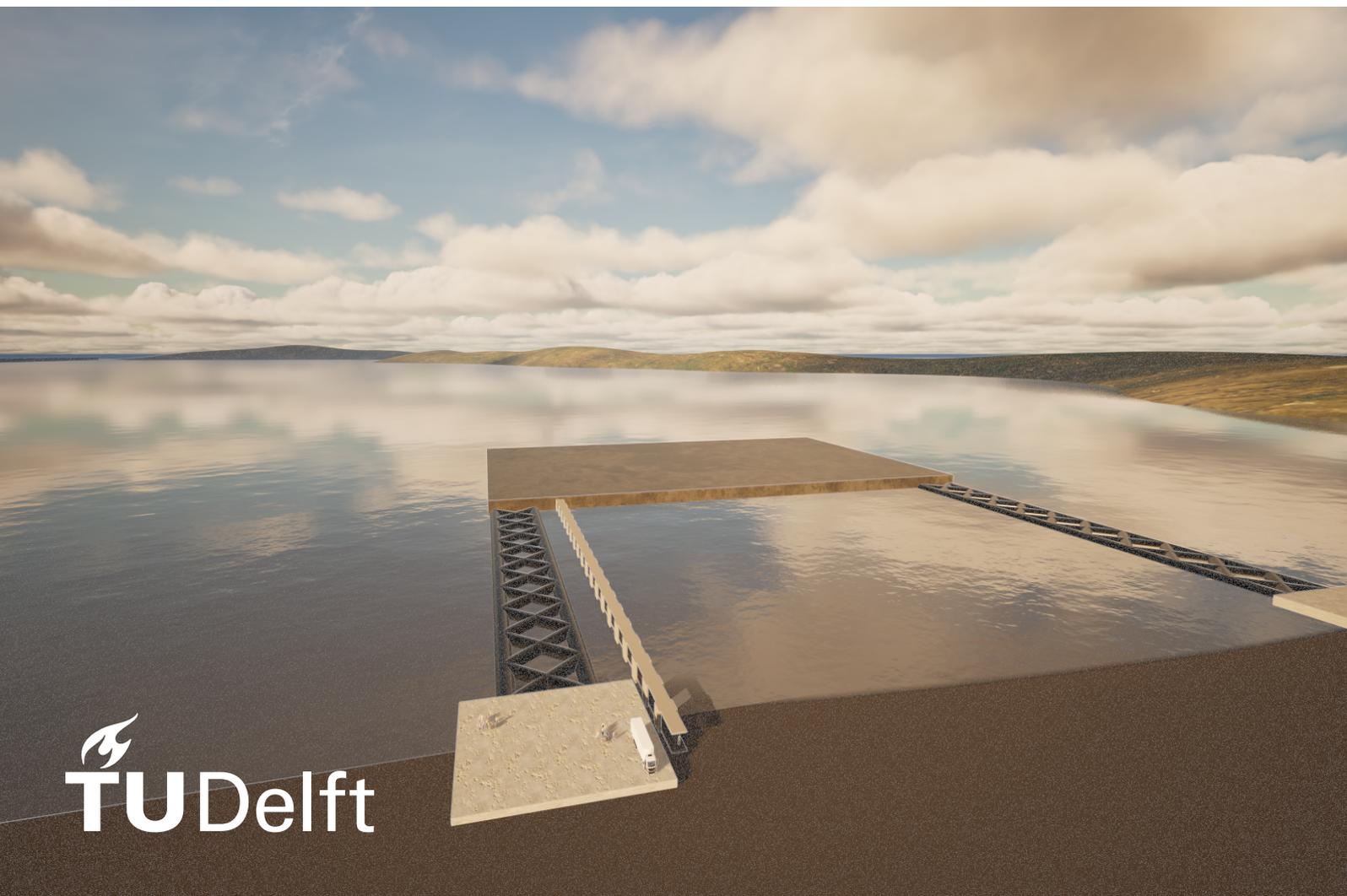


The design of a floating construction for a hyperscale data center on the energy storage lake of Delta21

A conceptual design of a floating pontoon and its mooring system

Faculty of Civil Engineering and Geoscience

I.A.J. Helwes



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Preface

Is my data truly safe? Who has access to it? These are questions that concern today's society. They are related to data centers whose importance is increasing with the rapid growth of artificial intelligence. Expanding storage capacity, preferably within the Netherlands, where it can be securely managed and controlled, is becoming essential. But doing so without using valuable land remains a challenge. A floating hyperscale data center might provide a promising solution.

Within the Delta21 project, the opportunity was given to further explore this idea and develop the concept of a floating hyperscale data center. I am honored to have the privilege to dedicate my master's thesis to this topic and I hope that my research, if only as an early step, can contribute to the path towards more secure, efficient and sustainable data storage for the future.

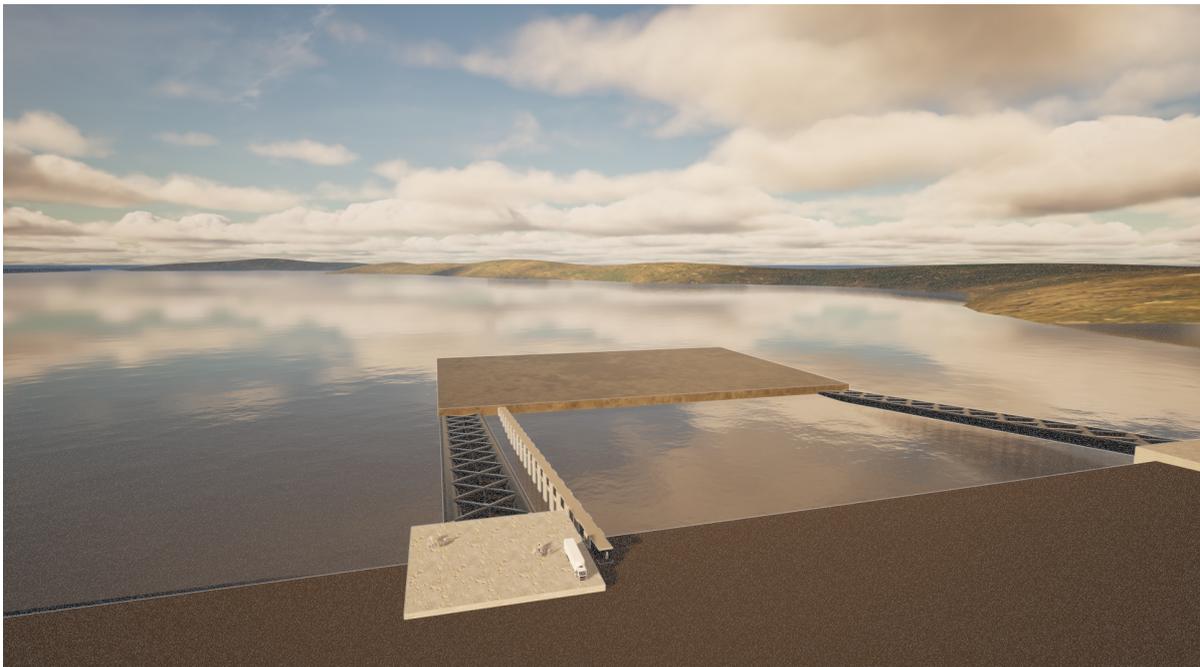
I would like to thank all members of my graduation committee for their support throughout this project. My grateful thanks to Frank for his supervision and for keeping me on track; to Oriol for his feedback during the progress meetings and for offering a welcome distraction through the engaging side project I did for his course; to Robert Jan for his critical questions during the progress meetings, which pushed me to think more deeply about the subject; and to Mark for his expertise in design thesis and his help structuring my report. I am also grateful to Huub for providing the space within his Delta21 project to explore this topic and for connecting me with specialists for valuable discussions. Finally, I want to thank my family and friends for the support they have given me during this final stage of my studies.

I hope you enjoy reading this report.

*I.A.J. Helwes
Delft, November 2025*

Summary

The growing demand for digital infrastructure presents the Netherlands with spatial and energy-related challenges. The objective of this study is to develop a functional and structural design of a support system for a floating hyperscale data center located on the Delta21 energy storage lake. The goal is to assess whether such a floating system can be realized as structurally safe, dynamically stable, and spatially compatible within specific boundary conditions. The study follows the methodology of the elementary design cycle, progressing from problem definition to verification. First, the functional design consisting of a rectangular pontoon anchored by rigid steel mooring arms was developed as illustrated in the figure below.



After verification of the boundary conditions, functional requirements, and evaluation criteria obtained from the system analysis and listened in the Basis of Design, the functional design is shown to be feasible at this design phase. The three main functional challenges were that the structure must continuously accommodate water level variations of up to 25 m, that it must provide a reliable support structure for the data center equipment, and that the structure is located within Natura2000 areas.

For the proposed functional design, a structural design was developed. Static and dynamic analyzes were performed to establish a preliminary understanding of feasibility and structural behavior. A first-order static analysis of horizontal wind loads demonstrates that the structure remains within allowable limits for both mooring arm strength and pontoon stability. Regarding the dynamic stability of the pontoon under environmental loads, no definitive conclusions can be drawn because the analysis indicates sensitivity rather than the actual response of the system. The results suggest that the system is likely to be susceptible to resonance from wind gusts. Therefore, structural feasibility has been partly demonstrated, but structural reliability cannot yet be assessed.

Currently, there are no standard design guidelines or reference projects for floating data centers. Consequently, the model was developed on the basis of assumptions derived from related maritime and offshore engineering practices and guidelines. Therefore, a sensitivity analysis was performed to provide additional insight into possible design optimizations. This analysis also indicated that the system is sensitive to vertical instability. Further studies can therefore challenge the proposed design and could even undermine its performance. The results should therefore be regarded as an initial technical exploration rather than a fully validated design.

The study concludes that the proposed concept is structurally robust, functionally feasible within this design phase, and future-oriented. Integrating a floating hyperscale data center into the Delta21 project combines digital capacity, sustainability, and spatial efficiency. For subsequent design phases, it is recommended to make iterations on the proposed design and to investigate the economic feasibility, environmental impact, and energy integration to fully assess the overall feasibility of the project.

Contents

Preface	i
Summary	ii
1 Introduction	1
1.1 Growth of data centers in the Netherlands	1
1.2 Introduction of Delta21	2
1.3 Problem Analysis	3
1.4 Design Objective	5
1.5 Design Scope	5
1.6 Design approach and report lay-out	5
1.6.1 Justification of the used design method	5
1.6.2 Implementation of the elementary design cycle	6
2 System Analysis	8
2.1 Location analysis	8
2.2 Operational modes Delta21	10
2.3 Function Analysis	12
2.4 Life cycle analysis	14
2.5 Environmental conditions	17
2.5.1 Water depth and bathymetry	17
2.5.2 Wind speed and direction	17
2.5.3 Wave height, period, and direction	19
2.5.4 Currents	21
2.5.5 Data center equipment vibration	21
2.5.6 Other environmental conditions	21
2.5.7 Conclusion Environmental Conditions	22
2.6 Stakeholder analysis	23
2.7 Conclusion System Analysis	25
3 Basis of design	26
3.1 Boundary conditions	26
3.2 Functional requirements	26
3.3 Structural requirements	27
3.4 Evaluation criteria	28
3.5 Conclusion Basis of Design	28
4 Functional designs and selection	29
4.1 Concept design development	29
4.1.1 The vision and design values	29
4.1.2 Concept creation hyperscale floating data center	31
4.2 Verification of the functional requirements	34
4.3 Concept evaluation and selection	35
4.3.1 Evaluation of identified criteria	35
4.3.2 Life cycle evaluation	36
4.3.3 Selection concept design	38
4.4 Initial dimensioning of the mooring arm and pontoon	40
4.4.1 Mooring arm	40
4.4.2 Pontoon structure	42
4.4.3 Conclusion initial dimensioning	42
4.5 Conclusion functional design and selection	43

5	Structural design	44
5.1	Fault tree review	44
5.1.1	Floating data center support system failure	44
5.1.2	Fault tree evaluation and conclusion	47
5.2	Determination of the design loads and conditions	50
5.2.1	Self-weight	50
5.2.2	Wind conditions	51
5.2.3	Wind generated waves	53
5.2.4	Turbine generated waves	56
5.2.5	Currents	58
5.2.6	Conclusion determination of the design loads	59
5.3	Static structural analysis of strength and stability	60
5.3.1	Static structural analysis definition	60
5.3.2	MatrixFrame Model	62
5.3.3	Results and conclusion static structural analysis of strength and stiffness	63
5.4	Dynamic structural analysis of stability	64
5.4.1	Physical model definition	64
5.4.2	Numerical Method	66
5.4.3	Results and conclusion dynamic structural analysis of stability	70
5.5	Sensitivity analysis	73
5.5.1	Sensitivity analysis definition	73
5.5.2	Sensitivity of the system to environmental wind load variation	73
5.5.3	Sensitivity of the system to design parameter variation	80
5.6	Conclusion and evaluation structural design	84
6	Discussion	87
7	Conclusions and recommendations	89
7.1	Conclusion	89
7.2	Recommendations	91
	References	93
A	Stakeholder analysis	97
B	Evaluation mooring system designs and pontoon shapes	101
C	Reasoning mooring system dimensioning	106
D	Calculations and results of design conditions	109
E	Static structural analysis outcome	114
F	Dynamic structural analysis outcome	119
G	Sensitivity analysis outcome	129

1

Introduction

This chapter provides an introduction to the reasoning behind this study. It introduces the Delta21 plan and discusses current developments in artificial intelligence, along with the growing demand for data centers. Then, a problem analysis is performed to examine both the current problem and potential future problems. The goal is to ensure that the design process does not progress toward a solution that does not address the fundamental problem. The information from the problem analysis forms the basis for defining the design objective and the design scope. Finally, the elementary design cycle is explained, which is the basis of the design approach in this study.

1.1. Growth of data centers in the Netherlands

Due to the increasing use of data and artificial intelligence (AI), the global demand for data centers is growing (BloombergNEF, 2024). The Netherlands is attractive for data centers due to its affordable renewable energy and low risk of natural disasters (Ipenburg, 2024). On 20 December 2023, it was decided in the Netherlands that hyperscale data centers with a floor area of more than 10 hectares and an electrical connection capacity of 70 MW or more cannot be built in the Netherlands (except for the municipality 'Het Hogeland' and 'Hollands Kroon') (de Jonge, 2023). This means that hyperscale companies in the Netherlands must consider alternative solutions (Grove et al., 2023). The Netherlands supports the growth of data centers, but aims to strike a balance between economic development and the sustainable use of land and energy (Rijksoverheid, 2022).

1. New data centers must develop solutions for efficient energy use and/or reuse, and connection to renewable energy (Kong & Liu, 2014). However, renewable energy, such as wind and solar, presents significant challenges for safe, economical operation and maintaining real-time energy balance. Improving the economic efficiency and utilization rate of renewable energy is essential to ensure a reliable energy supply (Su et al., 2025).
2. Floating constructions can be used to utilize extra space for urban development or to use space for water storage in a multifunctional way. In addition, floating constructions make it possible to build in flood prone areas that experience large water level fluctuations as these constructions are resistant to flooding (FloatingFuture, 2024). An additional advantage of floating constructions is their flexibility and potential for relocation (Koeze et al., 2022). The success of such structures ultimately depends on their feasibility and effectiveness within the specific context (WorkingGroupII – Impacts & Vulnerability, 2022).

In this thesis a case study is introduced to investigate whether it is possible to design a floating hyperscale data center in the Netherlands that is connected to a reliable renewable energy system.

1.2. Introduction of Delta21

Delta21 is a suitable location for use as a case study. In the future, the combination of rising sea levels and high river discharge could pose a flood risk in the Dutch Delta (NASA, 2024). Delta21 is a project aimed at improving flood protection by creating a lake with a pumping station at the mouth of the Haringvliet, as shown in Figure 1.1. The lake provides a large open water surface suitable for floating constructions. The scenario of simultaneously high sea levels and high river discharges is expected to occur approximately once every 10 years. Consequently, the pumping station would remain inactive most of the time, increasing the risk of pump failure. This issue can be mitigated by transforming the lake into an energy storage system, where the pumps can also operate as turbines (Mastrodimos, 2023). The energy generated by these turbines could serve as a reliable renewable energy source for data centers. In section 2.2, the operating principle of Delta21 is illustrated.



Figure 1.1: Visualization of the Delta21 plan (Delta21, 2024b)

Combining a floating hyperscale data center with Delta21, three elements of Delta21 must be considered: improving flood protection, large-scale energy storage, and increasing biodiversity (Delta21, 2024a).

