sub-question regarding the additional issues to demonstrate feasibility. The main findings of the thesis and the answers to the research questions are concluded in Chapter 8, and recommendations for further research are summarized in Chapter 9.

2

Design Basis

Before designing a transport and installation method for bottom-fixed wind, it is essential to define a design basis, including the criteria that the design must meet. This chapter explains the current situation and describes the methods and structures used for transport and installation, and the environmental conditions.

2.1. Problem Statement

At present, the most common method of installing offshore wind turbines is to drive monopiles into the seabed, followed by the installation of the wind turbine. This is known as the 'component' or 'partially integrated' installation method. These methods are cost-effective and well established, but face several challenges in the current offshore market and when considering future prospects for offshore installations, as outlined below [8, 18, 29]:

Challenges for the current and future offshore market:

- Increasing size of wind turbines leading to larger overturning moments,
- Installation in deeper water depths,
- Dependency on 'partially integrated' installation methods,
 - Time-consuming
 - Weather restrictions
- Noise and vibrations during installation.

To address these challenges, alternative structure types and installation methods need to be explored. Priority should be given to minimizing disturbance to marine life, accommodating greater water depths and larger wind turbines. Although floating wind could be a solution, its installation method is still under development. There are methods for installation but there has been no evaluation of these methods in terms of cost and time efficiency. BES is currently developing a Transport and Installation Frame for floating wind to improve their presence in the offshore wind market through multi-functionality for both floating and bottom-fixed wind installations. To use this frame for bottom-fixed wind and to address challenges in the current and future offshore market, design requirements and guidelines have been formulated for the development of this multi-functional Transport and Installation Frame for bottom-fixed wind at a water depth of 80 meters. This will be discussed in the following section [26, 34].

2.2. Design Requirements

To establish an understanding of the design problem and the design question, several design requirements are outlined that must be considered for the development of this transport and installation method specific for a bottom-fixed structure. These requirements will provide an answer to the main question [18].

Design requirements and guidelines:

- No structural changes on the structure of the TIF (requirement),
- Integrated installation method (requirement),
- Minimal environmental disturbance,
- Time efficiency,
- Minimal weather dependency,
- Cost-effectiveness.

The points described above will be incorporated into the transport and installation method. These serve as the fundamental principles guiding the design process that must be considered throughout the feasibility demonstration. The first point serves as a requirement to demonstrate the multi functionality of the frame. The second point is to distinguish the methodology from the current installation methods, thereby reducing the time offshore. The final four points represent guidelines that were considered during the design process and choices made but are not requirements.

2.3. Methodology Transport and Installation TLP with TIF

This section will introduce the design of the TIF, engineered by BES, in more detail and describes concept-defining properties. A particular focus on the transport and installation method, as the same frame will be used for this design research. As outlined in the primary design requirement, no structural changes on the TIF.

2.3.1. Characteristics of the TIF

The TIF is developed as a frame for the transport and installation of floating wind, specifically for the TLP. The TIF serves as a large frame for maintaining stability during transport and installation. The TLP itself lacks of stability and only achieves stability once the tendons are installed. Due to the significant dimensions of the TIF and its large waterplane area, it can provide enough stability. Figure 2.1 illustrates a 3D view of the TIF.

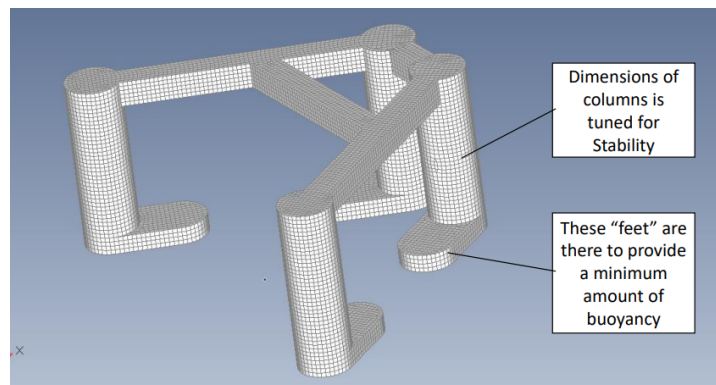


Figure 2.1: Transport and Installation Frame (TIF) Concept

2.3.2. TLP Installation Methodology with the TIF

Through the implementation of the integrated installation method, BES strategically aligns with a market opportunity. This approach addresses the challenge of the installation floating-to-floating, by optimising the installation process for both the structure and the turbine in the port. In the following, an explanation of the transport and installation method is provided and schematically illustrated in Figure 2.2.

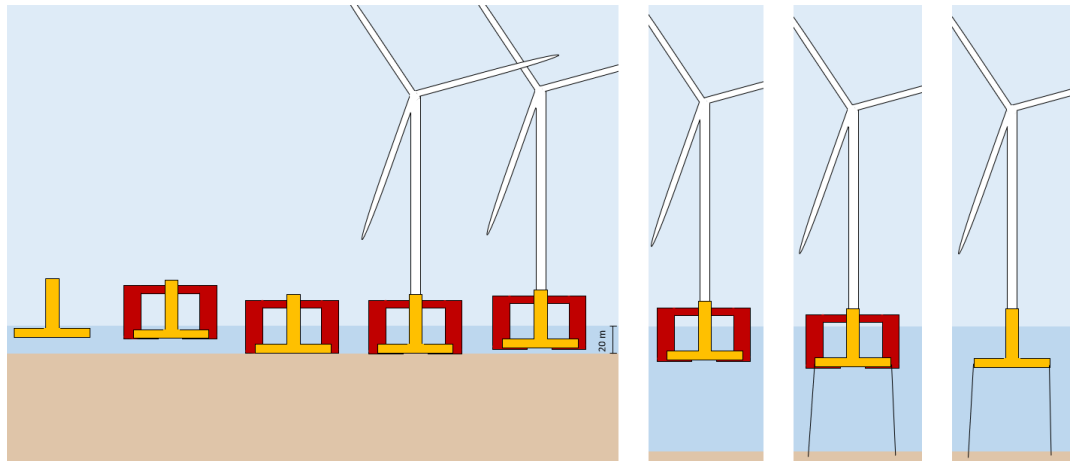


Figure 2.2: Installation Steps for the Installation of the TLP with the TIF

The TLP (without the wind turbine installed) will be floated out in the port. Following this, the TIF is floated over it, and ballast will be added to the TIF, allowing it to lower the TLP on the seabed of the port. Subsequently, the installation of the wind turbine is facilitated, a process made simpler by the structure's positioning on the seabed of the port and the presence of available cranes on the port side.

The next step is that the TIF will be deballasted (connected to the TLP) and floated to the offshore location of the wind farm. In the transport stage, the TIF maintains buoyancy, inducing an upward force on the TLP against the pontoons of the TIF. The introduction of ballast to the TIF increases its mass, thus exerting a downward force on the TLP, facilitating a connection between the two structures during transport.

During the installation stage, the structure should be slightly lowered. This can be done by additional ballasting the TIF. As the structure is lowered, it can be connected to the tendons. Subsequently, the TIF is deballasted, the tendons are tensioned, and the TLP achieves stability.

This installation method is still under development by BES and is currently being implemented for a 15 MW wind turbine.

2.4. Wind Turbine

The focus of this design is the transport and installation of offshore wind turbines with the integrated installation method. Therefore, the transport and installation methodology must be designed for a specific wind turbine. This section will outline the wind turbine selected for the design.

2.4.1. Characterizes of the Wind Turbine

The transport and installation method and bottom-fixed structure in this design research will be done for a 15 MW wind turbine. The 15 MW wind turbine of the International Energy Agency is currently the most widely used reference turbine in the context of upcoming projects. Therefore, this wind turbine will be used for the purposes of this research design. Appendix A contains the parameters that will be used within this research, as detailed in the IEA 15 MW Wind Turbine Technical Report [17]. Key parameters are outlined in Table 2.1.

Table 2.1: Key Parameters 15 MW Reference Wind Turbine

Parameter	Value	Units
Power rating	15	<i>MW</i>
Number of blades	3	-
Rotor diameter	240	<i>m</i>
Hub height	150	<i>m</i>
Total mass	1877	<i>tonnes</i>
Tower base diameter	10	<i>m</i>

2.5. Environmental Forces

In designing this transport and installation method, it is crucial to understand the magnitude of forces involved during transport, installation, and operation. Given that no specific location has been determined and the overall feasibility of this transport and installation method will be assessed, assumptions have been made. The chosen values for the environmental forces are further explained in Appendix B.

During transport, the wind turbine blades are not rotating, resulting in less thrust force. During the operational stage, when the wind turbine is active, there is a significant thrust force present. The bottom-fixed structure must withstand the environmental forces during all stages. During transport, the forces and moments apply to the upper part of the bottom-fixed structure, and during the operational stage, these forces and moments apply at seabed level [19].

An overview of the environmental forces and overturning moments during transport and operation are provided in Table 2.2 and Table 2.3, respectively.

Table 2.2: Environmental Forces and Overturning Moment during Transport Stage

Parameter	Value	Unit
Total horizontal load (F_B)	2	MN
Total vertical load (F_V)	- 23	MN
Overturning Moment (M_{OE})	213	MNm

Table 2.3: Environmental Forces and Overturning Moment during Operation Stage

Parameter	Value	Unit
Total horizontal load (F_B)	8	MN
Total vertical load (F_V)	- 45	MN
Overturning Moment (M_{OE})	832	MNm

3

Design Bottom-fixed Structure

To design a transport and installation method for the bottom-fixed wind, it is essential to design the bottom-fixed structure first. Several design requirements have been established. Subsequently, various types of foundation will be examined. Then, the different components of the structure, strength analysis, and finally, the parameters and values of the dimensions are provided.

3.1. Design Requirements

This section highlights the design requirements, the essential parameters and factors that guide the design process, ensuring thorough consideration for efficient implementation.

Design requirements:

- Ensuring connection with the TIF,
- Support the 15 MW wind turbine,
- Sizing of the structure to be used at water depths of up to 80 meters,
- Effectively transmit environmental loads, including those induced by the wind turbine, during operational conditions,
- Developing a design that facilitates transport and installation procedures using the TIF.

Additional considerations:

- Ensuring manufacturability,
- Cost-effectiveness.

3.2. Design Choices

In this section, the design decisions will be discussed. The first design decision concerns the design space for the bottom-fixed structure. Options were explored to extend the design space beyond the shape of the TIF. However, these showed to be less favorable, primarily because of the weight of the bottom-fixed structure. As a result, the design space is limited within the specified dimensions, as shown in Figure 3.1, which also provides the overall dimensions of the TIF.

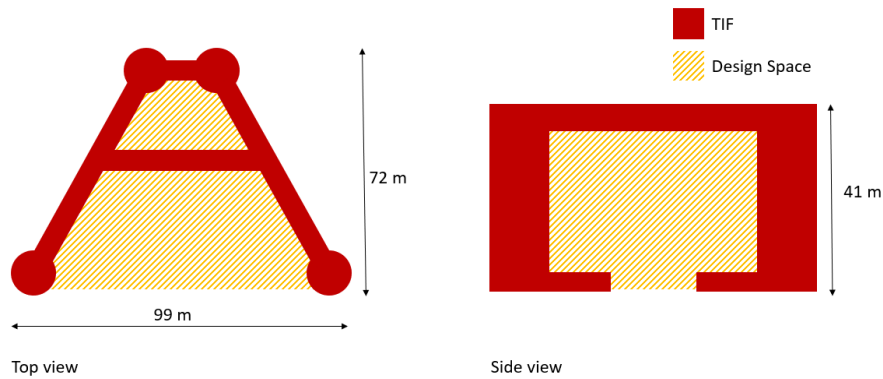


Figure 3.1: Design Space Bottom-fixed Structure

The analysis of the shape indicates that there are two options for the bottom-fixed structure. The structures most similar to the shape of the TIF are the jacket structure and the tripod. This characteristic improves the fit within the TIF, minimizing the need for structural adjustments.

The selection between these two structures is determined by the ratio of weight to buoyancy, taking into account the manufacturing capabilities. A jacket and tripod structure both involve higher initial costs, complex fabrication, and is challenging to transport due to its heavy and large construction [26, 34]. The decision to use a tripod as the main shape was made based on the requirements, particularly those related to transport and installation with the TIF. This shape allows flexibility in adjusting the height of the braces, ensuring that it can fit within the constraints of the TIF and a better weight/buoyancy ratio.

The selection of braces was based on their capacity to transfer forces from the wind turbine to the foundation in an efficient manner. To achieve this, two braces per footing were placed, totaling six braces. The height of the lower brace was variable during the design process, ultimately reaching a fixed height of 10 meters. The upper brace was positioned at the same height as the TIF.

The upper brace of the bottom-fixed structure is a straight cylindrical column, designed to connect the lower part and the wind turbine. Additionally, this adaptability allows the bottom-fixed structure to be used for various water depths, as only the top column needs to be changed. This modification will not impact its fit within the TIF. As a result, the bottom 41 meters of the bottom-fixed structure can maintain the same structure.

In order to achieve a symmetrical design and ensure a connection with the TIF, it is necessary to ensure that the foundation does not exceed a radius of 38.60 metres. This constraint formed the basis of the initial design decision. In determining the height of the lower braces, it was considered that a scour clearance of at least 1.00 meter should be allowed for. Consequently, the lower brace is positioned 1.00 meter above the seabed. In Figure 3.2, the various components are labeled and illustrating the positioning of the bottom-fixed structure within the TIF during transport.

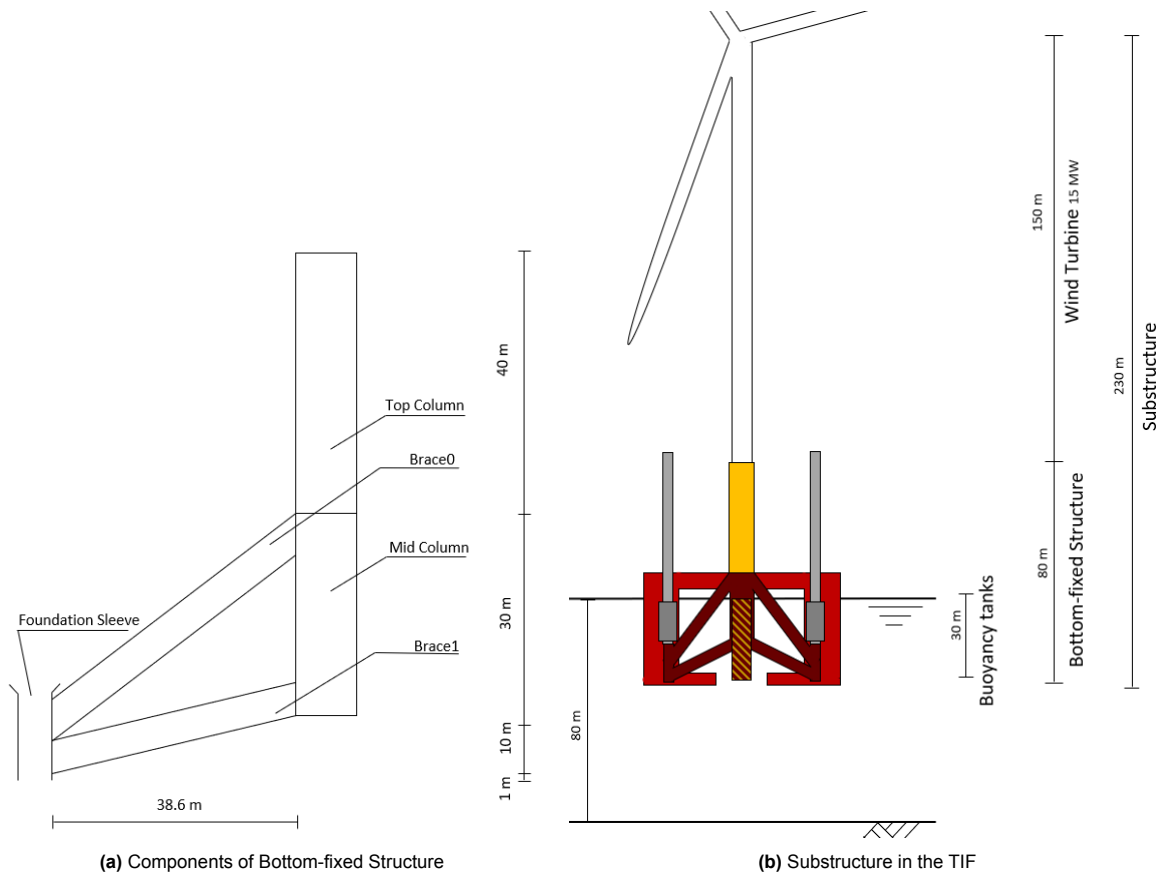


Figure 3.2: Bottom-fixed Structure Design

3.3. Foundation Types

During the operational stage, bottom-fixed wind structures rely on their foundations to transmit forces to the soil, ensuring on-bottom stability. This section explores two foundation types: pile foundations and suction bucket foundations [34].

Piles

The most dominant foundation used for offshore wind turbines is the open-ended tubular element, commonly known as a pile. Piles can be installed vertically or with inclination and serve as the foundational support for various offshore wind structures. Monopiles, which consist of a single pile, is one pile, while tripod and jacket structures may use three or four piles. The diameter of monopiles generally ranges from 5 to 12 meters, with a length of 30-70 m. For tripod and jacket structures diameters are ranging from 1.8 to 2.5 meters and depths from 30 to 120 meters [30, 42].

Suction Buckets

Another foundation option is the suction bucket, where the buckets are inverted into the seabed, generating resistance during installation by suction. Similarly to other methods, one or multiple suction buckets are possible. This foundation installation provides rapid and low-noise installation, simplified decommissioning, and eliminates the need for seabed preparation [36]. One of the primary limitations of suction buckets lies in their geotechnical constraints. Although suction buckets can be installed in nearly all soil types (except rocks), uncertainties surrounding soil parameters pose a challenge. Additionally, the relative rarity of suction bucket installations in the industry complicates both the manufacturing and installation processes, thus increasing costs.

For the further development in this design research, the focus will be on pile foundation. Piles meet all the design requirements for the bottom-fixed structure and the installation method. Piles offer greater flexibility in dealing with different types of soil during installation. Additionally, pile use is a widely used

technique in the offshore industry and is therefore more cost effective. Although driving piles can cause more disturbance to marine life than suction buckets, it is still less disturbance than hammering monopiles. This is because piles have a smaller diameter and penetrate less deeply into the soil.

3.4. Strength Analysis Bottom-fixed Structure

To conduct an initial analysis of the dimensions of the structure, the strength is evaluated according to the API standard RP 0002a WSD. This evaluation covers axial compression and bending, elastic hoop buckling stress, axial tension, hydrostatic pressure, as well as axial compression and hydrostatic pressure [2]. An explanation of the calculations of these checks and the parameters used can be found in Appendix C.

3.5. Dimensions Bottom-fixed Structure

The diameter and thickness of the braces were determined through strength analysis and design iterations. The definitive values resulting from this analysis are presented in Table 3.1, which provides the basis for the design of the transport and installation methodology.

Table 3.1: Key Parameters Bottom-fixed Structure

Parameter	Value	Unit
Radius Footprint	39	<i>m</i>
Height Bottom-fixed Structure	80	<i>m</i>
Outer diameter brace 0	5	<i>m</i>
Length brace 0	50	<i>m</i>
Thickness brace 0	40	<i>mm</i>
Outer diameter brace 1	5	<i>m</i>
Length brace 1	40	<i>m</i>
Thickness brace 1	40	<i>mm</i>
Outer diameter mid column	11	<i>m</i>
Length mid column	31	<i>m</i>
Thickness mid column	45	<i>mm</i>
Outer diameter top column	11	<i>m</i>
Length top column	39	<i>m</i>
Thickness top column	45	<i>mm</i>
Outer diameter foundation pile sleeve	5	<i>m</i>
Length foundation pile sleeve	12	<i>m</i>
Thickness pile sleeve	45	<i>mm</i>
Total mass	2861	<i>tonnes</i>

With this design of the bottom-fixed structure, the transport and installation methodology will be further explained in the following chapter.

4

Transport and Installation Methodology

In this chapter, the requirements of the transport and installation method will be outlined. Followed by an overview of the various structures along with their corresponding masses and buoyancy forces. Subsequently, two transport and installation methods will be briefly explained and evaluated, with one of the two chosen for further consideration. Following this, an explanation will be provided regarding the analysis applied in this design research.

4.1. Requirements for the Transport and Installation Methodology

This section outlines the essential requirements for the design of the transport and installation method. These include the installation of the bottom-fixed structure detailed in Chapter 3, use the integrated installation method, and transport and install in various weather conditions (a guideline).

Furthermore, for a complete design of a transport and installation method, it is crucial to address various stages early in the design process. This ensures a complete overview and mitigates significant issues later on. In this design research, five key stages will be considered: Port Preparation, Transport, Installation, Repositioning, and Operation. This design research will primarily focus on the port preparation, transport, and installation stages, and will give an overview of the repositioning and operation stages. The five stages are illustrated in Figure 4.1.

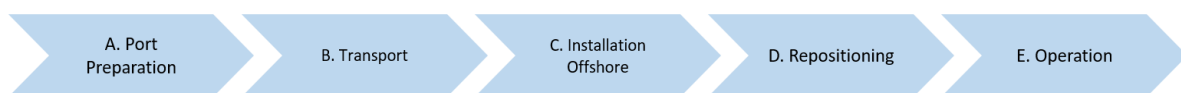


Figure 4.1: Five Stages of the Transport and Installation Method

4.2. Overview Gravitational and Buoyancy Forces

To achieve equilibrium in vertical direction for a floating structure, it is necessary to understand the gravitational and buoyancy forces of each structure. In order for a floating structure to be in equilibrium, the buoyancy force must be equal to the gravitational force. These forces will be discussed in this section.

Gravitational Forces

The gravitational force of the structures is equal to their mass. The mass of the wind turbine is based on the NREL reference turbine [17]. The mass of the TIF is provided by BES and is 5575 tonnes without additional ballast. The mass of the bottom-fixed structure is 2861 tonnes, and detailed calculations of the individual components are presented in Appendix D. An overview of the masses of the structures are given in Table 4.1.

Table 4.1: Gravitational Force of Structures

Total mass	Mass	Unit
Bottom-fixed Structure	2861	tonnes
Wind Turbine	1877	tonnes
TIF	5575	tonnes
Total Gravitational Force	10313	tonnes

Buoyancy Forces

In addition to gravitational force, the buoyancy force also contributes to the vertical equilibrium. The buoyancy forces are defined at different water depths acting on the draft of the bottom-fixed structure and the TIF. The draft refers to the depth at which the structure is submerged. The buoyancy force is the upward force exerted by a fluid on a submerged object and is equal to the volume of fluid displaced by the object [28]. The formula for buoyancy force is given by:

$$F_B = \rho \cdot g \cdot \nabla \quad (4.1)$$

where:

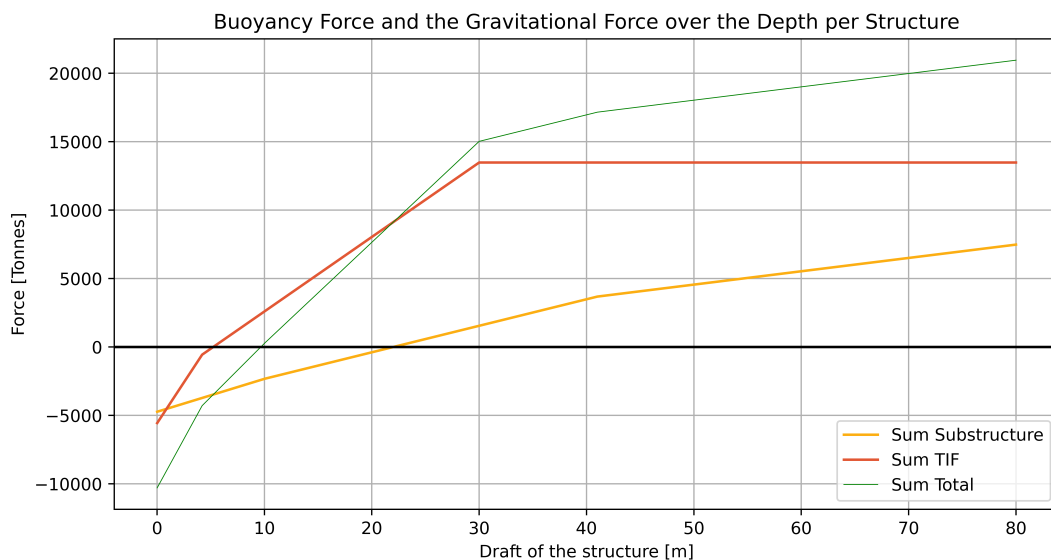
F_B is upwards buoyancy force,

∇ is submerged volume,

ρ is density of the fluid.

The buoyancy force as a function of the draft for the different structures has been calculated and the results are presented in Appendix D.

To analyse the situation and understand the interacting forces and the draft during the transport stage, the problem has been separated into two structures: the TIF and the substructure. Figure 4.2 provides a visual representation of the two structures, with the combined mass illustrated by the green line. The TIF, shown by the red line, has a maximum draft of 30 meters and so from this point on constant buoyancy force. The substructure consists of the bottom-fixed structure and the wind turbine, shown in yellow.

**Figure 4.2:** Graph of Buoyancy Force and the Gravitational Force as a function of the Draft

The graph shows that the TIF is significantly more buoyant than the substructure. The TIF has a draft of approximately 5 meters, excluding additional ballast, whereas the substructure has a draft of

approximately 20 meters, excluding additional buoyancy. Together, the system has a draft of 10 meters where the TIF is buoyant and the substructure experiences a gravitational force. Consequently, the TIF is a buoyancy-based structure and the substructure a gravity-based structure in this transport stage.

4.3. Two Transport and Installation Principles

There are two possible principles for the connection between the two structures. One principle involves applying compression forces to push the substructure on the TIF. The second method involves using tension to connect the two structures. Figure 4.3 on the left shows the scenario, during transport and installation, under compression, and the figure on the right illustrates the tension-based situation. As the TIF cannot be fully submerged to the seabed, an additional installation step is required to place the substructure on the seabed. These principles, involving either compression or tension, can be used during transport and during the lowering process (installation stage). In this section, both principles will be analysed and compared.

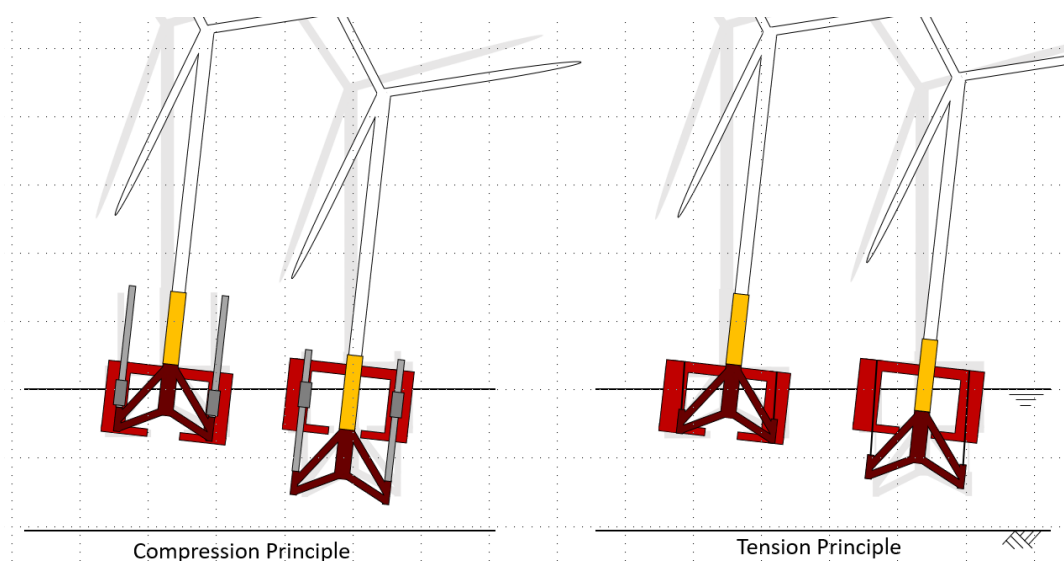


Figure 4.3: Two Principles for the Transport and Installation Method

4.3.1. Compression Principle

When considering the principle under compression, the transport stage follows the same methodology as the TLP transport with the TIF. The transport stage also occurs under compression, whereby the TLP is buoyant and exerts upward pressure against the TIF. By adding ballast to the TIF, the TIF will act like a gravity-based structure.

The installation stage of the bottom-fixed structure will proceed differently. An extra installation mechanism is required to place the substructure on the seabed floor. For this purpose, circular steel tubes can be used to push the structure downwards, known as spud piles. These spud piles must withstand significant axial force due to the large interface force between the structures. Furthermore, since the bottom-fixed structure must be placed at a depth of 80 meters, the spud piles must be long, resulting in significant bending and buckling forces, in cases of rotation.

One of the advantages of the installation method according to this principle is that the system will react as one body, this creates a controlled system during the lowering process.

However, there are drawbacks to this principle. Firstly, the bottom-fixed structure operates as a buoyancy-based structure. Therefore, a transition is needed from a buoyancy-based structure during transport to a gravity-based structure before operation, requiring an uncontrolled transition between buoyancy and gravity forces during installation, which poses challenges. Additionally, the bottom-fixed structure is unstable due to the relatively small amount of mass at its bottom (no extra mass added, and significant buoyancy), resulting in a relatively high center of gravity (CoG). This adds complexity to achieving overall system stability.

4.3.2. Tension Principle

The alternative transport and installation principle involves lowering the bottom-fixed structure under tension. In this case, the bottom-fixed structure operates as a gravity-based structure, while the TIF functions as a buoyancy-based structure. The significant mass of the bottom-fixed structure results in it exerting a downward force on the TIF.

In this principle, cables are used to apply tension to the structure (see Figure 4.3). At the top, connections with hinges are made to the TIF. As a result, the system reacts as two bodies, with the same rotation but with their centroids shifting relative to each other. This leads to a more complex dynamic interaction between the bodies.

One advantage of this principle is that the bottom-fixed structure is installed in the same manner as it is during operation stage, as a gravity-based structure. This allows for more optimal design possibilities. Another advantage is that the bottom-fixed structure has a higher own weight, resulting in a higher natural period and greater resistance to mismatches between the natural periods of wind and waves. Additionally, the center of gravity (CoG) in this system is lower due to the higher self-weight of the bottom-fixed structure, potentially making it more stable than the other principle.

However, since it operates as two separate bodies, it cannot be definite stated and requires a more in-depth analysis using dynamics models. Additionally, because the centroids are no longer aligned, this may lead to an unstable system. Furthermore, a practical issue arises when the bottom-fixed structure may begin to move independently from the TIF, potentially resulting in a collision of the two structures, which must be prevented.

4.3.3. Evaluation

For this design research, one of the two principles will be further developed to gain a deeper understanding of its feasibility.

When considering the relevance of a design study, practical experience shows that lowering a gravity-based structure to the seabed in a controlled manner has been more commonly implemented. The potential of lowering a buoyancy-based structure presents a more promising field of exploration. It offers the possibility of examining critical issues and assessing.

Consequently, given the controlled installation, single-body system, alignment with market demands, and the available research opportunities, the compression principle is the preferred option for this design research for the transport and installation of the bottom-fixed structure. The remaining critical issues will be further investigated in order to determine their magnitude and significance. The combination of a low CoB and a high CoG can result in an unstable system, so stability must be addressed. Additionally, determining the large bending moments in the spud piles, which influence the maximum angle of heel, is crucial. Another critical point identified is the transition from a buoyancy-based to a gravity-based structure. Lastly, due to the reduced mass, the natural period is likely to be relatively shorter, increasing the risk of resonance with wave periods. These critical points will be further discussed and their magnitude determined in Chapter 5 (Critical Issues).

4.4. The Transport and Installation Principle under Compression

This section outlines the methodology for the transport and installation principle under compression using the TIF. The approach for analysing the methodology is provided, followed by the identification of the requirement for additional ballast and buoyancy, and concluding with the initial design of the spud piles. A graphical overview of the transport and installation stages is provided in Figure 4.4.

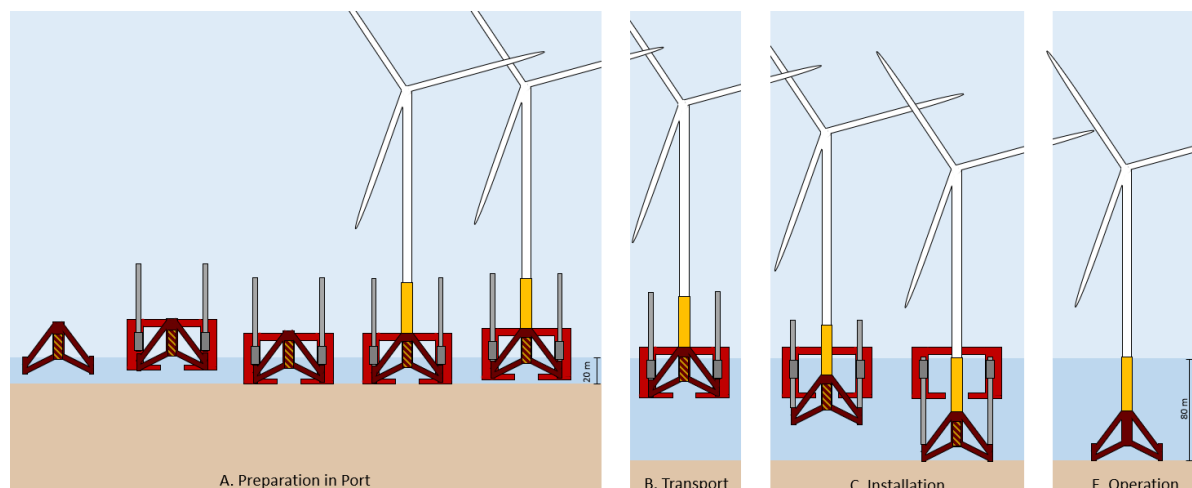


Figure 4.4: Overview of Key Stages of the Transport and Installation Method

4.4.1. Approach to Analysis

A static analysis will be conducted on three stages, port preparation (A), transport (B), and installation (C), focusing on vertical balance, interface forces and initial stability. The repositioning stage (D) will be described and evaluated, and the operational stage (E) will be analysed using an alternate analytical approach due to its non-floating condition (further explained in Chapter 6).

Vertical Equilibrium

One of the key considerations is the vertical equilibrium of the system, defined as a draft where the sum of all the vertical forces acting is equal to zero. The vertical forces involved include gravity force (mass and additional ballast) and buoyancy (and additional buoyancy). The buoyancy force depends on the draft and reacts in the opposite direction of the gravity force. This equilibrium can be used to determine the draft of the system, as well as the required additional ballast and buoyancy. It is of importance to ensure that the draft of the system does not exceed the maximum draft of the TIF during the transport stage. To determine the amount of additional buoyancy and ballast required for the transport stage, the draft of the TIF is set at 30 meters.

Interface Forces

Additionally, the static analysis will also consider the magnitude of the interface force. The interface force is the force between the two structures, the TIF and the substructure. In case of vertical equilibrium, the substructure has the same upward force (buoyancy force) as downward force of the TIF (gravitational force).