1.3. Problem Analysis

Based on extensive literature research, including various academic papers and discussions with experts, the main bottlenecks of a floating data center have been identified, which form the basis for the design objective and scope of this study. The floating data center industry is still emerging and relies on specialized knowledge and technologies related to floating structures, cooling systems, and mooring systems: expertise that is not yet available in the global scenario (Kanoetra & Shankar, 2022). The following knowledge gaps have been identified:

Cooling system problems

The design of the cooling system is critical to the efficiency and reliability of the data center because the physical environment inside the data center is rigorously controlled. There are two types of cooling: air-cooled and water-cooled systems. Water cooling systems can offer advantages compared to air cooling systems in terms of heat exchange (having a higher heat conduction coefficient), lower noise levels, and closer temperature control (Salom et al., 2017). According to research from 'Omgevingsdienst Noordzeekanaalgebied', further development of emerging cooling technology should be encouraged, as the use of water for cooling can lead to a significant reduction in electricity consumption (Lambregts et al., 2023). In addition, Nautilus Data Technologies is a company that has developed floating data centers utilizing fresh, salt, or brackish water for cooling (van der Klugt, 2022). However, very shallow water conditions presents unique challenges with respect to the water cooling system, due to the higher water temperatures, sediment build-up (higher sediment levels require filtration), and ecological impact (Ahmad, 2024a).

Water shortage

Data centers are increasing in number and in their environmental footprint, especially in terms of water demand (Ahmad, 2024b). In 2021, 'Noordhollands Dagblad' reported that Microsoft's hyperscale data center in Hollands-Kroon used 84 million liters of drinking water that year, while Microsoft stated that the facility requires 12 to 20 million liters of water annually to remain operational (Aquatech, 2022). Microsoft's activities have faced large opposition from farmers over their water consumption, but the Hollands-Kroon municipality approved new Microsoft data centers early in 2021 (alongside the existing data centers) (Judge, 2022). For civil engineers, helping data centers manage their water consumption to use water as efficiently and productively as possible represents a relatively new field that offers various opportunities and challenges (Ahmad, 2024b).

Mooring system challenges

A mooring system is essential to keep the data center in place with minimum movement based on project tolerances and to maintain sufficient clearance to other assets such as pipelines and cables (Kanoetra & Shankar, 2022). The challenge within the mooring system is when the mooring lines are too taut or too slack, causing excessive forces or movements. Anchor points may not remain in optimal positions due to large changes in water level leading to instability or misalignment of the pontoon (Whitaker et al., 2020). Even if the buoyancy is not aligned, problems can arise: it can rise too high, making it exposed to wind forces, or it may submerge too deeply, leading to flooding or structural collapse (Wang, 2022).

Environmental impact

Companies have recognized the potential of floating data centers as a sustainable and efficient solution to data infrastructure. Sustainability is increasingly prioritized in corporate operations (BISResearch, 2024). The Dutch Data Center Association (DDA) and many of its members have committed to the Climate Neutral Data Center Pact (CNDTCP), with the aim of being climate neutral by 2030 (Grove et al., 2023). Therefore, an environmental impact analysis is essential to assess the effects of the floating data center and its (sub)systems of the data center, because it could potentially disturb local ecosystems, impacting fish populations and biodiversity.

Economical feasibility

Data centers are a vital part of the national digital infrastructure and contribute to the increasingly digital Dutch economy (Association, 2025). Investing in floating data centers is both a technological innovation and a business opportunity: profitability is combined with environmental responsibility (BISResearch,

2024). However, the integration of a floating data center on an energy storage lake is a new concept and has not been done before. Existing knowledge from reference projects and prototype setups is not sufficient to guaranty success. This knowledge gap must be filled with additional research and expertise, which incurs additional costs. Investing in a new concept is uncertain. Therefore, the economic concerns of investors must be analyzed and reduced. Furthermore, the risks versus the benefits of the project must be examined to generate a sufficient return on investment.

Legal issues

The first step in the development of a floating pontoon is applying for a permit and fitting it into the spatial plan. For floating structures located in the internal waters of the Netherlands (Delta21 is located in the internal waters of the Netherlands), an environmental permit is required, provided that the floating structure meets the designated building regulations and policies. In addition, the legal status of floating platforms under Dutch law needs to be investigated, as there will be land (the platform) above land (the seabed). A method must be found to survey water areas and register these platforms. Furthermore, regulations must be established regarding who is allowed to build or introduce floating platforms (Lin et al., 2022).

Social acceptance

Nearby coastal communities and local industries may oppose the project (see section 2.6). Resistance from local communities and industries could lead to delays that increase costs and complexity. Therefore, public perception and stakeholder participation will be critical in determining the level of resistance and the feasibility of the project.

To conclude the problem analysis, the design of a hyperscale floating data center on an energy storage lake has never been done before, which means that there is little literature and few reference projects available. This creates knowledge gaps that must be filled to assess the viability of the project. To do so, a preliminary design must first be developed, where the focus of this study lies on the mooring system. The main challenges are:

- Missing design of a mooring system that can account for large vertical fluctuations. What does a robust system look like?
- Missing knowledge on how to verify the design. What are good design requirements?

1.4. Design Objective

A design objective has been formulated to provide direction for the design process.

The objective of this study is to develop a functional and structural design of a support system for a floating hyperscale data center located on the Delta21 energy storage lake.

1.5. Design Scope

The scope of the design is defined as follows.

- Location:
 - The Delta21 energy storage lake is used as the location for this study;
 - Legal issues for this location related to building on water are not considered.
- Technical design:
 - The structural design uses analytical methods and numerical tools and is limited to the optimization of the pontoon dimensions and the mooring system of the floating data center;
 - A detailed structural design of the pontoon structure and mooring system is beyond the scope of this study;
 - Similarly, the detailed design of the cooling system and the renewable energy supply system for the hyperscale data center is outside the scope of this study;
- Evaluation:
 - The design is evaluated to some extent on functional, environmental, economic, and social criteria;
 - A detailed analysis of environmental impact, economic feasibility, and social acceptance is beyond the scope of this study;
- Assumptions:
 - It is assumed that a floating structure contributes to solving 21st-century challenges, such as land shortages, climate change, urbanization, and overpopulation.
 - * The design supports the energy transition and promotes the shift to a sustainable circular economy;
 - * The system uses the energy storage lake for water-based cooling.

1.6. Design approach and report lay-out

1.6.1. Justification of the used design method

During the design process, the objective (section 1.4) is transformed into specific shapes and materials. To do so, the elementary design cycle will be the basis of the design approach in this study. The elementary design cycle is an iterative design method used in civil engineering to make complex projects manageable, structured, and verifiable. Each step in the cycle produces requirements, justifications, and design decisions, which are essential to substantiate the final design. Due to the many uncertainties inherent in civil engineering projects, iterative loops allow for progressively improved assumptions and analyzes (van Baars et al., 2009). This method is chosen because it has proven to be effective in developing civil engineering designs.

1.6.2. Implementation of the elementary design cycle

In this study, the elementary design cycle is implemented as illustrated in Figure 1.2. The steps taken in this design workflow are justified as follows. First, a problem analysis is performed to examine both the current problem and potential future problems. The goal is to ensure that the design process does not progress toward a solution that does not address the fundamental problem. The information from the problem analysis forms the basis for defining the design objective (section 1.4) and the design scope (section 1.5). In the next chapter, a system analysis is performed (chapter 2). The system analysis is carried out to break down, understand and manage complex systems. It forms the bridge between the design objective and the design development by:

- Defining what the system must do;
- Specifying the context and boundaries;
- Preparation of verification and evaluation.

In this study, the following analyzes are chosen to understand and control the system within the design process: location analysis (section 2.1), functional analysis (section 2.3), life cycle analysis (section 2.4), environmental load analysis (section 2.5), and stakeholder analysis (section 2.6). The system analysis in chapter 2 subsequently enables the formulation of the Basis of Design that guides the entire design process. In this chapter, boundary conditions (section 3.1), requirements, and evaluation criteria (section 3.4) are collected from the conclusions of the analyzes performed in the system analysis and have been completed through literature findings and discussions with experts. The requirements are divided into functional requirements (defining what has to be achieved: section 3.2) and structural requirements (determining how these functions are physically realized: section 3.3). This separation improves traceability within the design process: the next design steps are functional design and selection, followed by structural design.

First in chapter 4, functional concept designs (section 4.1) are developed to generate multiple possible solutions that meet the functional requirements and boundary conditions (section 4.2) defined in the Basis of Design. The goal is to explore, compare, and evaluate (section 4.3) different options broadly, with an evaluation review, a life cycle evaluation, and a multi criteria analysis, before converging towards a single final design. The initial dimensioning (section 4.4) of the most acceptable solution is performed after selection to ensure that detailed analyzes are performed efficiently on the most viable design option. Then in chapter 5, a structural design is performed for the proposed concept to account for the structural requirements defined in the Basis of Design. The goal is to translate the functional design into a technically substantiated and verifiable structural configuration. In this analysis, the robustness and structural safety of the proposed concept design is determined, which means that it can withstand loads in all kinds of situation. The following steps are taken.

- Fault tree review to obtain an overview of system failure mechanisms and identify design conditions using a qualitative approach (section 5.1);
- Determination of significant design loads (section 5.2);
Then, using analytical and numerical methods, the following analysis can be performed.
- Static structural analysis of strength and stability (section 5.3);
- Dynamic structural analysis of stability (section 5.4).

This design step is concluded with a sensitivity analysis (section 5.5) aimed at providing information on the optimization of the structural design. Finally, the goal of validation is to demonstrate that the model, the assumptions, and the methods used are appropriate and reliable for the intended design. This is addressed in the discussion (chapter 6) and conclusions (chapter 7). Recommendations are then provided for subsequent iterations and detailing loops.

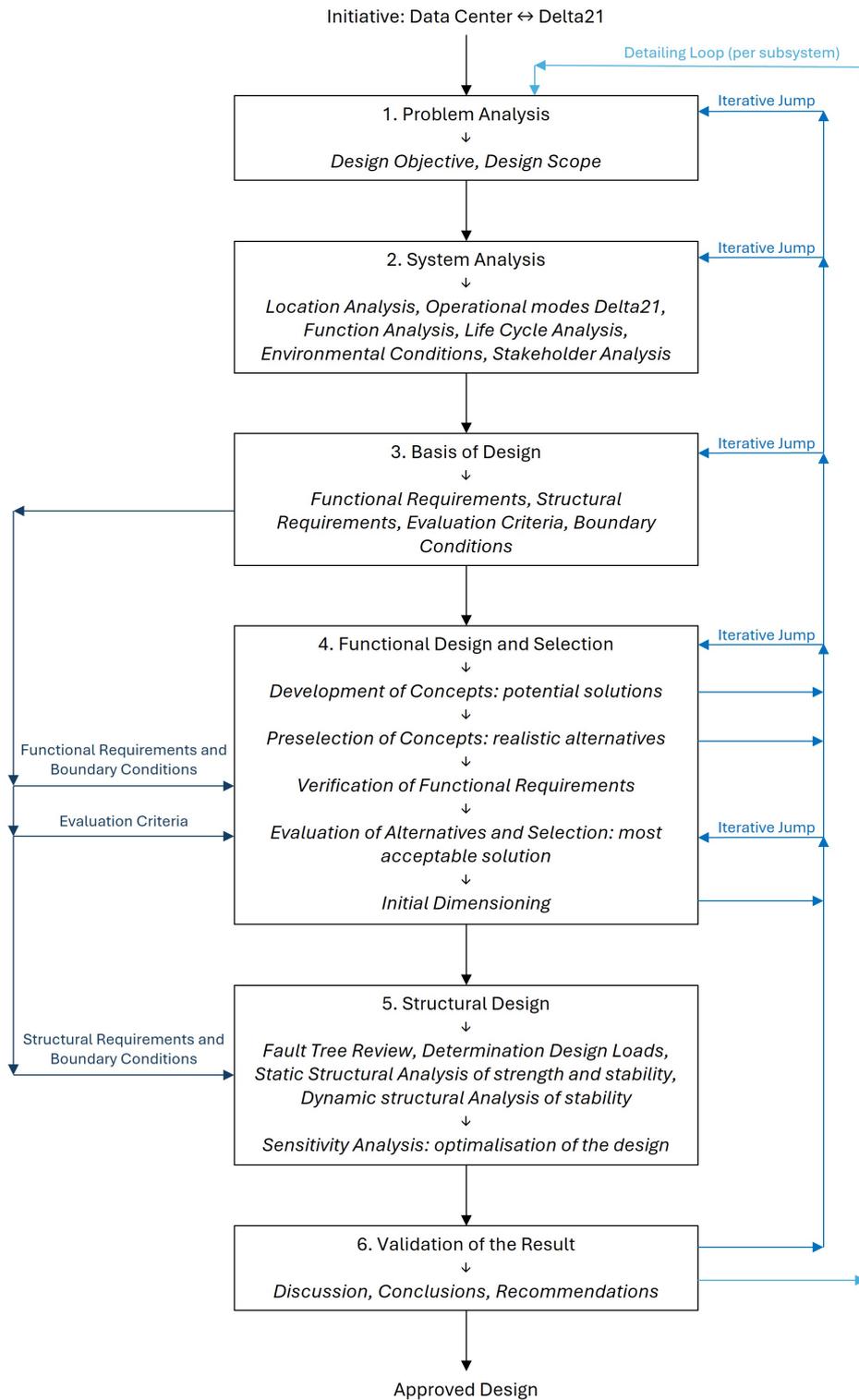


Figure 1.2: Design workflow according to the elementary design cycle applied in this study

2

System Analysis

In a early design phase, system analysis is performed to break down, understand, and manage complex systems (van Baars et al., 2009). Consequently, no design decisions are made in this analysis. Based on extensive literature research, including various academic papers and discussions with experts, requirements and boundary conditions for a floating hyperscale data center on the Delta21 energy storage lake are established. In this study, the following analyzes are chosen to understand and control the system within the design process: location analysis, functional analysis, life cycle analysis, environmental load analysis, and stakeholder analysis. The findings of this analysis are translated into design criteria in the Basis of Design (chapter 3).

2.1. Location analysis

The first analysis performed is the location analysis. This analysis helps to understand the interaction between the design and its surroundings before proceeding with further design development. The method is qualitative and exploratory and establishes location criteria (van Baars et al., 2009). The Delta21 energy storage lake covers an area of approximately 40 km² and is located in the Dutch Delta (within territorial waters). As shown in Figure 2.1, Delta21 is close to a coastal city: Rotterdam. The long-term vision is that floating data centers could better serve a larger population near coastal cities, because the data would have a shorter distance to travel (Schlosser, 2020). The locations consists of the following characteristics:

- No seismically active region;
- Located in four Natura2000 areas (Lavooij, 2024);
- The soil is mainly composed of fine to coarse sand (Dykmans, 2019);
- The water level fluctuates between NAP -3m and NAP -28m;
- The water is brackish because fresh river water and seawater mix in the energy storage lake. Therefore, a water density of 1015 kg/m³ is assumed.

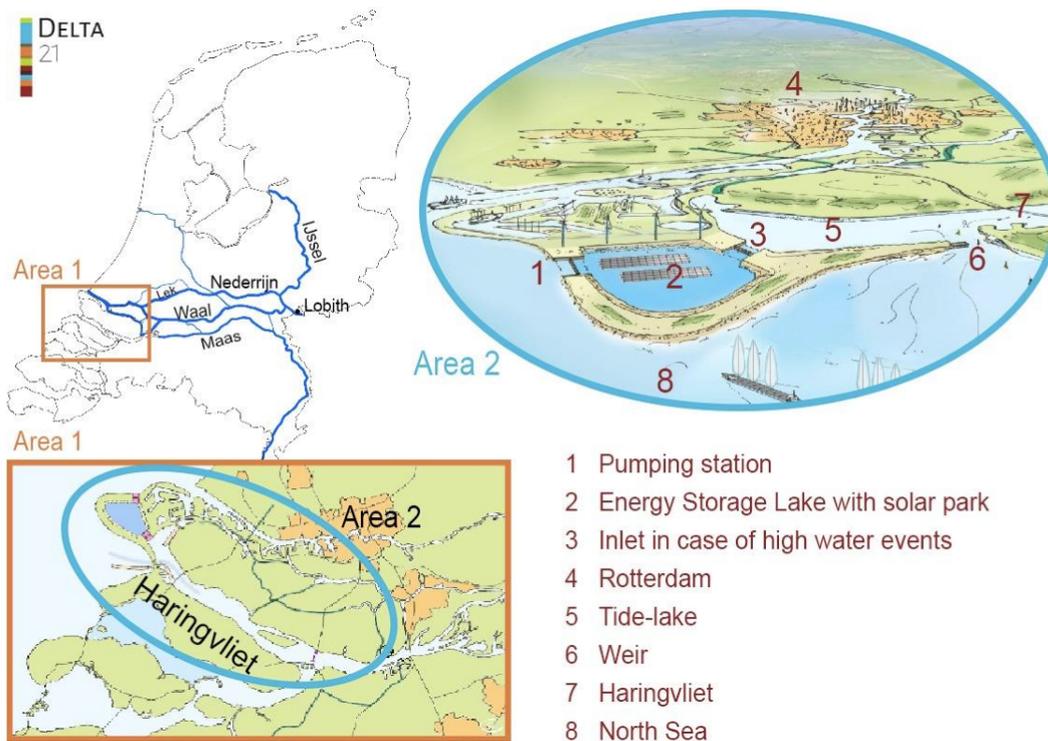


Figure 2.1: Location Delta21 (Dalderup et al., 2020)

Next, the location of the data center on the energy storage lake affects accessibility to employees and maintenance. Security problems can exist due to easement rules that can make parts of the data center property accessible to outsiders, for example, by means of a walking or cycling path (Gillin, 2020).

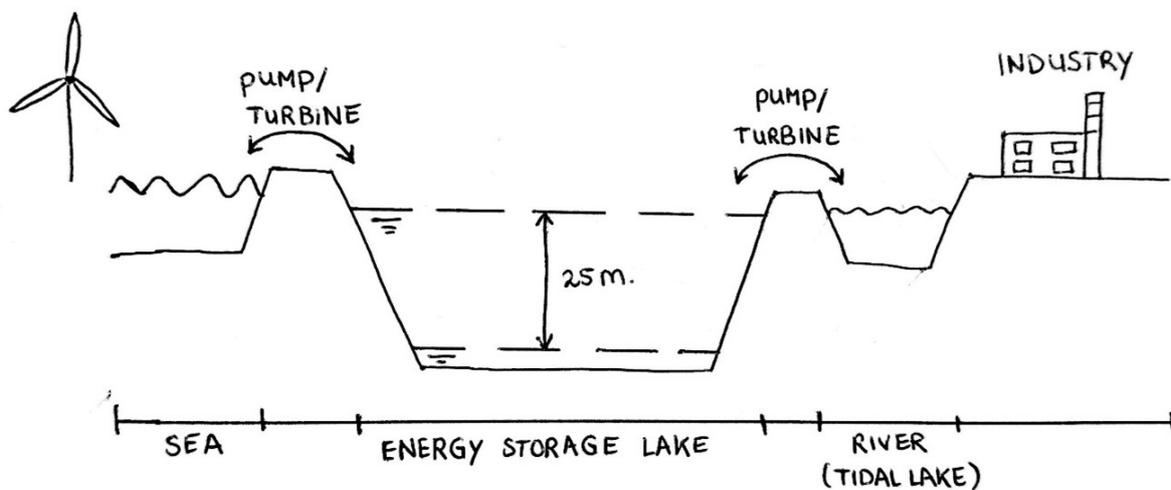
Conclusion location analysis

In conclusion, the primary criterion identified for the location is accessibility, which ensures that the data center remains accessible at all times for operation and maintenance. The main boundary condition derived from this analysis is the fact that the site is located within a Natura2000 area, which imposes environmental restrictions on construction and infrastructure development. Finally, two requirements have been identified: the structure must be designed to withstand fluctuation in water level of 25 meters and brackish water conditions.

2.2. Operational modes Delta21

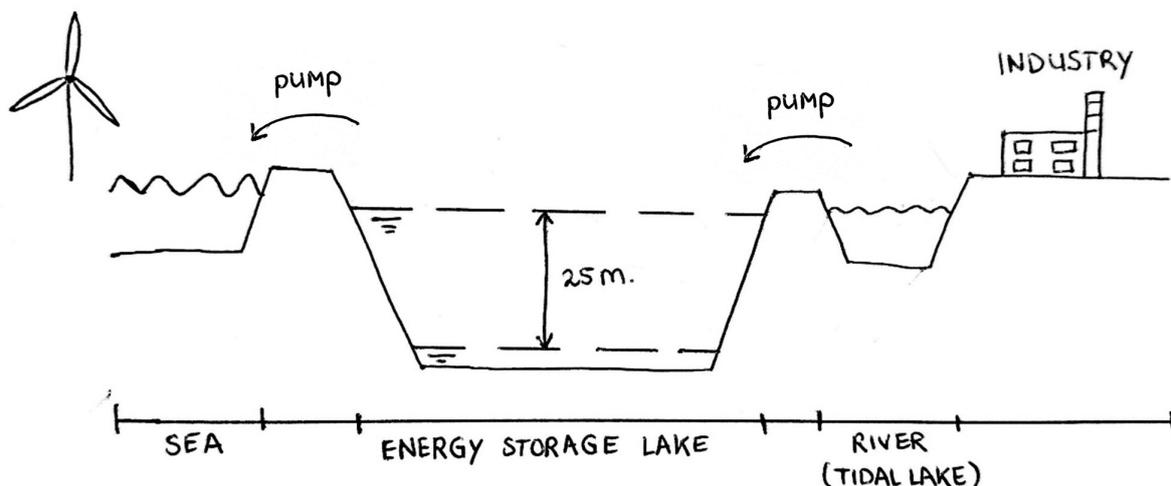
An interaction exists between the floating data center and the Delta21 system through the energy storage lake. To better understand the potential influence of this lake on the floating data center structure, in this section describes the operational modes of the Delta21 energy storage lake. The net energy content of the energy storage lake is 34 GWh, with a total installed capacity of 2 GWe, which can be expanded to 6 GWe. The installed pump-turbine capacity is 20 MW per pump-turbine. The design includes 100 pump turbines with an average pumping capacity of $100 \text{ m}^3/\text{s}$. The drainage time with 100 pump turbines is approximately 30 hours. De maximum pumping capacity of 100 pump/turbines is $200 \text{ m}^3/\text{s}$. For an area of 40 km^2 of the energy storage lake, this results in a maximum vertical velocity of $5 \cdot 10^{-4} \text{ m/s}$. A lock of 80 meters long and 15 meters wide will be constructed in the embankment of the energy storage lake (Delta21, 2024a). The water level can vary by up to 25 meters. In Figure 2.2, the working principle of Delta21 is drawn.

WIND ENERGY



(a) Schematic overview of the energy storage lake in normal operation

WIND ENERGY



(b) Schematic overview of the energy storage lake during a storm surge at sea, combined with peak discharge from the Haringvliet

Figure 2.2: Working principle Delta21 (based on (Voorendt & Timmermans, 2020))

Conclusion operational modes Delta21

In conclusion, the boundary condition identified for transport by water during the operational phase of Delta21 is the sluice lock, which has a maximum passage length of 80 meters and a width of 15 meters. In addition, the following requirement has been established: the structure must be able to withstand a maximum vertical velocity of $5 \cdot 10^{-4}$ m/s caused by in- and outflow of water in the energy storage lake.

2.3. Function Analysis

The function analysis is an essential part of the system analysis within the design process. Its objective is to understand the system in terms of its functions, rather than directly in terms of solutions or components. The core method of the function analysis is functional decomposition (van Baars et al., 2009). In this study, the system is divided into principal functions and preserving functions.

First, the principal functions of a hyperscale data center are determined. The goal of a data center is to ensure that computer servers with digital applications run continuously 24/7/365 (Association, 2025). The principal function of a floating hyperscale data center is as follows.

- Provide a central location for storing and managing large amounts of digital information;
 - Use at least Tier performance level 3. Tier performance level 3 implies that "each and every capacity component and distribution path in a site can be removed on a planned basis for maintenance or replacement without impacting operations. The site is still exposed to equipment failure or operator error" (UptimeInstitute, 2025);
 - Switching between power systems occurs in milliseconds (ms). Therefore, a fiber-optic cable is required;
 - Protect sensitive information through physical and digital security;
 - Ensure service continuity as data centers are designed with backup systems and emergency plans;
 - Ensure the performance of the equipment with power supply and climate control systems;
 - Facilitate connectivity between servers, storage devices, and external networks. These connections include a power cable from the land, a fiber optic cable for data, a drinking water supply, and a sewage outlet.

(R. Rosendaal, personal communication, 04-04-2025)

Second, the preserving functions of a floating hyperscale data center are as follows.

- Governed by the functions of the Delta21 energy storage lake:
 - Improving flood protection, large-scale energy storage, and increasing biodiversity (Delta21, 2024b);
 - The pump turbines must function reliably to effectively regulate the water level in the energy storage lake (Delta21, 2024a);
 - Monitoring and managing the system to ensure it supports ecological processes without negatively impacting the environment (Delta21, 2024b).
- When a cooling system is used that operates with brackish water, environmental control systems must be maintained to preserve the functions of preventing equipment from overheating (R. Rosendaal, personal communication, 04-04-2025);
- Maintain stable electrical grid operation when the data center is connected to the renewable energy system of the Delta21 energy storage lake (R. Rosendaal, personal communication, 04-04-2025);
- Ensure physical security of the data center, even when it is located on water (Association, 2025);
- The design must minimize vibrations because of the presence of hard disk drivers, which can be disrupted even by low levels of vibration (R. Rosendaal, personal communication, 04-04-2025). So, ensure continued protection of sensitive data chips from vibration-induced disturbances (DatacenterWorks, 2024).

Conclusion function analysis

In conclusion, this study focuses on the mooring system and the floating structure of the data center. Therefore, in this conclusion, only the boundary conditions, requirements, and criteria that directly influence these components are included. The boundary condition derived from the principal function refers to the motion limits that the connections for power, data, and cooling systems can withstand and to the available interface options for these connections. In addition, two key criteria are considered: the preserving functions of Delta21 and the physical security of the data center. Finally, a requirement resulting from the preserving functions is that sensitive data chips must be protected against vibration-induced disturbances to ensure reliable and continuous operation.

2.4. Life cycle analysis

A good design considers the performance of the system over its entire life cycle. Therefore, a life cycle analysis is performed to ensure that the design not only functions technically but is also sustainable, maintainable, and economically viable throughout its entire life span. The method involves dividing the system into phases of the life-cycle and analyzing the performance, costs, and risks associated with each phase (van Baars et al., 2009). Within this life-cycle assessment the following phases are considered: planning, design, fabrication, transport, installation, operation management, and decommissioning.

Planning and design

In section 1.3, it is mentioned that environmental permits are required and the floating structure must meet the specified building regulations and policies. The regulations considered are as follows.

- 'Besluit bouwwerken leefomgeving (Bbl)', which set out the technical requirements for the construction of buildings (Wettenbank, 2025a);
- NTA 8111:2011 - Floating Constructions, which set out a standard for floating constructions used as dwellings. It can be used as an indication, but does not cover the regulations and challenges of a floating hyperscale data center (NEN, 2011);
- 'Omgevingsregeling', municipalities incorporate spatial rules for floating structures into their plans and management regulations. In the spatial plan of the municipality of 'Goeree-Overflakkee', where Delta21 is located, no spatial rules for floating structures are included (Wettenbank, 2025b).
- 'Tier 3', the data center Tier classifications are recognizable in the industry as the standards to follow for data center performance (UptimeInstitute, 2025).

In section 1.1 alternative solutions for hyperscale data centers in the Netherlands are mentioned. A floating data center is innovative, and because little is known about regulations and policies, this could impact planning.

Fabrication

The surface area of a hyperscale data center is $> 50.000 \text{ m}^2$. This means that space is required to manufacture the construction. Elements can be made using prefabrication or need to be built in a dry dock. A dry dock is selected based on: location, material storage, bathing plants, prefabrication plants, warehouses, and offices (Fjeld, 2012). If a temporary dry dock is considered, the bearing capacity of the soil must be taken into account. Fine to coarse sand (section 2.1) can lose stability in wet conditions. Therefore, reinforcement measures may be necessary. In addition, the environmental impact of a temporary dock must be determined. Especially in Natura2000 areas (section 2.1). It requires careful planning, design, and alignment with local conditions.

Due to the high construction speed in the data sector, the data center is primarily built using prefabrication. While the main structure is being built, components can already be produced. These components arrive fully prefabricated and tested and only need to be installed and connected on-site (R. Rosendaal, personal communication, 04-04-2025).

Material

In the design of the buoyancy body, steel, concrete, and composite materials are considered. The chosen material must withstand brackish water (section 2.1) and dynamic loads (section 2.2). Concrete offers an advantage in its ability to dampen dynamic forces due to its mass. In addition, its weight contributes to a low center of gravity, which enhances overall stability (Fernández & Pardo, 2012). Composite materials, on the other hand, are extremely lightweight, which can present challenges to stability under extreme dynamic conditions. Steel is susceptible to fatigue under cyclic load and is also prone to corrosion, which can result in higher maintenance costs. In contrast, both concrete and composite are more resistant to corrosion and require less maintenance during the life time of the structure compared to steel. However, composites come with their own challenges: they are very difficult to recycle, are not yet widely adopted in large-scale floating structures, and have high production costs.

Transport

Transportation depends on the chosen manufacturing method. If prefabricated elements are transported by water, the Delta21 lock (15 m wide and 80 m long) must be considered (section 2.2), which imposes boundary conditions on component dimensions. If this proves structurally unfeasible, more investigation is required to assess the possibility of integrating the construction processes during the Delta21 development: first constructing and positioning the data center on site, followed by the completion and closure of the Delta21 energy storage lake. This approach would eliminate the need for a temporary construction site within a Natura2000 protected area. Next, if a crane is used to deliver materials to the lake, the lifting capacity of the crane limits the element size, and the quay's bearing capacity must also be verified. For road transport, the dimensions of the truck and the existing infrastructure influence logistics.

There are three maritime transport options for the structure: towed configuration, self-floating, and propelled vessels. Because the concept is a self-floating data center, this capability can be utilized during transport. An inland waterway route is preferable, as wave action is less severe than at sea, reducing construction loads during transit (Fjeld, 2012).

The largest single component of the data center is the generator, which is approximately the size of a container (R. Rosendaal, personal communication, 04-04-2025). Consequently, the most critical dimensional constraints arise from the floating structure.

Installation

The three primary installation methods for a floating structure are lift installation, self-installation, and float-over installation. If the data center is installed as a single unit, transport is required from the temporary assembly site to the installation site. To enable this, the following systems are required: a current-velocity measurement system, a navigation system, and a remotely operated ballast system. During installation, prevailing environmental conditions must be carefully considered (Fjeld, 2012). The loads induced during installation, such as the self-weight during lifting operations, must also be considered in the structural strength assessment of the system.

Operation management

During operation, the floating data center must be regularly maintained. The sluice gate on the embankment of the energy storage lake provides permanent access to all maintenance activities (Delta21, 2024a). Mechanical and instrumentation systems support the monitoring and maintenance of the floating hyperscale data center. The core systems include drainage, ventilation, ballast control, corrosion protection, and firefighting, and a monitoring system to track changes in extreme conditions.

Routine maintenance of electrical and mechanical installations, such as component replacement and upgrades, is required. In addition, 24/7 service management is ensured through security staff, cameras, and monitoring systems (R. Rosendaal, personal communication, 04-04-2025).

Operational noise is an important consideration: data centers typically emit 80–100 dB(A). With water cooling, pumps and ancillary equipment can be housed indoors, reducing overall noise emissions (R. Rosendaal, personal communication, 04-04-2025). Because the facility is built on water, it can use water cooling, which is generally more energy-efficient and environmentally friendly than air-cooled systems (Salom et al., 2017).

Decommissioning

Sustainability is a key consideration in the decommissioning phase. Strategies to minimize environmental impact at the end of life should be evaluated, and safe execution depends on good engineering, preparation, and planning. Material selection is particularly important for this phase.

First, the design life is considered. The electrical and mechanical installations of the data center have a lifespan of 15 years. Servers and IT equipment must be replaced every 3 years. Therefore, the construction is the determining factor for the design life. Given the relatively recent adoption of floating data center technology, companies such as Nautilus and Microsoft did not publicly disclose specific details about its design life. However, according to Sachdeva, a standard land-based data center has a design life of approximately 25 to 30 years (Sachdeva & McLaughlin, 2024).

Second, the choices made in the decommissioning phase also influence fabrication, transportation, and installation. Three approaches are possible: piecemeal removal, reverse installation, or integral removal. The objective is to maximize the reuse of components, selecting the method that best enables recovery and re-purposing. Where feasible, identifying a new application for the floating data center is the optimal decommissioning outcome.

Conclusion LCA

In conclusion, the life cycle analysis provides insight into the sustainability, cost-effectiveness, and long-term performance of the design. The results of this analysis can be translated into specific boundary conditions, criteria, and requirements for the design process. First, the following criteria have been identified: (i) since the site is located within a Natura2000 area, it is not desirable to construct a temporary dry dock. Therefore, the dimensions of the data center must allow fabrication at an alternative location, and (ii) the environmental impact of the structure at the end of its service life should be considered. Finally, the following requirements are established:

- The design must comply with the 'Besluit bouwwerken leefomgeving', NTA 8111:2011, 'Omgevingsregeling', and Tier 3 standards;
- The chosen material for the pontoon must be watertight, resistant to brackish water and structurally capable of accommodating the equipment of the data center;
- The material for the mooring system must withstand dynamic loading and, depending on the design configuration, also resist brackish water;
- The floating data center must remain accessible for maintenance during operation;
- The structure must withstand transport loads;
- The structure must withstand installation loads;
- The structure is designed for a design life of 30 years.

2.5. Environmental conditions

The environmental analysis is carried out to understand the influence of the environment on the design. Using available measurement data, literature, and/or standards, the environmental parameters are defined. The goal of this section is to identify the loads, boundary conditions, and risks arising from the environment, ensuring that the system can be designed to be safe, reliable, and sustainable (van Baars et al., 2009).