As stated in the design guideline for the transport and installation method, it is crucial to operate in various weather conditions. This requires understanding the operational limits with respect to the environmental forces. These parameters are dependent on the magnitude of the interface force. Further technical progress has been made with the design of the TLP installation method with the TIF. Dynamic calculations have already been done and indicate an interface force of approximately 2000-2500 tonnes per leg during the transport stage. To provide an initial estimation of the required additional ballast and buoyancy, magnitudes of similar orders will be assumed for the installation of bottom-fixed wind structure. However, it should be noted that precise values will need to be determined through dynamic analysis at a later stage. Nonetheless, these initial approximations offer a useful magnitude for interface force, which can be subsequently adjusted by adding more ballast or buoyancy force, thereby increasing the interface force.

Initial Stability

Finally, a stability analysis is performed to evaluate the initial static stability. The stability check includes the calculation of the centre of gravity (CoG), centre of buoyancy (CoB) and metacenter. A detailed explanation of these formulas and values used can be found in Section 5.1 and Appendix E.

4.4.2. Additional Ballast & Buoyancy during Transport Stage

As shown in Figure 4.2, the TIF has the largest buoyancy force, while the substructure initially experiences more gravitational force. If the system is intended to operate according to the compression principle, additional ballast is required to the TIF and additional buoyancy to the substructure. To prevent the draft from exceeding the maximum draft of the TIF during transport and to maintain interface forces at approximately 2000-2500 tonnes per leg (7000 tonnes total), approximately 20500 tonnes of ballast will be added to the TIF, along with an additional 6000 tonnes of buoyancy to the substructure during the transport stage. The substructure will as a result push up against the TIF, resulting in the system having a draft of 30 meters. The new vertical balance during the transport stage is shown in Figure 4.5.

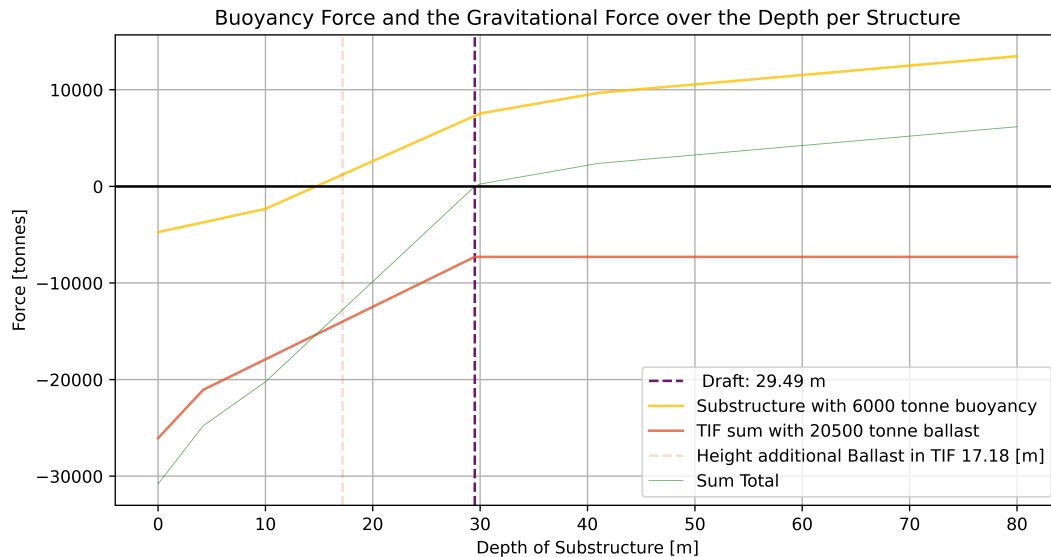


Figure 4.5: Graph of Buoyancy Force and the Gravitational Force as a function of the Draft: Compression Principle during Transport Stage

The ballast in the TIF will be added as seawater using pumps, which will direct it to the bottom of the TIF. The additional buoyancy can be incorporated to the substructure using buoyancy tanks attached to the sides. These tanks can be regulated, gradually filled with seawater, and subsequently removed from the substructure after installation. Three steel buoyancy tanks, each with a length of 20 meters and a radius of 5.5 meters will be positioned along the mid column, placed at the height of the bottom of the mid column. This is necessary to ensure sufficient buoyancy force when floating the substructure alone (without the TIF) during step 1 of the port preparation stage (A1), as described in Chapter 6. Additionally, given that stability is one of the critical issues, it is important to raise the CoB as much as possible. By positioning the buoyancy tanks as high as possible (while still beneath the transport draft), the CoB will also be elevated, resulting in a more stable system (as described in section 5.1).

In comparison to alternative buoyancy systems such as balloons, steel buoyancy tanks are preferred due to their ability to withstand significant depths and the water pressure. This pressure would compress balloons or bags, consequently reducing buoyancy force [15]. These steel buoyancy tanks offer a degree of flexibility, allowing them to be filled with either compressed air (or water), thereby adjusting buoyancy (or ballast) as needed during installation, repositioning, and decommissioning [35].

4.4.3. Design Spud Piles

The TIF is connected to the substructure with the use of spud piles. These spud piles serve as the connection during the installation stage, where the substructure is lowered and the TIF remains at water level. The round steel spud piles will be of significant length, and the dimensioning of these piles is a crucial aspect.

The interface forces are the forces that connect the TIF and the substructure. Through the spud piles, these interface forces acts axial, and additional moments due to the potential tilting of the system.

Initially, this section will describe the design and the necessary mechanisms. Further elaborated on the strength of the spud piles is provided in Section 5.2.

Dimensions

In the following section, the dimensions and specifications of the piles, including their length, diameter, and wall thickness, will be detailed.

The proposed design accounts for a water depth of 80 meters. With a draft of 30 meters for the TIF the piles should push the structure 50 meters down. Since the pile sleeve has a height of 12 meters, it will only extend 12 meters above the seabed floor when driven. However, the connection between the substructure and the spud piles is also situated 15 meters above the draft of the TIF, as illustrated in Figure 4.6. This 15 meters includes, 12 meters for the height of the pile sleeve, 1 meter for the height at which the substructure fits in the TIF, and an additional 2 meters between the substructure and the lowering mechanism, resulting in 53 meters of lowering length. The total length of the spud piles is 70 meters. The values for the parameters are provided in Table 4.2. For material properties and coefficients used in the calculations, please refer to Table C.5.

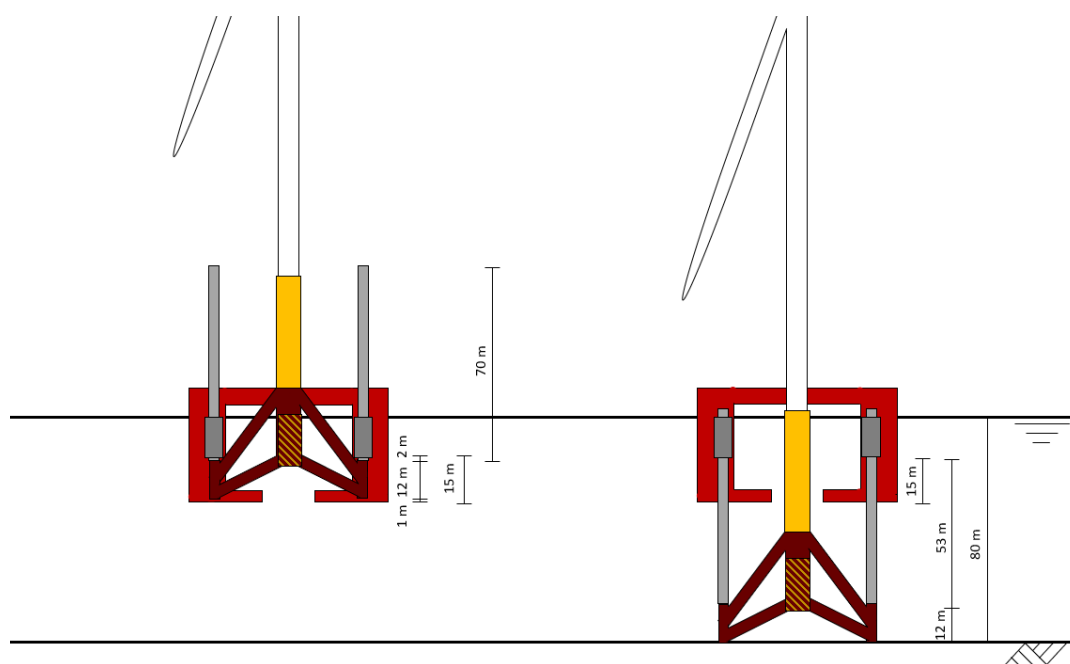


Figure 4.6: Spud Piles Lowering Principle and Dimensions

Table 4.2: Parameters Spud Piles

Parameter	Value	Units
Water Depth	80	<i>m</i>
Total Length	70	<i>m</i>
(Lowering) Length	53	<i>m</i>
Diameter	6	<i>m</i>
Wall Thickness	45	<i>mm</i>

Lowering Mechanism

The spud piles must be capable of push against the buoyancy force of 7000 tonnes. Therefore, the mechanism must exert a minimum force of 2333 tonnes per pile. This can be achieved with a hydraulic cylinder. Hydraulic cylinders leverage the pin-in-the-hole principle to ensure seamless operation on circular piles [16, 37].

Connection with Bottom-fixed Structure

In order to connect the spud piles to the substructure, several potential solutions exist. One possibility is to connect the spud piles within the pile sleeve. The advantage of this approach is its ability to withstand horizontal forces. However, a limitation was identified during the design phase regarding the foundation installation step, because this space in the pile had to be used for the connection with the foundation.

An alternative solution to place the connection on the (inclined) top side, it enables the absorption of horizontal forces and provides sufficient surface area to transmit the interface forces, as shown in Figure 4.7. This solution presents an opportunity to use the foundation sleeve for alternative applications.

Following an analysis of the foundation types detailed in Section 5.3, it was defined that the second option, which involves the placement of spud piles atop the pile sleeve, is the most preferred solution. For the installation of the substructure on the seabed, the bucket-and-pin principle will be used. In this method, the pile sleeve acts as the bucket, and the pin will be placed on the pre-installed mudmat. This approach ensures precise alignment during the installation process. This is graphically represented in Figure 4.7. The spud pile has a diameter of 6.0 meters, slightly wider than the foundation sleeve, providing sufficient surface area to transfer its forces.

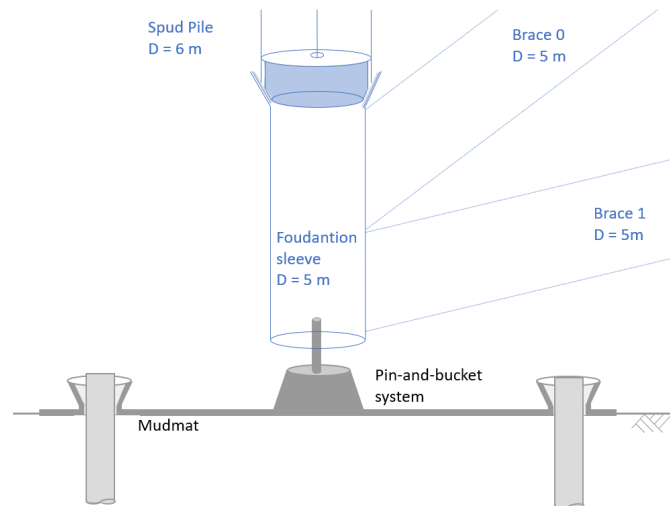


Figure 4.7: Spud Pile Design Connection with the Substructure

After making this design choice, redesigning the connection of the bottom-fixed structure becomes necessary, requiring another iteration through the design loop. Initially, the foundation sleeve was intended to drive a pile through. However, due to decisions such as placing mudmats on the seabed and connecting them using the bucket-and-pin principle, the foundation sleeve now serves only as a connection between the braces. Therefore, the design of the bottom-fixed structure may need further improvement, necessitating another iteration through the design loop, which will not be covered in this design research.

4.5. Conclusion

This chapter presents an explanation of the concept of the transport and installation methodology. The compression principle will be used to transport and position the substructure on the seabed. In order to achieve a transport draft of 30 meters, an additional ballast of 20500 tonnes and extra buoyancy of 6000 tonnes in buoyancy tanks are required. Spud piles function as the additional lowering mechanism to push the substructure downward. As outlined in this chapter, critical points of the compression principle include the stability of the system, the strength of the spud piles, and the transition from buoyancy-based to gravity-based structure (seabed placement), as well as the natural period of the system. These issues represent the most critical issues that require thorough analysis and will be addressed in the subsequent chapter.

5

Identifying Critical Issues

In this chapter, the critical issues that arose during previous analyses will be explored. The chapter begins with an examination of stability, addressing initial static stability. Furthermore, the determination of the maximum angle of heel will be addressed. Next, the focus shifts to the final installation step, seabed placement, where design choices will be discussed. Following this, an analysis of the system's natural period will be covered. Finally, the implications for the weather window will be described. The chapter concludes with a summary of the design choices, the limits, and the most critical stages of this transport and installation method.

5.1. Initial Static Stability

The assessment of initial stability during the transport and installation stages depends on key parameters such as the center of buoyancy (CoB), center of gravity (CoG), and metacenter, which are essential for determining the stability of a floating structure. The CoB represents the centroid of the volume of fluid displaced by a floating structure, whereas CoG signifies the point through which, the entire weight of the structure act. Subsequently, the initial metacenter is derived to evaluate the initial static stability.

For structures designed to adapt a range of relatively small angles of rotation, up to 10°, and for which the water plane remains similar in shape when rotated, the initial metacentric height is expressed by Equation 5.1. Although this specific consideration does not directly apply to the actual structure, it serves as a reasonable approximation for the first analytical purposes.

$$\overline{GM} = \overline{KB} + \overline{BM} - \overline{KG} \quad (5.1)$$

where:

$\overline{GM}$ is the metacentric height,

$\overline{KB}$ is the distance from the keel to the CoB,

$\overline{BM}$ is the distance from the keel to the metacenter,

$\overline{KG}$ is the distance from the keel to the CoG.

The distance from the keel to the metacenter is dependent on the moment of inertia of the water plane and the displacement volume, and given by the formula [28]:

$$\overline{BM} = \frac{I_T}{\nabla} \quad (5.2)$$

where:

I_T is the moment of inertia of the water plane,

∇ is the displacement volume (Figure D.3).

For stability, it is recommended that the $\overline{GM}$ be at least 1.0 meter for columns stabilized units. A $\overline{GM}$ of 1.0 meter provides sufficient stability during operational, transit, and severe storm conditions, as outlined in the HSE standards [20]. In systems with a larger $\overline{GM}$, stability is significantly improved, while a reduction in $\overline{GM}$ increases sensitivity to errors or unexpected movements. Therefore, in the current feasibility study, a $\overline{GM}$ of minimal 1.0 meter is assumed to ensure enough safety [28].

5.1.1. Identifying Initial Metacentric Height

This section provides the conclusions on the stability analysis. The formulas and values used to calculate the $\overline{GM}$, are provided in Appendix E.

The analysis of initial stability, which calculates the $\overline{GM}$ of the system as a function of the draft, shows that the $\overline{GM}$ falls below the minimum threshold of 1.0 meter at a draft of 75 meters, which is graphically illustrated in Figure 5.1.

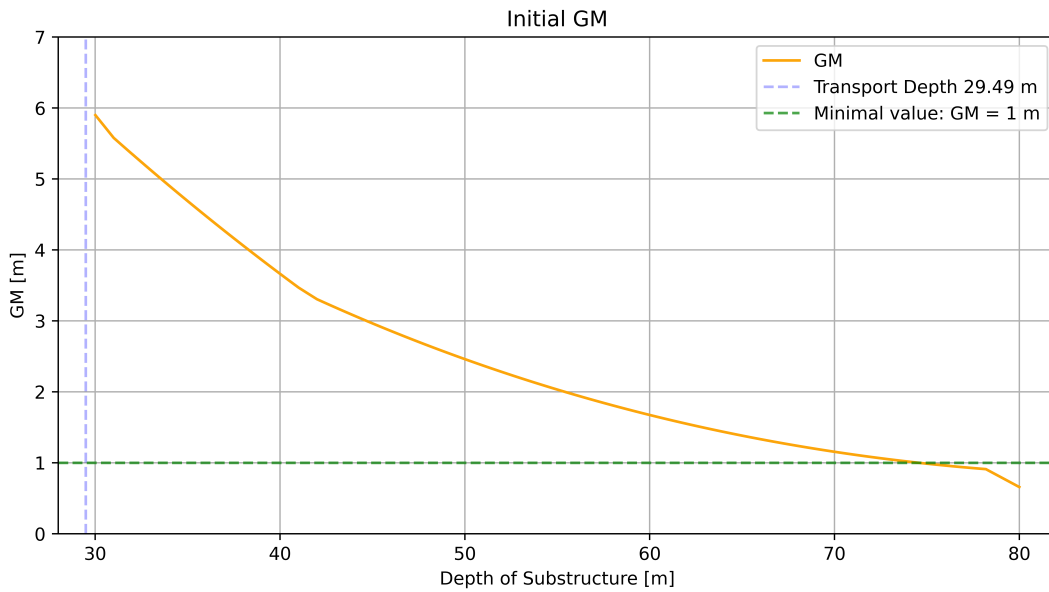


Figure 5.1: Initial Metacentric Height as a function of the Draft

In conclusion, the system is above the threshold of 1 meter during the transport stage, and therefore, it can be stated that the system is stable during this stage. However, its stability gradually decreases during the installation stage. As shown in the figure, there are a few kinks in the graph. These kinks result from simplifications made in the calculations, where simplified shapes were used. The first kink at 31 meters marks the top of the buoyancy tanks. The second kink at 41 meters indicates the transitions of the braces and the top column. Finally, there is a kink at 78 meters, which corresponds to the point where the buoyancy tanks are completely filled with ballast.

A critical point is reached at a draft of the substructure of 75 meters. Therefore, various options will be explored to address this stability problem.

5.1.2. Possible Solutions

In this section, two potential solutions to address the issue of a low metacentric height will be evaluated.

Evaluate Changes in Bottom-fixed Structure

This section outlines the modifications that can be made in order to achieve a higher metacentric height. Increasing the $\overline{KB}$, which can be achieved by increasing the CoB of the system, is one potential adjustment to achieve stability. Moreover, a higher $\overline{BM}$ represents another viable modification. This adjustment can be achieved by either increasing the moment of inertia or reducing the displaced volume. Lastly, lowering the $\overline{KG}$ presents another option, which involves positioning the CoG lower.

Increasing the diameter of the top column creates more buoyancy at the upper part of the structure, resulting in a higher CoB. Additionally, the cross-sectional area of the waterline increases for the last few meters, leading to a higher moment of inertia. However, a disadvantage is that the total displaced volume increases, which has a negative effect. Another disadvantage is that the wave loads increase with an increase in the diameter of the top column. These are not included in the calculations for the dimensions of the bottom-fixed structure, but will need to be addressed in further design stages. Table 5.1 presents the intersection of the $\overline{GM}$ and the threshold of the 1.0 meter, for different diameters of the top column.

Table 5.1: Changed Parameter for Initial Stability Analysis: Diameter Top Column

Diameter Top Column	Water depth at $\overline{GM} < 1.0 \text{ m}$
11 m	75.2 m
12 m	78.3 m
13 m	78.8 m
16 m	80.0 m

As shown in Table 5.1, increasing the diameter of the top column results in a gradual increase in $\overline{GM}$. The system becomes stable for the entire installation process only when the top column reaches an impractical diameter of 16 meters, considering the dimensions of the overall bottom-fixed structure and wind turbine. Another drawback to consider is that increasing the diameter of the top column will lead to a minor change in the overall mass. Consequently, the interface force between the two structures will decrease.

In conclusion, as increasing the diameter up to 12 meters has more positive than negative effects. The design will continue with a top column diameter of 12 meters. Even a minor increase plays a crucial role in maintaining stability, as a higher $\overline{GM}$ reduces the risk of instability. This minor change is therefore considered beneficial. As these changes may not provide sufficient initial stability for the entire installation stage, alternative solutions must be considered.

Evaluate Different Water Depth

After the change of parameters within the bottom-fixed structure, achieving complete stability at a depth of 80 meters appears to be a challenge with the current design. Therefore, this section will explore the impact of a reduced water depth.

A reduction in the water depth led to an increased $\overline{GM}$. This is due to the fact that the installation the structure at shallower water depths results in a reduction in the height of the bottom-fixed structure, consequently lowering the height of the wind turbine and the overall CoG. It is important to note that in this analysis, only the height of the top column was changed, with no changes made to the diameters of the braces. In practical terms, additional optimisation can be achieved by designing the structure in shallower waters.

By reducing the water depth (and the height of the top column), the draft for which the initial $\overline{GM}$ remains above 1.0 meter has been analysed. The CoB as a function of draft remains constant, and the waterplane area over the depth also remains the same for the two cases. Therefore, the calculation of $\overline{GM}$ only changes due to the variation in CoG. Figure 5.2 illustrates the change in metacentric height as a function of draft. This graph demonstrates that the initial $\overline{GM}$ remains above the value of 1.0 meter across the entire installation stage for the water depths of 70 and 75 meters.

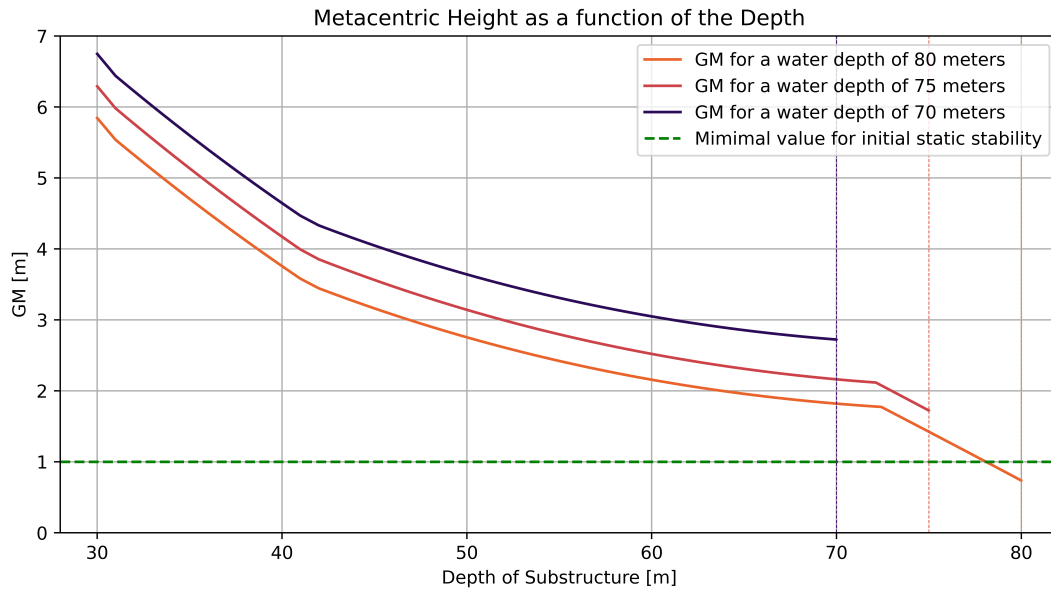


Figure 5.2: Initial Metacentric Height as a function of the Draft for Different Water Depths

5.1.3. Evaluation and Conclusion

Two options were explored to create initial stability. The first involved modifying the bottom-fixed structure to increase the metacentric height. Although changing the diameter of the top column demonstrated a positive effect, it was insufficient to meet the stability requirements. The analysis indicated that the stability during the entire installation stage remained sufficient when the water depth was changed to 70 and 75 meters.

The next critical issues will be analysed for both 70 meters and 80 meters water depth. This analysis aims to identify differences regarding the optimal installation water depth. Additionally, the design of the bottom-fixed structure will change to a top column diameter of 12 meters, which has a positive effect on the initial static stability of the design.

5.2. Maximum Heeling Angle

The next critical issue to be addressed is the maximum angle of heel during transport and installation. Delving into this issue is essential due to the relatively low CoG, requiring an analysis to understand its limitations. Two components exert influence over the maximum angle of heel, and both will be discussed in this section.

5.2.1. Angle of Deck Edge Immersion

One of the factors to be considered when defining the maximum angle of heel is the point at which the deck edge of the TIF becomes immersed, which is known as the angle of deck edge immersion. From this point, water will start to come over the TIF's edge, introducing extra external forces that impact rotational stability. Therefore, this point of maximum angle will be identified [28].

For a water depth of 70 meters, the maximum angle is 19° , and for a water depth of 80 meters, the maximum angle is 17° (calculations in Appendix Section E.6). The maximum angle represents a critical value during the transport stage. During the installation stage, when the draft of the substructure increases, the role of the spud piles also becomes relevant. It is therefore necessary to determine the critical angle of heel for this stage as well.

5.2.2. Strength of Spud Piles

As the lowering process begins and the spud piles push the substructure downwards, the length of the lever arm (the distance between the substructure and the TIF) increases, resulting in a moment

in the spud piles when rotating. The maximum angle of heel is defined by the intersection of the maximum allowable strength in the spud piles and the moment created by the rotation. This analysis was performed at five-meter intervals, with a range of 30 to 80 meters.

Maximum Moment in Spud Piles, API Standard

The maximum moment that can be achieved in the spud piles has been defined in accordance with the guidelines outlined in the API standard [2]. The distance between the stiffeners was maintained at a constant 6 meters for all drafts. For each draft, the maximum moment was defined by ensuring that all unity checks are less than 1.0. The maximum moments found per draft are presented in Table 5.2. Additionally, the unity checks for the two most critical requirements are presented include tension and hydrostatic pressure (yielding), and for the axial compression and hydrostatic pressure (buckling).

Table 5.2: Parameters Strength Analysis of the Spud Piles

Draft <i>m</i>	(Lowering) Length of Spud Pile <i>m</i>	Yielding Unity Check	Buckling Unity Check	Max Moment <i>MNm</i>
40	13	0.97	0.98	170
45	18	0.94	0.95	160
50	23	0.91	0.92	150
55	28	0.90	0.90	140
60	33	0.90	0.87	130
65	38	0.89	0.84	120
70	43	0.90	0.81	110
75	48	0.91	0.78	100
80	53	0.92	0.76	90

Buckling is predominant at lower drafts because it depends on the maximum allowable moments in the spud piles, which decrease with increasing draft. Yielding becomes the most significant factor after a draft of 55 meters. This is due to the increase in hydrostatic pressure with an increase in draft.

Righting Moment

In order to determine the maximum angle, it is necessary to define the moment generated by a rotation. Due to the lateral force from the substructure, a moment is induced in the spud piles. The lateral force is created by two components: the horizontal and vertical forces. The horizontal force is derived from the environmental force, and the vertical force is equal to the interface force. Additional explanation and illustrative details can be found in Appendix section E.6.

The increased moment in the spud piles is graphically illustrated in Figure 5.3, with the lines representing different drafts. It can be concluded from the plot that the moment increases as the angle increase. Additionally, it can be observed that an increasing in draft, results in an increasing moment in the spud piles.

Conclusion

The intersection of the maximum strength in the spud piles and the moment created by the rotation determines the maximum angle of heel.

In Figure 5.3 the maximum moment allowed according to the API code is represented by the horizontal dotted lines, and the inclined lines shows the righting moments created by rotation. The intersections between them, marked with a dot, indicate the maximum angle of heel for each draft.

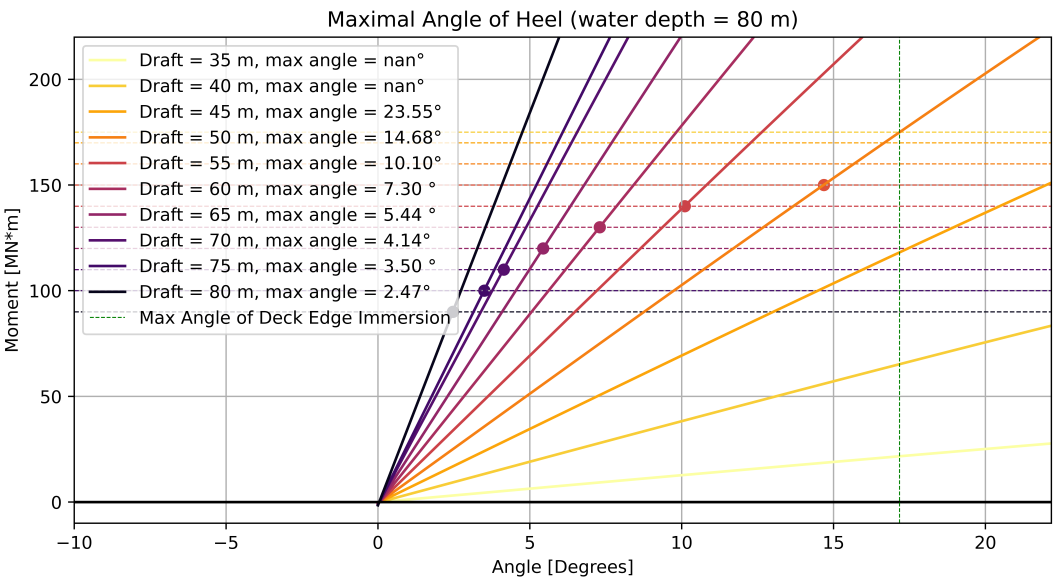


Figure 5.3: Maximum Moment in Spud Piles for a Water Depth of 80 meters

For the drafts 35 and 40 meters, there is no maximum angle of heel. The maximum angle of heel decreases from 23° to 2.5° for drafts from 45 meters onwards. This is illustrated by the purple line in Figure 5.4.

5.2.3. Evaluation and Conclusion

In Figure 5.4 the orange line represents the maximum angle of heel defined by the angle of deck edge immersion, and the purple line indicates the maximum angle of heel as influenced by the strength of the spud piles. The lowest line in the figure represents the maximum angle of heel, which notably decreases sharply once the moment in the spud piles becomes the critical factor. Up to a draft of around 48 meters, the angle of deck edge immersion represents the maximum angle of heel, beyond which the moment in the spud piles becomes more critical.

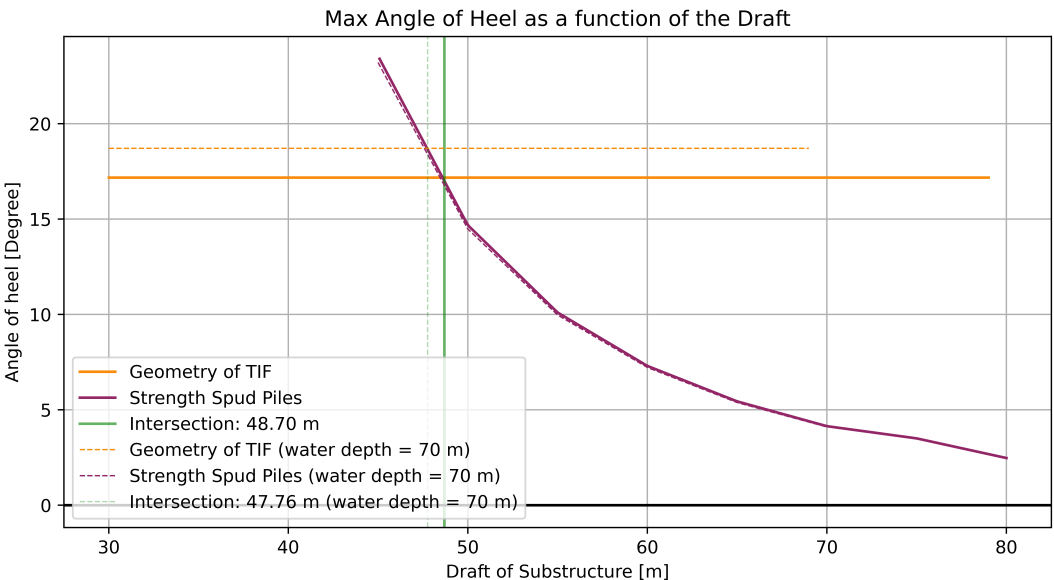


Figure 5.4: Max Angle of Heel as function of the Draft

The analysis suggests that the maximum angle of heel experiences a sharp decrease during the low-

ering process. During the transport stage, the maximum angle of heel is 17° and during installation stage (draft = 80 m), it reduced to 2.5° (Table E.6). In Section 5.5 (Weather Window), the impact of this maximum angle of heel on the environmental conditions will be discussed.

5.3. Seabed Placement

The next critical issue relates to the installation stage, where the substructure needs to be positioned on the seabed. While the structure is buoyancy-based during transport and installation, it is a gravity-based structure during operation. This will cause an (uncontrolled) transition from a buoyancy-based to a gravity-based structure during this final lowering stage, presenting challenges.

The challenge arises from the fact that the TIF is exerting gravitational force on the substructure, which in turn applies these force on the seabed. Dynamic wave forces act on the TIF, and since the substructure remains static on the seabed, the spud piles must withstand these forces. The magnitude of these forces can be considerable, requiring to mitigate it. Therefore, two alternative approaches will be explored to design the final installation step in a manner that mitigates these dynamic forces. One potential approach is to facilitate the transition from a buoyancy-based to a gravity-based just above the seabed. An alternative approach is to place the substructure buoyancy-based directly on the seabed.

The first approach is to change the buoyancy-based substructure into a gravity-based structure just above the seabed (a few meters). By filling the braces with seawater the substructure will be placed on the seabed due to the gravity force. However, a drawback is that it takes some time for such a large structure (in water) start moving. One method for accelerating the process is to use a kind of bellows, such as an air spring, whereby the substructure is pushed downwards by the air pressure within the bellows. Another option is to lower the pressure beneath the substructure so that it falls to the bottom more quickly. However, both options are uncontrolled, as the interface force gradually decreases and eventually must reach zero to allow the substructure to be placed on the seabed under gravitational force. This raises the probability of a collision between the TIF and the substructure, a scenario that must be avoided.

An alternative approach involves placing the substructure on the seabed buoyancy-based. In this approach, a final push is applied to the substructure, which lacks to withstand compression and horizontal forces. Therefore it is unable to withstand the dynamic forces. This method will be further elaborated below, as it was chosen for its effectiveness in achieving the desired outcome. Additionally, it was observed to have additional positive effects, which will be detailed in a subsequent section.

5.3.1. Method Explanation

To place the substructure on the seabed, a buoyancy-based approach will be used. However, to mitigate dynamic forces, a final push with heavy blocks attached to the TIF with wires will be used for the last few meters. This methodology ensures that the substructure is still buoyancy-based and that the blocks will take over the function of the TIF (gravity based structure), and that the wires (as they only work in tension) will ensure that the two bodies can move freely.