2.5.1. Water depth and bathymetry

As a basis for the design, the water level statistics are used for long- and short-term water conditions, because empirical statical data will cover a sufficiently long period of time (DNVGL, 2016).

The maximum water depth of the energy storage lake is NAP -33 m. The water level will vary from NAP - 28 m to NAP -3 m. At the pump turbine location, the water level must be 5 m above the bed level, to support the pump turbine drivers. Across the rest of the energy storage lake, a depth of 1 m is adequate (Delta21, 2024a). The energy storage lake is enclosed by dikes with a slope of 1:20. In Figure 2.3 the bathymetry of the vertical cross section of the energy storage lake is shown. However, local changes in bathymetry and/or dike slopes are acceptable within the Delta21 plan (H. Lavooij, personal communication, 28-08-2025).

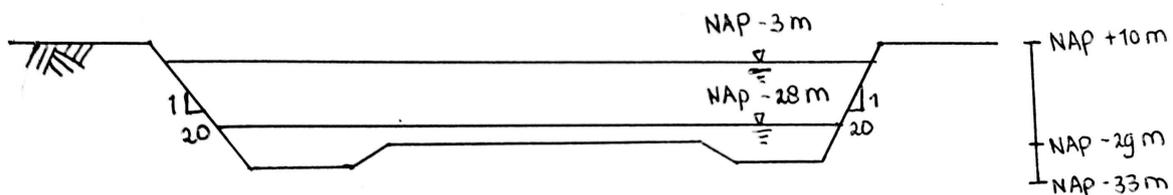


Figure 2.3: Vertical cross section bathymetry energy storage lake (not on scale)

2.5.2. Wind speed and direction

The aerodynamic loads are divided into quasi-static and dynamic components arising from the airflow and its interaction with stationary elements of the data center. These loads depend on wind shear, changes in wind direction, air density, and the aerodynamic shape of the data center.

An extreme value analysis is conducted to statistically extrapolate wind extremes from site-specific observations. In accordance with the guidelines on general requirements for offshore structures (ISO19900, 2019) and common practice in offshore design, this study uses a return period of 100 years for extreme environmental events (with an annual probability of occurrence of 10^{-2}), to ensure the safety and reliability of the floating data center. The extreme value analysis is chosen at this stage to prevent from over-dimensioning (compared to the Eurocode method, which applies generalized safety factors designed to be conservative). ERA5 hourly data on single levels from Copernicus (C3S, 2025) are used for these calculations. The wind data produced by this tool consist of two horizontal components: (i) the u_{10} -component represents the wind speed at 10 m height in the west–east direction, with positive values indicating flow from west to east, and (ii) the v_{10} -component represents the wind speed at 10 m height in the south–north direction, with positive values indicating flow from south to north. Note that this approach is conservative, since the historical data set does not take into account the sheltering effects of the dunes (surrounding the energy storage lake). Extremes are identified using the peak over threshold method. The threshold is selected using the graphical mean residual life method, after which an appropriate tail distribution is fitted (Lanzafame, 2025).

Using the wind force formula according to NEN 1991-1-4:

$$F_w = C_d q S \sin(\alpha)$$

Where:

- C_d : drag coefficient (= 1.05 if $h < 50\text{m}$ and $h/b < 5$, where b is the mean width of the structure perpendicular to the wind direction (NEN-EN, 2023))
- q : basic wind pressure or suction
- S : projection area normal to the direction of the surface
- α : angle between the direction of the wind and the axis of the exposed surface

$$q = \frac{1}{2} \rho_a U_{T,z}^2$$

Where:

- $\rho_a = 1,225 \text{ kg/m}^3$
- $U_{T,z}$: wind speed from extreme value analysis

Here α and $U_{T,z}$ are calculated using the following formulas and the 10m u- and v-components of the wind.

$$\alpha = \frac{180}{\pi} \operatorname{atan2}(-u_{10}, -v_{10}), \quad \theta = \begin{cases} \alpha, & \text{if } \phi \geq 0, \\ \alpha + 360^\circ, & \text{if } \phi < 0. \end{cases}$$

$$u = \sqrt{u_{10}^2 + v_{10}^2}$$

From the same data set, the wind direction is plotted in Figure 2.4. The figure shows that the significant wind direction is the South West.

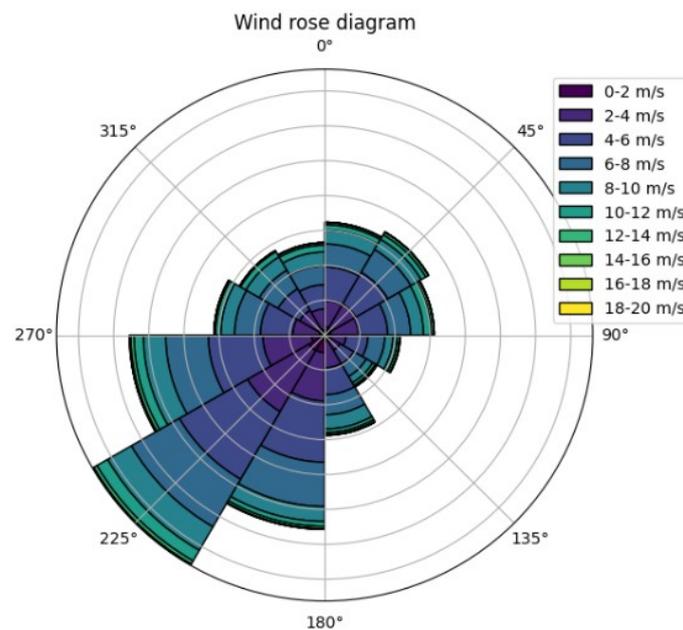


Figure 2.4: Wind rose

Wind induced setup

This section focuses on the water level setup in the energy storage lake, which is induced by persistent wind forcing. When the fetch length is sufficiently large, wind stress can generate a measurable setup in the water surface. The resulting slope arises from a momentum balance between the wind shear stress acting on the water surface and the pressure gradient force within the water column. The slope of the water surface, known as the wind setup is calculated using the following equation (Zitman, 2022).

$$i_w = c \cdot \frac{u^2}{g \cdot h}$$

Where:

- c: wind drag coefficient ($3.5 \cdot 10^{-6}$)
- h: mean water depth
- u: wind velocity

For the calculations of the wind setup, a closed system is assumed. In a closed system, the volume of water in the energy storage lake remains constant. Upstream and downstream water levels are determined by multiplying the fetch length over which the wind acts by the wind setup (i_w), and subsequently adding or subtracting this value from the initial water level.

2.5.3. Wave height, period, and direction

Sea waves

The dammed structure of Delta21 ensures complete protection from sea waves entering the energy storage lake. So, hydrodynamic forcing by ocean waves is not applicable to this research.

Translation waves due to the turbines

No calculations have yet been performed for the maximum discharge of the turbines. However, calculations are available for the maximum pump discharge of Delta21 (Delta21, 2024a). Therefore, it is assumed that the turbines can at least match the maximum pumping capacity, i.e. 200 m³/s per turbine. From Figure 2.5, it can be seen that the critical condition occurs when the water level is at its minimum and the turbines are operating at full capacity, allowing inflow into the storage lake.

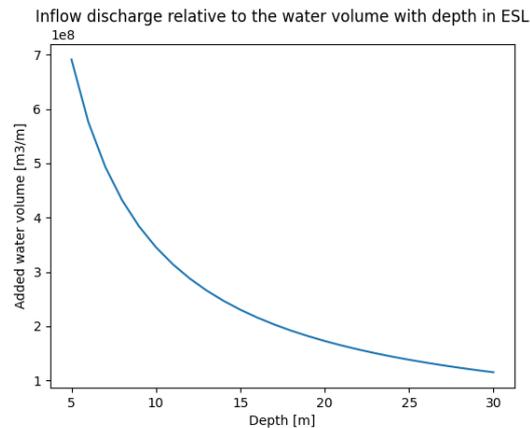


Figure 2.5: Discharge turbines relative to water volume ESL

For simplicity, a translational wave is assumed in a wide rectangular lake with uniform depth (h). The wave celerity is then:

$$c \simeq \sqrt{h \cdot g}$$

The wave height for an instantaneous increase in discharge (ΔQ) is:

$$\eta \simeq \frac{\Delta Q}{B \cdot c}$$

Where:

- η : water level rise
- B : the width over which the instantaneous change in discharge occurs
- h : still-water depth in front of the wave

This formula applies to long waves in shallow water, i.e. $B \gg h$, which holds in the present design case. The dependence of surface elevation on depth for different inflow discharges is shown in Figure 2.6.

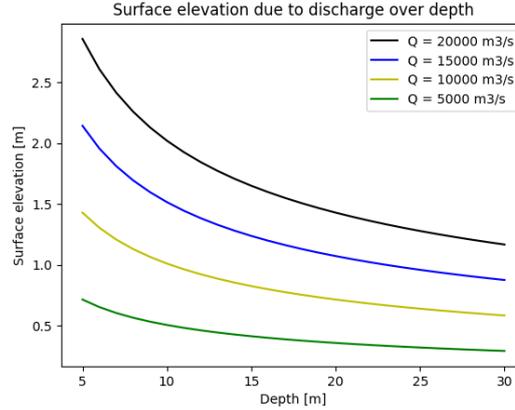


Figure 2.6: Surface elevation for different inflow discharges relative to the water depth

From Figure 2.6 it can be concluded that for a water depth of 5 m (NAP -28 m) the influence of the translation wave in the energy storage lake is the most significant.

Wind generated waves

The rate at which the momentum of the wind is transferred to the waves is represented by the wind stress factor (U_A). This factor is required for the calculation of wave growth over a fetch length, as such growth assumes the presence of steady wind.

$$U_A = 0.71U_{10}^{1.23}$$

Where:

- U_{10} : the average wind speed at 10 m above the mean water level

With the wind stress factor, the significant wave height and peak period can be calculated for different water levels (Ali et al., 2023).

$$H_s = \frac{U_A^2}{g} \times 0.283 \tanh \left[0.530 \left(\frac{gd_w}{U_A^2} \right)^{3/4} \right] \tanh \left\{ \frac{0.00565 \left(\frac{gF}{U_A^2} \right)^{1/2}}{\tanh \left[0.530 \left(\frac{gd_w}{U_A^2} \right)^{3/4} \right]} \right\}$$

$$T_p = \frac{U_A}{g} \times 7.54 \tanh \left[0.833 \left(\frac{gd_w}{U_A^2} \right)^{3/8} \right] \tanh \left\{ \frac{0.0379 \left(\frac{gF}{U_A^2} \right)^{1/3}}{\tanh \left[0.833 \left(\frac{gd_w}{U_A^2} \right)^{3/8} \right]} \right\}$$

Where:

- d_w : the water depth
- F : the fetch length
- g : 9.81 m/s^2

The angular frequency can then be calculated with the following formula: $\omega = \frac{2\pi}{T_p}$.

Waves at the boundary

The storage lake is a closed system, enclosed by dikes with a slope of 1:20. When waves reach the lake boundaries, they may be reflected or induce wave setup, depending on the boundary geometry. At the floating data center site, the influence of waves at the boundary is subject to design assumptions.

2.5.4. Currents

Currents arise only from the inflow and outflow generated by the pumps/turbines. Consequently, circulation within the energy storage lake is controlled by pump–turbine operation. The current speed can be calculated using the following formula:

$$U_0 = \frac{4Q}{\pi D^2}$$

At distance x from the outflow, the current can be calculated using the following formula:

$$U_c(x) \simeq K \frac{D}{x} U_0$$

Where K is in the range of 5-7.

This formula can be used at this stage of the study because the flow is turbulent ($Re \gg 2 \cdot 10^{-4}$). It also satisfies the far-field condition ($x \gg 20 \cdot D$), and no other currents are present in the energy storage lake. Throughout this study, brackish water is assumed (section 2.1). However, the water density affects this calculation. The lower density of river water influences the velocity at which the saline/brackish water flows into the energy storage lake.

2.5.5. Data center equipment vibration

In this section, both the vibrations generated by data center equipment and the effects of external vibrations on the equipment are considered.

First, datacenter equipment generates internal vibrations, mainly due to fans and cooling systems (Pellow, 2025). These vibrations are approximately in the range of 20–250 Hz.

Second, according to IBM's vibration and shock specification, the equipment is designed for a random vibration environment in the 5-500 Hz frequency range. The equipment has been tested and certified to withstand external vibrations up to a level of $0.05 \cdot g$ within the frequency range of 5 to 500 Hz (which represents a vibration load where g refers to gravitational acceleration). The shock and vibration environment will not exceed these limits except in abnormal situations, such as earthquakes or direct impacts (IBM, 2025).

2.5.6. Other environmental conditions

Snow and ice

The characteristic snow load that acts perpendicular to the surface is limited to 0.7 kN/m^2 (VMRG, 2024).

Marine growth

Assuming that fishery is allowed in the energy storage lake (section 2.6), marine growth must be taken into account. For the central and northern North Sea at a depth from -2 to 40 m below mean water level, a marine growth thickness of 100 mm should be taken into account. The density of marine growth is 1325 kg/m^3 (DNVGL, 2016).

2.5.7. Conclusion Environmental Conditions

In conclusion, the following boundary conditions have been identified and are classified as 'soft' boundary conditions, since local variations are acceptable: (i) a minimum water depth of 5 meters and (ii) a dike slope of 1:20. Next, the following criterion is derived from this analysis: the design should account for two water level conditions, a high-water level (depth of 30 meters) and a low-water level (depth of 5 meters), as each can be governing depending on the environmental load considered. Finally, the following requirements related to environmental conditions have been established:

- The structure must withstand wind loads, with the significant wind direction being from the south-west;
- The wind setup within the closed system of the energy storage lake must be taken into account;
- The potential impact of translation waves generated by pumps/turbines must be assessed, depending on the selected site;
- Depending on the site location, wind generated waves with a significant fetch length must be considered;
- The influence of the wave interaction at the boundary must be evaluated;
- It must be verified that the vibrations generated by the data center equipment ($\simeq 20 - 250$ Hz) do not excite the natural modes of the floating structure;
- For calculations of the vertical equilibrium of the system, snow loads, ice loads, and marine growth must be included.

2.6. Stakeholder analysis

Finally, a stakeholder analysis is performed to identify all parties involved, their interests and their power, and to integrate these into the design process, ensuring that the system fits within its social, legal, and organizational context. The applied method is a systematic approach based on system-engineering (van Baars et al., 2009).

First, the Delta21 stakeholder analysis provides information and/or predictions on the attitude of environmentalists, the energy sector, local parties, and the fishing sector towards the integration of a floating data center in the Delta21 energy lake, see Appendix B. Next, a stakeholder analysis for a floating hyperscale data center is performed, see Table 2.1.

Stakeholder	Details
The Government of the Netherlands	<p>Interest: Sustainable spatial planning and compliance with laws and regulations (de Graaf-van Dinther et al., 2024).</p> <p>Power: They are responsible for legislation and permitting (Morri, 2023).</p> <p>Attitude: Neutral to positive, depending on environmental and economic effects.</p>
Key players in the floating data center market (Nautilus Data Technologies, Beijing Highlander Digital Technology, Subsea Cloud, Denv-R, Microsoft and Keppel Data Centers)	<p>Interest: Expansion of their data center infrastructure and optimization of energy consumption (Morri, 2023).</p> <p>Power: They possess technical expertise (BISresearch, 2024).</p> <p>Attitude: Focused on their own business and success.</p>
Data center companies (Unica Datacenters)	<p>Interest: Expansion of their data center infrastructure and optimization of energy consumption (Morri, 2023).</p> <p>Power: They will be the future operators of the floating data center project.</p> <p>Attitude: Positive, provided that energy costs and safety are guaranteed (Gillin, 2020).</p>
Technology partners	<p>Interest: Provision of technology and innovation for the data center (BIS-research, 2024).</p> <p>Power: Their power is dependent on exclusive contracts.</p> <p>Attitude: Positive, provided there is a market advantage.</p>
Logistic and construction companies (BAM, Boskalis, Van Oord)	<p>Interest: Participation in the construction and operation.</p> <p>Power: Dependent on contracts.</p> <p>Attitude: Positive, provided the project is economically feasible.</p>
Data privacy organizations	<p>Interest: Ensuring digital security and privacy (Association, 2025).</p> <p>Power: They can exert influence through legislation and enforcement.</p> <p>Attitude: Neutral to critical, depending on compliance with regulations.</p>
Environmentalists	<p>Interest: Protection of nature and biodiversity (Ipenburg, 2024).</p> <p>Power: They can exert influence through public pressure and legal measures (Grove et al., 2023).</p> <p>Attitude: Critical, especially if ecological damage is at risk.</p>
Watersupply (Evines)	<p>Interest: Ensuring water quality and safety.</p> <p>Power: They have significant influence through regulations and permitting (Ipenburg, 2024).</p> <p>Attitude: Neutral to critical, depending on the environmental impacts.</p>
Energy sector (TenneT, Ste-din)	<p>Interest: Supply of sustainable energy and optimization of energy consumption (Lavooij, 2024).</p> <p>Power: They have significant influence due to the dependency of data centers on energy supply.</p> <p>Attitude: Interested in the renewable energy of Delta21 (Delta21, 2024a).</p>
Local parties	<p>Interest: Preservation of an attractive recreational environment (Delta21, 2024a).</p> <p>Power: What they find is important for public opinion.</p> <p>Attitude: The aim is to make the area attractive for living and recreation, but without extensive urban development, large offshore wind farms with tall turbines, and with minimal horizon pollution (Lavooij, 2024).</p>
Universities (TU Delft)	<p>Interest: Scientific research and innovation.</p> <p>Power: Limited, but influential through research findings.</p> <p>Attitude: Positive if the project promotes innovation and sustainability.</p>

Table 2.1: Stakeholder overview summary

Conclusion stakeholder analysis

This report examines only the impact of stakeholders interests on the design criteria of the floating hyperscale data center. However, Appendix A briefly discusses the influence of stakeholders interests on the project as a whole.

In conclusion, to identify evaluation criteria, interests from the stakeholders are considered. One of the main concerns of environmentalists and water suppliers is the environmental impact of the data center. In addition, local stakeholders aim to minimize horizon pollution to preserve the character of the surrounding environment. The client's interests mainly arise from the function analysis and are incorporated into the requirements.

2.7. Conclusion System Analysis

In conclusion, a system analysis is performed to obtain a complete and integrated understanding of the system and to ensure that all subsystems function together within the defined requirements and boundary conditions. The system analysis subsequently enables the formulation of the Basis of Design in the next chapter (chapter 3).

3

Basis of design

This chapter represents an essential design phase in which all requirements, boundary conditions, assumptions, and design principles are systematically defined. It serves as a key link between the system analysis, where the system and its context are understood, and the actual design and verification processes described in the following chapters. The approach consists of the following steps: systematically collecting, structuring, and documenting requirements and criteria (van Baars et al., 2009). Boundary conditions, requirements, and criteria are collected from the conclusions of the analyzes performed in the system analysis and have been completed through literature findings and discussions with experts. In this chapter, requirements are divided into functional requirements (defining what has to be achieved) and structural requirements (determining how these functions are physically realized). This separation improves traceability within the design process.

3.1. Boundary conditions

The following boundaries are identified.

- The site is located within a Natura2000 area, which imposes environmental restrictions on construction and infrastructure development (section 2.1);
- Transport by water during the operational phase of Delta21 is limited by the sluice lock, which has a maximum passage length of 80 meters and a width of 15 meters (section 2.2);
- The allowable motion limits that power, data, and cooling connections can withstand, as well as the interface options available for these connections (section 2.3);
- A minimum water depth of 5 meters (section 2.5);
- A dike slope of 1:20 (section 2.5);
- The height of a floor in a data center is between 5 and 6 meters (R. Rosendaal, personal communication, 04-04-2025);

3.2. Functional requirements

The following functional requirements are identified.

- Guarantee 99,98+% functional reliability (UptimeInstitute, 2025);
- The structure must be designed to withstand fluctuation in water level of 25 meters (section 2.1);
- The structure must be designed to withstand brackish water conditions (section 2.1);
- The structure must incorporate emergency and fire safety systems to ensure safe evacuation and operational safety (section 2.3);
- The sensitive data chips must be protected against vibration-induced disturbances to ensure reliable and continuous operation (section 2.3);

- The chosen material for the pontoon must be watertight, resistant to brackish water, sufficient buoyant, and structurally capable of accommodating the equipment of the data center (section 2.4);
- The material for the mooring system must withstand dynamic loading and, depending on the design configuration, also resist brackish water (section 2.4);
- The floating data center must remain accessible for workers and maintenance during operation (section 2.4);
- The structure is designed for a design life of 30 years (section 2.4);
- To minimize data, power, and cooling failures, all subsystems must be placed in the same building (R. Rosendaal, personal communication, 04-04-2025);
- The floor load from the data center equipment is between 15 and 20 kN/m^2 (R. Rosendaal, personal communication, 04-04-2025);
- For the surface area of a 1 GW data center, an area of 160000 m^2 is required ((Stalpers, 2025): floating data center that requires 8000 m^2 for 50 MW).

3.3. Structural requirements

The following structural requirements are identified.

- The structure shall be designed to allow safe, practical, and cost-efficient fabrication, transport, installation, and inspection.
 - The design must comply with the 'Besluit bouwwerken leefomgeving', NTA 8111:2011, 'Omgevingsregeling', and Tier 3 standards (section 2.4);
 - The structure must withstand transport loads (section 2.4);
 - The structure must withstand installation loads (section 2.4);
 - The system must include a ballast system for structural stability.
- The structure shall maintain global and local stability during all design stages and in all relevant load combinations.
 - The structure must be able to withstand a maximum vertical velocity of $5 \cdot 10^{-4}$ m/s caused by the inflow and outflow of water in the energy storage lake (section 2.2);
 - The structure must withstand wind loads corresponding to a 100-year return period, with the significant wind direction being from southwest (section 2.5);
 - The wind setup within the closed system of the energy storage lake must be taken into account (section 2.5);
 - The potential impact of translation waves generated by pumps/turbines must be assessed, depending on the selected site (section 2.5);
 - Depending on the site location, wind generated waves corresponding to a 100-year return period with a significant fetch length must be considered (section 2.5);
 - The influence of the wave interaction at the boundary on the floating structure must be evaluated (section 2.5);
 - For calculations of the vertical equilibrium of the system, snow loads, ice loads, and marine growth must be included (section 2.5);
- The structure shall withstand all applied loads without exceeding the allowable stress limits, in accordance with the governing design standards and safety factors;
- The structure shall exhibit sufficient stiffness to ensure that deformations, rotations, and dynamic responses remain within the required serviceability limits.
 - The structure must be designed such that vibrations induced by data center equipment (\simeq 20 – 250 Hz) do not excite its natural modes section 2.5.

3.4. Evaluation criteria

The following criteria are identified and categorized into economical, environmental, social, and constructable criteria.

Economical:

- Design a hyperscale data center of 1 GW to make the project compelling (L. Spin, personal communication, 26-03-2025).

Environmental:

- Preserving the functional integrity of the Delta21 system (section 2.3);
- Since the site is within a Natura2000 area, it is not desirable to construct a temporary dry dock. Therefore, the dimensions of the data center must allow fabrication at an alternative location (section 2.4);
- The environmental impact of the structure at the end of its service life should be considered (section 2.4);
- The design should account for two water level conditions, a high-water level (depth of 30 meters) and a low-water level (depth of 5 meters), since each can govern depending on the environmental load considered (section 2.5).

Social:

- Ensure physical security of the data center, even when the data center is located on water (section 2.3);
- Preserving the character of the islands along the coast, the influence factors are the construction height and the distance from the shore (section 2.6), where the construction height of the turbines is NAP +10 m (section 2.2);
- Enhance biodiversity (section 2.6).

Functional:

- For the cooling system, the structure should be partially or fully submerged (Ahmad, 2024a).

3.5. Conclusion Basis of Design

In conclusion, the Basis of Design defines the design criteria, boundary conditions, criteria, and functional and structural requirements that directly guide the design and form the basis for its verification.

4

Functional designs and selection

The functional design is regarded as the phase in which the concept and the intended functionality of the system are defined. In this chapter, concept designs are developed to generate multiple possible solutions that meet the requirements and boundary conditions defined in the Basis of Design (chapter 3). The aim is to explore, compare, and evaluate different options broadly before converging toward a single final design (van Baars et al., 2009).

For concept development, evaluation, and selection, a design vision with five associated design values (derived from chapter 2 and chapter 3) is used to formulate a paradigm for a floating hyperscale data center on the Delta21 energy storage lake. Guided by this paradigm, a brainstorming session was conducted to create design alternatives for the mooring system and pontoon structure that are integrally aligned with the vision and design values (design with nature, flexibility, systemic thinking, and sustainability). Then, four alternatives are created for the total floating structure and verified and evaluated against the requirements and criteria from the Basis of Design (chapter 3). Finally, a single concept is selected for which preliminary design dimensions are defined.

4.1. Concept design development

4.1.1. The vision and design values

This section presents the vision for creating concepts. A design vision with design values is a qualitative design method that guides design choices before technical detailing or calculations are made. Vision and design values are used to base design decisions and to compare alternatives in terms of their contribution to these values before technically converging towards a single solution. The vision for the floating data center design is as follows.

A future in which technological progress aligns with the conservation of nature and adaptation to climate. The vision is that innovative infrastructures, such as a floating data center within a larger system such as the Delta21 plan, not only contribute to the digital security of the Netherlands, but can also strengthen the relationship with the natural environment. By combining sustainable energy generation with climate-resilient digital networks, a bridge is created between ecology and technology. This vision thus contributes to a robust, safe, and sustainable Netherlands.

To outline a paradigm for the vision, four core design values are created in which requirements and criteria are integrated. The design values are design with nature, flexibility, systemic thinking, and sustainability and are derived from the findings obtained during chapter 2. These values serve as a guide for the design development, selection, and evaluation of a floating data center in the Delta21 plan.

Design with nature

'As we begin to understand the true complexity and holistic nature of the earth system, and begin to appreciate humanity's impact within it, we can build a new identity for society as a constructive part of nature. This is ethical. This is optimistic. This is a necessity.' (McHarg, 1969)

McHarg's work suggests adopting a methodology that respects and uses existing ecological systems and thinks beyond traditional anthropocentric design approaches. This involves engagement with the local environment, understanding the function of natural ecosystems, and recognizing the invaluable contributions to human well-being. This design value aligns with the perspective of environmentalists, water providers, and local parties (section 2.6). It also aligns with environmental criteria (chapter 3).

Flexibility

In the context of increasing challenges such as climate change, rapid urbanization, and fluctuating socio-economic conditions, it is essential that design strategies are resilient and forward-looking (National Academies of Sciences & Medicine, 1999). A floating data center design consists of multiple subsystems, each with its own distinct dynamics and rate of change. The interactions between these subsystems create a need for adaptive design solutions that can flexibly respond to evolving conditions and future uncertainties. A flexible design aims to integrate flexibility and robustness, allowing the design to evolve and remain functional even as demand shifts. This aligns with the economical and constructability criteria (chapter 3). It also aligns with the perspective of data center companies, data privacy organizations, and the Netherlands government (section 2.6).

Systemic thinking

One of the key principles of systemic thinking is the recognition of different scales within a system. Whether considering the data center, the Delta21 lake or national level, designers are required to think about how changes on one scale affect others (Hartung & Hillmert, 2019). Recall that environmental, social, and economic elements are part of a larger, dynamic system. In this approach, it is crucial to identify how different components interact. It enables designers to develop solutions that address long-standing and complex challenges by improving the functioning of the entire system instead of focusing on isolated threats or problems. This aligns with the perspective of the Netherlands government, logistic and construction companies, and universities (section 2.6). It also aligns with the requirements of chapter 3.

Sustainability

Sustainability is an integral part of the vision that aligns with the Sustainable Development Goal 9.4 of the United Nations.

'By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities.' (UN, 2024).

The Sustainable Development Goals demonstrate the scale and ambition of the development of innovative structures and will stimulate action. This design value involves integration of practices that ensure environmental protection, economic growth, and social equity. Relevant stakeholders with an interest in this design value are universities, technology partners, and the energy sector (section 2.6). It also aligns with environmental and social criteria (chapter 3).

4.1.2. Concept creation hyperscale floating data center

Mooring system concept creation

During the development phase, the following mooring designs were created from the aforementioned paradigm using brainstorming sessions as a methodological tool, see Figure 4.1. These different design concepts were developed to explore the design space broadly, to support well-founded design choices, and to avoid converging too early on a single solution.

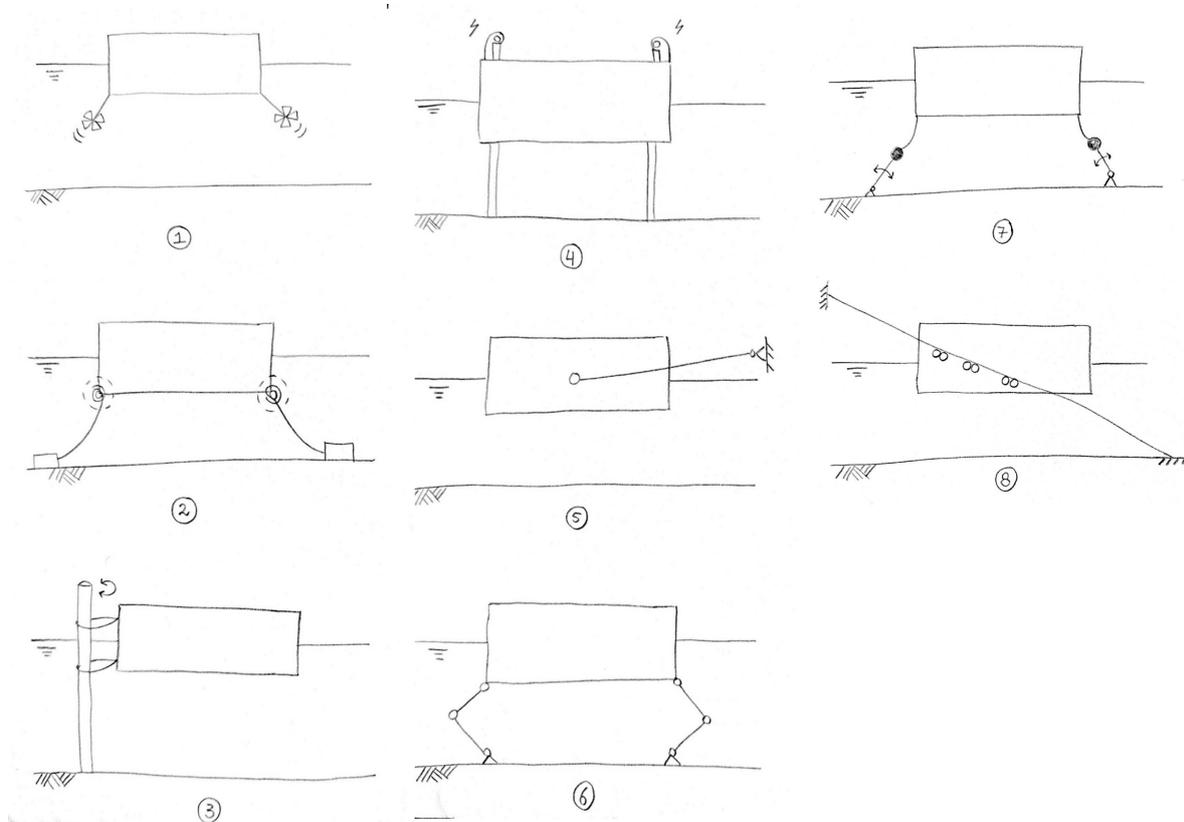


Figure 4.1: Concept designs

1. Boat mooring: this concept design includes a mechanical system of marine engines. The vision of this design focuses on flexibility, where the data center can be easily relocated in response to changing demand.
2. Mooring lines: this concept design includes a mooring system that has already been implemented. The vision of this design focuses on flexibility, where risks can be mitigated due to existing knowledge.
3. Wind adaptive mooring: this concept design includes a rotatable structure that can move with the wind direction. The vision of this design focuses on design with nature, where the impact of the wind load is minimized.
4. Energy-generating mooring: this concept design includes a gravity-based energy system that uses the self-weight of the structure to generate renewable energy. The vision of this design focuses on systemic thinking, where the data center can generate its own renewable energy to fill the energy gaps where needed.
5. Arm mooring: this concept design includes the infrastructure of the data center. The vision of this design focuses on systemic thinking, where the infrastructure scale interacts with the function of the mooring system.

6. Frock mooring: this concept design includes different 'legs' to stabilize the structure in different directions. The vision of this design focuses on sustainability, where the structure can adapt to changes in environmental conditions.
7. Flexible mass mooring: this concept design includes the construction of a stiff arm, masses, and lines to stabilize the structure. The vision of this design focuses on flexibility, where due to the different materials, the stiffness of the mooring system can be changed.
8. Rail mooring: this concept design also includes the infrastructure of the data center. The vision of this design focuses on systemic thinking, where the infrastructure scale interacts with the function of the mooring system.

Evaluation and preselection of mooring system concept creations

The designs above differ significantly from one another and are therefore first assessed in a preselection based on their alignment with the design vision. The evaluation method used is based on comparing the alternatives by assigning scores: plus (+) and/or minus (-). The baseline for this comparison is defined by the design values, which serve as the criteria for the qualitative evaluation of the alternatives. From the evaluation presented in Appendix B, the following preselection is derived.

Designs 1 and 2 include an extra mechanical system that does not align with the design value 'flexible' with the design principle 'robust'. Also from the 'systemic thinking' design value, integrating an extra system creates an extra scale that interacts in the design, which makes it more complex. Therefore design 1 and 2 are removed. Design 4 also includes an extra scale: generating energy.