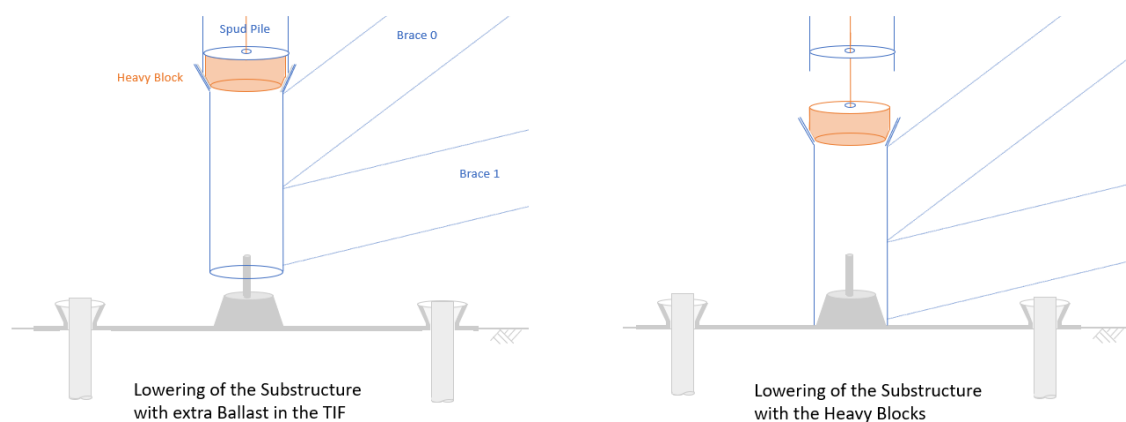


Figure 5.5: Methodology for Seabed Placement with Heavy Blocks

The blocks need to match the required interface force to get the substructure move downwards, totaling approximately 7000 tonnes. As illustrated in Figure 5.5, the blocks have limited height to ensure free movement. Furthermore, the total additional mass that can be added to the TIF without affecting other stages is limited. During the port preparation stage, the TIF should not exceed the maximum depth of the port, restricting the amount of extra weight. Refer to Section 6.1 on detailed information about port preparation stage. With both constraints in mind, the limiting height in the spud piles is set to 2 meters with a diameter of 5.8 meters. With these parameters, the heavy concrete blocks will have a total mass of 1200 tonnes (3 blocks in total).

Consequently, the interface force can only be 1200 tonnes, to push the substructure the final meter to the seabed. However, to ensure the substructure can be effectively pushed, a slightly lower interface force is required. This interface force will be maintained at 1000 tonnes. This interface force is limiting the environmental conditions under which operations can occur. The implications of this reduction for the feasibility of the transport and installation method will be discussed in more detail in Section 5.5.2. Below, a description will be provided of the the practical steps and the connections.

Connection Foundation

The installation of a substructure with a broad footprint requires seabed preparation to prevent the wind turbine from a tilt during the operation stage. Additionally, due to the weight of the substructure, for on-bottom stability, mudmats are required to prevent it from sinking into the seabed. The required surface area for sufficient bearing capacity is described in Appendix F.2.

Two approaches for the installation of mudmats for this installation method will be discussed. The first method involves fixing the mudmats directly on the substructure. This strategy saves time during installation by allowing the entire structure to be placed on the seabed at once. However, seabed preparation is still necessary, and attaching mudmats to the substructure adds weight and complicates design decisions due to increased area needed in the TIF. The second approach is to lay mudmats as a foundation frame on the seabed after seabed preparation. Then position the substructure using the bucket pin principle on the mudmat. The preferred installation method involves the pre-laid foundation frame which offers more flexibility in substructure design and reduces weight. The drawbacks of this method is that it requires an additional installation step and precise alignment of the substructure with the mudmats and pins, particularly challenging in environmental conditions. The detailed and schematic representation of the precise steps for the installation of the foundation frame can be found in Section 6.3 and Appendix F.2.

Connection Spud Piles, Heavy Blocks, and Substructure

During transport, the heavy blocks will be placed within the spud piles and will only provide as a connection between the spud piles and the substructure. The heavy blocks are made of concrete, and a strip of plastic will be placed between the heavy blocks and the substructure to absorb shocks.

During the lowering process, the spud piles are pushed downward by a hydraulic cylinder. Reaching the final five meters, the spud piles will no longer be driven downward. Instead, the buoyancy tanks and braces will be further filled with water until the substructure reach a buoyancy force equal of 1000 tonnes. After this point, additional ballast will be added to lower the substructure precisely above the thin pin of the mudmat, as illustrated in Figure 5.5. Once it is positioned around the initial thin pin, the heavy blocks can be lowered with a winch to place the substructure on the mudmat.

5.3.2. Effects of Stability Analysis

By placing heavy blocks into the spud piles, the mass of the TIF will increase, leading to greater weight and therefore a decrease of additional seawater ballast within the TIF. This adjustment will lower the CoG of the TIF and therefore the initial stability of the system. The implications of these changes on the initial stability will be discussed in the following section.

During transport, the difference in CoG is negligible, as the spud piles have not been lowered. However, as the spud piles lower, the CoG of the system will be more influenced by the presence of heavy blocks in the bottom of the spud piles. As the lowering process continues, the difference will become increasingly pronounced, thereby positively impacting the stability. The effects are illustrated in Figure 5.6, where the purple line represents the new design with spud piles and heavy blocks, and the orange line represents the initial design without spud piles and heavy blocks. The scenario for a water depth

of 70 meters is represented by dashed lines. The exact values of these changes are further detailed in the Appendix F.

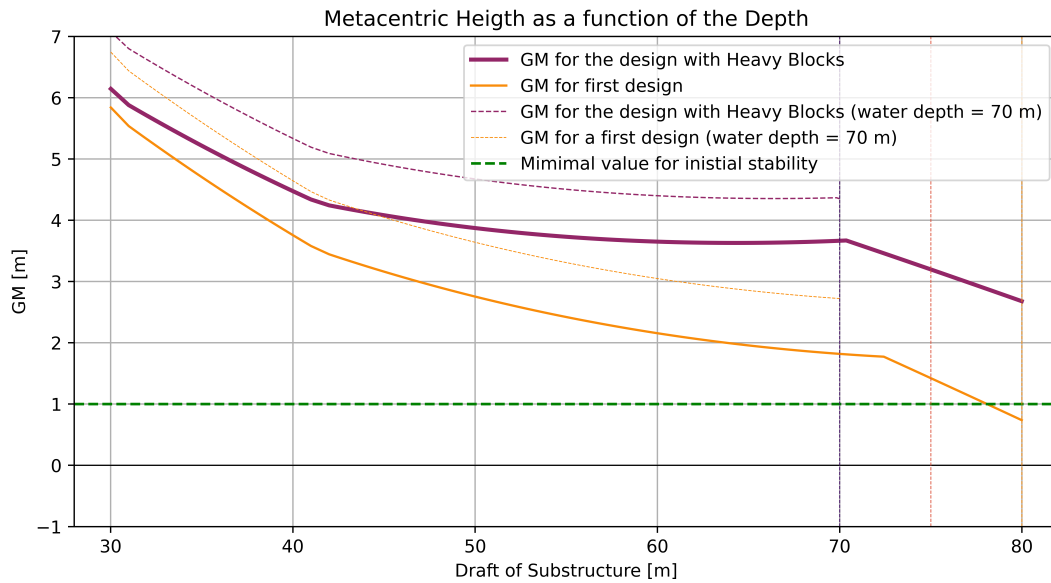


Figure 5.6: Initial Metacentric Height as a function of the Draft for Different Water Depths and for Two Different Designs

As illustrated in Figure 5.6, the inclusion of heavy blocks in the design has a beneficial impact on the initial stability. It can be observed that the curve for 80 meters meets the requirements set by HSE for a initial static stability during the entire installation stage.

5.3.3. Conclusion and Implementation in Design

It is necessary to mitigate the dynamic forces generated by environmental forces on the TIF to the static substructure on the seabed. This can be achieved by avoiding the use of spud piles to push the substructure the final few meters downward. Instead, heavy concrete blocks, attached to wires, can be used to push the substructure downward. These blocks can apply the necessary downward force without absorbing the dynamic forces. Consequently, the weight of the TIF increases, thereby allowing the additional ballast to be decreased. The additional mass in the spud piles, which will move downwards during the lowering process, has a positive effect on the CoG. This effect on the initial stability ensures that the installation remains feasible at water depths of up to 80 meters.

The implementation of heavy blocks into the design has been deemed beneficial for initial stability and effective performance of the seabed placement. Therefore, it has been decided to incorporating heavy blocks in the design. This analysis is statically determined, and it is essential to verify this solution dynamically with models.

5.4. Natural Period

To delve deeper into the dynamic behavior during transport and installation, a simplified dynamic model has been developed to provide valuable insights. This chapter outlines the analytical approach to simplify the dynamic model by a mass-spring system. This will be followed by the conclusions drawn from the calculated natural periods and their implications for typical sea states and the wind spectra.

5.4.1. Approach to Dynamic Analysis

For this analysis, the primary focus is on gaining initial insights into the dynamic behavior during transport and installation. Therefore, the system will be simplified and solved analytically. This is achieved by using a 2-dimensional system in the vertical plane: x (surge), z (heave), and ϕ (pitch). The coordinate system is centered at the middle of the system, precisely at the cross-section intersection of the waterline, as illustrated in Figure 5.7.

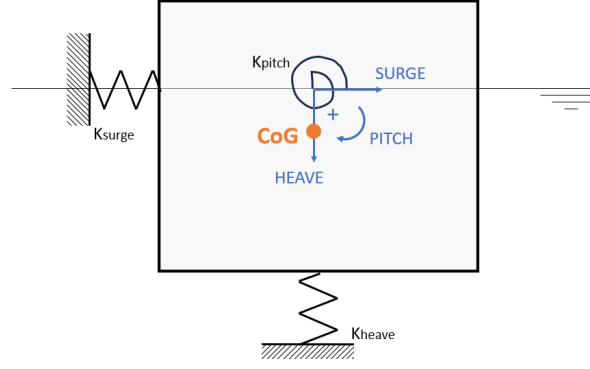


Figure 5.7: 2-dimensional Dynamic Model (3-DOF)

The equation of motion, which governs the dynamic behavior of a floating structure, describes its displacement and acceleration. This equation captures the interaction between the structure's mass and stiffness properties, enabling the determination of natural periods [39].

$$M \cdot \ddot{x} + K \cdot x = 0 \quad (5.3)$$

This analytical investigation focuses on two key aspects: pitch and heave. Pitch represents the rotational movement around the horizontal axis, while heave indicates the vertical movement of the body in response to waves and/or other external forces. Although surge, the horizontal movement along the y-axis, is considered to be the least significant factor for this design phase, it is included in the analysis as a coupled parameter, because of the physical interaction between surge and pitch. The linear forward or backward movement of surge influences the rotational motion, thereby influencing pitch. Although other degrees of freedom are present, their influence on the overall dynamics during transport and installation are more limited. Consequently, focusing on heave and pitch gives for this phase of design enough valuable insights.

In this section, a simplified model of the dynamic analysis will be provided, considered as a 2D mass-spring system in three directions: surge, heave, and pitch. This will be solved analytically, and the formulas used for this purpose will be explained.

5.4.2. Mass Matrix (M)

The symmetrical mass matrix (3x3) can be expressed as:

$$M_{total} = \begin{bmatrix} M & 0 & M \cdot CoG \\ 0 & M & 0 \\ M \cdot CoG & 0 & I_{yy} \end{bmatrix} \quad (5.4)$$

The values for mass are obtained from the total mass of the TIF and the substructure, including additional ballast. Below the parameters considered for the mass matrix are given [39].

$$M = M_{TIF} + M_{substructure} + M_{TIF, ballast} + M_{substructure, ballast} \quad (5.5)$$

To define the moment of inertia, the mass moment of inertia will be calculated. Equation E.14 will be used to sum up the different elements of the structure. Below the mass matrix for a draft of 30 meters is shown.

$$M(D : 30m)[kg, kgm^2] = \begin{bmatrix} 3.09 \cdot 10^7 & 0 & 2.15 \cdot 10^8 \\ 0 & 3.09 \cdot 10^7 & 0 \\ 2.15 \cdot 10^8 & 0 & 2.69 \cdot 10^{10} \end{bmatrix}$$

Added Mass

The added mass is a necessary term to describe the dynamics of a floating structure. This is the result of the interaction between a structure and a fluid. As the structure moves within the liquid, it displaces the fluid, which exerts a force on the structure. This extra force makes the structure behave as if it has extra mass.

$$M_{added} = \begin{bmatrix} M_a & 0 & -M_a \cdot (CoB - CoG) \\ 0 & M_a & 0 \\ -M_a \cdot (CoB - CoG) & 0 & +M_a \cdot (CoB - CoG)^2 \end{bmatrix} \quad (5.6)$$

The added mass for each structural component can be calculated individually. However, for this initial analysis, an assumption of 20% of the total mass is made. The impact of this approximation on the natural period has been analysed and discussed in Appendix G.

$$M_a = 0.2 \cdot M \quad (5.7)$$

$$M_a(D : 30m)[kg, kgm^2] = \begin{bmatrix} 6.22 \cdot 10^6 & 0 & -7.52 \cdot 10^7 \\ 0 & 6.22 \cdot 10^6 & 0 \\ -7.52 \cdot 10^7 & 0 & 9.09 \cdot 10^8 \end{bmatrix}$$

Total Mass Matrix

The following matrix represents the total mass matrix for a draft of 30 meters. This matrix the sum of the mass matrix and the added mass matrix. This matrix represents the mass distribution in surge, heave, and pitch directions, respectively.

$$M_{total}(D : 30m)[kg, kgm^2] = \begin{bmatrix} 3.71 \cdot 10^7 & 0 & 1.40 \cdot 10^8 \\ 0 & 3.71 \cdot 10^7 & 0 \\ 1.40 \cdot 10^8 & 0 & 2.78 \cdot 10^{10} \end{bmatrix}$$

5.4.3. Stiffness Matrix (K)

The stiffness matrix quantifies energy dissipation within the system caused by viscosity and the relative velocity between the structure and the water. The stiffness matrix (3x3) can be expressed as a restoring matrix:

$$K = \begin{bmatrix} K_{surge} & 0 & K_{surge} \cdot CoG \\ 0 & K_{heave} & 0 \\ K_{surge} \cdot CoG & 0 & K_{pitch} \end{bmatrix} \quad (5.8)$$

The horizontal spring is derived from the stiffness of the tugboats, crucial for maintaining the TIF in position. In heave motion, the restoring force is defined by the difference in buoyancy force. The restoring force of the rotational spring in pitch direction is governed by the generated moment by a rotation.

Restoring Force in Surge

A value of 30 kN/m for the restoring force in surge is assumed. The magnitude is not significant because only the natural period of heave and pitch are analysed in this design research. It is only considered as a coupling term between surge and pitch.

Restoring Force in Heave

The hydrostatic stiffness is related to the change in displaced volume [38]. To define the restoring force in heave for both the substructure and the TIF, the process begins by calculating the buoyancy force at two different depths. The buoyancy force is computed using formulas defined in Appendix D. The restoring forces for the structures at a draft of 30 and 70 meters are given in Table 5.3 and Table 5.4.

Table 5.3: Restoring Force in Heave ($D = 30m$)

Parameter	Value	Unit
Substructure	$4.84 \cdot 10^6$	N/m
TIF	$3.10 \cdot 10^6$	N/m
Total System (K_{heave})	$7.94 \cdot 10^6$	N/m

Table 5.4: Restoring Force in Heave ($D = 70m$)

Parameter	Value	Unit
Substructure	$1.14 \cdot 10^6$	N/m
TIF	$3.10 \cdot 10^6$	N/m
Total System (K_{heave})	$4.24 \cdot 10^6$	N/m

It can be observed that the restoring force of the TIF remains constant for both drafts, as the TIF stays at the waterline during installation. During transport, the contribution of the substructure is greater than the TIF. At a draft of 70 meters, the restoring force of the substructure decreases. This decrease can be attributed to a reduced difference in buoyancy force, as at a draft of 70 meters, only the top column is involved, whereas at a draft of 30 meters, brace 0 also contributes, resulting in a greater restoring force.

Restoring Force in Pitch

To define the values for the restoring force in pitch, the righting moment curves from the analysis of the stability curve (Section E.5) were used. It represents the change in $\overline{GZ}$ for increasing angles at different drafts, and indicates that a decrease in the draft of the substructure results in a reduction of the restoring force. For the restoring force in pitch, the components of the substructure and the TIF cannot be summed up together as they represent two different systems. In order to define the restoring force, it is essential to consider it as a single body and calculate it for the total system. The restoring force is equal to the difference in moment between two angles, $\phi_1 = 0^\circ$ and $\phi_2 = 1^\circ$ for the total system. In Table 5.5 the restoring forces in pitch are provided for each 5 meter draft.

Table 5.5: Restoring Force in Pitch

Draft m	Restoring Force ($\cdot 10^6$) Nm/rad
30	34.16
35	35.19
40	32.74
45	29.02
50	27.96
55	27.25
60	26.88
65	26.86
70	27.17
75	26.06
80	23.63

It can be observed that the trend of the line decreases. The decreasing restoring force with an increasing draft can be explained by a reduction in the $\overline{GM}$ of the total system. This indicates that the system has a reduced capacity to return the substructure to its neutral position.

Restoring Force Matrix

The following matrix illustrates the stiffness matrix for a draft of 30 meters. This matrix represents the mass distribution in surge, heave, and pitch directions, respectively.

$$K(D : 30m)[N/m, Nm/rad] = \begin{bmatrix} 3.00 \cdot 10^4 & 0 & 2.09 \cdot 10^5 \\ 0 & 7.94 \cdot 10^6 & 0 \\ 2.09 \cdot 10^5 & 0 & 3.42 \cdot 10^7 \end{bmatrix}$$

5.4.4. Natural Periods of the System

To define the natural periods, the equation of motion (Equation 5.3) needs to be solved. For an uncoupled parameter (in heave), the natural period can be determined using the formula for a single mass-spring system.

$$f_n = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \quad (5.9)$$

where:

f_n is the natural frequency [Hz],

k is the spring constant,

m is the mass.

The surge and pitch are analytically solved with a 2x2 matrix due to their coupling. The results are illustrated in Figure 5.8. In this figure, the orange line represents the pitch natural period, and the purple line represents the natural period of heave for a water depth of 80 meters.

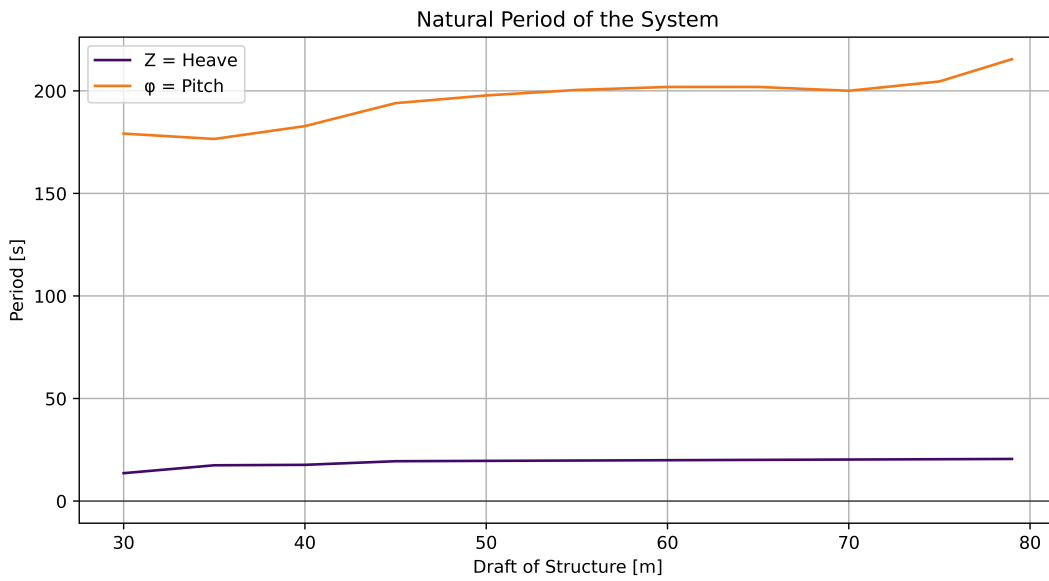


Figure 5.8: Natural Periods for Heave and Pitch as a function of the Draft

Figure 5.8 reveals that the natural period of the pitch increases as the draft of the substructure increases. This can be explained by the fact that the lever arm increases as the $\overline{GM}$ decreases. In general, the natural period for pitch is relatively high. This can be explained by the large mass of the TIF (8122 tonnes), the substructure (4781 tonnes), and the additional ballast in the TIF (18000 tonnes). This significant mass results in a high natural period.

For heave, the natural period increases with the draft of the substructure. This can be explained by the fact that during the lowering process, the difference in buoyancy force decreases, resulting in a reduction of the restoring force. This is due to the fact that during the lowering process, only the top column of the substructure acts as the restoring force. In contrast, during transport stage, the braces also contribute to the restoring force. Consequently, the system has a lower natural period for heave during transport.

The calculated natural periods are compared with external forces such as waves and wind. If the system's natural period aligns with external resonance sources, the system will oscillate, which can lead to fatigue and structural damage. If the natural period aligns with a resonance source in heave, the system experiences vertical oscillations. This issue is considered less critical because of the natural damping of water and the minimal direct impact on energy production compared to pitch oscillations. Oscillations in pitch induces rotational motion, which can lead to acceleration at the top of the wind

turbine. Controlling these accelerations is crucial to mitigate adverse effects for wind turbine manufacturers, ensuring structural integrity and operational efficiency [10]. Additionally, the pitch movement also results in increasing moments in the spud piles, which can be a limiting factor in the design and must therefore be kept to a minimum.

Longer natural periods indicate slower system responses, indicating high structural stiffness in ensuring stability. This suggests that resonance will only occur with very long external wave and wind periods, approximately 15 seconds for heave and about 200 seconds for pitch.

If the natural periods are too close to the external periods, design modifications may be necessary. This could involve redistributing masses or adjusting the geometry of the structure. To make an initial assessment of whether design adjustments are necessary, natural periods in heave and pitch will be compared with typical sea states, considering both first-order and second-order wave effects. Additionally, the analysis will include the effects of wind loads [12].

5.4.5. Typical Sea States

The initial step will be to compare the natural periods of the system with the first-order wave periods. In Figure 5.9, the wave periods of two typical sea states are plotted. One has a period of 8 seconds with a significant wave height of 2.5 meters, and the other has a longer wave period of 14.5 seconds with a lower significant wave height of 1.0 meter. The wave periods are plotted using the JONSWAP spectra. This spectral model provides a realistic representation of sea state conditions by incorporating factors such as significant wave height and wave-period. It can be suggested that the higher peaks possess a greater degree of energy as a result of the larger amplitudes with a shorter period. The two typical wave periods are shown in green in Figure 5.9. The natural periods of heave are plotted in purple and the natural periods of pitch are plotted in orange.

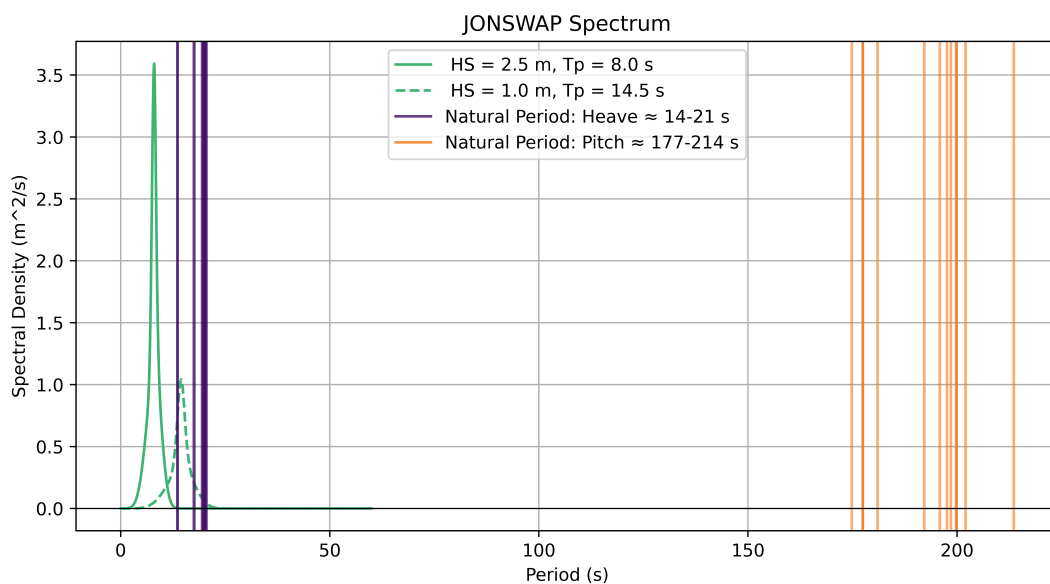


Figure 5.9: Natural Period as a function of the Draft for different Sea States

It can be observed that the natural periods in pitch are high and are outside the first-order wave spectrum. They will only resonate with very long waves, and it can be concluded that these waves are highly unlikely to occur. This suggests that these first-order wave spectra are non-critical for the natural period in pitch. Furthermore, it can be observed that the natural periods of heave are close to the wave periods. The analysis leads to the conclusion that, in terms of criticality, the lowest natural period in heave, which occurs at a draft of 30 meters during the transport stage, is the most significant. Thereafter, the level of criticality decreases.

First-order wave spectra have been analysed however, there are other external sources that can resonate with the natural periods as well. Due to the criticality of pitch oscillations and their higher natural

periods, further focus will be on the longer periods of second-order waves. Additionally, the wind spectra, which include higher periods, will also be analysed for its potential resonance with the natural periods of the system.

Second-order Wave Effects

Second-order waves refer to the interactions between primary first-order waves, which can lead to a complex wave pattern. These interactions are characterised by nonlinear effects where wave amplitudes and periods may differ from those of the first-order waves. Second-order wave loads are proportional to the square of the wave amplitude and occur at periods corresponding to the sum and difference of incident wave periods. There are two components of nonlinear wave motions: the mean wave drift force and the low-frequency wave drift forces. It is likely that low-frequency forces can resonate with the high periods of the natural period in pitch of the system. Given the criticality of pitch oscillations, it is crucial to analyse these periods and their effects [11, 28].

The calculations of the natural periods of the system fall outside the scope of this initial design stage due to their analytical complexity. However, analysis of the system's natural periods indicates the potential for resonance, which requires examination in next design iterations.

5.4.6. Wind Spectra

In addition to the potential resonance with first- and second-order wave loads, wind loads can also induce oscillations. Therefore, it is essential to analyse the wind spectra as well, which will be addressed in this section.

Wind varies in speed and direction over time, and wind spectra show the distribution of wind speeds across different periods. These spectra are typically characterised by parameters such as mean wind speed, wind direction, and the period of gusts. There are two types of wind: one is characterised by variations of less than 10 minutes and the other is characterised by variations of more than 10 minutes in the long term wind speed distribution. Given that the natural periods of this system are shorter than 10 minutes, further examination will focus on turbulence models and gusts events.

To thoroughly analyse the resonance effects caused by wind, a specific location is required. This is because the analysis depends significantly on the mean wind speed and direction at the given location. Therefore, this section will only explain the types of models that can be used, without making further conclusions about resonance [10].

Turbulence Models

Turbulence is characterised by small variations in wind speed and described using turbulence models. According to the DNV-RP-0286 code various models can describe wind turbulence spectra for wind turbines. The various wind spectra indicate that the critical range lies between 10 and 200 seconds, depending on specific wind speeds and other offshore conditions. Without a specific location, it is challenging to obtain the exact turbulence model and draw conclusions about potential resonance at this phase of the design. However, it can be concluded that further study on the specific turbulence wind spectra range is necessary, as the natural periods of the system are within this range [10].

Gust Events

In the low-frequency range, the consequences of gust events must also be analysed. Gusts are defined by their rise time, magnitude, and duration. To capture the largest dynamic responses, it is necessary to consider the system's natural periods when selecting gust duration. Smaller gusts with short periods are less likely to cause resonance due to their shorter duration and smaller magnitudes. Conversely, larger gusts with longer periods have greater duration and magnitudes, increasing the potential for resonance with the system's natural periods, which are around 200 seconds for pitch. It can be concluded from this that if resonance were to occur, it would have significant consequences. Therefore, further study is necessary to determine whether resonance occurs in pitch [11, 12, 14].

5.4.7. Conclusion

In conclusion, the natural periods of the system vary significantly between heave and pitch, with heave have a natural period of approximately 15-20 seconds and pitch around 200 seconds. For first-order

wave spectra, the natural period in heave is critical during the transport stage. The second-order wave spectra could potentially include the natural periods of both heave and pitch, requiring further analysis.

Regarding wind spectra, further analysis is needed with turbulence models and the impact of gust events.

The natural period in pitch is most critical under resonance conditions due to its influence on the acceleration at the top of the turbine, which must be avoided. Therefore, it is essential to conduct detailed analyses of both second-order waves and wind spectra to mitigate these risks.

5.5. Weather Window

In the context of previous critical issues, this section will discuss the impact of these issues on the weather window. These parameters can be used to estimate the weather conditions for executing the transport and installation method. The maximum angle of heel will be used to estimate the maximum heeling moment. Additionally, the consequences of the critical issue of the seabed placement, where the interface force is only 1000 tonnes, will be evaluated

5.5.1. Heeling Moment

After determining the maximum angle of heel, the heeling moment can be calculated. The heeling moment arises from external forces, such as wind, causing the floating system to rotate. This design research considers only the wind to determine the heeling moment, with other external forces being excluded in this context. The righting moment is the moment required to return a floating structure to the stable position. According to DNV standards, the area under the righting moment curve up to the maximum angle of heel should exceed the area under the heeling moment curve by at least 30%. This requirement ensures that the system can sufficiently manage dynamic responses. The calculations for the righting and heeling moment are performed incrementally for each 5-meter draft and elaborated in Section E.7, including the corresponding graphs.

The outcomes reveal that the horizontal external force decreases progressively throughout installation stage, as illustrated in Figure 5.10.

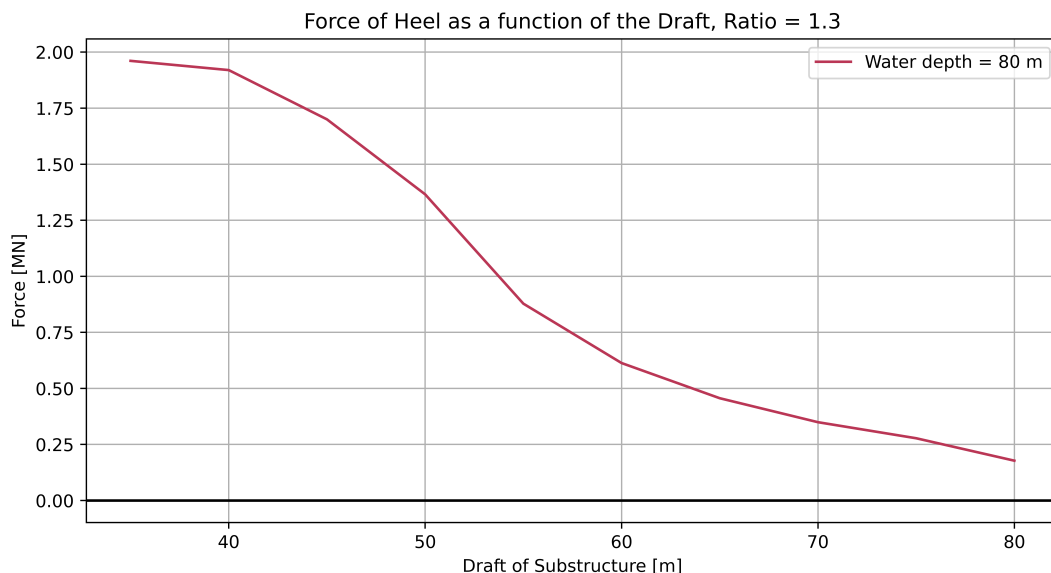


Figure 5.10: Maximum Allowable Horizontal External Force as a function of the Draft from Heeling Moment Analysis

The sharp decrease in horizontal environmental force (wind) is defined by the corresponding decrease in maximum angle of heel (Figure 5.4). The installation becomes increasingly more critical as the installation stage progresses. The horizontal environmental force decreases from 2 MN during the transport stage to 0.2 MN during the installation stage ($D = 80$ m). Note that other environmental

influences, such as sea conditions, play a role in weather window and are excluded in this consideration.

5.5.2. Interface Force

One of the critical issues identified from the seabed placement analysis is the need to reduce the interface force from 7000 to 1000 tonnes, which is a reduction of 1/7. Consequently, will the system be more sensitive to external forces. Additionally, conclusions drawn from the analysis of the heeling moment indicates that environmental forces during the lowering process must also decrease due to the maximum strength of the spud piles. This results in the horizontal external force decreasing from 2 MN during transport to 0.2 MN during lowering. A comparison of the two analyses shows a reduction in external forces in both the seabed placement and maximum heeling moment analyses.

Although both analyses do represent approximations of the forces, they both indicate a comparable decline during the lowering process. This suggests that the environmental conditions during the installation stage are critical and further analysis of the weather window during this stage is required for both aspects in a next design phase.

5.6. Conclusion and Implementation

This chapter presents several critical issues, including initial stability, maximum heeling angle, seabed placement, natural period, and weather window. The final conclusions drawn from these findings will be outlined.

Initial Stability

- Increasing the diameter of the top column of the bottom-fixed structure increases the stability.
- During installation stage the stability decreases.
- The deeper the total water depth, the lower the static stability.
- The installation stage is feasible up to a water depth of 80 meters, but this require adding weight in the bottom of the spud piles (heavy blocks).

Maximum Angle of Heel

- *During Transport*: the angle of deck edge immersion is the most critical factor. Gives a maximum angle of heel of 17°.
- *During Lowering*: during the lowering process, the strength of the spud piles becomes the pre-dominant factor. The maximum angle of heel decreases, from 17° to 2.5° during the installation stage.

Seabed Placement

- During the final installation step (placement on the seabed), heavy blocks will be used to prevent dynamic forces in the spud piles.
- The substructure will be placed using the pin-and-bucket principle on a foundation frame, which requires precise placement.

Natural Period

- The natural period in pitch is approximately between 177 and 214 seconds. It is not critical for first-order waves and wind, but the forces from second-order waves require further investigation. Oscillations in pitch are critical due to accelerations experienced at the top of the wind turbine.
- The natural period in heave is approximately 14-21 seconds. It is most critical during the transport stage, with the criticality gradually decreasing during the installation stage for first-order wave loads. In addition to first-order waves, second-order wave and wind effects also need to be analysed further. Oscillations in heave are less critical because they cause vertical movements, which have a less significant impact on structural dynamics.

Weather Window

- The maximum allowable horizontal environmental force decreases during the installation stage from 2 to 0.2 MN.

- Due to the use of heavy blocks for seabed placement, minimal environmental forces can be expected due to the lower interface force, reduced from 7000 to 1000 tonnes.

The design changes made during this analysis are:

- Change the diameter of the top column of the bottom-fixed structure from 11 to 12 meters, resulting in the following effects:
 - Increase static stability during installation stage,
 - An increase of wave loads on bottom-fixed structure.
- Implement heavy blocks in the spud piles, resulting in the following effects:
 - Increase static stability during installation stage,
 - An increase of the mass of the TIF.

Several limitations have been identified, outlining the requirements of the transport and installation method. The identified limitations and critical issues are listed in Table 5.6.

Parameter	Transport Draft = 30 m	Installation Draft = 75-80 m	Unit
Maximum angle of heel	17	2.5	<i>degrees</i>
Maximum environmental force horizontally	2	0.2	<i>MN</i>
Natural period for heave	14	21	<i>s</i>
Natural period for pitch	177	214	<i>s</i>
Interface force total	7000	1000	<i>tonnes</i>

Table 5.6: Limitations and Critical Issues

Based on this analysis, it can be concluded that during the transport stage, the natural period in heave aligns closely with the period of the first-order waves, potentially leading to resonance. The transport stage is important to consider in the design due to its duration and exposure to various weather conditions. It is crucial to conduct an analysis of these weather conditions during this stage and be prepared for various conditions. Therefore, in addition to evaluating the oscillations with the natural periods, further dynamic modeling is necessary to assess the system's response under various environmental conditions during the transport stage.