Designs 2, 4 and 8 have a combination of a stiff support structure close to the floating structure, this can cause vibrations which will impact the operational function of the data center. Vibration isolation or adjusting the mass or stiffness can limit vibrations. Decoupling the floating structure and the mooring structure also prevent direct transmission of vibrations. Since almost no vibrations are allowed for the operational function of the data center (see chapter 3), the first step is to assess whether the other decoupled mooring designs are good alternatives.

Designs 5, 6 and 7 are decoupled alternatives to limit vibrations. Design 5 has two additional advantages compared to design 6 and 7. It contributes to the design value 'design with nature', because it requires no bed disruption. It also aligns with the design value 'systemic thinking', because an additional function is added to the mooring system as it also serves as infrastructure route for electricity, data, drinking water, sewage and walking road. Therefore, design 5 (the arm mooring) is selected.

Pontoon structure concept creations

In chapter 3, it is stated that a 1 GW floating data center requires a floor area of 160.000 m². In addition, it must satisfy the 99.999% reliability requirement, with all data center equipment housed within a single building. This requires a robust design comprising a single pontoon structure, which aligns with the design value of 'flexibility'. The following pontoon shapes are considered, shown in Figure 4.2. See Appendix B for the reasoning behind the chosen shapes.

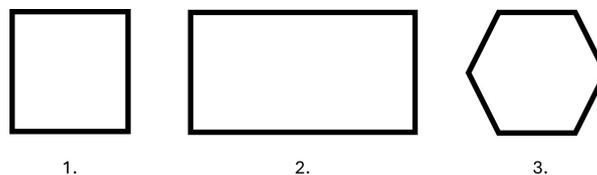


Figure 4.2: Pontoon designs (top view)

In addition, two different configurations are possible: a pontoon with only a ground floor or a pontoon with a ground floor and first floor. A pontoon with an additional second floor is excluded from consideration, given the bathymetry (subsection 2.5.1) which has a minimum depth of 5 m, and the substantial expected draft of the structure.

Evaluation and selection pontoon shape

A preselection of the pontoon shape is also made. This is done because the design currently consists of two separate components: the mooring system and the pontoon structure. It is more valuable to verify and evaluate a complete design of the floating data center in the following sections.

Therefore, the pontoon shapes are qualitatively evaluated on the basis of their alignment with the design vision, as well as insights from literature and offshore industry experience. This early selection step (before the verification) is performed to limit the number of concept designs and to focus on the most promising configurations.

The alternative geometric designs of the rectangular and hexagonal pontoon structures are compared with cost, constructability, and risk. Rectangular units use standard formwork, simple reinforcement layouts, and widely available fabrication expertise, reducing uncertainty and keeping costs predictable. Hexagonal units could offer better space utilization or hydrodynamic advantages, but realizing large hexagonal concrete modules would require non-standard formwork. The feasibility and costs are uncertain without further experiments. Given the objective of this study, the rectangular pontoon is adopted as the baseline because it provides the most reliable and lowest risk design. Hexagonal options can be reconsidered if research and development demonstrate feasibility.

Next, pontoon configurations are evaluated on the basis of design values. An advantage of a pontoon with a ground floor and first floor, compared to a pontoon with only a ground floor, is that it requires less space on the water surface, resulting in reduced bed disruption due to shadowing (aligning with design value 'design with nature'). In addition, limiting the structure to a ground floor and first floor benefit the local stakeholders' horizon-impact criterion, since its height is lower than that of the pump-turbine units planned at Delta21.

In conclusion, a rectangular pontoon with two floors is selected. The exact dimensions of the shape have not yet been determined at this stage of the design.

More detailed concept creations of the total floating structure

At this stage, concept designs have been selected for the mooring system (design 5: arm mooring) and the pontoon structure (rectangular shape), for which several design variations are possible. Based on experience from other industries and findings from the literature (see Appendix C), the following four design alternatives for the floating data center are developed.

1. Single tube;
2. Double tube with diagonals;
3. Double tube with crossings;
4. Triple tube (3D).

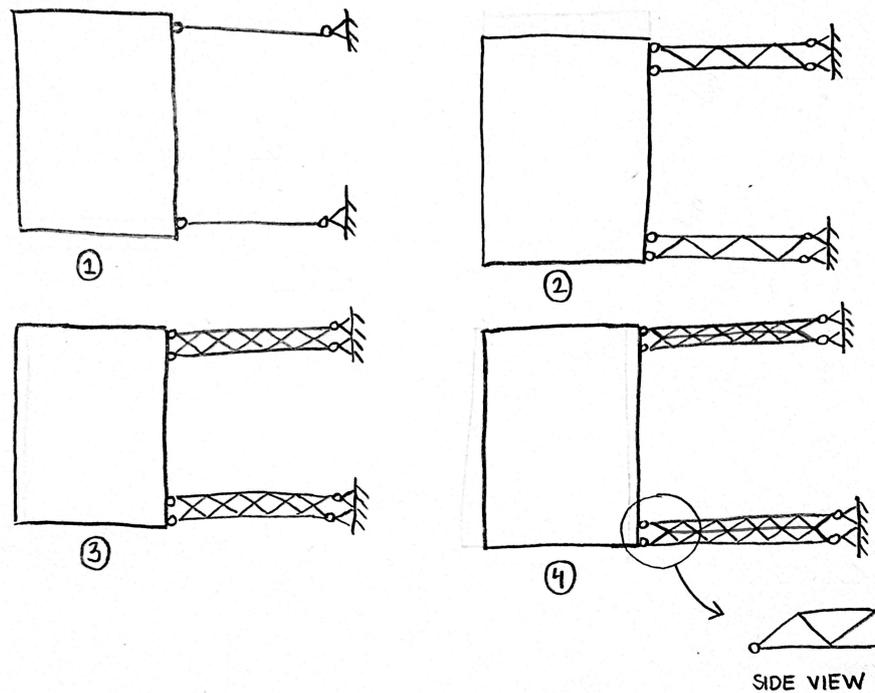


Figure 4.3: Top view of detailed concept creations of the mooring system

Note that, at this stage, the pontoon structure can be of any dimension. For simplicity, only one dimension configuration is illustrated in Figure 4.3.

4.2. Verification of the functional requirements

The verification of the functional requirements is performed qualitatively to check whether the design meets the functional requirements defined in chapter 3. This section answers the question: 'Are we doing what we agreed to do?'. This step is performed before the evaluation and selection of more detailed concept creations of the total floating structure, because if the proposed four alternatives does not meet the functional requirements at this stage, further evaluation would not be meaningful.

Functional requirements verified

The structure is designed to withstand water level variations of up to 25 meters by implementing hinges in the mooring system. For the pontoon structure, concrete is selected as the most appropriate material (section 2.4). It is cost-effective to manufacture, well-established in the floating construction industry, and provides reliable structural performance (Fernández & Pardo, 2012). The use of concrete also ensures resistance to exposure to brackish water. The mooring system is positioned above the water surface, to avoid direct exposure. The mooring arms will be made of steel, consistent with comparable rigid mooring systems documented in the literature (Whittaker et al., 2020), as this material provides stiffness and ductility to accommodate dynamic loading.

Furthermore, the proposed design alternatives aim to minimize the interaction between the pontoon and the mooring system. The configuration is intentionally massive and stiff, thereby reducing the potential for vibration transfer to sensitive data equipment. The system is connected to land, which enables the placement of supporting infrastructure either above or next to the mooring structure, ensuring continuous accessibility for inspection and maintenance. Maintenance activities can be performed from the shore or from vessels. Finally, the design accommodates all subsystems within a single building, with a total floor area of approximately 0.16 km^2 , which contributes to the operational efficiency of the data center.

Functional requirements not verified

The requirement to guarantee a functional reliability of 99.98% or higher is considered in the design development phase, but cannot be demonstrated within the scope of this study, because this depends on the performance of the entire system (and not only the mooring system). However, the findings of the structural design (see chapter 5) can contribute to some extent to the 99.98+% functional reliability.

Regarding the preserving function of the Delta21 system, the design must not interfere with the flood-protection function of Delta21 (section 2.3). Ensuring this could be achieved by specifying a design life of 100 years, consistent with the Delta21 design life (Delta21, 2024a). However, this cannot be verified in this study, as no detailed fatigue or lifetime analysis will be performed (see section 1.5). Consequently, the 30-year design life cannot be verified either. However, the design incorporates redundancy to mitigate the probability of failure within its design life.

Conclusion functional requirement verification

In conclusion, this verification is based on design choices that contribute to meeting functional requirements. The verification therefore demonstrates that the design process has been carried out with these functional requirements in mind. However, uncertainty remains about how the structure will respond to a height difference of 25 meters. It is also still unclear whether the design decisions are sufficient to protect the sensitive data chips from vibration. In addition, the functional reliability and the design-life requirement cannot be verified in this study, as detailed calculations are not performed that could substantiate these functional requirements (see section 1.5). The following sections will provide a more substantiated basis for the verified functional requirements, as they include specific choices for material properties and dimensions, and an analysis of structural performance.

4.3. Concept evaluation and selection

This concept evaluation and selection section consists of three parts. First, the evaluation criteria from chapter 3 are reviewed qualitatively. The evaluation of the design criteria is carried out to determine whether the design is moving in the right direction. It also helps decide whether the design can progress to the next design phase. Second, a life cycle evaluation is performed to assess the performance of the proposed concept for the floating data center throughout their entire service life. Third, to determine which of the four design alternatives for more detailed concepts creations of the total floating structure is the most suitable within the requirements and boundary conditions (chapter 3), a multi criteria analysis is applied. The multi criteria analysis is a systematic evaluation method used to compare design concepts based on multiple assessment criteria, which are weighted according to their relative importance.

4.3.1. Evaluation of identified criteria

The design of the pontoon has been developed for a 1 GW data center, taking into account the floor area required for a facility of this scale. The Delta21 energy storage lake can supply 1 GW of renewable energy to the data center. However, more studies are required to determine whether this supply is sufficiently reliable in accordance with the operational requirements of the data center. Physical security can be ensured if the access route to the data center is controlled and not publicly accessible to unauthorized individuals.

The design, to some extent, ensures that the preservation functions of Delta21 are not negatively affected by the integration of the floating data center. However, it is beyond the scope of this study to demonstrate that biodiversity will not be affected by introducing the data center into the Delta21 system. The criteria that the data center is dimensioned so that it can be manufactured off-site, due to construction within a Natura2000 area, is addressed in the life cycle evaluation. The life cycle evaluation also discusses the consideration regarding the environmental impact of the structure at the end of its service life.

Furthermore, the criteria that the design must account for two water level conditions will be evaluated in the structural design section (chapter 5), where the governing environmental design conditions are assessed. In addition, the criterion regarding the preservation of the character of the islands along the coast cannot yet be evaluated, as initial dimensioning has not been performed at this stage. This will therefore be considered during further analysis later in this study. Finally, since the structure is floating and partially submerged, there are opportunities to integrate a water-cooling system.

4.3.2. Life cycle evaluation

Planning and design

The location influences the planning and design of the floating data center. Given that Delta21 lies within a Natura2000 area, environmental considerations must be taken into account during the design. This leads to the following design considerations.

- The design is configured to be attached to the quay, which excludes sites located in the middle of the storage lake.
- The design must ensure accessibility. Since infrastructure within a Natura2000 area is not preferred, locations along the surrounding dike are excluded.

Then, the following site on the Delta21 energy storage lake is selected as it allows the implementation of the proposed design, see Figure 4.4.



Figure 4.4: Location and orientation data center on Delta21 energy storage lake

Fabrication

Environmental considerations must also be taken into account during fabrication, installation, and operation. A temporary construction site is not permitted within a Natura2000 area. Therefore, the pontoon structure will be designed as multiple modules for assembly on site. The pontoon structure can be manufactured at the Keppel Verolme dry dock in Rotterdam. The dry dock can accommodate constructions up to 395 m × 84 m. In addition, the rectangular pontoon shape was chosen because it provides a simpler and more efficient fabrication process compared to a hexagonal alternative.

Next, large offshore structures are constructed at several locations in the Netherlands, including the Port of Rotterdam (Maasvlakte 2). The port is developing a dedicated Offshore Center to support the construction and maintenance of offshore wind energy infrastructure (of Rotterdam, 2017). Therefore, it is assumed that the mooring arm, made of steel and comparable in size to a wind turbine monopile, can also be manufactured at this location.

Finally, data center equipment is not produced on a single site, but is supplied from various manufacturers worldwide.

Transport

Transport of the pontoon modules by water from the Keppel Verolme dry dock to the Delta21 site is feasible, but only by sea and not via inland waterways (Figure 4.5). Because the modules will be self-floating, this property can be used during transport.



Figure 4.5: Transport pontoon structure (Google Earth, 2025)

Next, transportation of the mooring arm by road is feasible if the structure can be manufactured at Maasvlakte 2 (see Figure 4.5). The logistics and safety of this operation can be guided by the practices used in the offshore wind energy industry.

Finally, the data center equipment is no larger than a standard container and therefore allows for various transport options.

Installation

For the installation of the pontoon modules, the surrounding dike of the Delta21 energy storage lake must remain partially open during construction, since the proposed modules cannot pass through the sluice gate. As a result, the construction process of Delta21 becomes dependent on the installation schedule of the floating data center, which therefore must be carefully coordinated in the overall project planning. Once the pontoon modules are transported to the site, they will be connected and assembled on site.

Next, the installation of the mooring arm could potentially be carried out using a sliding method, similar to techniques commonly applied in the maritime industry to deploy large vessels in the water. In this case, a temporary floating structure will be required to support the installation of the mooring arm between the pontoon and its supports.

Finally, the data center equipment will be fully prefabricated and tested off-site, requiring only final installation and connection at the project site.

Operation management

The design has been developed with consideration for potential vibration disturbances that could affect sensitive data chips. This is achieved by: (i) minimizing the interaction between the pontoon structure and the mooring system, and (ii) designing for high overall structural stiffness.

Furthermore, the selected location ensures 24/7 access to the data center. The data center is located relative to the south-west wind direction, ensuring that the mooring system is aligned with the significant wind direction and the corresponding environmental forces (see Figure 4.4). However, the influence of these environmental loads on the design must still be quantified through static and dynamic analysis. In addition, the crest height of the selected design remains below the turbine and pump levels, which is in line with the preferences of local residents regarding visual impact.

In addition, a simple configuration was chosen to reduce potential failure risks and to improve maintainability. For the same reason, the support structure is positioned above the maximum water level, keeping the mooring arms accessible for inspection and maintenance. An additional advantage is that the structure is not continuously exposed to water, which reduces the risk of corrosion and degradation. Maintenance operations can be carried out either from land or by boat.

Decommissioning

The proposed data center design cannot be relocated because it is too large to pass through the sluice gate.

Conclusion life cycle evaluation

In conclusion, the life cycle evaluation demonstrates the performance of the proposed floating data center concept throughout its entire service life.

4.3.3. Selection concept design

In this section, the four alternatives of Figure 4.3 are evaluated based on the criteria defined in Table 4.1, to select a concept that will be further assessed for its structural performance in the following sections. The selection is carried out using a multi criteria analysis, which in this study is based on findings from the offshore floating wind industry (Leimeister et al., 2018).

Criterion	Included aspects
1. Volume production	Outer dimension, mooring footprint, ease of manufacturing
2. Ease of handling	Total weight, assembly, transport, installation, decommissioning, required equipment and vessels
3. Durability	Corrosion resistance, fatigue resistance, redundancy
4. Flexibility	Water depth, environmental loading
5. Certification	Time to achieve, ease to achieve
6. Performance	Deflections, displacements, dynamic response, overturning resistance, torsion resistance
7. Maintenance	Frequency, redundant components

Table 4.1: Evaluation criteria and included aspects

Since this evaluation takes place in the conceptual design phase, detailed quantitative data are not yet available. Therefore, the assessment was performed using expert judgment and reasoning based on the available design information. The purpose of the scoring is not to produce absolute quantitative outcomes, but to provide a structured and transparent comparison of alternatives based on the available design knowledge. For the reasoning of the scores, see Appendix B. The weights assigned in this analysis are based on expert knowledge from the offshore wind energy sector (Leimeister et al., 2018). In this study, it is assumed that these weights can be applied, as the structure under consideration is of a similar type. Finally, the average score for each criterion was calculated using the following formula.

$$Average = \frac{\sum c_i \cdot w_i}{c_{total}}$$

Where:

- $i = (1, \dots, 7)$: criteria number
- c_i : criteria i
- w_i : weight of criteria i
- c_{total} : total weight of the criteria

Criterion	Single tube	Double tube with diagonals	Double tube with crossings	Triple tube (3D)	Weight
1. Volume production	1.5	1.4	1.3	1.0	1.65
2. Ease of handling	1.3	1.4	1.3	1.2	1.45
3. Durability	0.8	1.2	1.3	1.6	1.44
4. Flexibility	1.0	1.3	1.4	1.5	1.50
5. Certification	1.3	1.2	1.1	0.7	1.55
6. Performance	0.9	1.3	1.5	1.7	1.60
7. Maintenance	1.0	1.3	1.5	1.3	1.46
Average	1.12	1.31	1.34	1.28	

Table 4.2: Calculated average per criteria

In conclusion, the double tube with crossings is identified as the most suitable concept based on the multi-criteria evaluation. It features two mooring arms, each consisting of two tubular elements with cross bracing, offering a balanced compromise between strength, redundancy, and constructability. The initial dimensioning of the mooring arm and pontoon structure is performed at this stage (after selection) to ensure that detailed analyzes are performed efficiently on the most promising design option: double tube with crossings.