The natural period in pitch is relatively high, which is advantageous, but this does not eliminate the potential for resonance with external loads. Consequently, it remains essential to examine second-order wave and wind effects. This is crucial because oscillations in pitch are significant as they generate acceleration at the top of the wind turbine, which must be avoided.

During the installation stage, there is a greater flexibility in choosing when and under which weather conditions operations it can proceed. In contrast to the transport stage, the criticality of this stage does not lie in its duration, but rather in the understanding the specific weather conditions under which operations can be conducted safely. This is crucial because certain limitations identified in this report become more critical during installation. For instance, it is observed that during the installation stage the maximum angle of heel decreases as well as the interface force during seabed placement should be reduced. This increase in criticality during the installation stage highlights the importance of dynamically analysing these factors and assessing their impact on the weather window.

6

Transport and Installation Stages

In this chapter, the steps of the five installation will be explained. Delving deeper into the actions and providing examples of values to better illustrate their functioning. Conclusions will be provided for each stage regarding the actions and procedures to be executed. The stages include port preparation, transport, installation, repositioning, and operation.

This will be further explained for a water depth of 80 meters and a top column diameter of 12 meters, including the weight of the spud piles and the heavy blocks added to the total weight of the TIF. Table 6.1 provides the updated values, with the mass of the spud piles being 1341 tonnes and the mass of the heavy blocks being 1206 tonnes.

Table 6.1: Conclusion: Masses of Structures

Total mass		Value	Unit
Bottom-fixed Structure		2904	<i>tonnes</i>
Wind Turbine		1877	<i>tonnes</i>
TIF	$\text{Mass}_{TIF} + \text{Mass}_{\text{Spudpiles}} + \text{Mass}_{\text{heavy blocks}}$	8122	<i>tonnes</i>
Total Gravitational Force		12903	<i>tonnes</i>

6.1. Stage A: Port Preparation

In the port preparation stage, the main focus is on the preparation and installation of the TIF, substructures and wind turbine, making it ready for the transport to the offshore location. One of the challenges in this stage is the shallow water depth in the port. An estimation of the water depth can be observed from the port of Rotterdam. This provides an approximate estimation of the water depth of 20 meters [40]. However, it is important to note that water depth can vary between ports and may be shallower in some cases. In Figure 6.1, the preparation steps are schematically illustrated and will be further explained throughout this section.

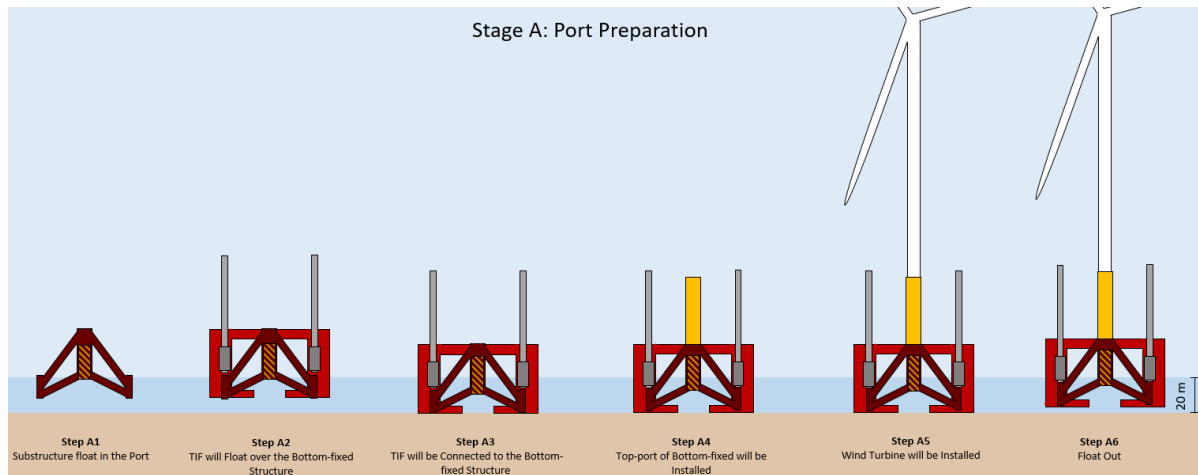


Figure 6.1: Installation Steps in Port

Step A1: Substructure Float in the Port

In the first step, the bottom-fixed structure (excluding the top column and wind turbine) is floated to the port. The buoyancy tanks are already installed on the structure at this stage, positioned at the mid column to ensure sufficient draft for the TIF to pass over in the next step. This setup allows for flexibility in adjusting the height of the buoyancy tanks based on the water depth of the port. Since the top column of the bottom-fixed structure has not yet been installed, the CoG is relatively low, and the bottom-fixed structure remains stable. The main values from this calculation and for this step are presented in Table 6.2.

Table 6.2: Key Parameters Step A1

Parameter		Value	Unit
Draft Substructure		11	<i>m</i>
Gravitational Force	$M_{\text{bottom-fixed structure}} - M_{\text{topcolumn}}$	2387	<i>tonnes</i>
Buoyancy Force	Formula D.15($D = 11$)	2387	<i>tonnes</i>
CoG		5	<i>m</i>
CoB		-6	<i>m</i>
$\overline{GM}$		37	<i>m</i>

The high metacentric height ($\overline{GM}$) is attributed to the larger water plane area, to which brace 0, the mid column, and buoyancy tanks contribute. The system meets the stability requirements and is stable in this stage.

Step A2: TIF will Float over the Bottom-fixed Structure

In step 2, the TIF will pass over the bottom-fixed structure with clearance. The draft of the TIF without the addition of extra seawater ballast is 9.50 meters. Note that this is higher than in Figure 4.2, because in this phase the spud piles and heavy blocks have been added to the weight of the TIF.

A draft of at most 11 meters is required for the TIF to pass over the bottom-fixed structure. To achieve this draft, 545 tonnes of ballast is required, which results in a height of 0.5 meters of seawater ballast in the TIF. In this step, the two structures are not connected yet and are still considered as two separate systems. The TIF is a stable system, so no additional stability analysis is required at this stage.

Table 6.3: Key Parameters Step A2

Parameter		Value	Unit
Draft TIF	= Draft substructure	11	<i>m</i>
Additional ballast in TIF		545	<i>tonnes</i>
Height Ballast TIF	Formula D.16($V = 532 \text{ m}^3$)	0.5	<i>m</i>
Gravitational Force	$M_{\text{TIF}} - M_{\text{ballast, TIF, stepA2}}$	8668	<i>tonnes</i>
Buoyancy Force	Formula D.13($D = 11$)	8668	<i>tonnes</i>

Step A3: TIF will be Connected to the Bottom-fixed Structure

In step 3, the two structures will be connected. This will be done by ballasting the TIF so it will push the bottom-fixed downwards. As a result, the TIF will rest on the seabed floor of the port and the bottom-fixed structure will exert a buoyancy force on the TIF. The bottom-fixed structure will not make contact with the seabed, as it is positioned one meter above the bottom of the TIF and exerts buoyant force. The draft of the TIF will be equal to the water depth of the port. This also ensures a stable system with the TIF grounded at the seabed of the port. To execute this action, the draft will be fixed for these calculations at a water depth of 20 meters in the port. This water depth can vary without affecting the principle.

To ensure that the bottom-fixed structure remains on the seabed floor of the port, a total of 9952 additional ballast in the TIF is required. This amount is necessary to compensate for the structure's own buoyancy as well as the buoyancy of the bottom-fixed structure.

Step A4 & A5: Top-part of Bottom-fixed Structure and Wind Turbine will be Installed

In the following steps, the top column of the bottom-fixed structure will be installed along with the wind turbine. In this process, only gravitational force will be added to the substructure, and no additional ballast need to be added in the TIF.

This process will be relatively easy because the TIF is grounded, making it a stationary structure that is not affected by wave movements. Additionally, being in the port is advantageous, as the cranes are stationed on the quay, facilitating the installation of the components.

However, a potential issue in this step involves the high gravitational force, which the seabed floor of the port cannot withstand. After the installation of the wind turbine, the total force will peak at 4314 tonnes. If the maximum allowable gravitational force of the seabed floor of the port is less than 4314 tonnes, this force can be reduced by removing a portion of the ballast from the TIF, thereby maintaining the maximum possible gravitational force within the port's limits. It is still necessary to ensure that there is sufficient ballast in the TIF to maintain the system on the seabed.

Step A6: Float Out

After installing the wind turbine on the bottom-fixed structure, it is ready for transport. For this purpose, ballast needs to be removed from the TIF so that it comes just above the seabed floor of the port. To provide an example, a scenario where the draft is assumed to be 17 meters, offering insight into the associated values.

Table 6.4: Key Parameters Step A6

Parameter		Value	Unit
Draft System		17	<i>m</i>
Additional ballast in TIF		4443	<i>tonnes</i>
Height Ballast TIF	Formula D.16($V = 4293 \text{ m}^3$)	4	<i>m</i>
Gravitational Force	= - Buoyancy Force	589	<i>tonnes</i>

The interface force is approximately 600 tonnes, making it highly sensitive to environmental forces. During the initial stage of the tow-out to the offshore location, a reduction in interface forces may occur due to the short duration of this phase and the lower environmental forces near the shore. However, it is crucial to mention the significance of the low interface force during this step.

Summary: Port Preparation

A summary of the draft, the amount of ballast, and extra buoyancy is presented in Table 6.5 for each preparation step.

Table 6.5: Summary of Draft Values for the Systems and Required Actions During Port Preparation Stage

Step	Draft <i>m</i>	Add/Reduce Ballast in TIF	Action <i>tonnes</i>	Total Ballast in TIF <i>tonnes</i>	Interface Force <i>tonnes</i>
A1	11				
A2	11	Add	+546	546	
A3	20	Add	+9406	9952	4465
A4	20			9952	4465
A5	20			9952	4465
A6	17	Reduce	-5508	4443	589

6.2. Stage B: Transport

This section will describe the transport stage, which is the tow-out of the TIF using tugboats. Multiple tugboats will be positioned around the TIF, guiding it to the correct offshore location. The quantity of tugboats and their speed have not yet been finalised.

The system will have a draft of 17 meters, when exits the port. However, as previously discussed, to ensure a large enough weather window, an interface force of 7000 tonnes, and a draft of approximately 30 meters during transport is needed. This means that as soon as the water depth allows, the draft, and consequently the interface force, can be increased. This can simply be achieved by adding ballast to the TIF. As a result, the additional ballast increases from 4443 tonnes (at 17 meters draft) to 16960 tonnes during the transport stage.

Table 6.6: Key Parameters Transport Stage

Parameter	Value	Unit
Draft System	29.10	<i>m</i>
Additional ballast in TIF	16960	<i>tonnes</i>
Gravitational Force = - Buoyancy Force	6544	<i>tonnes</i>

One of the most crucial aspects to be addressed during this stage was the verification of stability, which is sufficient for the transport stage, followed by the requirements of the HSE standards [20]. The parameters are provided in Table 6.7.

Table 6.7: CoG, CoB, and $\overline{GM}$ during Transport Stage

Parameter	Value	Unit
CoG	-5	<i>m</i>
CoB	-21	<i>m</i>
$\overline{GM}$	6	<i>m</i>

6.3. Stage C: Installation Offshore

After transport, the installation of the substructure will take place. This process involves lowering the substructure while the TIF remains at sea level. This process occurs under compression, causing the substructure to experience a buoyancy force while the TIF applies a gravitational force to push the substructure downwards.

Step C0: Seabed Preparation

Step 0 involves seabed preparation, a crucial phase for establishing a straight foundation. This process starts with surveys to evaluate seabed characteristics and identify potential obstructions. As previously

discussed in Section 5.3.1, a mudmat will be installed. This approach enables seabed preparation to be conducted well in advance, minimising the likelihood of returning to previous conditions due to sea movements. The mudmats can be installed perfectly straight by hammering the foundation piles. This precision is necessary to ensure the wind turbine maintains aligned. This method fulfills the requirement that the tilt of an offshore wind turbine is limited to 0.25 degrees, as stated in DNV-ST-0126 [13].

Step C1: Lowering Process (30-75 m)

Reaching the offshore location, the substructure will be lowered to the seabed. During lowering, the interface remain constant, as well as the draft of the TIF. To maintain constant interface force while the buoyancy force of the substructure increases, additional weight needs to be added to the substructure. This can be achieved by gradually refilling the buoyancy tanks with seawater ballast. The buoyancy tanks are completely filled with seawater at a depth of approximately 78 meters. After that, the substructure braces can be filled. During this step, the interface force will remain constant at 6802 tonnes, and there will be no change in the ballasting of the TIF. The draft of the TIF will remain constant at 30 meters with a constant ballast of 17502 tonnes.

Please refer to Figure D.5 for the illustration represent the progression of adding seawater to the buoyancy tanks. Below, in Table 6.8, a summary of the steps to be taken every 5 meters is provided.

Table 6.8: Step C1: Summary of Draft Values for the Substructure and Required Actions During Lowering Process

Draft <i>m</i>	Add Ballast: Buoyancy Tanks <i>tonnes</i>	Brace 1 <i>tonnes</i>	Total Ballast in Substructure <i>tonnes</i>	$\overline{GM}$ <i>m</i>
30-35	+1430		1430	6.23
35-40	+969		2402	5.27
40-45	+656		3059	4.50
45-50	+580		3638	4.07
50-55	+580		4218	3.82
55-60	+580		4798	3.63
60-65	+580		5377	3.51
65-70	+580		5957	3.45
70-75	+43	+537	6537	3.45

After this process, the buoyancy tanks are completely filled, and brace 1 is filled with a total of 537 tonnes of seawater ballast, resulting in being approximately 23% filled with water.

For the stability in this stage, the initial static stability checks have been done, and are represented by the purple line in Figure 5.6. The $\overline{GM}$ during these steps are shown in Table 6.8, indicating that the $\overline{GM}$ decreases during installation but remains above the minimum value of 1.0 for sufficient initial stability.

Step C2: Right Location (75 - 77 m)

The first step involves precisely positioning of the foundation sleeve (with a diameter of 5 meters) above the thin pin on the mudmat. By adding extra ballast to the TIF, the substructure can be lowered exact over the thin pin of the mudmat. The Remotely Operated Vehicles (ROVs) will locate the precise position, and the tugboats will ensure that the TIF is precisely positioned above the pins. The lowering process will do the initial 2 meters, after which it will proceed with the next steps of lowering and seabed placement.

Step C3: Seabed Placement (77 - 80 m)

The final 3 meters of the process will be executed using heavy blocks. The interface force needs to be decreased from approximately 7000 tonnes to 1000 tonnes (considering the blocks weight 1200 tonnes) during the final 3 meters before placing the substructure on the mudmat.

The buoyancy force of the substructure must be reduced to 1000 tonnes, which can be achieved by adding additional ballast to the remaining braces with seawater. Additionally, the gravitational force of the TIF must also be reduced to 1000 tonnes to maintain vertical equilibrium. This can be achieved

by pumping seawater ballast out of the TIF.

In Table 6.9, the draft and the required actions for adding or reducing ballast in both the TIF and the substructure are provided. In the substructure, the braces are filled with seawater to reduce the buoyancy force. Brace 1 is initially fully filled, followed by the mid column. Brace 0 is filled to 780 tonnes, which is 33% of the total brace capacity.

Table 6.9: Step C3: Summary of Draft Values for the Substructure and Required Actions During Seabed Placement

Structure	Add Ballast <i>tonnes</i>	Reduce Ballast <i>tonnes</i>	Total Additional Ballast <i>tonnes</i>
TIF:		-5545	11417
Substructure:	+5545		6081 (+ 6000) _{Buoyancy tanks}
(Brace 1	+1794)		
(Mid column	+2970)		
(Brace0	+780)		

Filling the braces of the bottom-fixed structure must occur simultaneously with pumping seawater ballast out of the TIF. This can be executed at a draft of 77 meters.

Once this is completed, and the TIF and substructure has the right amount of interface force, the heavy blocks can be released, causing the substructure to lower. Ensuring precise positioning of the TIF above the substructure by the ROVs is crucial during this installation step. This ensures minimal environmental influences during this installation step.

Step C4: On-Bottom Stability

After the heavy blocks have placed the substructure on the mudmat, it is essential to ensure sufficient on-bottom stability. To achieve this, the remaining braces are also filled. The substructure will experience a gravitational force of 4666 tonnes after filling all braces. Further elaboration on this topic is provided in Appendix section F.1.2.

Step C5: Uncoupling the TIF

To prevent contact between the TIF and the substructure due to sea movements and the stationary position of the structure, it is crucial for the tugboats to remain connected to the TIF to prevent this. Once the substructure has gained sufficient on-bottom stability, it is possible to disconnect the substructure and the TIF. This can be achieved by lifting the heavy blocks in the spud piles again. Afterward, the spud piles can be raised. Following this, the TIF can be towed away.

Step C6: Foundation Grouting

The next step is the grouting of the mudmat and the pile sleeves of the bottom-fixed structure. Grout is an essential component to provide structural stability and integrity to the foundation, while also facilitating the efficient transfer of loads from the wind turbine to the seabed [1].

Step C7: Removing the Buoyancy Tanks

Once this procedure has been completed, the buoyancy tanks can be removed. Although currently filled, they are still connected to the substructure, making them quite heavy. Each buoyancy tank weights 2000 tonnes and can be lifted by heavy-lift vessels. Compressing the air inside the tanks underwater is not feasible due to the risk of sudden rise, which could lead to hazardous situations. Once at the water level, the buoyancy tanks can be emptied and refilled with compressed air for the transport back to the port [35]. Their removal allows for reuse in other installations.

The step can potentially be swapped with C6, which may be more logistically and practically convenient. From a feasibility standpoint, the order does not impact the outcome, as the on-bottom gravitational force remains consistent regardless of the presence of buoyancy force.

6.4. Stage D: Repositioning and Decommissioning

This stage will present a description of the consequences of incorrect placement of the substructure and the decommissioning process.

6.4.1. Repositioning

Due to the irreversible possibility of using heavy blocks, an extra thin pin has been implemented to the mudmat. Before lowering the heavy blocks, a initial pin-and-bucket system will be used to ensure precise alignment of the substructure at the mudmat. Using ROVs, checks are done to verify the accuracy of placement. The lowering of the TIF over the first pin is achieved by ballasting the TIF. In case of misalignment, adjustments can be made by deballasting the TIF again. This process allows the structure to be raised, providing an opportunity for repositioning. As a result, the heavy blocks system does not need to be reversible.

By adding these initial thin pins, it becomes possible to better verify whether the substructure is positioned correctly. Once the structure is correctly positioned, the heavy blocks can be released.

6.4.2. Decommissioning

For the decommissioning process, the situation differs, as the substructure has been resting on the seabed floor for some time. Before decommissioning begins, an inspection is done to assess the condition of the foundation and bottom-fixed structure.

At this stage of the design process, it is not yet feasible to use the TIF for the decommissioning of the bottom-fixed structure and the wind turbine with an integrated method. The initial step will be to disassemble the wind turbine from the bottom-fixed structure. Subsequently, the BTA (buoyancy tanks assembly) can be used to decommission the bottom-fixed structure and the mudmats. After the BTA being attached to the bottom-fixed structure, they can be filled with compressed air. This causes the bottom-fixed structure to rise and float to the waterline, enabling them to be towed back to port. This method is a well-established technique in offshore decommissioning for jacket and tripod structures and will therefore be applied in the decommissioning of this transport and installation method [35].

6.5. Stage E: Operation

During the operation stage, the wind turbine will rotate to generate energy. At this stage, all braces and columns of the bottom-fixed structure are filled with seawater ballast, and the buoyancy tanks are removed, resulting in a vertical gravity load of 45 MN. This load is supported by the sufficient bearing capacity of the mudmats.

A critical aspect of this stage is that the rotation of the blades will generate thrust force, significantly impacting the structure and creating a moment at the seabed. Consequently, this stage is crucial for the forces acting on the braces, and therefore, the braces are dimensioned based on these forces. Further explanations can be found in Chapter 3 and Appendix B and C.

The analysis considered a vertical load of 45 MN and a horizontal load of 8 MN, resulting in an overturning moment of 830 MNm at the seabed. It was concluded that, under these conditions, there is sufficient bottom stability and no tensile force on the foundation piles. However, foundation piles were included in the design to provide additional horizontal resistance and to allow for more extreme weather conditions as the calculations were based on the rated wind speed.

Addressing Remaining Challenges

This chapter will investigate the assumptions and simplifications made and evaluate whether the overarching aim of this design research has been achieved. Additionally, it will assess the flexibility of the design, given its current conceptual stage. Finally, this chapter will identify and evaluate the remaining challenges to provide answers to the research question.

7.1. Discussion

This section reflects on the design of the developed transport and installation methodology. The evaluation includes a review of the assumptions and assessment of whether the overarching objectives have been met.

Following the design circles, this research was analysed in three phases (Figure 1.1). Initially, a broad examination of the problem was conducted to define the scope and creating an overview of all transport and installation stages. Subsequently, the design of the bottom-fixed structure, which could be installed using the TIF, was explored. Finally, the limitations of this transport and installation methodology were examined, particularly focusing on the maximum angle of heel, natural period, and environmental conditions. Each design decision was carefully considered to understand the underlying processes and implementation.

This design research aimed primarily to investigate the initial feasibility, requiring assumptions. These key considerations and their implications will be described below.

- The first assumption made relates to the selection of the wind turbine. The IEA 15 MW reference turbine was selected based on market research and anticipated future developments. The feasibility of smaller wind turbines may be maintained due to a lower CoG. In contrast, enlarging the wind turbine is expected to have predominantly negative effects on the methodology. For this reason, it must be noted that the results of this research are not conclusive, and that they apply exclusively to the selected 15 MW wind turbine.
- Furthermore, the objective of this design research is to provide a generalised approach, rather than proving a solution for a specific location. Consequently, no metocean data was available, and assumptions have been made to define the order of magnitude of the environmental conditions. Only the most critical parameters (wind, wave, and current) were included in the analysis and simplified formulas were used. This was sufficient for the current phase of the design, as the environmental forces were used for the dimensioning of the bottom-fixed structure, and did not significantly impact the transport and installation methodology.
- Another simplification was implemented in the calculations of the buoyancy forces and static stability. Simplified shapes were used for surface areas, volumes, and inertia's of the TIF and the substructure. Although these calculations do not precisely reflect the exact shapes, they do provide a reliable indication of the order of magnitude, as the main dimensions are accurate.

Simplifications regarding the connections between the braces may not be accurate, but these connections are not expected to significantly impact the outcome. This is because they are related to the values of the braces, ensuring their alignment within the calculated range.

- Furthermore, it was assumed to use the same interface force during the transport stage of the TLP for the installation of the bottom-fixed structure. This decision was based on the continued progression in the development and analysis of dynamic models for the TLP installation. The incorporation of this value provides an approximation of the order of magnitude. However, the precision of this approximation remains limited. It is probable that for the installation of the bottom-fixed structure, the interface force will be greater than required for TLP transport. This is because the wind turbine is approximately 40 meters higher, resulting in a higher CoG. Consequently, it is more sensitive to instability, potentially requiring a greater interface force to operate under similar weather conditions. As a result, this assumption leads to an optimistic outcome for the required additional ballast and buoyancy.
- The natural period was defined using a simplified model focusing on heave, pitch, and surge. Simplified formulas and values were used for the calculation of the inertia and the restoring forces. Additionally, an assumption was made regarding the added mass, although the influence of this parameter has been assessed. With all these simplifications and assumptions, it cannot be concluded that this critical issue will be sufficiently resolved. However, this analysis provides valuable insights into which degree of freedom and which stage are most critical and requires further investigation.
- Finally, in the analysis on the weather window, certain environmental conditions were excluded. In this design research, only horizontal wind forces were taken into account to define the heeling moment, while factors such as waves and currents are disregarded. Consequently, the weather window is likely to be less favourable than currently determined.

In this research, to identify the critical issues and limitations, assumptions and simplifications have been made. Each design choice provided a more in-depth level and thereby narrowed the design flexibility. The following section will discuss the remaining design flexibility and future implementations.

7.2. Assessing Design Flexibility

This section will discuss the flexibility of the design and identify which elements allow adjustment. Specifically, the interface force, the strength of the spud piles, and the bottom-fixed structure will be examined. In addition, the impact of potential future implementations will be discussed.

Interface Force

One of the assumptions made is regarding the interface force, which was estimated based on the order of magnitude of the interface force used for the TLP transport. Therefore, there is a possibility that this value may change after doing a dynamic analysis to define a more precise value. The interface force represents the net buoyancy of the substructures and the net gravitational force of the TIF. These values are crucial for defining the weather window and the forces acting on the spud piles, which in turn determine the dimensions of the spud piles.

If the interface force is defined to be larger, it would require larger buoyancy tanks on the bottom-fixed structure and an increase in ballast in the TIF. This is less favorable due to the need for larger tanks, but the transport and installation methodology allows for these possibilities. On the other hand, if the interface force turns out to be smaller, it would be advantageous. This would mean smaller buoyancy tanks and less ballast in the TIF, which is also feasible within this methodology.

In conclusion, this transport and installation methodology provides the flexibility needed to manage the interface force as required using the compression principle. There are constraints on the maximum interface force. The size of the buoyancy tanks are restricted, and the capacity for ballast in the TIF is finite. Additionally, with large interface force, the strength of the spud piles will also become critical and would need to be re-evaluated.

Strength Spud Piles

The dimensions of the spud piles are defined by the API strength standards, which determine the maximum forces based on their dimensions. Currently, dynamic loads are excluded from these design calculations. Consequently, dynamic loads have the potential to increase the forces in the spud piles, potentially requiring an increase in their dimensions.

Larger dimensions will result in increased mass, which can be compensated for by reducing the ballast in the TIF. In addition, larger spud piles will increase buoyancy, which can be balanced by adding more ballast in the TIF. Although changes in the dimensions of the spud piles will affect the CoB and the CoG, these adjustments are unlikely to have significant impacts due to their proportional insignificance. In conclusion, there is flexibility to accommodate changes in the dimensions of the spud piles within this design without changing the transport and installation methodology.

Strength Bottom-fixed Structure

In the initial design phase of the bottom-fixed structure, API standards were used to define the dimensions. As a result, unity checks ranged from 0.6 to 0.98, which fulfills the requirement that unity checks should be below 1 (Appendix C). During this initial stage of design, it is recommended to maintain unity checks between 0.6 and 0.8 to have sufficient flexibility for adjustments. A unity check of 0.98 for brace 0 indicates limited flexibility in the design. To address this particular high unity check, it can be improved by increasing the brace thickness or increasing the number of stiffeners. It is important to consider that these changes will also increase the mass, which will subsequently decrease the interface force.

To conclude, these unity checks are assumed to provide an indication of the magnitude of order for the dimensions of the bottom-fixed structure, but they do not necessarily represent the maximum unity checks. This example highlights that there are opportunities to change the bottom-fixed structure to lower the unity checks, thereby increasing flexibility for further design phases.

7.2.1. Potential Future Implementations

As discussed in the first section, this design is specifically designed for a 15 MW wind turbine at a water depth of 80 meters. However, it is crucial to consider potential variations of this design for different wind turbines and varying water depths to provide flexibility for future applications. This analysis focuses on implementing larger wind turbines and exploring greater water depths.

Increasing Wind Turbine Size

As described in the introduction, there is a growing demand for larger wind turbines due to increasing energy consumption. This trend requires wind turbines with higher energy production, resulting in an increase in the size of the wind turbine. To remain viable in the market, the transport and installation method must be adaptable to accommodate larger turbines.

This research has focused on a 15 MW wind turbine, one of the remaining challenges is to assess the implications of larger turbines on the design of the bottom-fixed structure and the transport and installation methodology. Larger turbines have an increase in mass, which requires a greater buoyancy in the bottom-fixed structure to maintain the same interface force. Additionally, taller turbines have a negative effect on stability because of the higher CoG of the wind turbine. The current design maintains a margin above the stability threshold of 1 meter in the static stability analysis. Therefore, it can be derived that there is some flexibility for larger wind turbines based on this research. However, this analysis only considers static stability without considering dynamic loads. Therefore, evaluating the flexibility of the design for a larger wind turbine is challenging, as the implications on dynamic stability remain uncertain in this study.

In conclusion, an increase in the size of the wind turbine has a negative effect on stability and the interface force, requiring increased buoyancy in the bottom-fixed structure.

Greater Water Depths

In addition to larger turbines, future offshore wind installations may also be located in deeper waters. Deeper water requires extending the bottom-fixed structure, which impacts weight and buoyancy considerations. Furthermore, if the structure is placed at a deeper water depth, the height of the wind turbine increases, raising the CoG and impacting the stability.

The current design provides sufficient static stability margin for water depths up to 90 meters, maintaining a $\overline{GM}$ above the 1 meter threshold during the installation stage. In this case only the top column

has increased with 10 meters, to be installed at a water depth of 90 meters. However, this assumes that there are no changes to the rest of the bottom-fixed structure design. In reality, deeper water depths introduce greater internal forces and moments, requiring other structural changes as well. Furthermore, this assessment focuses only on static stability, without considering dynamic behavior, which presents additional remaining challenges.

In conclusion, this design expected has limited capability to accommodate deeper water depths. Extending the top column could potentially allow installation at water depths of up to 90 meters, but this aspect of the design still requires further evaluation. Therefore, further investigation is needed to understand the implications and explore potential flexibility to make the design future proof.

By identifying and resolving the most critical issues, assumptions and design choices were made, thereby narrowing the design flexibility. These steps were taken to develop an initial response to assess the feasibility of the TIF for bottom-fixed wind. However, fully addressing the feasibility of the TIF for bottom-fixed wind also requires the examination of other challenges. The next section will provide an overview of challenges needed to complete the feasibility.

7.3. Remaining Challenges

This section will outline the most significant factors that must be addressed to achieve complete feasibility. These factors include technical feasibility and other feasibility assessments such as logistic feasibility, economic feasibility, environmental impact assessment, and social & legal feasibility. In Chapter 9, the recommendations for addressing these remaining challenges will be explained.

7.3.1. Technical Feasibility Assessment

One of the key aspects addressed in this design research is technical feasibility. As the scope was narrowed down from a broad perspective to address and resolve critical technical issues, the technical feasibility was explored. In this design report, the analyses are primarily statically defined, and despite delving deeper each time, some issues remain unaddressed or unresolved. One of the remaining challenges is the dynamic behavior of the identified critical issues, which will require a more in-depth assessment. This involves using models within computer programs like OrcaFlex to accurately evaluate the dynamic response. The remaining technical issues, which have been identified, are listed below.

Weather Window

One remaining challenge in this research is to gain a better understanding of how the findings relate to the weather window, including specifying values of significant wave height, wind speed, and wave period. In this research, the critical stages for the weather window have been identified. However, the installation duration and the implications of the weather window are still undefined. The weather window can be a critical aspect of an offshore transport and installation method, and if too narrow, the design or methodology may need to be changed.

Dynamic Stability

Another remaining challenge that needs to be investigated is the dynamic stability. Dynamic stability include to the time dependent response of a system to external loads. It examines whether movements dampen or increase (unstable response) over time. In this report, static stability has been verified and meets the requirements. However, the system's responses to dynamic loads, which also influence the stability, remain a challenge.

Seabed Placement

The next remaining challenge concerns the final installation step. Although this step has been statically analysed, it requires further dynamic analysis. It concerns the moment just before releasing the heavy blocks above the seabed. In this step the interface force changes significantly, from 7000 tonnes to 1000 tonnes. The impact on the weather window resulting from this change still needs to be investigated.

Furthermore, the system's behaviour when the heavy blocks are hanging on the wires and being pushed to the seabed introduces an additional complexity. It will operate as a two-body system, which requires dynamic analysis. Only static analysis is conducted and further research is therefore needed to understand how these systems interact during this step.

Second-order Wave Effects

Another significant challenge involves the second-order wave effects on the system and the potential for resonance with its natural periods. Due to the relatively high natural periods in pitch and the criticality of pitch oscillations, analysing these periods is essential, as resonance could have a significant impact on the system.

Wind Induced Effects

Another remaining challenge is to examine the impact of the wind loads. The natural periods of the system are relatively high, similar to the periods of the wind loads. Therefore, it is necessary to conduct a more in-depth analysis of the wind periods and resonance effects for a specific location.

Vortex Induced Vibrations

The next challenge not addressed in this report is the influence of Vortex Induced Vibrations on the top of the wind turbine during transport and installation. Vortex Induced Vibrations arises when vortex shedding induces vibrations that align with the systems natural period. These vibrations are increasingly common for larger wind turbines, as they are more sensitive to oscillations due to higher natural periods. These oscillations must be mitigated, due to the significant accelerations experienced at the top and potential blade stresses that could induce fatigue [10, 11, 31].

Structural Design

Another remaining challenge is the strength of the members of the bottom-fixed structure. The initial estimation of the dimensions of the braces in this report was derived from design codes [2]. However, confirming their strength will require more advanced modeling techniques. This requires more precise values of the hydrostatic, hydrodynamic, and wind loads.

Fatigue is another critical aspect that has not been addressed. This research provides an initial understanding of the structural integrity under static loads, but the impact of dynamic loads such as waves and wind on fatigue damage remains unexplored. Understanding fatigue behavior is essential for ensuring structural integrity, safety, and lifespan. Fatigue occurs when structures are subjected to cyclic loads due to environmental factors or operational loads.

Given the large diameters and large joints of braces in the design of bottom-fixed structures, fatigue is a significant issue that warrants further investigation. This is because fatigue failure is most likely to occur at stress hot spots, particularly in tubular welded joints subjected to bending stresses [41].

7.3.2. Comprehensive Feasibility Assessments

In addition to the technical feasibility of this transport and installation method, it is crucial to consider broader feasibility aspects to mitigate potential issues during further development. This includes discussing logistic feasibility, economic feasibility, environmental impact assessment, and social & legal feasibility.

Logistic Feasibility

In this research, an analysis has been done to explore the different installation stages and to find the critical stages. Certain areas require further investigation to achieve a complete understanding, and will be mentioned below.

Further clarification is necessary regarding the project location in order to define the environmental conditions and facilities. Another aspect to be taken into account is manufacturability of the structures. It is essential to define whether there are suitable facilities capable of manufacturing (multiple) and delivering the structures to the port.

Another crucial aspect to be considered during the early design phase is safety. This include assessing potential risks associated within the transport and installation method, as well as implementing measures to mitigate these risks.

Economic Feasibility

Another aspect not addressed in this design research is the costs associated with this methodology. This is essential for comparing it with alternative installation methods in offshore wind, in order to identify

market opportunities. This involves the initial costs of construction, as well as the costs for execution of the method. In order to achieve the objective of this design research, it is essential to consider the multi-functionality of the frame. Obtaining an estimate of these costs at an early stage of the feasibility study is essential because this stage still allows flexibility to adjust the design.

Environmental Impact Assessment

In offshore projects, considering the environmental impact is crucial. The Environmental Impact Assessment evaluates the project's effects on marine ecosystems, encompassing factors such as water pollution, underwater noise, air quality, and emissions. The aim of Environmental Impact Assessment is to identify and assess these impacts, implementing measures to minimise them in accordance with regulations and standards [3]. Additionally, the life cycle is a crucial aspect to demonstrate the market potential of this methodology, including the construction, operation, and decommissioning stages.

Social & Legal Feasibility

This design research was commissioned by BES, which developed the research objective. Since the project is approached from a business perspective, a stakeholder analysis is required to identify the interests of all relevant parties. Conducting this analysis is crucial from the initial phase and must be maintained throughout the design process to ensure that all interests are addressed. Given the dynamic character of the offshore wind sector, it is essential to remain informed and adaptable. Furthermore, legal feasibility is also a crucial aspect in achieving complete feasibility, although it may not be one of the essential follow-up studies that must be conducted.

7.4. Conclusion

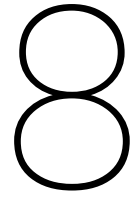
The objective of this research was to assess the feasibility of the TIF for bottom-fixed wind. In this analysis, assumptions and simplifications of the problem have been made and their consequences have been discussed. The assumptions regarding the interface force and environmental force are likely to result in less favorable values. For the overarching objective of this research, assumptions and simplifications are sufficient to identify the most significant issues. However, further refinement in the next design phases is necessary to assign more precise values.

This design demonstrates flexibility, accommodating adjustments in interface force, spud pile strength, and the dimensions in the bottom-fixed structure. This design gives an initial estimate of the values. The interface force, whether increasing or decreasing, can be managed by modifying buoyancy tanks and ballast in the TIF. Spud piles can be resized to withstand greater forces. Each aspect has its limitations, but minor adjustments are possible to maintain the same transport and installation principle.

To future-proof the design, it is essential to consider larger wind turbines and deeper water depths, both will negatively affect the stability. Although this design has analysed static stability, the impact on dynamic stability remains uncertain. This highlights the need for further research to ensure adaptability for future applications in varying conditions.

Additionally, the remaining challenges in this design have been discussed. For technical feasibility, an analysis with advanced models is needed, focusing on critical aspects highlighted in this study, including the weather window, dynamic analysis, and structural design. Key considerations for the dynamic analysis will include seabed placement, second-order wave effects, wind- and vortex-induced vibrations, and fatigue of the structural design. These aspects will be further detailed in Chapter 9, where the recommendations will be given.

In addition, this chapter underscores the importance of gaining an overview of all required elements to evaluate the feasibility of a transport and installation method. It highlights that there is more to consider than technical feasibility and it outlines the components necessary to get to the next step in the feasibility study. Additional considerations include logistical feasibility, which requires a detailed analysis of each stage and refinement of the project location, installation time, and a cost estimation is required.



Conclusion

The aim of this research project is to assess the feasibility of the Transport and Installation Frame for bottom-fixed wind.

This aim was achieved by addressing four sub-questions, each of which provides further clarification.

What is the transport and installation methodology with the TIF?

The transport and installation methodology of a bottom-fixed structure and wind turbine using the TIF will be divided in multiple steps. Beginning with the port preparation stage, where the three structures, bottom-fixed structure, 15 MW wind turbine and the TIF, are assembled and made ready for transport. In the transport stage, additional ballast is added to the TIF to achieve a gravity-based structure, in contrast to the buoyancy-based bottom-fixed structure, to ensure a connection. The large surface area of the TIF provides sufficient stability during this stage. During the installation stage, the bottom-fixed structure and the wind turbine are pushed down to the seabed at 80 meters by spud piles. The process is initiated by a hydraulic cylinder, which gradually pushes the buoyancy-based bottom-fixed structure downward. The last few meters, heavy blocks (attached to a wire in the spud piles) are released, thereby placing the bottom-fixed structure as a buoyancy-based structure on a pre-installed mudmat on the seabed. To position the bottom-fixed structure on the mudmat a pin-and-bucket system is used. After the placement of the bottom-fixed structure the TIF can repeat the transport and installation process for the next bottom-fixed structure with wind turbine.

What is the design of the bottom-fixed structure?

The design of the bottom-fixed structure is a tripod structure that is well-suited for integration into the TIF. This design offers essential buoyancy to facilitate the transport and installation stages. During transport and installation, additional buoyancy tanks will be attached to provide a large enough interface force. This interface force is required to ensure a sufficient connection between the structures. During the operation stage, these tanks will be removed, and the braces will be filled with water to ensure on-bottom stability. The bottom-fixed structure will be placed on the mudmats to provide sufficient bearing capacity and to maintain the wind turbine in an upright position.

At what loading does transport and installation remain feasible?

The weather window during installation process become increasingly narrower. This reduction is due to the decrease in the maximum angle of heel from 17 degrees during transport to 2.5 degrees during installation, limited by deck edge immersion and the strength of the spud piles. Additionally, during the installation, the interface force will decrease from 7000 tonnes to 1000 tonnes due to the implementation of heavy blocks for the seabed placement, which negatively impacts the weather window for this stage. The natural periods in heave and pitch are approximately 15 and 200 seconds, respectively. During the transport stage, the natural period in heave is most critical, particularly regarding the first-order wave spectrum. Resonance with the system's natural period in pitch would be more critical. Further investigation into the natural periods is needed for second-order wave and wind loads, as this could potentially lead to resonance.

Which additional issues must be addressed to demonstrate feasibility?

Additional issues that must be addressed include logistical feasibility, including refinement the project location and installation time. Conducting an initial cost estimation and market opportunity assessment is essential as well. Furthermore, a more comprehensive technical analysis should be performed using advanced models. This analysis should examine critical aspects highlighted in this study, including dynamic behavior, weather window, and static optimisation. With a focus on the dynamic effects of the seabed placement, the interface force reduction, dynamic stability, and potential resonance with wave and wind loads.

By addressing the sub-questions based on this design research and the conclusions drawn, a statement regarding the aim can be formulated.

The aim of this research project is to assess the feasibility of the Transport and Installation Frame for bottom-fixed wind.

Based on this design research, in which the compression principle has been investigated, there is no reason to assume that the transport and installation of a bottom-fixed structure with the TIF is not feasible within the identified limitations. This conclusion is based on analytical and static calculations in which various critical issues have been identified and resolved.

This transport and installation method has been evaluated for static stability, maximum heeling angles, deck or edge immersion, spud pile strength, seabed placement, and the natural periods in heave and pitch. The findings of this research highlight that as the installation stage progresses, the static stability and the weather window becomes increasingly more critical. These issues require further investigation in future design research. Focusing on understanding the dynamic behavior during seabed placement, dynamic responses to external loads, and the impact on the weather window when reducing the interface force. In addition, for future research, it is recommended to provide an overview of the specific location, cost estimation, and installation time.

9

Recommendations

Based on the results of this design research, insights gained from analysis, and conclusions, a set of recommendations is formulated. These recommendations are divided into two categories: further investigation on the current design and broader implications and applications.

9.1. Recommendations on Current Design

In this design research, the scope was initially defined, design choices were made, and issues were identified (and solved). Each design choice and issue were thoroughly verified in this report, delving into its feasibility.

This design research provided a basis for continuing with the design of the transport and installation method for bottom-fixed wind. However, in Chapter 7, Identifying Remaining Challenges, the essential aspects required for feasibility have been outlined and discussed. In this section, the following recommendations are provided for further development of the current design based on these remaining challenges.

9.1.1. Technical Feasibility

This report has focused primarily on the technical feasibility of the transport and installation method. The recommendations set out below will provide further elaboration on the specific technical aspects.

Dynamic Analysis

- It is recommended to define specific weather windows for each transport and installation step. This involves determining significant wave heights, wind speeds, and wave periods at which the methodology remains feasible. In addition, defining the duration of each phase is crucial.
- It is recommended to further investigate and refine the natural periods in all six directions by using a dynamic model in OrcaFlex to gain deeper insights into the dynamic behaviour.
- A recommendation is to conduct a dynamic analysis focused on the final installation step, particularly during the release of heavy blocks. While this study has demonstrated practical feasibility for the seabed placement, the use of cables introduces a two-body system. Therefore, a comprehensive study using a dynamic model is recommended to understand the interaction between the bodies and the response to external loads.
- It is recommended to perform a Response Amplitude Operator analysis to evaluate how the system responds to wave induced motions. It will provide insights into the system's response across different periods, including resonance effects.
- This report has analysed the static stability. However, it is also recommended to investigate time dependent responses to assess the influence of dynamic loads on the stability. By understanding the response to dynamic external forces, dynamic stability can be evaluated.
- It is recommended to analyse the effect of the second-order wave loads into the dynamic analysis. Given the relatively high natural period, especially in pitch, there is an increased potential for resonance with long waves generated by regular wave groups. Including second-order effects will improve the accuracy of the dynamic model under realistic wave conditions.

- It is recommended to incorporate wind induced loads into the dynamic model and analyse the potential for resonance. Furthermore, it is recommended to assess the potential for resonance in vortex-induced vibrations.

Structural Design

In this design research, the focus was on the design of the transport and installation methodology, and an initial design for the bottom-fixed structure was developed. Therefore, the following discussion will discuss whether the current design of the bottom-fixed structure requires further adjustments or deeper design iteration.

- It is recommended to explore possible optimisations for the connection between brace 0 and brace 1. The practical use of the foundation sleeve has shifted from driving foundation piles through it, to serve as a connection. Reevaluating this connection is crucial for optimising the design of the bottom-fixed structure and will be necessary in subsequent design iterations.
- Furthermore, the change to a larger diameter of the top column in the new design introduces higher wave loads on the structure. It is recommended that these increased loads be incorporated into the design calculations and iterated, to verify the strength and stability of the structure.
- After performing design iterations analytically, it may be beneficial to analyse the structure using more complex models. Developing a model in software such as ANSYS would enable a more detailed analysis of the structural implications. These models can provide a better understanding of the dynamic behavior and allow for conducting fatigue analysis to ensure long-term durability, which is a recommended next step.

9.1.2. Comprehensive Feasibility Assessments

In addition to the technical recommendations for this design, several other recommendations can be formulated to further develop of this design. These additional recommendations will address broader aspects and ensure a comprehensive approach to assess the overall feasibility.

- To demonstrate feasibility, it is recommended to refine the offshore location. This will allow for a detailed analysis of the external loads present at these locations. Additionally, it will enable an investigation into manufacturability and potential facilities to further assess the feasibility.
- It is recommended to assess the estimated duration of the transport and installation process. This will provide an understanding of the project's timeline and potential logistical challenges. Additionally, it will provide information to define the weather window.
- Furthermore, it is also recommended to make an initial estimation of the costs for the construction and execution of the project. This will evaluate the overall viability of the methodology.

9.2. Broader Perspective

In addition to refining the design developed in this research, it is also valuable to zoom out and take a broader perspective on the feasibility of the project. This approach allows for the exploration and development of alternative design options. The following recommendations are provided for further development for a broader perspective.

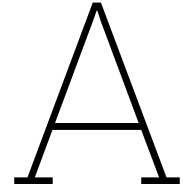
- Following this initial feasibility study, it is recommended to be critical on design choices and to potentially perform a similar in-depth analysis for alternative design options. This allows for a better comparison of options without delving too deeply into the design. Below, recommendations will be provided for exploring potential alternative design options.
 - A similar feasibility study could be performed for the tension principle to improve the understanding and facilitate comparative analysis between different design options.
 - It is recommended to investigate further design alternatives for the bottom-fixed structures. Although this design of the tripod meets the design requirements, there is still potential for optimisation, in terms of manufacturability, feasibility, and attractiveness in the offshore market.
- Additionally, it is recommended to assess the potential future implications of this transport and installation methodology. Evaluating its suitability for various applications, such as deeper waters or

larger turbines, can assist in determining the potential for implementation in various situations and making the system future-proof. Furthermore, it is recommended to explore the multi functionality of the frame, not limited to a specific type of TLP or bottom-fixed structure, but rather allowing the TIF concept to accommodate for multiple designs of bottom-fixed structures, allowing for adaptability within the dynamic offshore wind sector. Evaluating the forward-thinking approach and design's adaptability is essential to ensure its long-term effectiveness.

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Wind Turbine Parameters

This Appendix provides the parameters used for the wind turbine. The IEA 15 MW turbine is developed based on the IEA Wind reference turbine, jointly designed by NREL, DTU, and UMaine [17]. This reference turbine is used in this research and the main parameters are given in Table A.1.

Table A.1: IEA 15 MW Reference Wind Turbine Parameters

Parameter	Value	Unit
Power rating	15	<i>MW</i>
Turbine class	IEC Class IB	-
Specific rating	332	<i>W/m²</i>
Rotor orientation	Upwind	-
Number of blades	3	-
Control	Variable speed, Collective pitch	-
Cut-in wind speed	3	<i>m/s</i>
Rated wind speed	10.59	<i>m/s</i>
Cut-out wind speed	25	<i>m/s</i>
Design tip speed ratio	9	-
Minimum rotor speed	5.0	<i>rpm</i>
Maximum rotor speed	7.56	<i>rpm</i>
Maximum tip speed	95	<i>m/s</i>
Rotor diameter	240	<i>m</i>
Airfoil series	FFA-W3	-
Hub height	150	<i>m</i>
Hub diameter	7.94	<i>m</i>
Hub overhang	11.35	<i>m</i>
Rotor precone angle	-4.0	<i>deg</i>
Blade prebend	4	<i>m</i>
Drivetrain	Direct drive	-
Shaft tilt angle	6	<i>deg</i>
Rotor nacelle assembly mass	1,017	<i>tonnes</i>
Transition piece height	15	<i>m</i>
Monopile embedment depth	45	<i>m</i>
Monopile base diameter	10	<i>m</i>
Tower mass	860	<i>tonnes</i>

B

Environmental Forces

This Appendix covers the calculation of horizontal environmental forces and moments in two scenarios: during transport and during operation. This design research focuses on the feasibility of the transport and installation method, rather than a specific offshore location. Therefore, initial assumptions are made regarding various environmental conditions to facilitate the preliminary design iteration and to estimate the magnitude of forces, subsequently enabling the determination of the dimensions of the bottom-fixed structure. The formulas used to determine the external forces acting on the wind turbine provide preliminary approximations of the wind and hydro forces; further refinement is imperative to achieve a more accurate and precise analysis [11, 12].

$$F_{\text{wind_thrust}} = 0.5 \cdot \rho_{\text{air}} \cdot C_T \cdot A_{\text{rotor}} \cdot u^2 \quad (\text{B.1})$$

$$F_{\text{wind_drag}} = 0.5 \cdot \rho_{\text{air}} \cdot C_D \cdot A_{\text{turbine tower}} \cdot u^2 \quad (\text{B.2})$$

$$F_{\text{hydro}} = \rho_{\text{seawater}}(1 + C_A)A_{\text{water}} \cdot \dot{u} + 0.5 \cdot \rho_{\text{seawater}} \cdot C_D \cdot D_{\text{water}} \cdot u_{\text{water}}^2 \quad (\text{B.3})$$

Table B.1: Parameters Environmental Forces

Parameter	Formula	Value	Unit
ρ_{air}		1.293	kg/m^3
C_D		0.47	-
D_{rotor}		242	m
A_{rotor}	$(\frac{D_{\text{rotor}}}{2})^2 * \pi$	45996	m^2
D_{tower}		10	m
H_{turbine}		150	m
L_{arm}		37.9	m

The forces are dependent on the dimensions of the bottom-fixed structure, as indicated by the parameters. Therefore, the two values are interrelated and the design process has been iterative to determine the appropriate area values for calculating the environmental forces.

B.1. During Transport

In this section, the wind forces during transport will be discussed. Figure B.1 illustrates the stage where only the thrust force acts on the rotor area and the drag force is exerted on the wind turbine tower. In which Equations B.1 and B.2 are use.



Figure B.1: Wind Forces during Transport Stage

During transport, the blades of the wind turbine are stationary, resulting in significantly less thrust force compared to the thrust force during operation when the blades are rotating. Two wind speed values are analysed: the 1-year return period with a wind speed of 40 m/s and the 50-year return period with a wind speed of 50 m/s, as documented for the reference wind turbine [17]. These are the wind speeds of the 10-minute average extreme wind speed, at hub height [6]. For both scenarios, a yaw angle of 90 degrees is used. The parameters used for the calculation of environmental forces are presented in Table B.2.

Table B.2: Parameters used for Calculation Forces and Moments during Transport Stage

Parameter	Formula	Value	Unit
C_T		0.015	-
u_1		40	m/s
u_{50}		50	m/s
A_{tower}	$D_{tower} \cdot H_{turbine} + L_{top\ column}$	1890	m ²
Arm_{thrust}	$(H_{turbine} + H_{TIF})$	191	m
Arm_{drag}	$(H_{turbine} + H_{TIF}) \cdot \frac{7}{16}$	83.56	m

During transport, hydrodynamic forces have a negligible effect on the horizontal forces acting on the turbine. The assumption of a drag force during the cut-out stage was provided by BES. A coefficient of 0.47 is used for the drag force on the wind turbine tower, which corresponds to the coefficient for a cylindrical shape. The moments and horizontal forces are computed just below the top column of the substructure. In practice, there are external forces exerted on the top of the TIF. However, these are excluded from the initial calculation of forces and moments.

To determine the vertical force, the masses above this point are divided into the mass of the top column of the substructure and the mass of the wind turbine.

$$F_{V, transport} = M_{top\ column} + M_{turbine}, \quad (B.4)$$

$$F_{V, transport} = 474 + 1877 = 2351 \text{ tonnes.}$$

The calculated horizontal, vertical forces, and overturning moment are provided in Table B.3 and Table B.4.

Table B.3: Horizontal Force, Vertical Force and Moment during Operation Stage for Return Period 1 year with wind speed 40 m/s

Parameter	Value	Unit
Total horizontal load (F_B)	1.63	MN
Total vertical load (F_V)	23.06	MN
Overturning Moment (M_{OE})	213.09	MNm

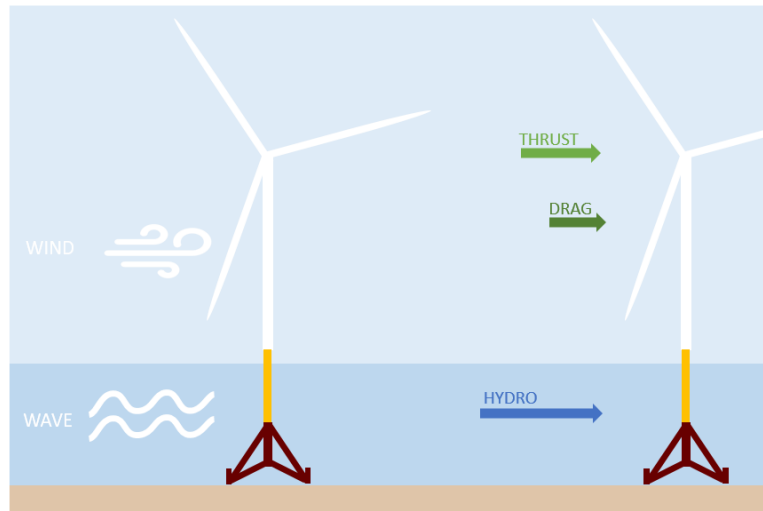
Table B.4: Horizontal Force, Vertical Force and Moment during Operation Stage for Return Period 50 year with wind speed 50 m/s

Parameter	Value	Unit
Total horizontal load (F_B)	2.55	MN
Total vertical load (F_V)	23.06	MN
Overturning Moment (M_{OE})	332.96	MNm

This research focuses on wind turbine transport. Transport operations are assumed to not occur during extreme weather events with a 50-year return period storm [17]. Therefore, for further analysis, the wind conditions corresponding to the 1-year return period will be used.

B.2. During Operation

This section analyses the wind and hydro forces during the operation stage. Figure B.2 illustrates that the rotor experiences a thrust force, while the wind turbine tower experiences a drag force and the substructure is subjected to hydro forces. Equations B.1, B.2 and B.3 are use.

**Figure B.2:** Wind and Hydro Forces during Operation Stage

The parameters used for computing environmental forces are outlined in Table E.1. The coefficient C_T and wind speeds are obtained from the report of the reference wind turbine [17]. A value of 1.00 is assumed for the added mass coefficient according to the DNV standard [11]. For the velocity and acceleration of the waves and current, certain assumptions and simplified calculations have been made due to the nonlinearity and variability of waves, depending on specific site conditions, as described in the DNV-OS-C101 offshore standard [9]. However, for the purposes of this design, specific assumptions have been made. For offshore classifications, the OC category is used, indicating low turbulence intensity and significant wave height [14]. Assuming a wave height (H) of 2 meters and a period (T) of 5.5 seconds, the airy wave theory can be used to calculate the wave velocity.

$$c = \frac{g \cdot T}{2\pi} \quad (\text{B.5})$$

where:

- c is the fluid particle velocity,
- g is the acceleration due to gravity,
- T is the wave period.

This formula applies to deep water waves, where the water depth is much greater than the wavelength. A velocity of 15.61 m/s is assumed. The acceleration of a water particle at depth z is given by:

$$a_{\text{wave}}(z) = \frac{H\omega^2 \cosh(k(-z + d))}{2 \cdot \sinh(kd)} \quad (\text{B.6})$$

where:

- $a_{\text{wave}}(z)$ is the acceleration of the water particle at depth z ,
- z is the vertical position of the water particle,
- H is the significant reference wave height,
- ω is the angular frequency of the wave,
- k is the wave number,
- d is the water depth.

In this phase of the design, earthquakes, ice/snow, marine growth, and tidal currents are not considered [9].

The estimation and calculation of the area of the bottom-fixed structure below the waterline are given by Formula B.7. The methodology was selected due to the iterative design process, which includes the adjustment of the bottom-fixed structure. Consequently, the primary focus was not on achieving precise calculations, but rather on obtaining order-of-magnitude estimates of the environmental forces involved.

$$\begin{aligned} A_{\text{water}} = & 2 \cdot \sqrt{L_{\text{view}}^2 + H_{\text{brace0}}^2} \cdot D_{\text{Outer, brace0}} \\ & + 2 \cdot \sqrt{L_{\text{view}}^2 + H_{\text{mid column}}^2} \cdot D_{\text{Outer, brace1}} \\ & + D_{\text{Outer, mid column}} \cdot L_{\text{mid column}} \\ & + D_{\text{Outer, top column}} \cdot L_{\text{top column}} \end{aligned} \quad (\text{B.7})$$

The parameters used for the calculation of environmental forces are presented in Table E.1.

Table B.5: Parameters used for Calculation Forces and Moments during Operation Stage

Parameter	Formula	Value	Unit
C_T		0.804	-
C_A		1.00	-
A_{tower}	$D_{\text{tower}} \cdot H_{\text{turbine}}$	1500	m^2
A_{water}	Formula B.7	1651.60	m^2
T		5.5	s
$H_{\text{significant wave}}$		2	m
λ	$\frac{g \cdot T^2}{2 \cdot \pi}$	47.23	m
u_{rated}		10.66	m/s
u_{water}	$\frac{g \cdot T}{2 \cdot \pi}$	8.59	m/s
$\dot{u}_{\text{water}}$	Formula B.6($z = 0$, $\zeta = \frac{H}{2}$, $\omega = \frac{2\pi}{T}$, $k = \frac{2\pi}{\lambda}$, $d = \text{water depth}$)	1.31	m/s^2
$\text{Arm}_{\text{thrust}}$	$H_{\text{turbine}} + \text{water depth}$	230	m
Arm_{drag}	$H_{\text{turbine}} + \text{water depth} \cdot \frac{7}{16}$	100.63	m
$\text{Arm}_{\text{hydro}}$	$0.5 \cdot \text{water depth}$	40.00	m

The hydrodynamic force acts linearly on the structure, with its point of application at 2/3 of its height. This is due to the linear profile of the wave, but as there will be more drag at the bottom due to the shape of the bottom-fixed structure, the point of application will shift downwards (1/2 of its height). For the vertical force, the scenario is considered where all braces are filled with seawater to attain the maximum value.

In order to determine the vertical force, it is necessary to consider the masses and buoyancy above the seabed floor.

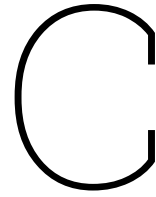
$$F_{V, \text{operation}} = M_{\text{bottom-fixed structure}} + M_{\text{turbine}} + M_{\text{ballast in braces}} - B_{\text{bottom-fixed structure}}, \quad (\text{B.8})$$

$$F_{V, \text{operation}} = 2861 + 1877 + 11933 - 12117 = 4554 \text{ tonnes}$$

The calculated horizontal and vertical forces, and with the overturning moment, are presented in Table B.6.

Table B.6: Horizontal Force, Vertical Force and Moment during Operation Stage

Parameter	Value	Unit
Total horizontal load (F_B)	7.81	MN
Total vertical load (F_V)	44.66	MN
Overturning Moment (M_{OE})	831.77	MNm



Strength Analysis Bottom-fixed Structure

In this Appendix, the design of the bottom-fixed structure used for the initial analysis will be provided. This design is based on the environmental forces and moments calculated in Appendix B. Subsequently, member checks will be done following the API standard [2]. This preliminary assessment aims to provide an estimation of the dimensions of the bottom-fixed structure, facilitating an approximate understanding of its order of magnitude for the analysis in the transport and installation methodology. Note that this is an initial check for the dimensions, and for a more accurate analysis and precise calculations will be necessary. In Figure 3.2a, the distribution and names of the various components are illustrated.

For optimal force distribution from the wind turbine to the foundation on the seabed, the placement of braces has been chosen as follows: the forces are transmitted through the top column, while the moments are absorbed by the wider base and transmitted through the lower braces to the foundation. The forces are further distributed to the soil through foundation piles. The substructure design consists of three legs to ensure connection to TIF. This appendix will present an analysis of the dimensions, including an examination of the member loads.

C.1. Member Loads

The horizontal environmental loads will be translated into reaction forces of the foundation piles. In the Push-and-Pull mechanism, the horizontal forces will be distributed as a combination of tension and compression forces for the various foundation piles [5]. Two cases will be investigated for this purpose, as illustrated in Figure C.1.

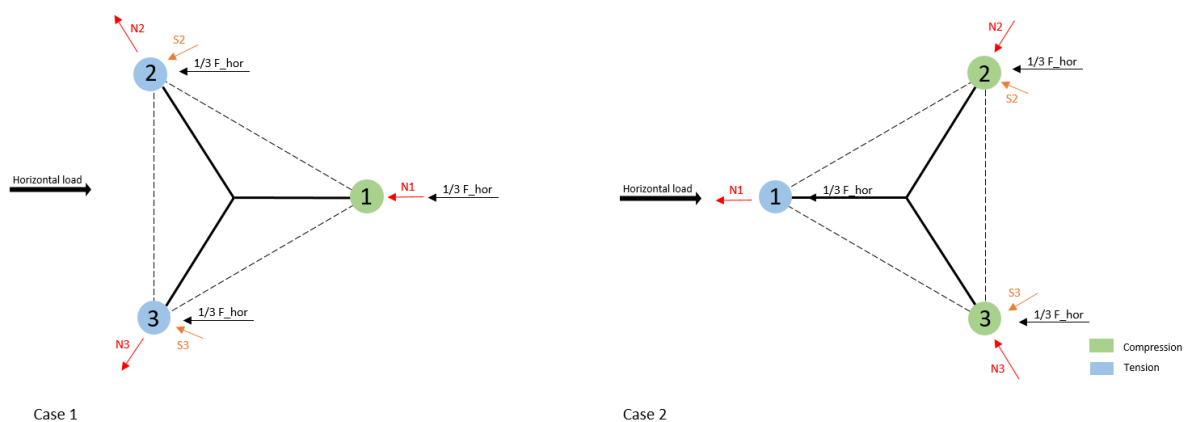


Figure C.1: Two Cases of Push-and-Pull Mechanism

The horizontal forces are distributed in the three piles of the bottom-fixed structure. Subsequently, these forces undergo further decomposition into normal (N-force) and perpendicular (S-force) components. This decomposition is necessary, as not all braces align with the direction of the environmental force. When the normal forces are disassembled, the dimensional specifications of the braces can be evaluated, ensuring to the standards. Note that, because of the perpendicular S-forces, a moment is generated on the central column.

$$\begin{aligned}
 \text{Case 1: } N1 &= -\frac{F_B}{3} & \text{Case 2: } N1 &= \frac{F_B}{3} & (C.1) \\
 N2 = N3 &= \frac{F_B}{3} \cdot \sin\left(\frac{\pi}{6}\right) & N2 = N3 &= -\frac{F_B}{3} \cdot \sin\left(\frac{\pi}{6}\right) \\
 S2 = S3 &= -\frac{F_B}{3} \cdot \cos\left(\frac{\pi}{6}\right) & S2 = S3 &= -\frac{F_B}{3} \cdot \cos\left(\frac{\pi}{6}\right) \\
 V1 &= -\frac{F_V}{3} - \frac{M_{OE}}{arm} & V1 &= -\frac{F_V}{3} + \frac{M_{OE}}{arm} \\
 V2 = V3 &= -\frac{F_V}{3} + \frac{M_{OE}}{2 \cdot arm} & V2 = V3 &= -\frac{F_V}{3} - \frac{M_{OE}}{2 \cdot arm}
 \end{aligned}$$

where:

$$\begin{aligned}
 F_B &: \text{Horizontal force} = 7.81 \text{ MN}, \\
 F_V &: \text{Vertical force} = 44.66 \text{ MN}, \\
 M_{OE} &: \text{Overturning Moment} = 831.77 \text{ MNm}, \\
 Arm &: \text{Arm between piles} = 57.90 \text{ m}.
 \end{aligned}$$

In Table C.1 and Table C.2, the normal forces, perpendicular forces, and vertical forces per member are presented. These forces will be represented for each brace in the following section.

Table C.1: Member Forces in Bottom-fixed Structure for Case 1

Support	Force	Unit
N1	- 2.60	MN
V1	- 27.01	MN
N2/N3	+ 1.30	MN
S2/S3	- 2.25	MN
V2/V3	- 8.35	MN

Table C.2: Member Forces in Bottom-fixed Structure for Case 2

Support	Force	Unit
N1	+ 2.60	MN
V1	- 2.13	MN
N2/N3	- 1.30	MN
S2/S3	- 2.25	MN
V2/V3	- 20.79	MN

This analysis indicates that, under these specified environmental conditions, where the rated wind speed is considered, and assuming the braces are filled, all vertical forces on the structure are negative. Consequently, the foundation piles primarily function under compression, with no tensile forces in the foundation piles. Under these circumstances, the on-bottom stability of the structure appears to be sufficient addressed. However, it is essential to conduct an examination that incorporates various environmental factors to ensure the foundation piles are appropriately dimensioned.

C.1.1. Axial Forces in the Braces

By decomposing the forces (N and S) into horizontal and vertical components, determined by trigonometric functions based on the angles of the braces, it calculates the reactions in the braces necessary to maintain equilibrium. These brace reactions, depend on the load paths established by the brace angles, ensuring structural integrity.

$$\begin{aligned}
F_{\text{brace,ver}} &= N \cdot \sin(0) + V \cdot \sin(90) \\
F_{\text{brace,hor}} &= N \cdot \cos(0) + V \cdot \cos(90)
\end{aligned}
\tag{C.2}$$

$$\begin{aligned}
F_{\text{tot,ver}} &= F_{\text{axial, brace0}} \cdot \sin(\theta_{\text{brace0}}) + F_{\text{axial, brace1}} \cdot \sin(\theta_{\text{brace1}}) \\
F_{\text{tot,hor}} &= F_{\text{axial, brace0}} \cdot \cos(\theta_{\text{brace0}}) + F_{\text{axial, brace1}} \cdot \cos(\theta_{\text{brace1}})
\end{aligned}$$

if: $F_{\text{brace,ver}} = F_{\text{tot,ver}}$ and if: $F_{\text{brace,hor}} = F_{\text{tot,hor}}$

$$\begin{aligned}
F_{\text{axial, brace0}} &= \sqrt{(F_{\text{axial, brace0}} \cdot \sin(\theta_{\text{brace0}}))^2 + (F_{\text{axial, brace1}} \cdot \cos(\theta_{\text{brace1}}))^2} \\
F_{\text{axial, brace1}} &= \sqrt{(F_{\text{axial, brace1}} \cdot \sin(\theta_{\text{brace1}}))^2 + (F_{\text{axial, brace1}} \cdot \cos(\theta_{\text{brace1}}))^2}
\end{aligned}
\tag{C.3}$$

where:

θ_{brace0} : Angle of brace 0 = 38.77 degrees,
 θ_{brace1} : Angle of brace 1 = 14.52 degrees.

Subsequently, the axial forces in the braces for each cases have been calculated and are presented in Table C.8 and Table C.9.

Table C.3: Axial Forces in the Braces for Case 1

	Brace 0 [MN]	Brace 1 [MN]
Pile 1	- 62.30	+ 47.50
Piles 2 & 3	+ 20.70	- 18.00

Table C.4: Axial Forces in the Braces for Case 2

	Brace 0 [MN]	Brace 1 [MN]
Pile 1	+ 6.80	- 8.10
Piles 2 & 3	- 48.50	+ 37.80

C.1.2. Bending in the Braces

For the bending in the braces, the S-forces are critical. These forces act perpendicular to the direction of the brace, generating maximum moments at the mid column. This force is shared between two braces, with the distribution dependent on the geometry of the brace. To estimate this distribution, a ratio is calculated based on the inertia and length of the two braces. This yields a $\text{Ratio}_{\text{moment}} = 0.45$ to absorb the moment generated by force S.

The ratio moment of inertia is given by:

$$I_{\text{circle}}(D, t) = \frac{\pi}{64} (D - 2t)^4 \tag{C.4}$$

where:

T_{brace} : Wall thickness of brace,
 $D_{\text{Outer, brace}}$: Outer diameter of brace.

The ratio moment of brace1 to brace0 is given by:

$$\text{Ratio}_{\text{moment}} = \frac{I_{\text{brace1}} \cdot L_{\text{brace1}}}{I_{\text{brace0}} \cdot L_{\text{brace0}} + I_{\text{brace1}} \cdot L_{\text{brace1}}} \tag{C.5}$$

$$\text{Ratio}_{\text{moment}} = \frac{28.76 \cdot 39.87}{28.76 \cdot 49.51 + 28.76 \cdot 39.87} = 0.45$$

The moment in braces is given by:

$$\begin{aligned} \text{Moment}_{\text{brace0}} &= S^2 \cdot L_x \cdot (1 - \text{Ratio}_{\text{moment}}) \\ \text{Moment}_{\text{brace1}} &= S^2 \cdot L_x \cdot \text{Ratio}_{\text{moment}} \end{aligned} \quad (\text{C.6})$$

Consequently, the moment in brace 0 is -48.21 MNm and in brace 1 is -38.83 MNm. They are the same for case 1 and case 2.

C.2. Buckling Checks

In this section, the buckling checks for the substructure are conducted in accordance with the guidelines outlined in API RP 0002A WSD. Buckling, a critical structural failure mode, is evaluated to ensure the integrity and safety of the substructure under various loading conditions. Following the methodologies described in API standard [2], analyses are performed to assess the buckling resistance of the substructure components. In Table C.5, the parameters used for the buckling checks are provided.