4.4. Initial dimensioning of the mooring arm and pontoon

The initial dimensioning of the mooring arm and pontoon structure is used to assess the functional and technical feasibility of the concept and to provide first-order estimates of key dimensions before proceeding to detailed analysis. The method used in this section is a preliminary design approach based on the boundary conditions of chapter 3, scaling of reference projects, and simple analytical calculations. Initial dimensioning is performed in this phase to reduce design space before initiating detailed and time-intensive analyzes.

4.4.1. Mooring arm

The mooring concept is described by two mooring arms consisting of two parallel steel tubes anchored to hinges on the pontoon and the headland (see Appendix C for reasoning). The vertical displacement is 25 m and follows a circular arch with a radius of 250 m. The horizontal displacement is 1.25 m in the y-direction (with depth) and is fixed in the x-direction. The landfalls are located at NAP -3 m to ensure that the mooring arms are only exposed to air and to ensure a horizontal orientation in the case of a maximum water level. The mooring arm rises from the pontoon with a 10% slope up to the head land (see Appendix C for reasoning).

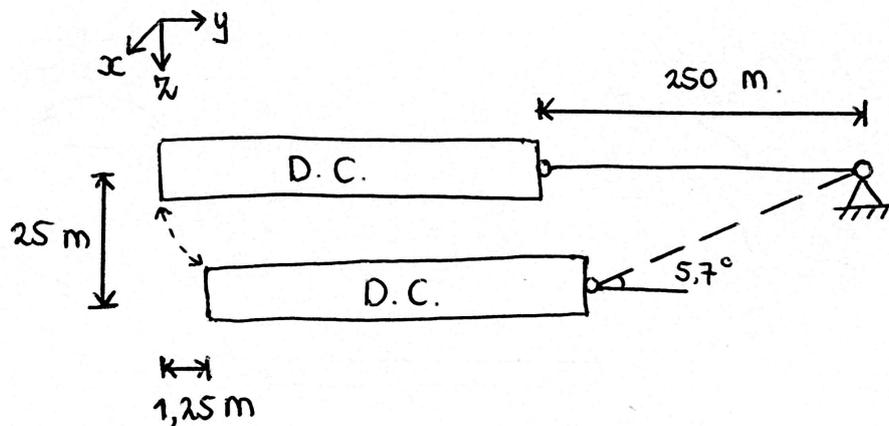


Figure 4.6: Basic configuration Data Center

Vertical displacements and roll and pitch rotations are controlled by the hydraulic stiffness of the pontoon (see subsection 4.4.2). The general distance between the mooring tubes need to be determined in the analysis but will be in the range of 25 to 50 m. In a future project phase, it would be valuable to perform a parametric study on the center distance between the mooring tubes of the mooring arm with model experiments in order to enhance the dynamic behavior and constructability of the floating data center.

The mooring arm consists of two steel tubes with a length of 250 m, a diameter of 3 m, and a wall thickness of 30 mm (see Appendix C for reasoning diameter and wall thickness). The horizontal bracing of the mooring arm tubes consists of crosses with a constant inclination of about 40 degrees. The bracing elements are foreseen as circular steel tubes that have an outer diameter of 3 m and a wall thickness of 30 mm. Throughout the length of the mooring arm, 10 bracing crosses will be placed. The components of the data center mooring arm are illustrated in Figure 4.7.

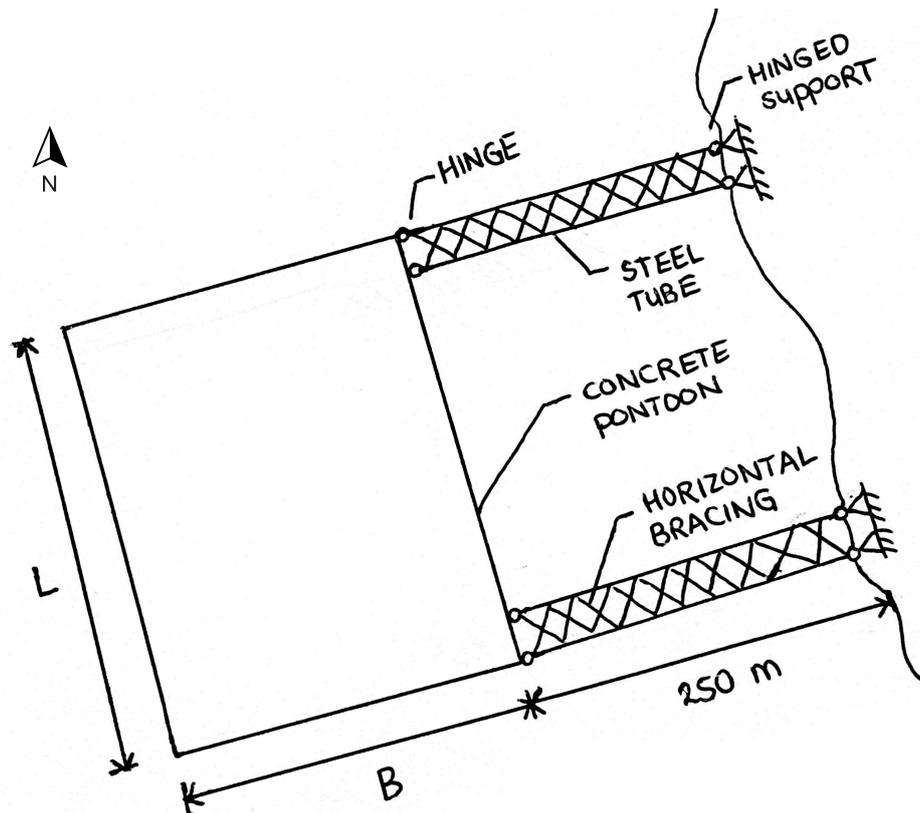


Figure 4.7: Components data center mooring

Key figures mooring arm

Length of the arm:	250	m
Number of arms:	2	-
Crossing length:	35.4	m
Horizontal displacement:	1.3	m
Vertical displacement:	25	m
Total steel volume:	1359.4	m ³
Total steel weight:	10670	tonnes

Support

The support is designed at NAP -3 m. Two design water levels are introduced: the first is for the maximum water level, where the mooring arm is guided horizontally to the support, and the second is for the minimum water level, where the mooring arm is guided with an angle of 5.7 degrees to the support. The effect of water level variation can be controlled by adjustable water ballasting of the pontoons at the opposite end of the mooring connection. This will require an active ballasting scheme, which means effects of operation and maintenance conditions.

Accessibility

The mooring system can be designed in later phases with a double function, where the data center infrastructure is integrated. If needed, an increase in the diameter of the mooring arm components is not a problem from a structural point of view, but it will, of course, increase the steel volumes and quantities. Corresponding calculations, fall outside the scope of this study.

4.4.2. Pontoon structure

The pontoon accommodates two functions of the data center: the 'grey space' where there is room for technical installations and the 'white space' where there is room for racks to house IT equipment. Escape ways are integrated into the entire structure. To meet the minimum floor area of 160.000 m² for a 1 GW floating data center, the structure must be divided into three modules of approximately 350 m × 84 m (given the dimensions of the Keppel Verolme dry dock, with the governing constraint being width 84 m). This statement is based on the assumption that each module is built to the dry dock's maximum practicable dimensions. This results in a tentative water plane area of 350 x 250 m. From chapter 3, the height of the pontoon must be at least 12 meters. It is chosen to be 15 meters to account for floor thicknesses and to create space for ballast compartments of 1 meter in height at the bottom of the structure. The draft (D) is unknown at this stage, see Figure 4.8.

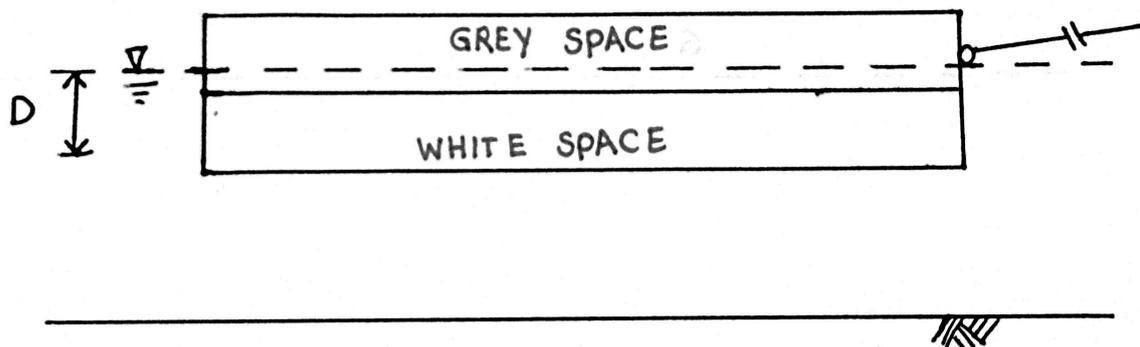


Figure 4.8: Pontoon draft (D)

Concrete grade

The concrete grade B55 M40 is suggested for the pontoons. To avoid spalling and improve the fire resistance of the data center, plastic fibers will be added to the mix in the cast of the inner face (Fjeld, 2012). The pontoons are post-tensioned by longitudinal tendons to achieve water tightness when exposed to bending moments (F. van der Woerdt, personal communication, 28-08-2025). In order to realize this, the concrete pontoons have a general outer wall thickness of 0.8 m.

Key figures pontoon

Dimensions:	350 × 250 × 15	m
Height (per floor):	6	m
Number of floors:	2	-
Columns volume:	4266	m ³
Total concrete volume:	154400	m ³

4.4.3. Conclusion initial dimensioning

In conclusion, the design choices for the initial dimensioning have taken into account the boundary conditions (chapter 3). To minimize disturbance within the Natura2000 area: (i) the support is positioned at NAP -3 m, and (ii) a double floor configuration for the pontoon is selected to minimize shadowing. Next, large construction modules were chosen. Although these cannot pass through the Delta21 sluice gate, they offer significant advantages because they reduce the number of structural connections, improve water tightness and reliability, and reduce alignment issues. They also minimize on-site activities, which is beneficial in environmentally sensitive areas. In addition, the design takes into account: (i) allowable motion limits that the connections can withstand, and (ii) a floor height of 6 meters. Finally, the dike slope must be locally adjusted from 1:20 to approximately 1:8 due to structural and cost-effective considerations of the mooring system.

4.5. Conclusion functional design and selection

In conclusion, the design can progress to the next step of the elementary design cycle: the structural design. Significant uncertainties remain, as many aspects have not yet been fully developed or validated. However, these elements have been considered in conceptual reasoning, indicating that the design has the potential to be successful. The proposed conceptual design is illustrated in Figure 4.9 and Figure 4.10. Note that in these figures, a separate bridge has been drawn to illustrate access to the data center. This is done because this study does not assess whether the mooring arms can withstand pedestrian and/or vehicle loads.

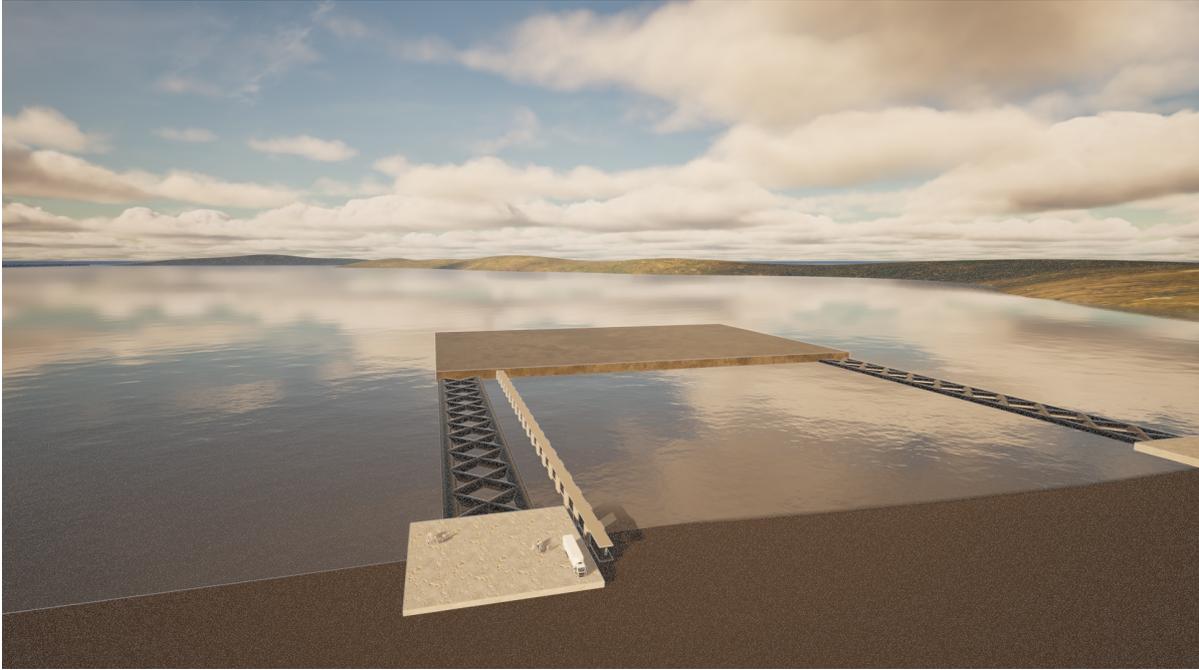


Figure 4.9: Concept design for 1 GW floating data center in high water level condition

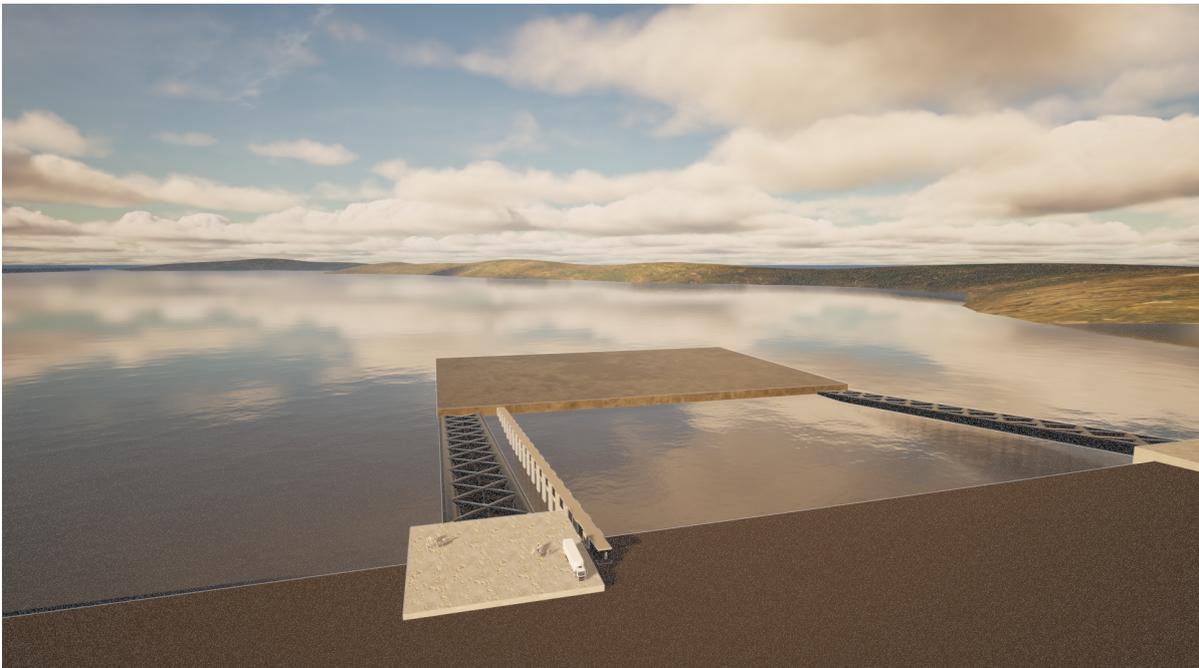


Figure 4.10: Concept design for 1 GW floating data center in low water level condition

5

Structural design

Now that the functional design has been completed, this chapter addresses the next step in the design process: the structural design. In this design, the focus is on analytical evaluation and system dimensioning. This will support the feasibility decision and implies the level of documentation of safety and technical integrity.

To do so, a fault tree analysis is conducted to obtain an overview of the failure mechanisms and identify the design conditions using a qualitative approach. Next, all relevant loads and load combinations that can act on the structure under normal design conditions are determined, ensuring that the structure can be analyzed in a reliable and consistent way. Then, two analyzes are performed: (i) a static structural analysis to verify that the floating data center structure can safely and reliably withstand all design loads without exceeding the limits of material strength or losing global stability, and (ii) a dynamic structural analysis to provide a first-order estimate of the risk of resonance. Next, a sensitivity analysis is performed to provide information on the robustness and reliability of the floating data center structure. Finally, the structural design is verified for the structural requirements of chapter 3.