Table C.5: Parameter for Buckling Checks for the Calculations with API Standard

Parameter	Value	Unit
Yield Strength (F_y)	345	N/mm^2
Young's Modulus (E)	210000	N/mm^2
Poisson's Ratio (ν)	0.3	-
Buckling Factor (K)	1	-
Critical Elastic Buckling Coefficient (C)	0.3	-
Coefficient Axial Compression and Bending (C_m)	0.85	-
Safety factor for hoop compression (SF_h)	2	-
Safety factor for axial compression (SF_{xc})	1.67	-

Unity Checks

The following conditions are checked according to API RP 0002A WSD from Chapter 6, Structural Steel Design (Allowable Stresses for Cylindrical Members). The numbers following the points represent the equations from the standard that the substructure design complies with. These checks do not indicate that the substructure meets all requirements. However, because this is in the initial phase of the design, an initial estimate of the dimensions of the substructure has been made. The substructure has been verified against the following unity checks:

- UF1 = Allowable Compression Stress
- UF2 = Allowable Bending Stress
- UF3, 4 & 5 = Combined Axial Compression and Bending (6.20 and 6.21 and 6.22)
- UF6 = Hoop Buckling Stress (6.28)
- UF7 = Axial Tension and Hydrostatic Pressure (6.26)
- UF8 = Maximum Compressive Stress Combination (6.27)
- UF9 = Axial Compression and Hydrostatic Pressure (6.29)
- Safety = Safety Factor for Axial Compression (Table 6.2 [DC:1])

These checks were performed using the axial forces and moments calculated in Section C.1.1 and C.1.2. The checks were conducted for pile 1, characterized by maximal axial force, as well as for piles 2 and 3, where the axial force is lower but with a moment. Compression and tension do not occur simultaneously but instead represent two separate cases. The values are shown in Table C.6 and Table C.7.

Table C.6: Load Combinations for Pile 1

	Value	Unit
Brace 0		
$T_{\text{axial load}}$ (Compression)	- 69.30	MN
$T_{\text{axial load}}$ (Tension)	+ 6.80	MN
M_{Bending}	0	MNm
Brace 1		
$T_{\text{axial load}}$ (Compression)	- 8.10	MN
$T_{\text{axial load}}$ (Tension)	+ 47.50	MN
M_{Bending}	0	MNm

Table C.7: Load Combinations for the Piles 2 and 3

	Value	Unit
Brace 0		
$T_{\text{axial load}}$ (Compression)	- 48.50	MN
$T_{\text{axial load}}$ (Tension)	+ 20.70	MN
M_{Bending}	48.21	MNm
Brace 1		
$T_{\text{axial load}}$ (Compression)	- 18.00	MN
$T_{\text{axial load}}$ (Tension)	+ 37.80	MN
M_{Bending}	38.83	MNm

Unity checks were performed for four combinations, and the values used for diameter, wall thickness, length, and number of stiffeners, which were determined through iterative processes, are listed in Table C.8 and Table C.9.

Table C.8: Parameters Brace 0

Parameter	value	Unit
Diameter	5.00	m
Wall thickness	40	mm
Length	49.51	m
# Stiffeners	10	-

Table C.9: Parameters Brace 1

Parameter	value	Unit
Diameter	5.00	m
Wall thickness	40	mm
Length	39.87	m
# Stiffeners	7	-

The maximum Unity checks for each combination are provided below.

Table C.10: Unity Checks in the Braces for Pile 1

	Value	Compression	Tension
Brace 0	UF_{max}	0.80	0.64
Brace 1	UF_{max}	0.73	0.75

Table C.11: Unity Checks in the Brace for the Piles 2 & 3

	Value	Compression	Tension
Brace 0	UF_{max}	0.98	0.65
Brace 1	UF_{max}	0.73	0.93

The requirement for the unity checks specifies that the value of the check should be less than or equal to 1. This demonstrates which braces are currently the most critical and which ones may still have potential for optimization in terms of strength.

C.3. Dimensions Bottom-fixed Structure

The final dimensions of the substructure, which fulfill the requirements to support the load in the braces, determine the properties of the substructure. These properties are listed in Table C.12.

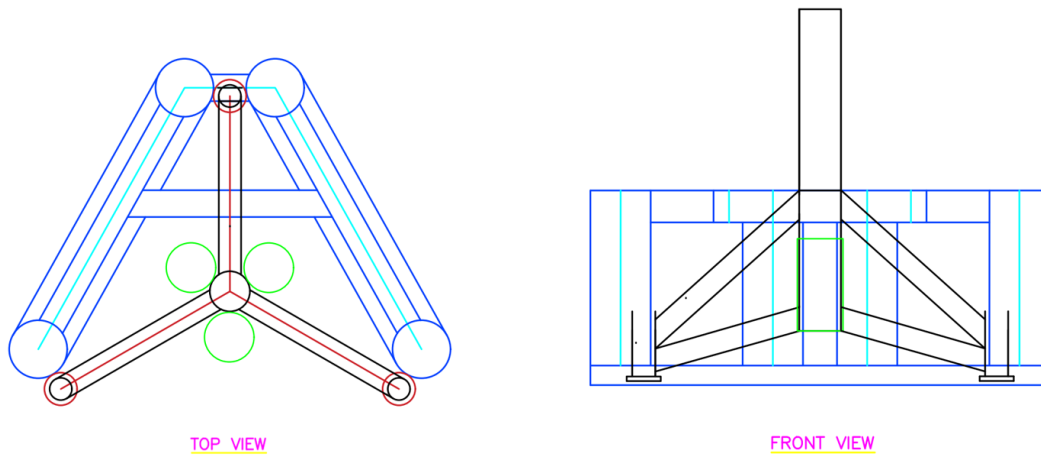


Figure C.2: Top and Front View of the Bottom-fixed Structure in the TIF

Table C.12: Parameters Bottom-fixed Structure

Parameter	Value	Unit
Density steel	7850	kg/m^3
Length x	38.6	m
Height z	41.00	m
Outer diameter brace 0	5.00	m
Thickness brace 0	40.00	mm
Mass brace 0	242.23	tonnes
Height mid column	10.00	m
Outer diameter brace1	5.00	m
Thickness brace1	40.00	mm
Mass brace1	195.10	tonnes
Outer diameter mid column	11.00	m
Thickness mid column	45.00	mm
Mass mid column	376.88	tonnes
Outer diameter top column	11.00	m
Thickness top column	45.00	mm
Mass top column	474.14	tonnes
Length pilecase	12.00	m
Diameter pilecase	5.00	m
Thickness pilecase	45.00	mm
Mass pilecase	65.99	tonnes
Mass secondarysteel	500.00	tonnes
Total mass	2860.97	tonnes

D

Buoyancy and Gravitational Forces

In this Appendix, an extension of Chapter 4, the determination of masses and buoyancy forces for various structures are provided. It includes the formulas used for calculation, the values, and additional graphs to illustrate these formulas. Additionally, the assumptions made to simplify the research for a clear overview of the problem are described.

Initially, general parameters will be presented, followed by the determination of masses and buoyancy forces for the TIF and the bottom-fixed structure. Subsequently, the gravitational forces (masses) and buoyancy forces will be detailed. Finally, explanations and graphs related to the compression principles will be provided.

The general parameters used for the buoyancy and gravitational forces are presented in Table D.1.

Table D.1: Parameters and Values for the Buoyancy and Gravitational Forces Analysis

Parameter	Value	Unit
Density Seawater	1025	kg/m^3
Gravitational acceleration (g)	9.81	m/s^2
Water depth	80	m
Density Steel	7850	kg/m^3

D.1. Parameters TIF

In Table D.2, the parameters of the TIF are listed. These were provided by BES at the beginning of the design process.

Table D.2: Parameters and Values of design of the TIF

Parameter	Value	Unit
H_{TIF}	41	m
Height Feet	4.2	m
Length Feet	28.5	m
Height Brace	6	m
Length Brace 1	54	m
Length Brace 2	7.3	m
Length Brace 3	42	m
Width Brace	6.5	m
Diameter Pontoon	13	m
Wall Thickness Pontoon	45	mm
M_{TIF}	5575	$tonnes$
CoG_{TIF0}	23.35	m

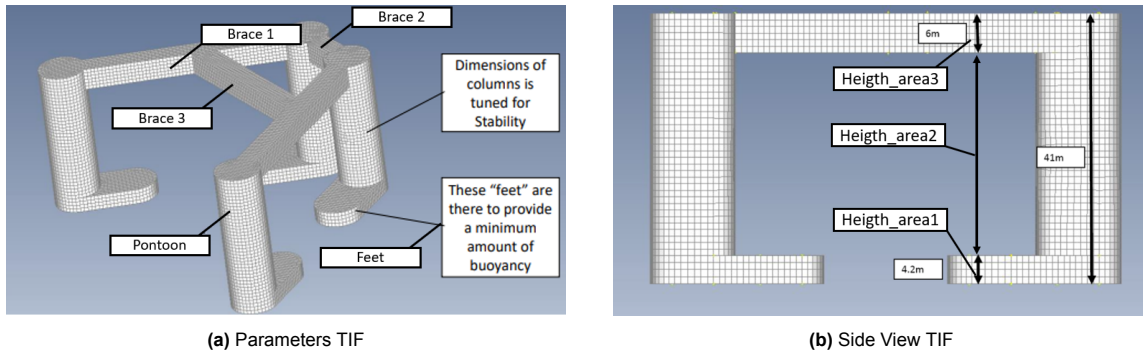


Figure D.1: Graphic representations with all components of the TIF

To simplify the buoyancy force and stability calculations, the TIF has been divided into three parts, with simplified shapes to determine the height and water cross-sectional area. The formulas used for these calculations are provided below, along with the outputs.

$$H_{TIF\ 1} = H_{feet} \quad (D.1)$$

$$H_{TIF\ 2} = H_{total} - H_{feet} - H_{brace} \quad (D.2)$$

$$H_{TIF\ 3} = H_{brace} \quad (D.3)$$

$$A_{TIF1} = 4 \cdot a \cdot b = 4 \cdot \left(\pi \cdot \frac{L_{feet}}{2} \cdot \frac{D_{pontoon}}{2} \right) \quad (D.4)$$

$$A_{TIF2} = 4 \cdot r^2 = 4 \cdot \left(\pi \cdot \left(\frac{D_{pontoon}}{2} \right)^2 \right) \quad (D.5)$$

$$\begin{aligned} A_{TIF3} = & A_{TIF2} + 2 \cdot (L_{brace\ 1} \cdot W_{brace}) \\ & + (L_{brace\ 2} \cdot W_{brace}) \\ & + (L_{brace\ 3} \cdot W_{brace}) \end{aligned}$$

Table D.3: Heights of three areas of TIF

Parameter	$H_{TIF\ 1}$	$H_{TIF\ 2}$	$H_{TIF\ 3}$
Value [m]	4.2	30.8	6.0

Table D.4: Areas TIF

Parameter	Area 1	Area 2	Area 3
Value [m ²]	1163.96	530.93	1553.38

D.2. Parameters Bottom-fixed Structure

The following section will outline the mass of the bottom-fixed structures, which is derived from a strength analysis outlined in Appendix C. This section will present the resulting masses. In Figure D.2, both a side view with the buoyancy tanks and a 3D view of the bottom-fixed structure are illustrated, providing an understanding of the proportions of the bottom-fixed structure.

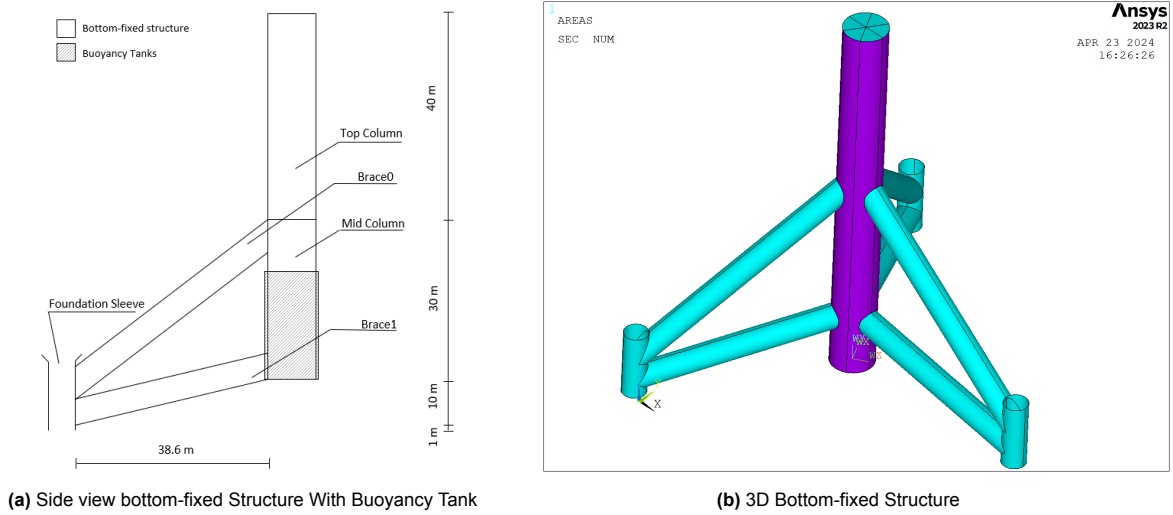


Figure D.2: Graphic representations with all components of the Bottom-fixed Structure

In Table D.5, the parameters are listed, followed by the formulas used for this calculation.

Table D.5: General parameters and values of bottom-fixed structure

Parameter	Value	Unit
L_x	38.60	<i>m</i>
H_z	$H_{TIF} = 41.00$	<i>m</i>

Formulas

$$\text{Length brace}(x, y) = \sqrt{x^2 + y^2} \quad (\text{D.6})$$

$$V_{\text{cyl shell}}(D, h, t) = \frac{\pi h}{4} (D^2 - (D - 2t)^2) \quad (\text{D.7})$$

$$\text{Angle brace}(h, l) = \arctan\left(\frac{h}{l}\right) \quad (\text{D.8})$$

$$M_{\text{mass}}(v, \rho) = \frac{V \cdot \rho}{1000} \quad (\text{D.9})$$

Table D.6: Parameters Brace0

Parameter	Formula	Value	Unit
Outer diameter brace0		5	<i>m</i>
Thickness brace0		40	<i>mm</i>
Height brace0	$H_z - 10$	31.00	<i>m</i>
Length brace0	Formula D.6 ($x = L_x, y = H_{\text{brace0}}$)	49.51	<i>m</i>
Volume brace0	Formula D.7 ($D = D_{\text{outer, brace0}}, h = L_{\text{brace0}}, t = T_{\text{brace0}}$)	30.86	<i>m</i> ³
Angle brace0	Formula D.8 ($h = H_{\text{brace0}}, l = L_x$)	38.76	<i>degrees</i>
Mass brace0	Formula D.9 ($V = V_{\text{brace0}}, \rho = \rho_{\text{steel}}$)	242.23	<i>tonne</i>

Table D.7: Parameters Brace1

Parameter	Formula	Value	Unit
Outer diameter brace1		5	<i>m</i>
Thickness brace1		40	<i>mm</i>
Height brace1		10	<i>m</i>
Length brace1	Formula D.6 ($x = L_x, y = H_{\text{brace1}}$)	39.87	<i>m</i>
Volume brace1	Formula D.7 ($D = D_{\text{outer, brace1}}, h = L_{\text{brace1}}, t = T_{\text{brace1}}$)	24.85	m^3
Angle brace1	Formula D.8 ($h = H_{\text{brace0}}, l = L_x$)	15.52	<i>degrees</i>
Mass brace1	Formula D.9 ($V = V_{\text{brace1}}, \rho = \rho_{\text{steel}}$)	195.10	<i>tonne</i>

Table D.8: Parameters Mid Column

Parameter	Formula	Value	Unit
Outer diameter mid column		11	<i>m</i>
Thickness mid column		45	<i>mm</i>
Length mid column	$H_z - H_{\text{brace1}}$	31	<i>m</i>
Volume mid column	Formula D.7 ($D = D_{\text{outer, mid column}}, h = L_{\text{mid column}}, t = T_{\text{mid column}}$)	48.01	m^3
Mass mid column	Formula D.9 ($V = V_{\text{mid column}}, \rho = \rho_{\text{steel}}$)	376.88	<i>tonne</i>

Table D.9: Parameters Top Column

Parameter	Formula	Value	Unit
Outer diameter top column		11	<i>m</i>
Thickness top column		45	<i>mm</i>
Length top column	Water depth - H_z	39.00	<i>m</i>
Volume top column	Formula D.7 ($D = D_{\text{outer, top column}}, h = L_{\text{top column}}, t = T_{\text{top column}}$)	60.40	m^3
Mass top column	Formula D.9 ($V = V_{\text{top column}}, \rho = \rho_{\text{steel}}$)	474.14	<i>tonne</i>

Table D.10: Parameters Foundation

Parameter	Formula	Value	Unit
Outer diameter pile sleeve		5	<i>m</i>
Thickness pile sleeve		45	<i>mm</i>
Length pile sleeve		12	<i>m</i>
Volume top column	Formula D.7 ($D = D_{\text{outer, pile sleeve}}, h = L_{\text{pile sleeve}}, t = T_{\text{pile sleeve}}$)	8.41	m^3
Mass pile sleeve	Formula D.9 ($V = V_{\text{pile, sleeve}}, \rho = \rho_{\text{steel}}$)	65.99	<i>tonne</i>

D.3. Gravitational Forces

An overview is provided of the masses, for both the bottom-fixed structure and the various components of the wind turbine.

The total gravitational force for the bottom-fixed structure is given by:

$$M_{\text{bottom-fixed structure}} = 3 \cdot M_{\text{brace0}} + 3 \cdot M_{\text{brace1}} + M_{\text{mid column}} + M_{\text{top column}} + 3 \cdot M_{\text{foundation}} + M_{\text{secondary steel}} \quad (\text{D.10})$$

$$M_{\text{bottom-fixed structure}} = 3 \cdot 242 + 3 \cdot 195 + 377 + 474 + 3 \cdot 66 + 500 = 2861 \text{ tonnes.}$$

The total gravitational force for the wind turbine is given by:

$$M_{\text{Total, wind turbine}} = M_{\text{RNA}} + M_{\text{tower}} \quad (\text{D.11})$$

$$M_{\text{Total, wind turbine}} = 1017 + 860 = 1877 \text{ tonnes.}$$

D.4. Buoyancy Forces

The following section presents the calculations for the buoyancy force for both the TIF and the substructure.

TIF

The formula for the buoyancy force computes the displaced volume for a given draft D according to the following expression:

$$V_{\text{displaced, TIF}}(D) = \begin{cases} D \cdot A_{\text{TIF1}} & \text{if } D \leq H_{\text{TIF1}} \\ H_{\text{TIF1}} \cdot A_{\text{TIF1}} + (D - H_{\text{TIF1}}) \cdot A_{\text{TIF2}} & \text{if } H_{\text{TIF1}} < D \leq D_{\text{max}} \\ H_{\text{TIF1}} \cdot A_{\text{TIF1}} + (D_{\text{max}} - H_{\text{TIF1}}) \cdot A_{\text{TIF2}} & \text{if } D > D_{\text{max}} \end{cases} \quad (\text{D.12})$$

where:

$V_{\text{displaced, TIF}}$: displaced volume of the TIF,
 D_{max} : maximum draft = 35 m,

This equation divides the calculation of the buoyancy force into different cases based on the depth of the structure. Each part accounts for a different area of the TIF and calculates the buoyancy force based on the amount of water displaced by that specific area.

$$F_B = \rho \cdot \nabla \quad (\text{D.13})$$

where:

F_B is upwards buoyancy force,
 ∇ is submerged volume,
 ρ is density of the fluid.

Substructure

The same principle is used to calculate the buoyancy force of the substructure. The buoyancy is calculated by multiplying the displaced area with density of seawater (ρ_{seawater}), Equation D.13.

$$A_{\text{sliced cylinder}}(r, \theta) = \pi r \frac{r}{\sin(\theta)} \quad (\text{D.14})$$

$$V_{\text{displaced, sub}}(D) = \begin{cases}
= 3 \cdot \text{Formula D.14} \left(r = \frac{D_{\text{Outer, brace1}}}{2}, \theta = \theta_{\text{brace1}} \right) \cdot D & \text{if } D < H_{\text{brace1}} \\
= 3 \cdot \text{Formula D.14} \left(r = \frac{D_{\text{Outer, brace1}}}{2}, \theta = \theta_{\text{brace1}} \right) \cdot (H_{\text{brace1}}) \\
+ 3 \cdot \text{Formula D.14} \left(r = \frac{D_{\text{Outer, brace0}}}{2}, \theta = \theta_{\text{brace0}} \right) \cdot (D - H_{\text{brace1}}) \\
+ \text{Formula D.14} \left(r = \frac{D_{\text{Outer, mid column}}}{2}, \theta = 90 \right) \cdot (D - H_{\text{brace1}}) \\
- \max \left[\frac{V_{\text{buoyancy tank}} \cdot D}{L_{\text{buoyancy tank}}}, V_{\text{buoyancy tank}} \right] & \text{if } D \geq H_{\text{brace1}} \text{ and } D < H_{\text{TIF}} \\
= 3 \cdot \text{Formula D.14} \left(r = \frac{D_{\text{Outer, brace1}}}{2}, \theta = \theta_{\text{brace1}} \right) \cdot (H_{\text{brace1}}) \\
+ 3 \cdot \text{Formula D.14} \left(r = \frac{D_{\text{Outer, brace0}}}{2}, \theta = \theta_{\text{brace0}} \right) \cdot (H_{\text{TIF}} - H_{\text{brace1}}) \\
+ \text{Formula D.14} \left(r = \frac{D_{\text{Outer, mid column}}}{2}, \theta = 90 \right) \cdot (H_{\text{TIF}} - H_{\text{brace1}}) \\
+ \text{Formula D.14} \left(r = \frac{D_{\text{Outer, top column}}}{2}, \theta = 90 \right) \cdot (D - H_{\text{TIF}}) \\
- V_{\text{buoyancy tank}} & \text{if } D \geq H_{\text{TIF}}
\end{cases} \quad (\text{D.15})$$

Below in Figure D.3 the displaced volume as a function of the draft is illustrated and in Figure D.4 the gravitational forces and buoyancy forces of both the substructure (yellow) and the TIF (red), as well as the combined system (green) are illustrated.

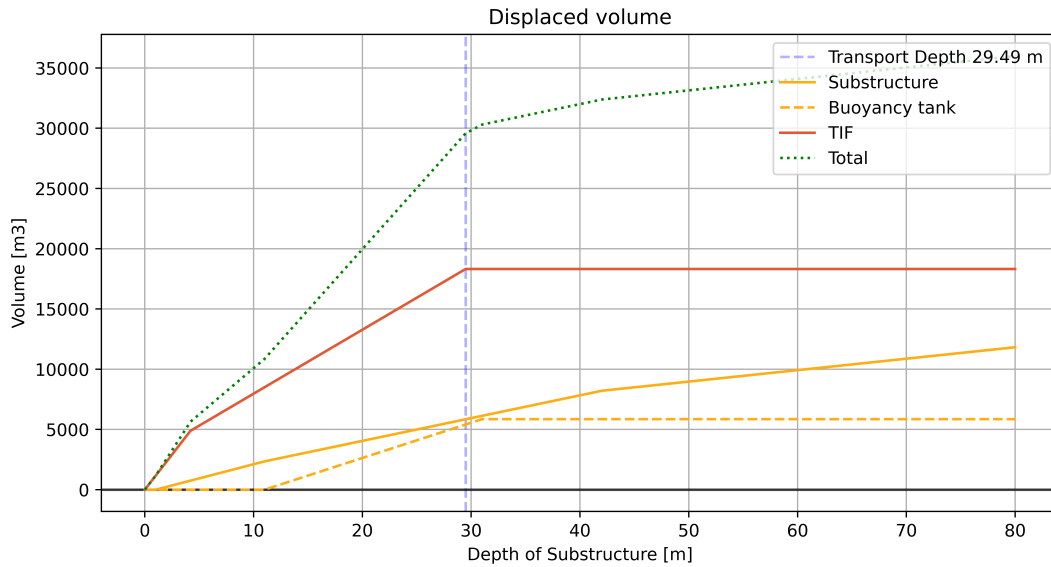


Figure D.3: Displaced Volume as a function of the Draft

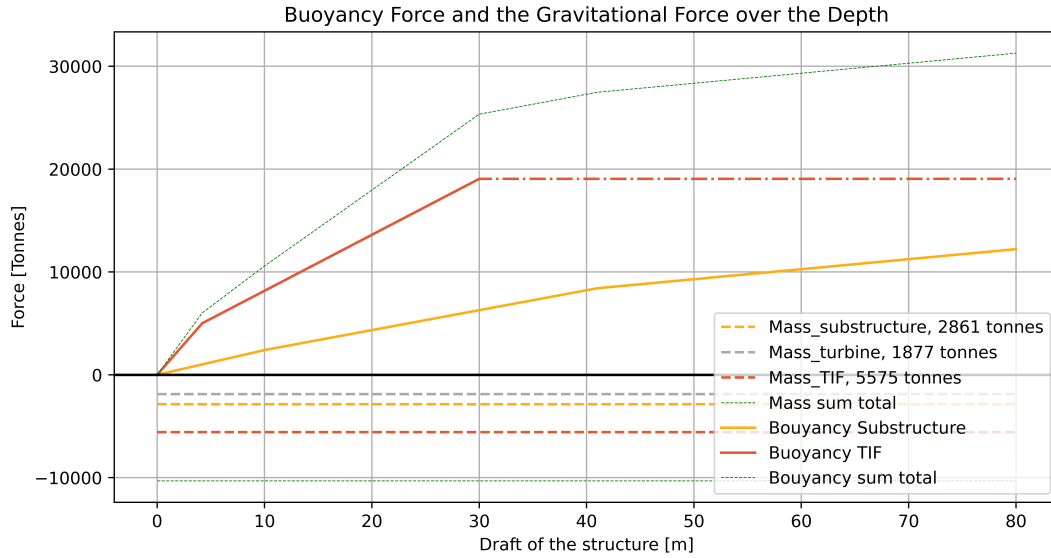


Figure D.4: Graph of Buoyancy Force and the Gravitational Force as a function of the Draft

D.5. Compression Principle

D.5.1. Transport Stage

To transport and installation the substructure with the compression principle, additional ballast in the TIF and extra buoyancy to the substructure are needed. This section will define the amount of additional ballast and buoyancy required to achieve the interface force of 7000 tonnes total.

Additional ballast in the TIF

The ballast is added as seawater into the TIF. The formula below will determine the height of the ballast within the TIF based on the volume of ballast.

$$H_{\text{Ballast, TIF}}(V) = \begin{cases} \frac{V}{A_{\text{TIF1}}} & \text{if } V < A_{\text{TIF1}} \cdot H_{\text{TIF1}} \\ \frac{V - (A_{\text{TIF1}} \cdot H_{\text{TIF1}})}{A_{\text{TIF2}}} + H_{\text{TIF1}} & \text{if } V \geq A_{\text{TIF1}} \cdot H_{\text{TIF1}} \end{cases} \quad (\text{D.16})$$

Additional buoyancy on the bottom-fixed structure

For the bottom-fixed structure, it is necessary to ensure sufficient buoyancy. This will be added with buoyancy tanks (6000 tonnes). To fit properly against the bottom-fixed structure, three large buoyancy tanks with a radius of 5.57 meters and a height of 20 meters are installed. The buoyancy tanks are already included in the formula for calculating the buoyancy of the substructure and it is linearly added for the lower 20 meters (Equation D.15).

Draft of System during transport

In the Figure 4.5, it can be observed that the draft is 30 meters during the transport stage, and the height of ballast in the TIF is equal to 17.18 meters (equation D.16 ($V = 20000 \text{ m}^3$)), which is equivalent to a ballast of 20500 tonnes of seawater. The interface force in this stage is 7045 tonnes. This is shown in Figure 4.5 from the forces present at the draft of 30 meters.

D.5.2. Installation Stage

After the transport stage, the installation of the substructure will take place. This process involves lowering the substructure while the TIF remains at water level. This process occurs under compression, causing the substructure to experience a buoyancy force while the TIF applies a gravitational force to push the substructure downwards.

Filling the Buoyancy Tanks

To maintain the interface force and the draft of the TIF constant during the lowering, the buoyancy force of the substructure must decrease during the lowering process. This can be achieved by compensating for extra ballast in the buoyancy tanks by allowing them to fill with seawater during lowering. The increasing buoyancy force (due to the lowering of the bottom-fixed structure) is illustrated by the green line in Figure 4.5. Upon reaching 6000 tonnes of buoyancy from the buoyancy tanks, they will be filled with seawater. This is graphically illustrated in Figure D.5.

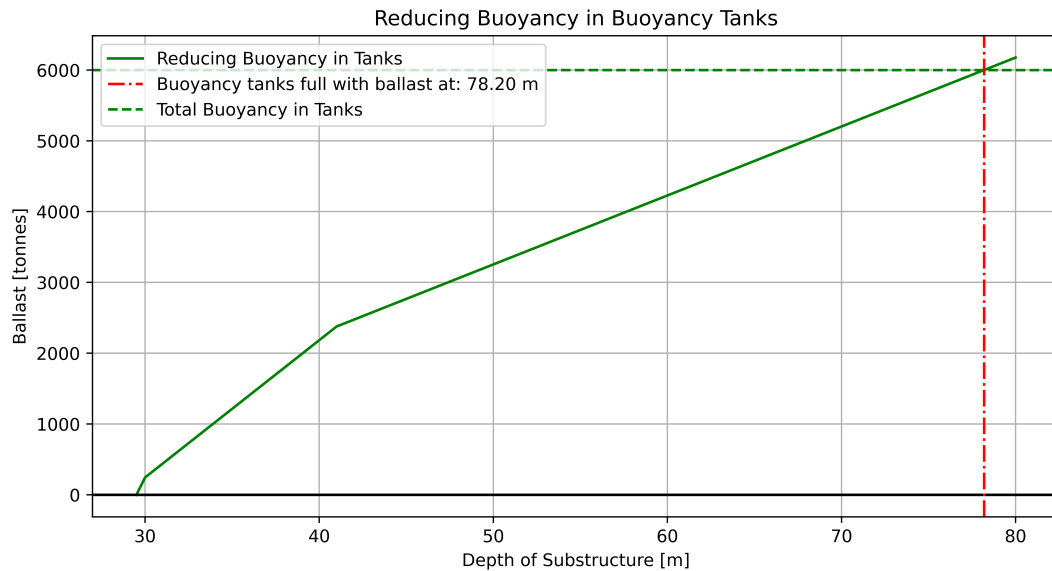
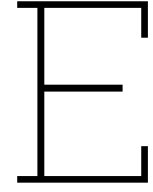


Figure D.5: Filling buoyancy tanks as a function of the Draft

In this scenario, it can be observed that the buoyancy tanks are fully filled at a depth of 78.20 meters. This point is called the D_{buoyancy} .



Stability Analysis

In this Appendix, the methodology for the stability analysis is outlined. The approach follows the principles described in the offshore hydromechanics literature, specifically focusing on the chapter on static floating stability [28]. This appendix serves as an extension of the section 'Initial Static Stability' (Section 5.1) and section 'Maximum Heeling Angle' (Section 5.2).

E.1. Center of Gravity

In the calculation of the CoG, the waterline serves as the reference axis. Positive values are assigned above the waterline, while negative values are assigned below it. The CoG will be determined in three parts: for the TIF, for the wind turbine, and for the bottom-fixed structure. These values will be combined to calculate the CoG of the total system.

TIF

The CoG of the TIF is provided by BES and is 23.35 meters without extra ballast. During transport and installation, the TIF will be partially filled with ballast (seawater). As a result, the CoG of the total TIF will shift downward, and the height of the ballast must be taken into account in the calculations of the vertical location of the CoG. During transport, the draft of the TIF will be 30 meters and the ballast in the TIF will have a height of 17.18 meters (equation D.16).

$$\text{CoG}_{\text{TIF}}(D) = \begin{cases} - (H_{\text{TIF}} - \text{CoG}_{\text{TIF}0}) - D + H_{\text{TIF}}, & \text{if } D = D_{\text{TIF,transport}} \\ \text{CoG}_{\text{TIF}}[-1], & \text{if } D > D_{\text{TIF,transport}} \end{cases} \quad (\text{E.1})$$

$$\text{CoG}_{\text{TIF, ballast}}(D) = \begin{cases} (H_{\text{TIF, ballast}}/2.5) - D, & \text{if } D = D_{\text{TIF,transport}} \\ \text{CoG}_{\text{TIF, ballast}}[-1], & \text{if } D > D_{\text{TIF,transport}} \end{cases} \quad (\text{E.2})$$

where:

- $D_{\text{TIF,transport}}$: draft of TIF during transport = 30 m,
- H_{TIF} : height of the TIF = 41 m,
- $H_{\text{TIF, ballast}}$: height of ballast in the TIF = 17.18 m,
- $\text{CoG}_{\text{TIF}0}$: 23.35 m,
- $\text{CoG}_{\text{TIF}}[-1]$: CoG of step before

In Figure E.1, a graphical representation is provided of the CoG of the TIF in red as a function of depth.

Wind Turbine

For the wind turbine, the parameters of the reference turbines from NREL will be used [21]. In determining the total CoG of a wind turbine, attention is given to its primary components: the RNA and the turbine tower. The RNA, situated at a height of 148.27 meters, and the tower, with its CoG positioned at 76.48 meters, contribute to the overall CoG. With respective masses of 1017 and 860 tonnes, calculations give a total CoG placement at 116.37 meters above the tower's base. The wind turbine will be lowered to the seabed with the same steps as the lowering steps for the bottom-fixed structure.

Bottom-fixed Structure

For defining the CoG of the bottom-fixed structure, the masses and vertical points of CoG are determined separately for each part of the bottom-fixed structure. Note that this calculation does not take into account the filled braces.

Table E.1: Parameters and Formulas used for Calculation of CoG Bottom-fixed Structure

Parameter	Formula	Value	Unit
CoG _{top column}	$-0.5 \cdot L_{\text{top column}} + \text{water depth}$	60.50	m
CoG _{mid column}	$-L_{\text{top column}} - 0.5 \cdot L_{\text{mid column}} + \text{water depth}$	25.50	m
CoG _{foundation}	$0.3 \cdot L_{\text{pile sleeve}}$	3.60	m
CoG _{brace0}	$-L_{\text{top column}} - 0.5 \cdot H_{\text{brace0}} - 0.5 \cdot D_{\text{Outer, brace0}} + \text{water depth}$	23.00	m
CoG _{brace1}	$-L_{\text{top column}} - (H_{\text{TIF}} - H_{\text{mid column}}) - 0.5 \cdot H_{\text{mid column}} + \text{water depth}$	5.00	m

The formula for calculating the total CoG of the bottom-fixed structure is given by:

$$\text{CoG}_{\text{bottom-fixed structure}} = \frac{(\text{CoG} \cdot M)_{\text{top}} + (\text{CoG} \cdot M)_{\text{mid column}} + (\text{CoG} \cdot 3 \cdot M)_{\text{pile sleeve and mudmat}} + 3 \cdot (\text{CoG} \cdot M)_{\text{brace0}} + 3 \cdot (\text{CoG} \cdot M)_{\text{brace1}}}{M_{\text{total, bottom-fixed structure}} - M_{\text{secondary steel}}} \quad (\text{E.3})$$

It indicates a CoG_{bottom-fixed structure} of 24.84 m, with the bottom of the substructure as the reference line. The CoG as a function of the draft can be determined using the following formula:

$$\text{CoG}_{\text{bottom-fixed structure}}(D) = \text{CoG}_{\text{bottom-fixed structure}} - D \quad (\text{E.4})$$

As described in Appendix D, buoyancy tanks are added to the substructure. These will be filled with seawater during lowering, introducing an additional gravitational force and thus shifting the position of the CoG of the substructure. The formula for determining the CoG of the buoyancy force depends on the depth (and how much they are filled) and is given by:

$$\text{CoG}_{\text{Buoyancy Tanks}}(D) = \begin{cases} 0, & \text{if } D \leq D_{\text{TIF,transport}} \\ \left(\frac{(D_{\text{buoyancy}} - D)}{(D_{\text{TIF,transport}} - D_{\text{buoyancy}})} + 1 \right) \left(\frac{L_{\text{buoyancy}}}{2} \right) - D, & \text{if } D > D_{\text{TIF,transport}} \text{ and } D \leq D_{\text{buoyancy}} \\ \left(\frac{L_{\text{buoyancy}}}{2} - D \right), & \text{if } D > D_{\text{buoyancy}} \end{cases} \quad (\text{E.5})$$

where:

D_{buoyancy} : point of filled buoyancy tanks = 78.20 m,

L_{buoyancy} : length buoyancy tanks = 20 m.

Total System

Below is the formula provided for determining the CoG of the substructure, which consists of the wind turbine, bottom-fixed structure, and the buoyancy tanks.

$$\text{CoG}_{\text{Substructure}}(D) = \frac{(\text{CoG}(D) \cdot M)_{\text{bottom-fixed}} + \left(\left(\frac{D_{\text{buoyancy}} - D}{D_{\text{TIF,transport}} - D_{\text{buoyancy}}} + 1 \right) \cdot \text{CoG}(D) \cdot M \right)_{\text{Buoyancy tank}} + (\text{CoG} \cdot M)_{\text{turbine}}}{M_{\text{substructure}} + \left(\frac{D_{\text{buoyancy}} - D}{D_{\text{TIF,transport}} - D_{\text{buoyancy}}} + 1 \right) \cdot M_{\text{buoyancy tanks}} + M_{\text{turbine}}} \quad (\text{E.6})$$

To determine the CoG of the total system, the CoG of the structures are relative to the mass, as described below in this formula:

$$\text{CoG}_{\text{total}}(D) = \frac{(\text{CoG}(D) \cdot M)_{\text{substructure}} + (\text{CoG}(D) \cdot M)_{\text{TIF}} + (\text{CoG}(D) \cdot M)_{\text{TIF, ballast}}}{M_{\text{substructure}} + M_{\text{TIF}} + M_{\text{TIF, ballast}}} \quad (\text{E.7})$$

where:

$$\begin{aligned} M_{\text{substructure}} &= 4737.97 \text{ tonnes,} \\ M_{\text{TIF}} &= 5575.00 \text{ tonnes,} \\ M_{\text{TIF, ballast}} &= 20500.00 \text{ tonnes,} \end{aligned}$$

Table E.2: CoG values during Transport Stage

CoG	Value	Unit
RNA	199.30	m
Tower	127.51	m
Turbine = RNA + Tower	166.41	m
Bottom-fixed structure	-3.66	m
TIF	-6.15	m
Ballast in the TIF	-22.63	m
TIF + ballast in the TIF	-19.10	m
Total System	-5.90	m

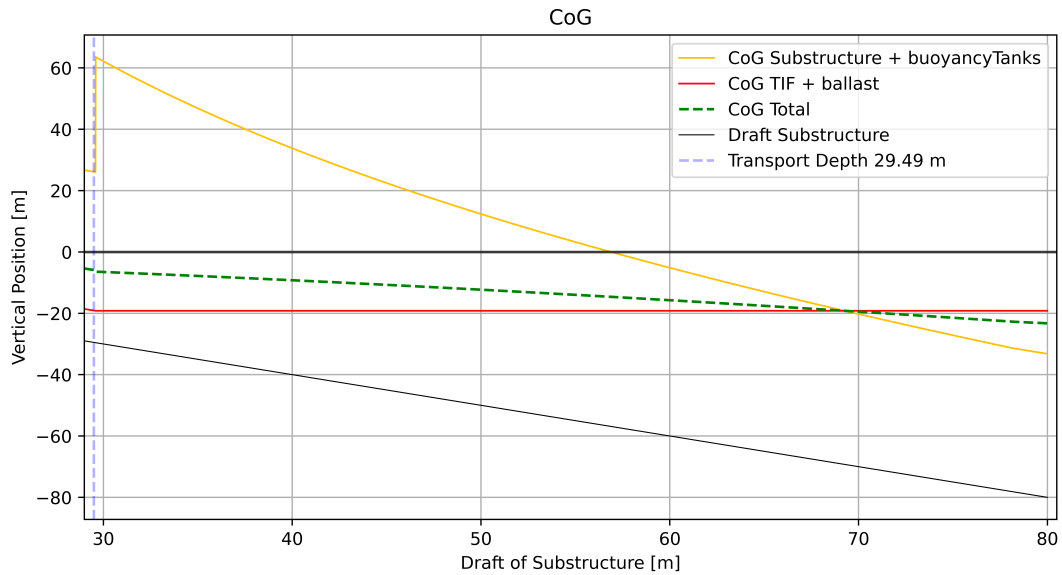


Figure E.1: CoG as a function of the Draft

E.2. Center of Buoyancy

The CoB of a floating structure is defined by the distribution of its displacement, which varies with the draft of the structure (equation D.13).

TIF

During installation, the TIF will have a constant draft, so also a constant CoB, given by:

$$\text{CoB}_{\text{TIF}} = - \frac{(D - 0.5 \cdot H_{\text{TIF, area 1}}) \cdot A_{\text{TIF, area 1}} + 0.5 \cdot (D - H_{\text{TIF, area 1}}) \cdot A_{\text{TIF, area 2}}}{A_{\text{TIF, area 2}} + A_{\text{TIF, area 1}}} \quad (\text{E.8})$$

where:

D: Draft during installation = 29.49 m.

Substructure

The turbine and the bottom-fixed structure are considered as one system in this analysis, referred to as the substructure. The displaced volumes as a function of draft are divided into three parts:

1. If $D \leq H_{\text{mid column}}$,
2. If $D \leq H_{\text{mid column}}$ and $D \leq H_{\text{TIF}}$,
3. If $D > H_{\text{TIF}}$.

For each part, the CoG is determined using different formulas.

1. If $D \leq H_{\text{mid column}}$:

$$\begin{cases} V_{\text{brace1}} = 3 \cdot \text{Formula D.14}\left(\frac{(D_{\text{outer, brace1}} - 2 \cdot T_{\text{brace1}})}{2}, \theta_{\text{brace1}}\right) \cdot D \\ V_{\text{brace0}} = 0 \\ V_{\text{mid column}} = 0 \\ V_{\text{top column}} = 0 \end{cases} \quad (\text{E.9})$$

$$\text{CoB}_{\text{substructure}}(D) = -\frac{V_{\text{brace1}} \cdot 0.5 \cdot D}{V_{\text{brace1}}}$$

2. If $D \leq H_{\text{mid column}}$ and $D \leq H_{\text{TIF}}$:

$$\begin{cases} V_{\text{brace1}} = 3 \cdot \text{Formula D.14}\left(\frac{(D_{\text{outer, brace1}} - 2 \cdot T_{\text{brace1}})}{2}, \theta_{\text{brace1}}\right) \cdot H_{\text{mid column}} \\ V_{\text{brace0}} = 3 \cdot \text{Formula D.14}\left(\frac{(D_{\text{outer, brace0}} - 2 \cdot T_{\text{brace0}})}{2}, \theta_{\text{brace0}}\right) \cdot (D - H_{\text{mid column}}) \\ V_{\text{mid column}} = \text{Formula D.14}\left(\frac{(D_{\text{outer, mid column}} - 2 \cdot T_{\text{mid column}})}{2}, 90\right) \cdot (D - H_{\text{mid column}}) \\ V_{\text{top column}} = 0 \end{cases} \quad (\text{E.10})$$

$$\text{CoB}_{\text{substructure}}(D) = -\frac{V_{\text{brace1}} \cdot 0.5 \cdot (-H_{\text{mid column}} + D) + V_{\text{brace0}} \cdot 0.5 \cdot (D - H_{\text{mid column}}) + V_{\text{mid column}} \cdot (0.5 \cdot (D - H_{\text{mid column}}))}{V_{\text{brace1}} + V_{\text{brace0}} + V_{\text{mid column}}}$$

3. If $D > H_{\text{TIF}}$:

$$\begin{cases} V_{\text{brace1}} = 3 \cdot \text{Formula D.14}\left(\frac{(D_{\text{outer, brace1}} - 2 \cdot T_{\text{brace1}})}{2}, \theta_{\text{brace1}}\right) \cdot H_{\text{mid column}} \\ V_{\text{brace0}} = 3 \cdot \text{Formula D.14}\left(\frac{(D_{\text{outer, brace0}} - 2 \cdot T_{\text{brace0}})}{2}, \theta_{\text{brace0}}\right) \cdot (H_{\text{TIF}} - H_{\text{mid column}}) \\ V_{\text{mid column}} = \text{Formula D.14}\left(\frac{(D_{\text{outer, mid column}} - 2 \cdot T_{\text{mid column}})}{2}, 90\right) \cdot (H_{\text{TIF}} - H_{\text{mid column}}) \\ V_{\text{top column}} = \text{Formula D.14}\left(\frac{(D_{\text{outer, top column}} - 2 \cdot T_{\text{top column}})}{2}, 90\right) \cdot (D - H_{\text{TIF}}) \end{cases} \quad (\text{E.11})$$

$$\text{CoB}_{\text{substructure}}(D) = -\frac{V_{\text{brace1}} \cdot (D + 0.5 \cdot (-H_{\text{mid column}})) + V_{\text{brace0}} \cdot (D - H_{\text{mid column}} - 0.5 \cdot L_{\text{mid column}}) + V_{\text{mid column}} \cdot (D - H_{\text{mid column}} - 0.5 \cdot L_{\text{mid column}}) + V_{\text{top column}} \cdot 0.5 \cdot (D - H_{\text{TIF}})}{V_{\text{brace1}} + V_{\text{brace0}} + V_{\text{mid column}} + V_{\text{top column}}}$$

Buoyancy tanks

$$\text{CoB}_{\text{buoyancy tanks}}(D) = \begin{cases} -0.5 \cdot D, & \text{if } D \leq L_{\text{buoyancy tank}} \\ -(D - 0.5 \cdot L_{\text{buoyancy tank}}), & \text{if } D > L_{\text{buoyancy tank}} \end{cases} \quad (\text{E.12})$$

Total System CoB

$$\text{CoG}_{\text{total}}(D) = \frac{(\text{CoB} \cdot V)_{\text{TIF}} + (\text{CoB} \cdot V)_{\text{substructure}} + (\text{CoB} \cdot V)_{\text{buoyancy tank}}}{V_{\text{tot}}} \quad (\text{E.13})$$

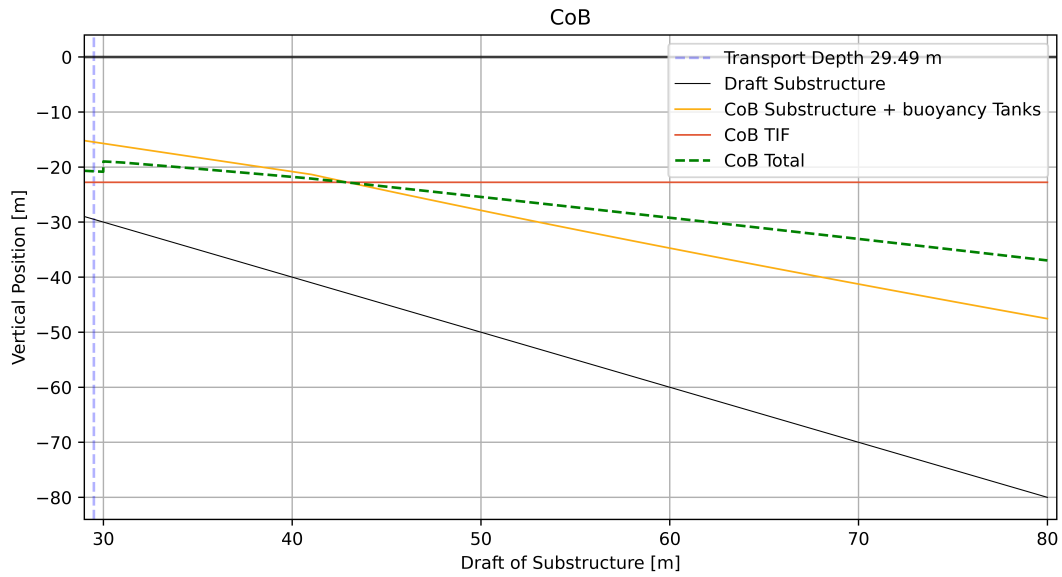


Figure E.2: CoB as a function of the Draft

E.3. Metacenter

The metacenter acts as a point within a floating object, to ensure stability during rotation and playing a central role in assessing the stability of floating structures. The formulas used are provided in Chapter 5.1, in Equation 5.2. The moment of inertia of the TIF combined with the substructure, Equation E.14 can be used.

$$I_{\text{combined}} = \sum_{i=0}^n (I_i + A_i d_i^2) \quad (\text{E.14})$$

where:

I is the moment of inertia,

A_i is the area of the i -th structure,

d_i is the distance of the i -th structure from the rotation axis.

TIF

The inertia of the TIF during transport and installation remains consistent due to the constant draft. The water cross-sectional area passes through the four pontoons, with Pontoon 1 equating Pontoon 2, and Pontoon 3 equating Pontoon 4.

$$A_{\text{circle}} = \pi \cdot r^2 \quad (\text{E.15})$$

Table E.3: Inertia TIF

Parameter	Formula	Value	Unit
Pontoon 1 & 2	I_{pontoon1} Formula C.4($D_{\text{pontoon}}, T_{\text{pontoon}}$)	2824.68	m^4
	A_{pontoon1} Formula E.15($r = (D_{\text{pontoon}} - 2 \cdot T_{\text{pontoon}})/2$)	131.59	m^2
	Distance _{pontoon1}	43	m
Pontoon 3 & 4	I_{pontoon2} Formula C.4($D_{\text{pontoon}}, T_{\text{pontoon}}$)	2824.68	m^4
	A_{pontoon2} Formula E.15($r = (D_{\text{pontoon}} - 2 \cdot T_{\text{pontoon}})/2$)	131.59	m^2
	Distance _{pontoon2}	10	m
I_{TIF}	Formula E.14	515705.64	m^4

Substructure

The moment of inertia is dependent on the waterplane area, and therefore dependent on the draft of the substructure. The values in table E.4 are calculated for a draft of 29.98 meter (during transport stage).

Table E.4: Inertia Substructure during Transport Stage

Parameter	Formula	Value	Unit
Mid column			
$I_{\text{mid column}}$	Formula C.4($D_{\text{outer, mid column}}$, $T_{\text{mid column}}$)	1479.36	m^4
$A_{\text{mid column}}$	Formula E.15($r = (D_{\text{outer, mid column}} - 2 \cdot T_{\text{mid column}})/2$)	93.48	m^2
Distance _{mid column}		0	m
2 · Brace0			
I_{brace0}	Formula E.20($D_{\text{outer, brace0}}$, T_{brace0} , θ_{brace0})	97.57	m^4
A_{brace0}	Formula D.14($(D_{\text{outer, brace0}} - 2 \cdot T_{\text{brace0}})/2$, θ_{brace0})	30.36	m^2
Distance _{brace0}	$L_x - (D_{\text{TIF, transport}} - H_{\text{mid column}}) \cdot \tan(\theta_{\text{brace0}})$	22.83	m
Brace0			
I_{brace0}	Formula E.20($D_{\text{outer, brace0}}$, T_{brace0} , θ_{brace0})	97.57	m^4
A_{brace0}	Formula D.14($(D_{\text{outer, brace0}} - 2 \cdot T_{\text{brace0}})/2$, θ_{brace0})	30.36	m^2
Distance _{brace0}		0	m
$I_{\text{Substructure}}$	Formula E.14	32629.31	m^4

To determine the moment of inertia of the substructure during the entire installation (lowering process), it is assumed that the moment of inertia decreases linearly from the draft of $D_{\text{transport}}$ to H_{TIF} . From H_{TIF} onwards, the inertia will remain constant because only the mid column plays a role.

E.4. Stability Check

If the metacentric height is known, the initial static stability of a floating body can be determined by calculating the $\overline{GM}$. In Figure E.3, the draft (K: yellow line), center of buoyancy (B: purple line), center of gravity (G: green line), and metacenter (M: red line) are shown as functions of the draft of the substructure.

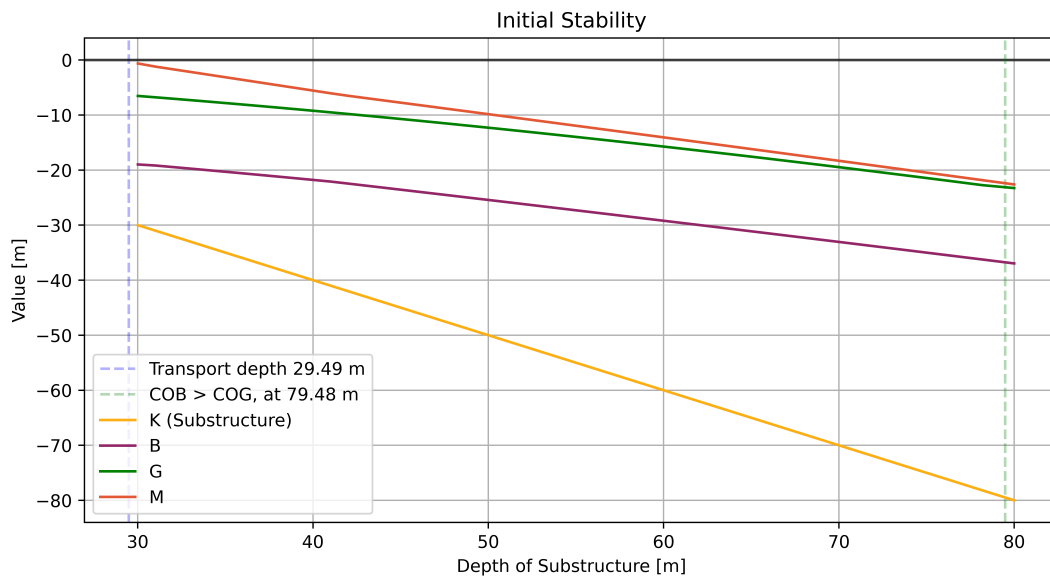


Figure E.3: Initial Stability as a function of the Draft

$\overline{KB}$ increases continuously because the buoyancy increases relatively slower compared to the draft of the substructure. This difference is depicted by the gap between the purple and yellow lines in Figure E.3.

$\overline{BM}$ is defined by Formula 5.2. $\overline{BM}$ becomes smaller as the depth of the substructure decreases. This is because the moment of inertia remains constant during the decrease of the draft (at least at a depth of 41 meters). However, the displaced volume will increase as the draft becomes larger. Therefore, the $\overline{BM}$ becomes smaller. In Figure E.3, it is the difference between the purple and red line.

The $\overline{KG}$ is the difference between the draft of the substructure and the CoG. During the lowering process the CoG of the substructure will decrease as well as the buoyancy tanks that are filled with seawater during this process. However, because it is considered as one system and the TIF remains at the same draft, this decrease will not be as rapid as the increase in draft of the substructure. The $\overline{KG}$ is the difference between the purple and green line in Figure E.3.

The $\overline{GM}$ values as a function of the draft for each structure are individually plotted in Figure E.4.

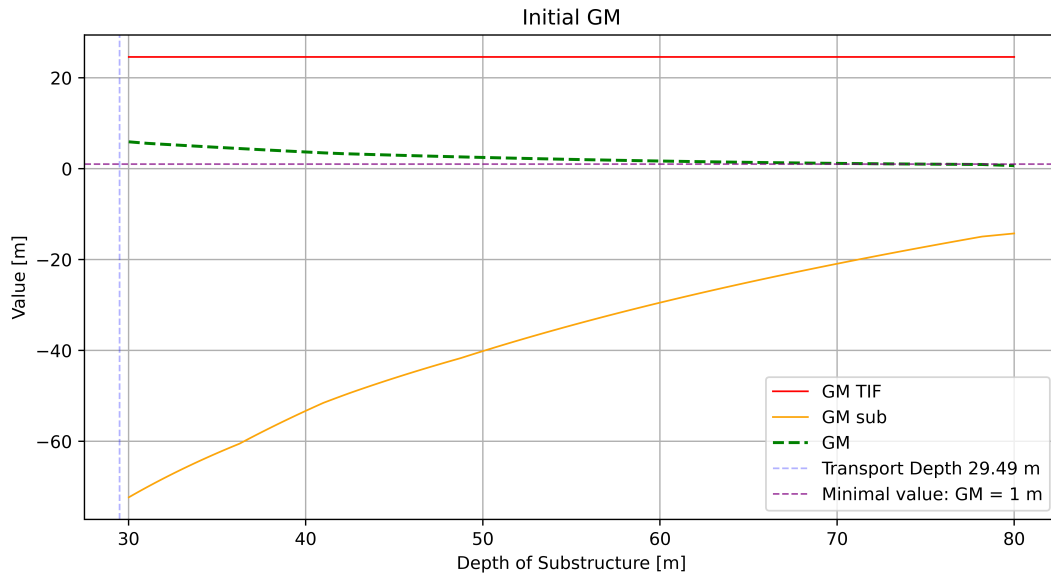


Figure E.4: Initial Stability per Structure as a function of the Draft

It can be observed that the TIF, illustrated in red, maintains a constant $\overline{GM}$ as it remains at waterline level during installation. The $\overline{GM}$ of the substructure (the bottom-fixed structure and wind turbine), illustrated in yellow, will increase as the draft increases. This can be explained by the fact that the CoG decrease faster than the CoB (due to the filling of the buoyancy tanks).

The green line represents the total system, which decreases as the draft increases. This is because the displaced area increases as draft increases. The inertia decreases gradually, resulting in a decrease in the total $\overline{GM}$.

E.5. Stability Curve

This section presents the formulas and explanations relevant to the calculation of the maximum righting moment, as detailed in Section 5.2. This analysis will focus on a water depth of 80 meters, and a top column diameter of 12 meters. Dotted lines will represent the scenario for a water depth of 70 meters.

The stability curve has been determined for three cases: the TIF, the substructure, and the total system. These curves can be used to find the restoring rotational force for the stiffness matrix later on (Section 5.4).

The stability curve is given by $\overline{GN}$, for which the formula is provided below and is the same for all three structures. These formulas are dependent on the draft (D) of the structure.

$$\overline{BN} = \frac{I}{\nabla} \left(1 + 0.5 \left(\tan \left(\frac{\theta_{\text{of heel}}}{D_{\text{transport}}} \right) \right)^2 \right) \quad (\text{E.16})$$

$$\overline{KB} = D_{\text{transport}} + \text{CoB}(D) \quad (\text{E.17})$$

$$\overline{KG} = D_{\text{transport}} + \text{CoG}(D) \quad (\text{E.18})$$

$$\overline{GN} = \overline{KB} + \overline{BN} - \overline{KG} \quad (\text{E.19})$$

TIF

The stability curve is calculated to define the restoring force of the stiffness matrix. For the TIF, the stability curve remains constant throughout the transport and installation stages, as it maintains a constant draft.

The formula for the moment of inertia for an oval is given by:

$$I_{\text{oval}}(D, t, \theta) = \frac{\pi}{4} \cdot \frac{(D - 2t)^2}{\sin^2(90 - \theta)} \left(\frac{(D - 2t)^2}{\sin^2(90 - \theta)} + (D - 2t)^2 \right) \quad (\text{E.20})$$

Formula E.14 is used to compute the combined inertia of the TIF. Formula D.14 is used to calculate the cross-sectional area of the cylinder. The formulas for the area and individual inertia provided by:

$$I_{\text{pontoon1}}(\theta_{\text{of heel}}) = \text{Formula E.20}(D_{\text{pontoon}}, T_{\text{pontoon}}, \theta_{\text{of heel}}) \quad (\text{E.21})$$

$$A_{\text{pontoon}}(\theta_{\text{of heel}}) = \text{Formula D.14}((D_{\text{pontoon}} - 2 \cdot T_{\text{pontoon}})/2, 90 - \theta_{\text{of heel}}) \quad (\text{E.22})$$

Taking into account four pontoons with twice the distance of $\text{Distance}_{\text{pontoon1}} = 43$ m and twice the distance of $\text{Distance}_{\text{pontoon2}} = 10$ m.

Furthermore, the displaced volume remains constant as a function of the draft of the substructure. Formula D.13 (with $D = 29.53$ m) has been used. Subsequently, Formulas E.16 and E.19 have been used to define the $\overline{GN}$ for the various angles of heel, where:

$D_{\text{TIF, transport}}$	is the draft during transport	= 29.58 m	= 29.53 m
CoG_{TIF}	is the center of Gravity at	= -6.24 m	= -6.19 m
CoB_{TIF}	is the center of Buoyancy at	= -22.84 m	= -22.81 m

The graphical representation can be found in Figure E.5, where the TIF is represented by the red line.

Substructure

This calculation is used to define the restoring force and to determine the maximum axial force that must be transmitted by the spud piles. Below in Table E.5 the inertia, areas, and distances used for the various braces of the substructures are given to calculate the combined inertia. Formula E.14 is used for this calculation. The calculations and values provided below are for a draft during transport of 29.53 meters. However, the inertia of the substructures varies according to the draft.

Table E.5: Inertia Substructure during Transport Stage as a Function of the Draft

Parameter	Symbol	Formula
Mid Column	$I_{\text{mid column}}$	Formula E.20($D_{\text{outer, mid column}}$, $T_{\text{mid column}}$, $\theta_{\text{of heel}}$)
	$A_{\text{mid column}}$	Formula D.14($(D_{\text{outer, mid column}} - 2 \cdot T_{\text{mid column}})/2$, $90 - \theta_{\text{of heel}}$)
	$\text{Distance}_{\text{mid column}}$	$= 0 \text{ m}$
Brace0	I_{brace0}	Formula E.20($D_{\text{outer, brace0}}$, T_{brace0} , θ_{brace0})
	A_{brace0}	Formula D.14($(D_{\text{outer, brace0}} - 2 \cdot T_{\text{brace0}})/2$, θ_{brace0})
	$\text{Distance}_{\text{brace0}}$	$= 0 \text{ m}$
Brace0	I_{brace0}	Formula E.20($D_{\text{outer, brace0}}$, T_{brace0} , $\theta_{\text{brace0}} - \theta_{\text{of heel}}$)
	A_{brace0}	Formula D.14($(D_{\text{outer, brace0}} - 2 \cdot T_{\text{brace0}})/2$, $\theta_{\text{brace0}} - \theta_{\text{of heel}}$)
	$\text{Distance}_{\text{brace0}}$	$L_x - (D_{\text{TIF, transport}} - H_{\text{mid column}}) \cdot \tan(\theta_{\text{brace0}}) = 22.57 \text{ m}$
Brace0	I_{brace0}	Formula E.20($D_{\text{outer, brace0}}$, T_{brace0} , $\theta_{\text{brace0}} + \theta_{\text{of heel}}$)
	A_{brace0}	Formula D.14($(D_{\text{outer, brace0}} - 2 \cdot T_{\text{brace0}})/2$, $\theta_{\text{brace0}} + \theta_{\text{of heel}}$)
	$\text{Distance}_{\text{brace0}}$	$L_x - (D_{\text{TIF, transport}} - H_{\text{mid column}}) \cdot \tan(\theta_{\text{brace0}}) = 22.57 \text{ m}$
$I_{\text{Substructure}}$		Formula E.14

It is assumed that the displaced volume remains constant throughout the rotation angle. This assumption is valid because the angles involved are small. Using Formula D.15 (with $D = 29.53 \text{ m}$) gives a value of 11276 m^3 . Subsequently, Formulas E.16 and E.19 were used to define $\overline{GN}$.

Total System

The $\overline{GN}$ of the total system is used to define the maximum rotation for the entire system during transport and installation, as well as to find the maximum horizontal forces (external) possible during transport. To calculate this, the two inertia's are added together, as well as the displaced volume. Formulas E.16 and E.19, are used to calculate the $\overline{GN}$, with:

$$\begin{array}{lll}
 I = I_{\text{TIF}} + I_{\text{Substructure}} & = 586365 & 588120 \text{ m}^4, \\
 \nabla = \nabla_{\text{TIF}} + \nabla_{\text{Substructure}} & = 29622 & 29613 \text{ m}^3, \\
 D_{\text{TIF, transport}} \text{ is draft during transport} & = 29.64 & 29.53 \text{ m}, \\
 \text{CoG}_{\text{total}} & = -6.94 & -5.79 \text{ m}, \\
 \text{CoB}_{\text{total}} & = -19.93 & -20.80 \text{ m}.
 \end{array}$$

The stability lever arm can be determined using Equation E.23 (scribanti formula):

$$\overline{GZ} = \overline{GN} \cdot \sin(\phi) \quad (\text{E.23})$$

In Figure E.5, graphical representations of the $\overline{GZ}$ are provided for the different structures. This is extended up to the maximum angle of heel of 17.17° for 70 meters and 18.71° for 80 meters, as described in Equation E.24.

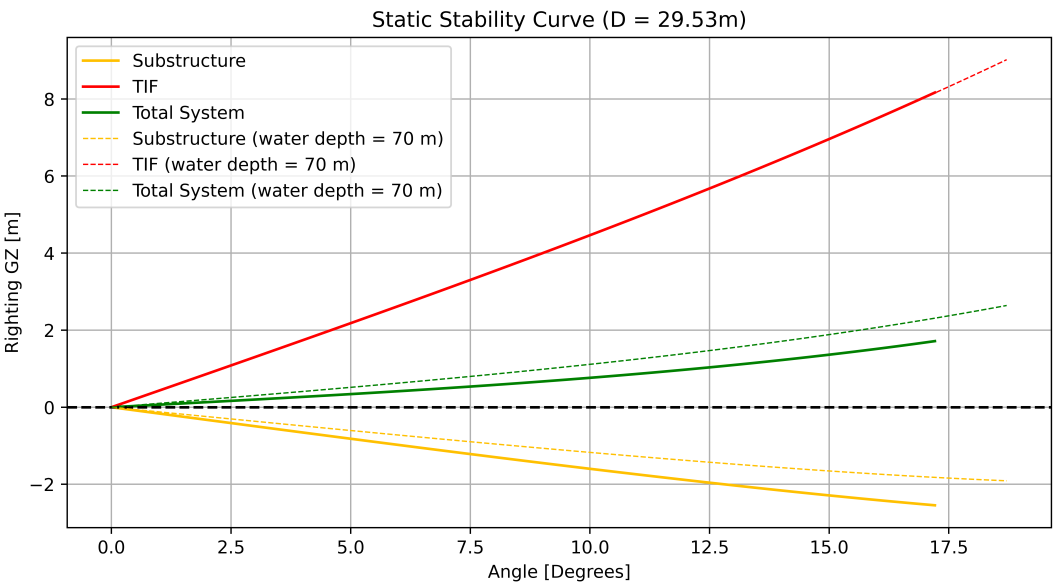


Figure E.5: Static Stability Curve

In this graph, it can be observed that the yellow line (substructure) lies below the x-axis, indicating that this structure lacks of rotational stability. The green line consistently remains positioned above the x-axis, signifying stability during the transport stage. Below, the stability curves for each draft will be given.

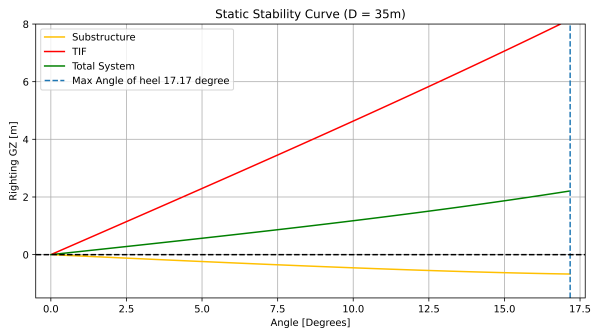


Figure E.6: Static Stability Curve for a Draft of 35 meters.

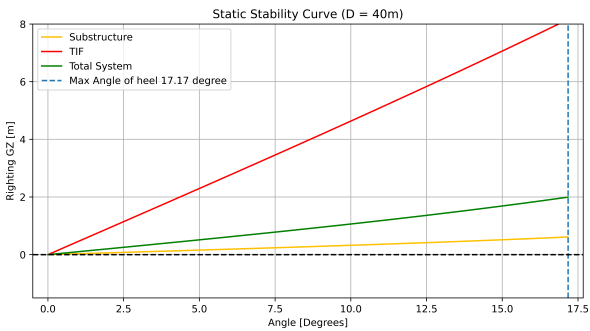


Figure E.7: Static Stability Curve for a Draft of 40 meters.

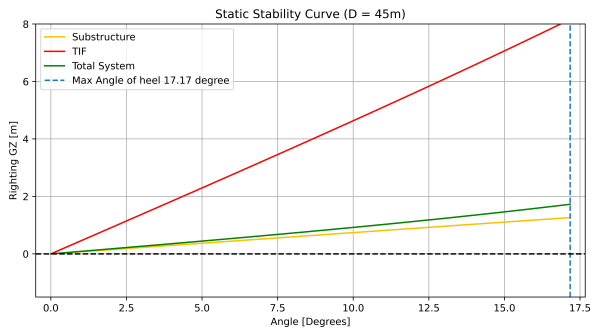


Figure E.8: Static Stability Curve for a Draft of 45 meters.

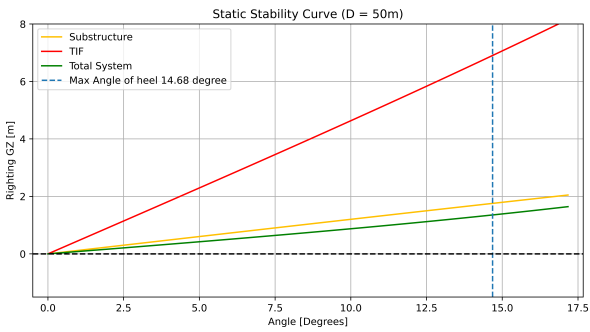


Figure E.9: Static Stability Curve for a Draft of 50 meters.

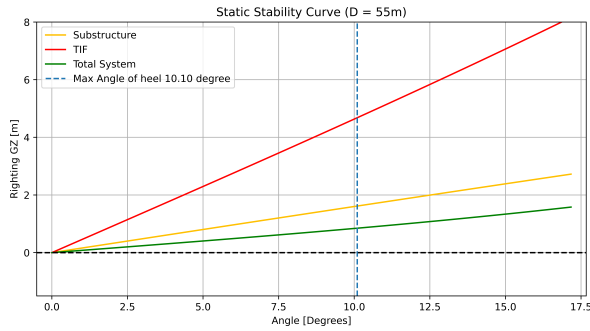


Figure E.10: Static Stability Curve for a Draft of 55 meters.

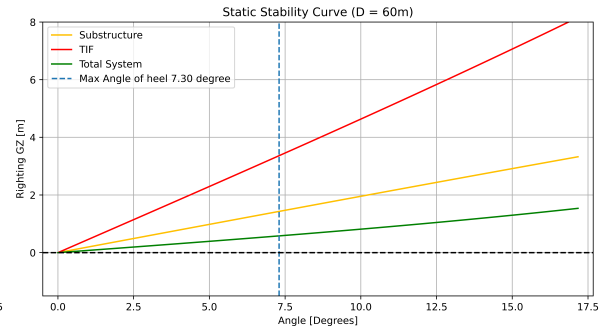


Figure E.11: Static Stability Curve for a Draft of 60 meters.

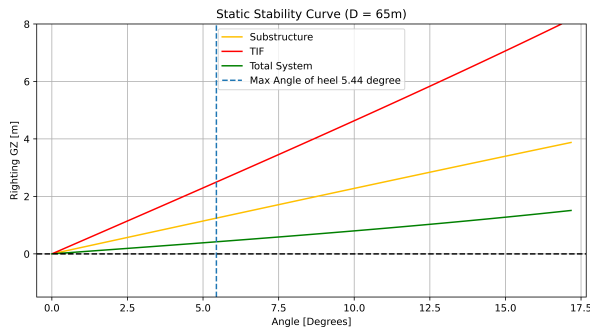


Figure E.12: Static Stability Curve for a Draft of 65 meters.

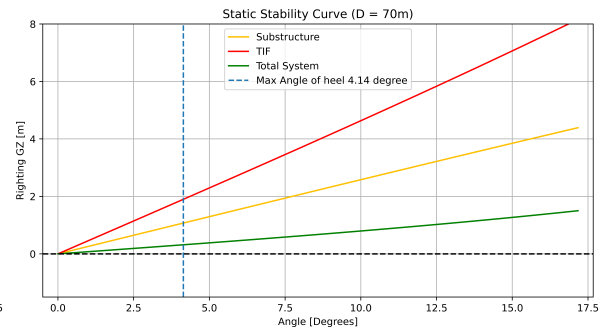


Figure E.13: Static Stability Curve for a Draft of 70 meters.

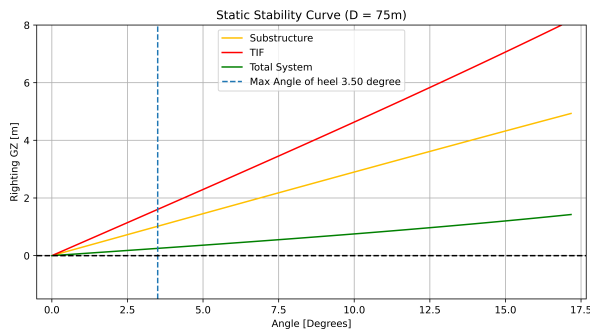


Figure E.14: Static Stability Curve for a Draft of 75 meters.

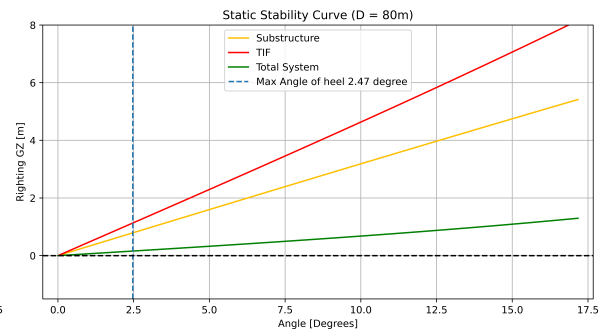


Figure E.15: Static Stability Curve for a Draft of 80 meters.

It can be observed that the $\overline{GZ}$ of the TIF, represented by the red line, remains constant for all drafts. The $\overline{GZ}$ of the substructure, illustrated by the yellow line, increases. This corresponds with what is shown in Figure E.4, which can be explained by the decrease of the CoG with an increase in draft. Additionally, for the green line, there is a slight downward shift, indicating that the $\overline{GZ}$ of the total system decreases with increasing draft. The alignment of the $\overline{GZ}$ between the substructure and the TIF is not feasible due to their distinct CoG and CoB, necessitating independent positioning. However, when considered as a unified system, these components are integrated, leading to adjustments in their collective $\overline{GZ}$ characteristics.

The dotted blue lines indicate the maximum angle, which will be calculated in the next section.

E.6. Maximum Angle of Heel

The initial static stability and the rotational stability curve for each draft were defined. The stability curve is assessed for the substructure, the TIF, and the total system. To determine the critical maximum angle

of heel constrained by the strength of the spud piles, the lateral (and thus moments) and axial forces transferring from the substructure to the TIF must be assessed. Subsequently, based on the stability curve of only the substructure, the maximum angle of heel can be determined.

E.6.1. Angle of Deck Edge Immersion

One crucial factor in defining the maximum angle of heel is the angle of deck edge immersion, marking the point where water starts to come over the vessel edge, introducing additional external forces affecting rotational stability. This maximum angle is determined by the formula [28]:

$$\phi_{\max} = \arctan \left(\frac{H_{\text{TIF}} - D_{\text{TIF, transport}} - \text{CoG}_{\text{total}}}{\text{arm}/2} \right) \quad (\text{E.24})$$

where:

H_{TIF}	is the height of TIF
$D_{\text{TIF, transport}}$	is the draft during transport
$\text{CoG}_{\text{transport}}$	is the center of Gravity during transport
Arm	is the distance between pontoons of TIF

The maximum angle for a water depth of 70 meters is 18.71° , and for a water depth of 80 meters, it is 17.17° .

E.6.2. Strength Spud Piles

The maximum axial force and moments that the spud piles can withstand were defined according to the API code [2]. The water pressure, which increases in proportion to the draft, was found to be the primary factor influencing the maximum moment. The length of the spud piles had less impact, as the distance between the stiffeners was maintained at a constant 6 meters for all drafts. These maximum moments in the spud piles are provided in Table 5.2 and illustrated as horizontal lines in Figure 5.3.

Moment in Spud Piles due to Rotation

To define the forces transmitted through the spud piles, the forces acting on the substructure will be divided into lateral and axial forces by the spud piles, as illustrated in Figure E.16.

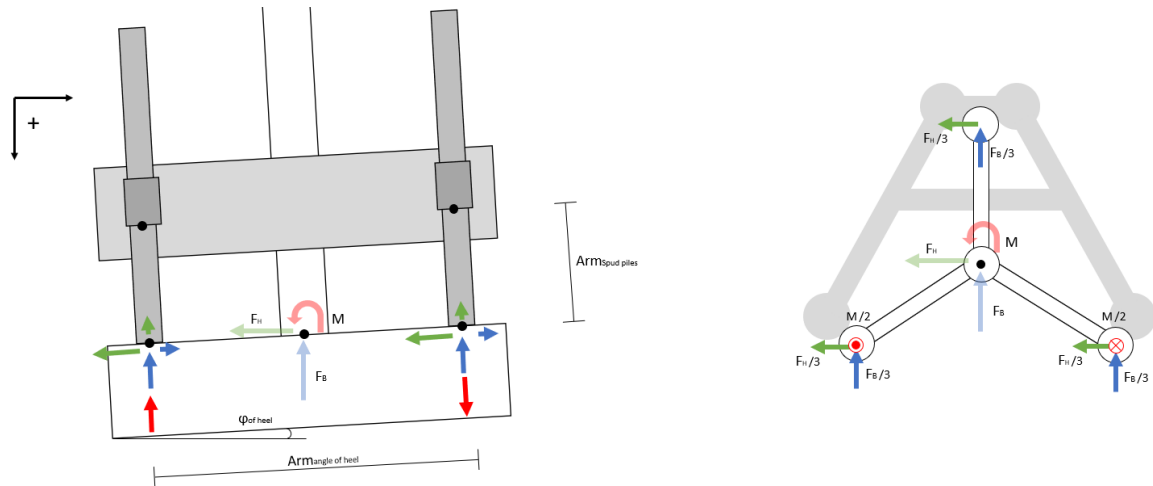


Figure E.16: Graphical Representation of Forces on the Spud Piles

The first force involved in this situation is the moment (righting moment), as illustrated in Figure E.17, which can be derived from the stability curve of the substructure (Equation E.26).

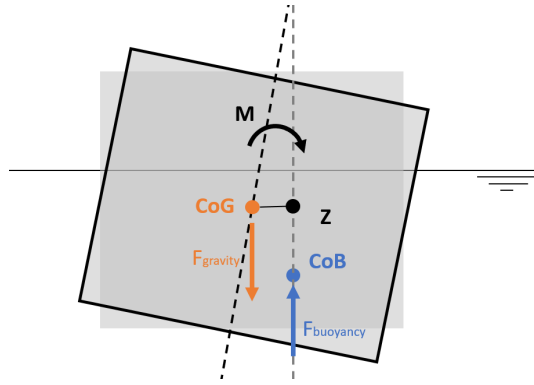


Figure E.17: Righting Moment

$$M_{\text{righting}} = \overline{GZ} * F_{\text{buoyancy of substructure}} \quad (\text{E.25})$$

The vertical force acting on the substructure, is equivalent to the net vertical force (buoyancy force), and the horizontal force on the substructure, is taken as the environmental force [28].

$$\begin{aligned} F_V &= \text{vertical force (buoyancy force),} \\ F_H &= \text{horizontal force (external force).} \end{aligned} \quad (\text{E.26})$$

These forces act on the substructure and need to be distributed among the three spud piles. This is illustrated in the right illustration of Figure E.16. The forces will be decomposed into axial and lateral forces by the spud piles.

$$\begin{aligned} \text{Lateral: } F_{\text{lateral, V}} &= \frac{F_V \cdot \sin\left(\frac{\theta_{\text{of heel}}}{3}\right)}{3} & \text{Axial: } F_{\text{axial, V}} &= \frac{F_V \cdot \cos\left(\frac{\theta_{\text{of heel}}}{3}\right)}{3} \\ F_{\text{lateral, H}} &= \frac{F_H \cdot \cos\left(\frac{\theta_{\text{of heel}}}{3}\right)}{3} & F_{\text{axial, H}} &= \frac{F_H \cdot \sin\left(\frac{\theta_{\text{of heel}}}{3}\right)}{3} \end{aligned} \quad (\text{E.27})$$

The individual axial forces exerted by the spud piles are defined using the formulas described below. Each of the three spud piles has a different axial force due to the direction of rotation.

$$\begin{aligned} F_{\text{axial, Spudpile1}} &= -\frac{F_{\text{axial, V}}}{3} - \frac{M_{\text{righting}}}{2 \cdot \text{arm}} - \frac{F_{\text{axial, H}}}{3} \\ F_{\text{axial, Spudpile2}} &= -\frac{F_{\text{axial, V}}}{3} + \frac{M_{\text{righting}}}{2 \cdot \text{arm}} - \frac{F_{\text{axial, H}}}{3} \\ F_{\text{axial, Spudpile3}} &= -\frac{F_{\text{axial, V}}}{3} - \frac{F_{\text{axial, H}}}{3} \end{aligned} \quad (\text{E.28})$$

The arm is equal to the horizontal distance between the spud piles, which is 78 meters. The individual lateral forces exerted by the spud piles are defined using the formulas described below. All three spud piles have the same lateral forces.

$$F_{\text{lateral, Spudpiles1,2,3}} = -\frac{F_{\text{lateral, H}}}{3} + \frac{F_{\text{lateral, V}}}{3} \quad (\text{E.29})$$

By decomposing the forces into lateral and axial components, the moment in the spud piles can be found. The moment is calculated by multiplying the lateral force by the $\text{arm}_{\text{spudpiles}}$, as outlined below:

$$F_{\text{moment, spudpiles1,2,3}} = F_{\text{lateral, Spudpiles1,2,3}} \cdot \text{arm}_{\text{spudpiles}} \quad (\text{E.30})$$

The $\text{arm}_{\text{spudpiles}}$ is dependent on the draft and has a maximum length of 53 meters.

The moments in the spud piles can be plotted as a function of the angle for different drafts (in steps of 5 meters). The moment increases as the angle becomes larger. In Figure 5.3, the case for 80 meters water depth is illustrated. The horizontal dotted lines represent the maximum moment possible in the spud piles, calculated according to the API standard.

E.6.3. Conclusion

As discussed in Section 5.2, two factors contribute to determining the maximum angle of heel: the angle of deck edge immersion and the strength of the spud piles. The corresponding values are presented in Table E.6.

Table E.6: Conclusion on Maximum Angle of Heel

Draft	Max Moment in the Spud Piles	Max Angle of Heel Water depth = 70 m	Max Angle of Heel Water depth = 80 m
<i>m</i>	<i>MNm</i>	<i>Degree</i>	<i>Degree</i>
35	175	18.67	17.17
40	170	18.67	17.17
45	160	18.67	17.17
50	150	14.48	14.68
55	140	9.97	10.10
60	130	7.22	7.30
65	120	5.38	5.44
70	110	4.10	4.14
75	100		3.50
80	90		2.47

E.7. Heeling Moment Curve

The heeling moment, crucial in assessing stability, refers to the rotational force experienced by a structure due to external factors like wind. According to DNV regulations, the area of the righting moment should be 1.3 times greater than the area under the curve of the heeling moment. In this chapter will calculate the heeling moment required to meet this criterion, based on the calculated stability curve in Section E.5 and maximum angle of heel.

E.7.1. External Horizontal Forces

The heeling moment is defined as the moment that results from a horizontal external force, which causes the system to rotate. In which the horizontal external force acts on H_{heeling} , as given by the formula:

$$H_{\text{heeling}} = \frac{(H_{\text{turbine}} + H_{\text{TIF}}) \cdot \frac{7}{16} \cdot F_{\text{drag}} + F_{\text{thrust}} \cdot (H_{\text{turbine}} + H_{\text{TIF}})}{F_{\text{drag}} + F_{\text{thrust}}} + \text{CoG}_{\text{total, transport}} \quad (\text{E.31})$$

H_{heeling} (124 meters) is multiplied by the external force to obtain the heeling moment. In Figure E.18, an example is plotted for the case of the righting moment and heeling moment curve for the installation stage with a draft of 35 meters.

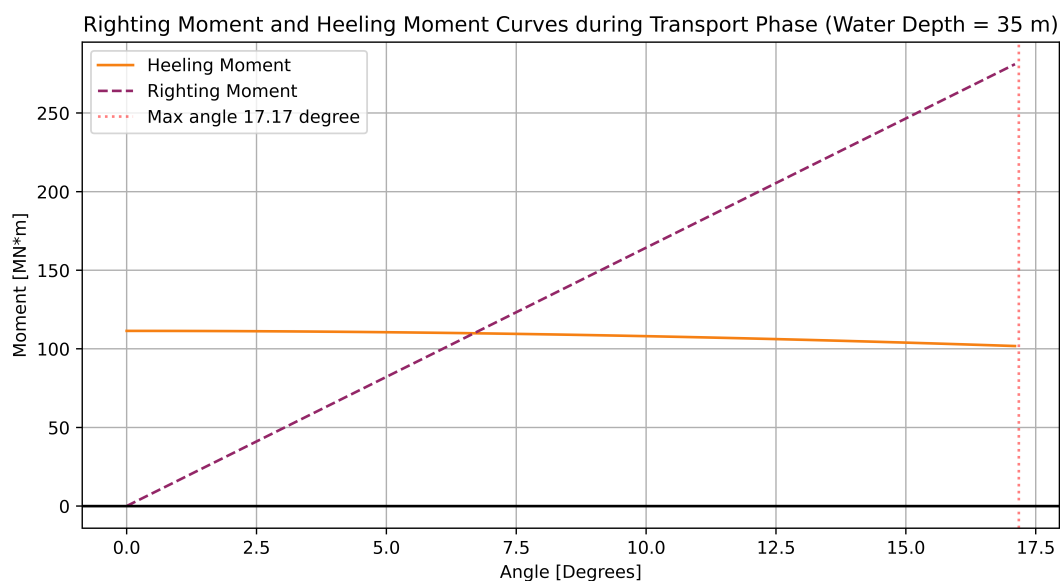
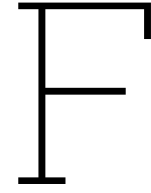


Figure E.18: Righting Moment Curve during Transport Stage

These calculations have been performed for different drafts (steps of 5 meter), and from these, the maximum external forces have been determined. These are provided in Table E.7.

Table E.7: External Horizontal Force at Different Drafts

Draft	External Horizontal Force Water depth = 70 m	External Horizontal Force Water depth = 80 m
<i>m</i>	<i>MN</i>	<i>MN</i>
35	0.98	0.93
40	0.98	0.93
45	0.67	0.71
50	0.48	0.51
55	0.36	0.38
60	0.27	0.29
65	0.21	0.22
70	0.17	0.18
75		0.16
80		0.11



Seabed Placement Analysis

In this Appendix, further explanations and calculations for the analysis of the installation stage, particularly the seabed placement, as discussed in Section 5.3. It will discuss the effects of implementing heavy blocks into the design, followed by an explanation on the on-bottom stability during the operation stage and the foundation frame and mudmat.

F.1. Effects of the Implementation of Heavy Blocks in the Design

The 1200 tonnes blocks in the spud piles will impact the CoG of the system. The weight of the heavy blocks is subtracted from the total amount of ballast in the TIF, resulting in no change to the total gravity force of the TIF, as summarized in Table F.1.

Table F.1: Changed Gravity Force in the TIF between the Initial Design and After the Implementation of Heavy Blocks

Parameter	First Design	Implementations of Heavy Blocks	Unit
Total mass TIF	5575.00	8122.31	<i>tonnes</i>
Total mass Ballast TIF	20500.00	17952.69	<i>tonnes</i>
Total Gravity Force TIF	26075.00	26075.00	<i>tonnes</i>

It can be observed that the difference becomes increasingly larger as the installation stage progresses. This can be explained by the lowering of the spud piles, along with their heavy blocks, and shifting the CoG.

F.1.1. Effects on Initial Stability

The differences in CoG are documented in Table F.2.

Table F.2: Changed CoG of the TIF between the Initial Design and after the Implementation of Heavy Blocks

CoG _{total}	First Design	Implementations of Heavy Blocks	Unit
Draft = 30 <i>m</i>	-6.60	-6.99	<i>m</i>
Draft = 50 <i>m</i>	-12.75	-13.80	<i>m</i>
Draft = 65 <i>m</i>	-19.68	-21.31	<i>m</i>

F.1.2. On-bottom Stability

The braces are filled with seawater ballast during the Operation Stage to provide on-bottom stability. The ballast in the braces is calculated using the formula:

$$M_{\text{sliced cylinder}}(r, \theta) = \pi r \frac{r}{\sin(\theta) \cdot 1000} \cdot \rho_{\text{seawater}} \quad (\text{F.1})$$

Table F.3: Total Ballast Filling the Braces of the Bottom-fixed Structure

Ballast Filling		Value	Unit
$M_{\text{ballast,brace0}}$	3 · Formula F.1 $\left(\frac{D_{\text{Outer, brace0}} - 2 \cdot T_{\text{brace0}}}{2}, \theta_{\text{brace0}} \right) \cdot L_{\text{mid column}}$	2894.23	tonnes
$M_{\text{ballast,brace1}}$	3 · Formula F.1 $\left(\frac{D_{\text{Outer, brace1}} - 2 \cdot T_{\text{brace1}}}{2}, \theta_{\text{brace1}} \right) \cdot H_{\text{brace1}}$	2331.09	tonnes
$M_{\text{ballast,mid column}}$	Formula F.1 $\left(\frac{D_{\text{Outer, mid column}} - 2 \cdot T_{\text{mid column}}}{2}, 90 \right) \cdot L_{\text{mid column}}$	2970.47	tonnes
$M_{\text{ballast,top column}}$	Formula F.1 $\left(\frac{D_{\text{Outer, top column}} - 2 \cdot T_{\text{top column}}}{2}, 90 \right) \cdot L_{\text{top column}}$	5232.76	tonnes
$M_{\text{ballast,total braces}}$		13428.55	tonnes

The on-bottom stability, is calculated before and after the disconnecting of the buoyancy tanks.

Before disconnecting the buoyancy tanks:

$$\begin{aligned}
 F_{V,\text{on-bottom stability}} &= M_{\text{ballast in braces}} (=13428.55 \text{ tonnes}) \\
 &+ M_{\text{bottom-fixed structure}} (= 2947.54 \text{ tonnes}) \\
 &+ M_{\text{turbine}} (= 1877.00 \text{ tonnes}) \\
 &+ M_{\text{ballast in Buoyancy tanks}} (= 6000.00 \text{ tonnes}) \\
 &- B_{\text{substructure}} (=19586.23.26 \text{ tonnes})
 \end{aligned} \tag{F.2}$$

After disconnecting the buoyancy tanks:

$$\begin{aligned}
 F_{V,\text{on-bottom stability}} &= M_{\text{ballast in braces}} (=13428.55 \text{ tonnes}) \\
 &+ M_{\text{bottom-fixed structure}} (= 2947.54 \text{ tonnes}) \\
 &+ M_{\text{turbine}} (= 1877.00 \text{ tonnes}) \\
 &- B_{\text{substructure}} (=13586.23 \text{ tonnes})
 \end{aligned} \tag{F.3}$$

This gives a vertical gravitational force of 4666.85 tonnes (45.78 MN) for both situations.

F.2. Foundation Frame

A more in-depth design has been developed for the critical issue of seabed placement. A temporary foundation frame has been designed to position the mudmats accurately on the seabed.

First, the design of the mudmats will be described, including the calculations on the bearing capacity. Following this, the step-by-step process of their placement will be outlined.

Bearing Capacity

To determine the required dimensions of the mudmats, a calculation of the bearing capacity must be performed. The ultimate soil bearing capacity should be defined through a geotechnical survey of the soil. However, for this phase of the design, an estimation will be made using Skempton's procedure and Davis & Booker's method. The calculation of the bearing pressure (Q_{ult}) varies depending on the effective width of the bearing area [33].

$$Q_{\text{ult}} = \begin{cases} (20.00 + 1.39B) \times (1 + 0.2 \times \frac{B}{L}) & \text{for } B < 6.5 \text{ meters} \\ (23.94 + 0.78B) \times (1 + 0.2 \times \frac{B}{L}) & \text{for } B \geq 6.5 \text{ meters} \end{cases} \tag{F.4}$$

where:

Q_{ult} is the ultimate bearing pressure [kPa],
 B is the effective width of the bearing area,
 L is the effective length of the bearing area .

According to these formulas, a square mudmat with dimensions of 18x18 meters is required to provide sufficient bearing capacity for the gravitational force during the operation stage. For the design of the

mudmat, an equilateral triangle has been chosen, allowing for a foundation pile to pass through each corner of the triangle. The length of the sides of the equilateral triangle will be 28 meters. Three mudmats will be used, each supporting one foundation sleeve of the bottom-fixed structure. To ensure that the mudmats are placed at the correct distance from each other, a temporary foundation frame will be attached to them. This frame will ensure equal spacing.

The parameters used for the Mudmat frame are outlined in Table F.4. Subsequently, further details will be provided regarding the connections between the foundation frame and mudmat, as well as the installation steps.

Table F.4: Parameters Mudmat Frame

Parameter	Value	Unit
Length	28	m
# Foundation piles per mudmat	3	-
Diameter Foundation piles	2.5	m
Diameter Foundation sleeve (on bottom-fixed structure)	5.00	m

In Figure F.9, a top view of the temporary foundation frame (in red) and the mudmats (in grey) is presented. The temporary foundation frame ensures sufficient spacing between the mudmats, measured at 78 meters. Additionally, the mudmats provide sufficient bearing capacity during the operational stage.

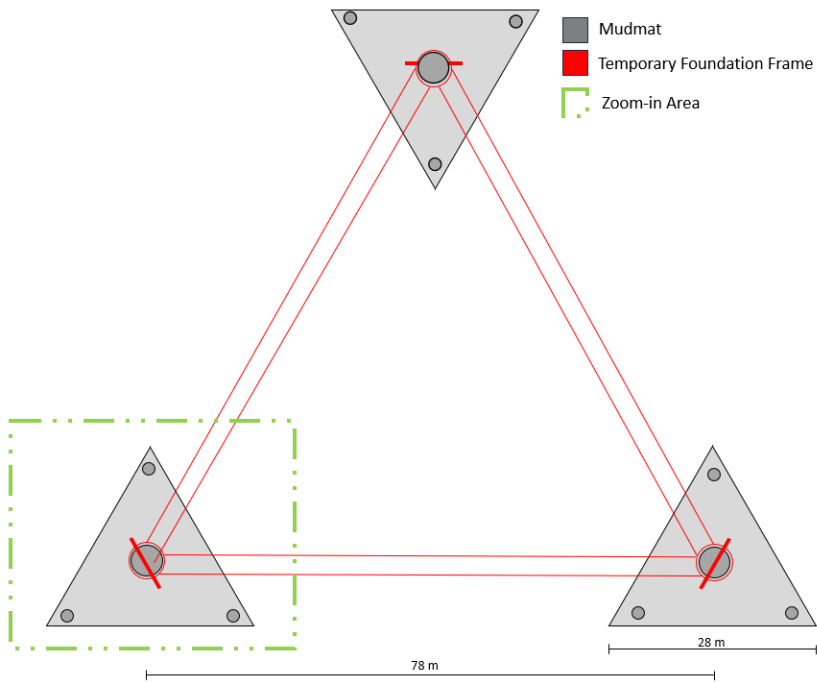


Figure F.1: Top View Temporary Foundation Frame and Mudmats

F.2.1. Placement of the Foundation Frame and Mudmat

Within this section, a step-by-step explanation will be provided on the installation process of the temporary foundation frame and the mudmats. It will include a side view representation of the mudmat in the green area illustrated in Figure F.9.

Step 1:

In this step, the mudmat connected to the temporary foundation frame will be lowered to the seabed at the offshore location and using a crane. The temporary foundation frame and the mudmats are connected to each other with a pin, allowing them to be disconnected from each other at a later stage.

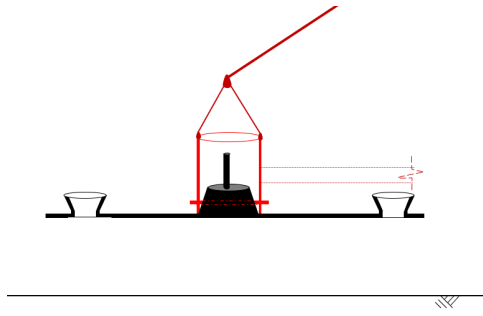


Figure F.2: Step 1A: Lowering of the Temporary Foundation Frame and Mudmats

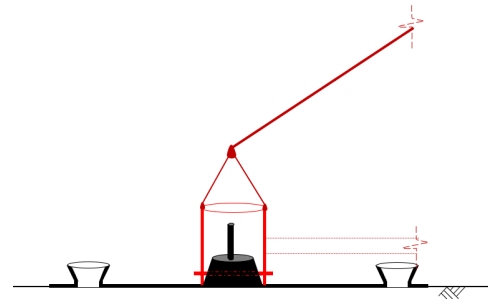


Figure F.3: Step 1B: Placement of the Temporary Foundation Frame and Mudmats on Seabed

Step 2:

While the mudmat remains connected to the frame, three piles can be driven into the seabed through the sleeves of the mudmats. The pile hammering process can ensure that the mudmats are aligned, positioning the wind turbine aligned. Once the piles are in place, the system can be grouted.

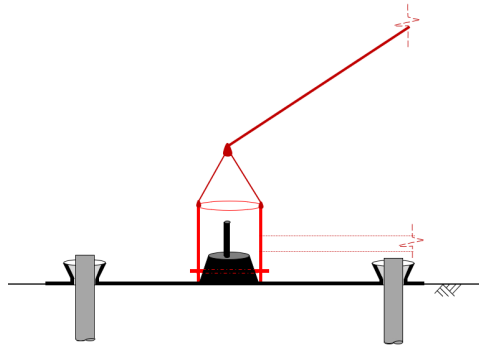


Figure F.4: Step 2: Foundation Piles Installation through Pile Sleeves in Mudmats

Step 3:

In step 3, the pin connecting between the temporary foundation frame and the mudmat frame can be released, allowing the temporary foundation frame to be lifted upward.

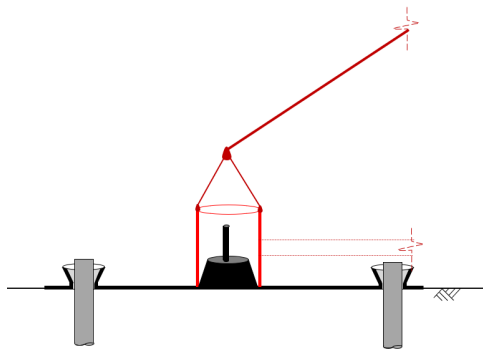


Figure F.5: Step 3A: Disconnection of the Pin between Temporary Foundation Frame and Mudmat

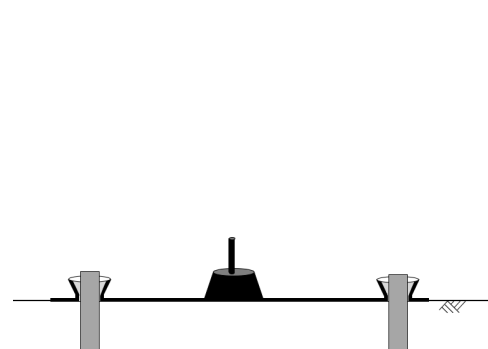


Figure F.6: Step 3B: Rise Temporary Foundation Frame

Step 4:

In this step, the TIF is positioned above the mudmats, and the location is verified with the assistance of a ROV. For the first two meters, the system will be gradually lowering with ballast in the TIF, until it reaches the thin pin. This is verified by a ROV. This action ensures that the substructure precisely aligns over the pin of the mudmat. If alignment is confirmed, the final installation step can be executed by releasing the heavy blocks.

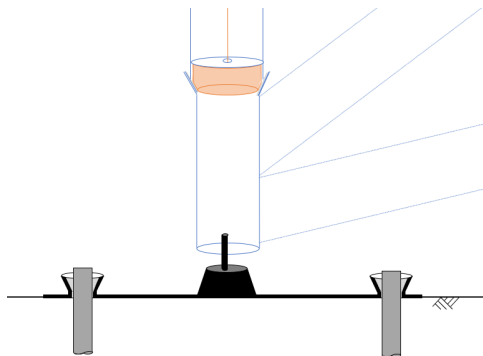


Figure F.7: Step 4A: Substructure Lowered just above the Mudmat, by Ballasting the TIF

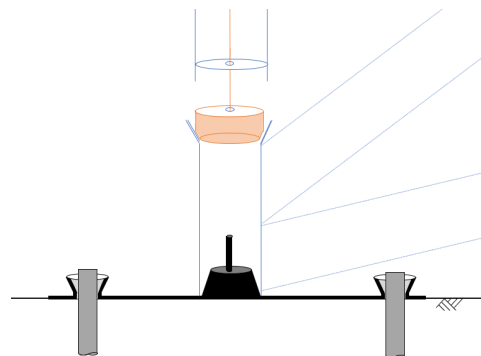


Figure F.8: Step 4B: Seabed Placement, Lowering of the Heavy Blocks

Step 5:

Subsequently, the braces of the bottom-fixed structure will be filled with seawater, and the heavy blocks and spud piles will be lifted. To provide sufficient horizontal resistance, the pin and the foundation sleeve of the bottom-fixed structure will be grouted.

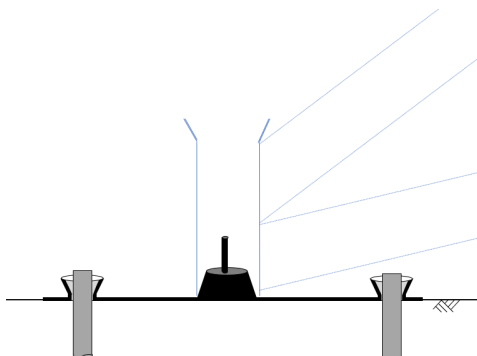


Figure F.9: Step 5: Substructure Placement on Mudmat, Grouting Foundation Sleeve and Mudmat

F.2.2. Advantages of this Foundation Option

Below, the advantages of these foundation options are summarized:

- **Consistent spacing:** The use of the temporary foundation frame ensures that the distance between the three mudmats remains the same. This ensures a standardised installation process.
- **Timing flexibility:** There may be a gap between seabed preparation and the installation of the bottom-fixed structure using the TIF. During this time, the mudmats remain in place, allowing for a more flexible installation schedule.
- **Design flexibility:** Installing mudmats separately from the substructure provides greater design flexibility for the bottom-fixed structure.
- **Sustainability:** Using a temporary frame reduces the amount of steel required for the foundation, leading to cost savings and promoting sustainability with reuse of the frame.



Eigen Period Analysis

In this appendix, further elaboration is provided on Section 5.4. The assumptions regarding the added mass will be further explained.

G.1. Assumption: Added Mass

The added mass can be calculated for each component of the structure separately. However, considering the primary concern for feasibility and the goal to provide the most critical stage for the natural periods, an assumption is made for this purpose. In this analysis, a preliminary estimate of 20% of the total mass has been used for the added mass. The impact on the natural period of this approximation is illustrated in Figure G.1.

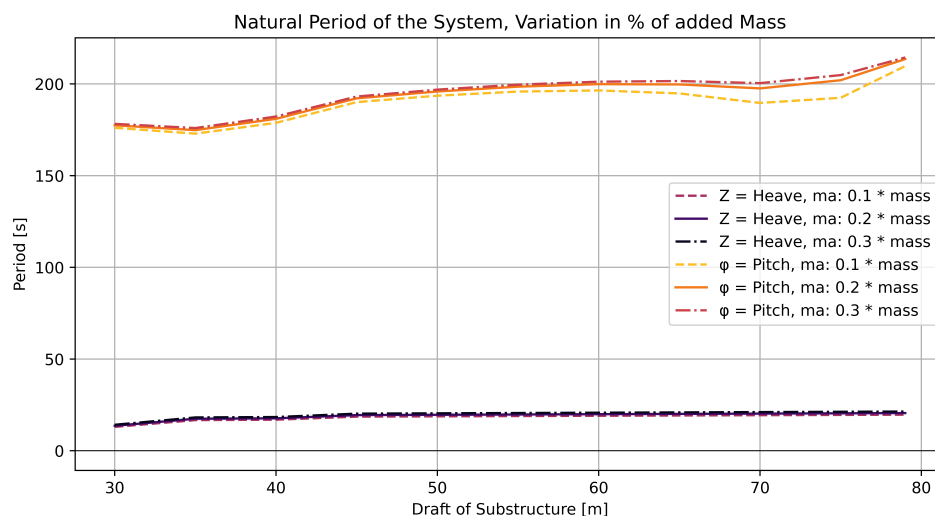


Figure G.1: Influence of the Variation of Added Mass

From this, it can be observed that the natural period increases as more percent of added mass is present. This is because a higher mass, makes the system more stiff. For the natural period in heave, the variation will be minimal, while for the natural period in pitch, it may be slightly more pronounced. These lines illustrate that the actual period is likely to fall within this range.

The difference in added mass affects both degrees, but it has a greater impact on the natural period in pitch. This can be explained by examining the added mass Matrix 5.6, which shows that the squared differences in CoB and CoG are also accounted for in the pitch direction. This adjustment appears to have a more significant effect than the actual percentage of the added mass itself.