5.1. Fault tree review

This section presents a fault tree review based on the functional decomposition of the proposed floating data center design during the operation phase, as analyzed in chapter 2. A fault tree identifies the causes that can lead to an undesired event and provides information on combinations of failures. It uses a top-down approach that gives a complete picture of a specific failure scenario. In addition, the method offers a clear and visual representation (van Baars et al., 2009).

Since the project is still in the early design phase and this analysis is intended as a qualitative tool, failure probabilities (which are often part of a fault tree for quantitative risk analysis) have not yet been applied. Consequently, this fault tree review focuses on defining the relevant events and corresponding logic gates, providing a structured framework to identify potential failure paths and critical components for further investigation in this study.

5.1.1. Floating data center support system failure

The fault tree is built up with subsystems, sub-subsystems, and two types of gates ('AND' and 'OR'). An 'AND' gate represents a parallel system that results in the failure of all components of the subsystem. An 'OR' gate represents a series system that results in failure of any components of the subsystem.

At the top of the fault tree is the functional failure of the data center, selected from the requirements in chapter 3. This failure has been determined to be the result of a support system failure, a data center system failure, or a Delta21 pump/turbine failure. Failure of one of these subsystems undermines the ability of the floating data center system to function. For this research, the data center equipment failure sub-tree is simplified and modeled as an undeveloped event (represented by a square), due to the readily available fault tree analysis of land-based data center systems (Association, 2025). In addition, it is assumed that the data center meets at least the Tier 3 requirements, which means that

it achieves a typical uptime of 99.98+% (UptimeInstitute, 2025). Furthermore, for this research, it is assumed that the Delta21 energy storage lake failure sub-tree is covered by adopting the same design lifetime of 100 years for the floating data center (Delta21, 2024b).

Finally, the failure of a system occurs if stress (S) > resistance (R): this is the failure inequality. The nodes where the fault tree ends are marked with a circle. The nodes that are expanded in a sub-tree are marked with a triangle. This applies to mooring failure, internal connection failure, and pontoon failure, see Figure 5.1.

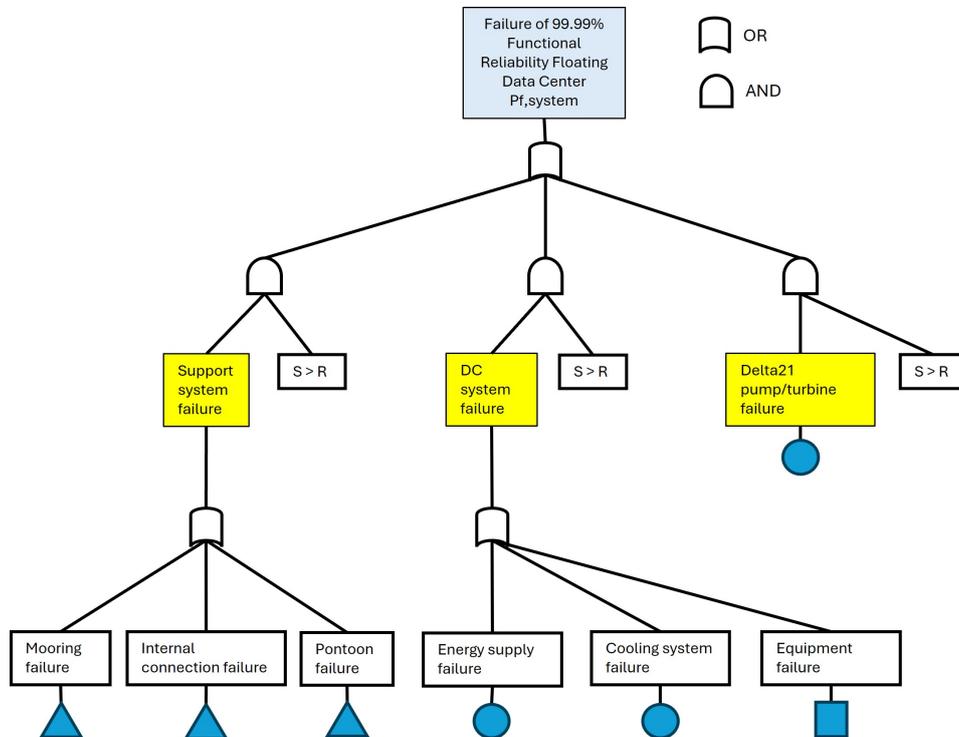


Figure 5.1: Fault tree Functional Reliability Failure floating data center from system-level to sub-system level

Sub-fault tree mooring failure

The mooring system consists of (i) pinned supports and (ii) two mooring arms, each consisting of two tubes, horizontal bracing and tube/bracing connections. The basic events that can cause the failure of the components can be seen in Figure 5.2. Basic events can occur due to environmental conditions (see section 2.5). In this fault tree analysis, the environmental conditions consist of:

- Wind;
- Waves;
- Currents;
- Snow and ice;
- Marine growth.

In addition, failure of the components can also occur due to external hazards. In this fault tree analysis, the external hazards consist of:

- Human errors: ship impact, explosions, fire, flooding;
- Surrounding factors: corrosion, extreme temperatures, water density changes.

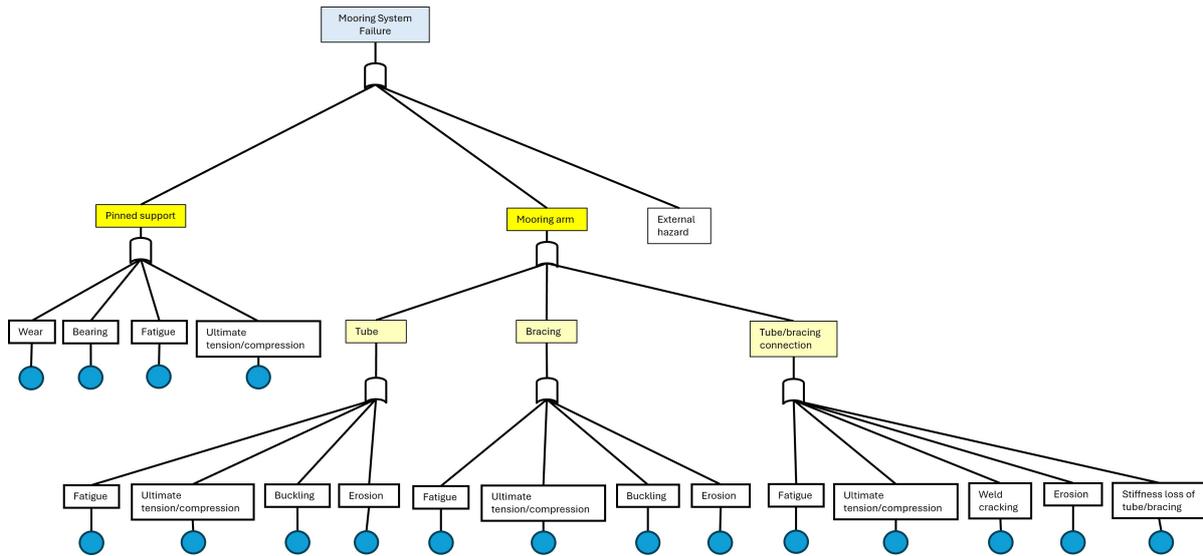


Figure 5.2: Developed sub fault tree of the mooring system

Sub-fault tree pontoon failure

The pontoon system consists of the mooring, the ballast system, and the pontoon structure. The basic events that can cause the failure of the components can be seen in Figure 5.3. Basic events can occur due to environmental conditions, as described above. In addition, failure of the components can also occur due to external hazards, as described above. In this sub-fault tree, three failure mechanisms (i.e. stability loss, sludging/slugging, buoyancy loss) are added for a better understanding of the failure modes.

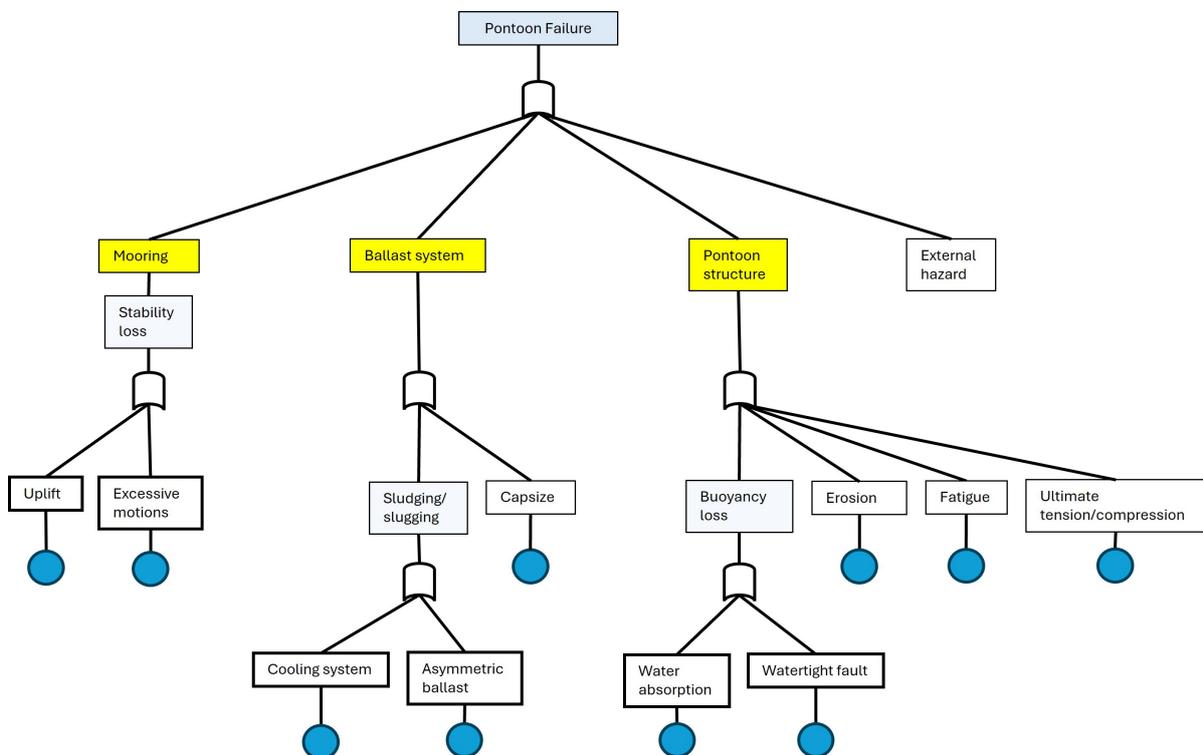


Figure 5.3: Developed sub fault tree of the pontoon system

Sub-fault tree connection failure

The internal connections consists of (i) hinges (xr') between the pontoon and the mooring arm, and (ii) bolted connections. The basic events that can cause the failure of the components can be seen in Figure 5.4. Basic events can occur due to environmental conditions, as described above. In addition, failure of the components can also occur due to external hazards, as described above. In this sub-fault tree, a failure mechanism (i.e. bolted shear/pull-out) is added for a better understanding of the failure mode.

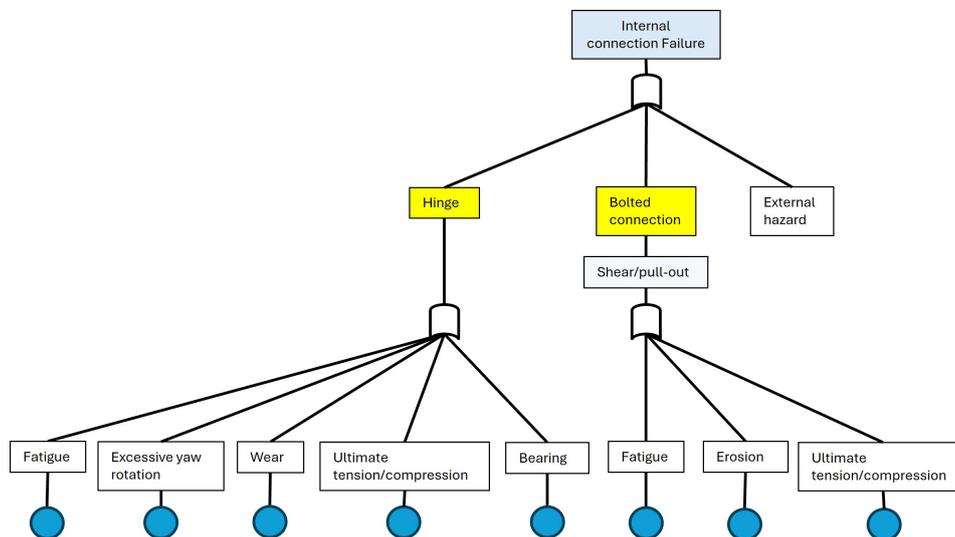


Figure 5.4: Developed sub fault tree of the internal connections

5.1.2. Fault tree evaluation and conclusion

This fault tree review provides an overview of the failure of the components of the floating data center. It is decided that the external hazard is included in every sub-fault tree. In addition, basic events are mainly caused by environmental conditions. Consequently, this section evaluates external hazards, component failures, and environmental conditions, after which a conclusion is drawn to identify the potential governing components/conditions that require further investigation in this study.

External Hazards

External hazards are classified as accidental loads, characterized by a low probability of occurrence but potentially severe consequences. The following external hazards have been introduced into the fault tree and are evaluated.

- *Temperature*

Temperature has an influence on buoyancy and stability. The density of the water varies under the influence of different temperatures. If a closed water cooling system is assumed, comprising a heat exchanger that uses water from the Delta21 energy-storage lake, the water temperature will increase. However, if the rejected heat is recovered for secondary use, the resultant temperature rise is not expected to have a significant effect on the structure. The feasibility of such a cooling system should be investigated in subsequent studies, and the influence of temperature variations must be explicitly accounted for in the detailed design phase.

- *Ship impact*

A vessel impact on the floating data center constitutes an impulsive excitation. It is an accidental force for a short time: an extreme situation. The likelihood of a maintenance vessel colliding with the data center is extremely low (the data center is located about 8 km from the pump-turbines).

- *Flooding*

In the event of compartment damage and consequent flooding, the structure must maintain buoyancy and stability. Functional reliability can be increased for this case by providing flood-resistant compartments around technical installations, see Figure 5.5. Detailing should be elaborated in later design stages.

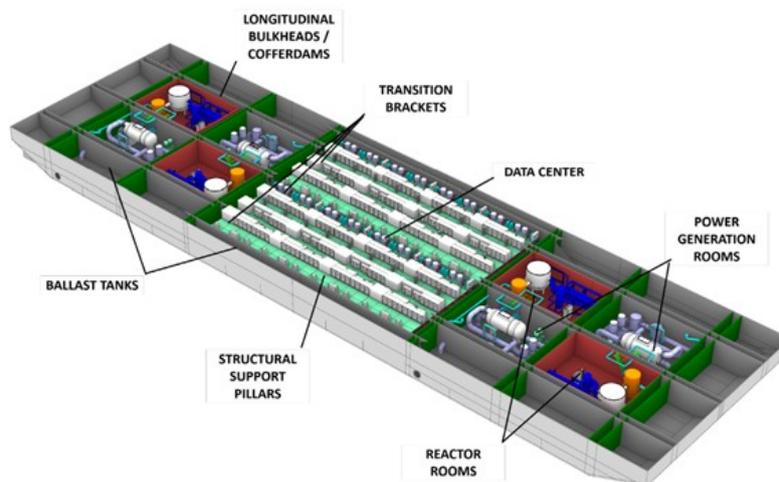


Figure 5.5: Compartments for flooding resistance (ABS, 2025)

- *Water density changes*

In this study, a constant water density of 1015 kg/m^3 is used (representative of brackish water). Since this value in reality varies with depth, seasonal effects, and the inflow of fresh or salt water into the Delta21 energy storage lake, it is recommended to model the buoyant force as a variable parameter in more detailed analysis. This would improve the accuracy of the stability predictions under long-term operational loading conditions.

- *Other external hazards*

- Explosions and fire
- Corrosion

For explosions and fire, the risk analysis should assess the probability of occurrence and additional mitigation strategies should be considered if necessary. For corrosion, protective coatings can be used as a mitigation measure if required. In such cases, the potential environmental impact should also be evaluated.

In conclusion, external hazards have a low probability of occurrence and are specifically addressed in a separate safety analysis or risk assessment.

Component sub failures

The components considered in the sub fault trees are the pontoon structure, the mooring system, and the internal connections. The structural performance of these components that are potentially essential for functional reliability is investigated.

- The overall stability governs the failure mode of the pontoon, as stability first determines whether the concept is functional. A detailed internal force analysis of the pontoon requires a level of design detail that is not yet available and is outside the scope of this study. In addition, the fault tree identifies stability as the governing failure mechanism of the pontoon. Therefore, this will be further elaborated on in the next sections.

- The mooring system consists of various potential failure mechanisms, making it a structurally important component. In this early feasibility phase, it is not feasible to quantify all these failure mechanisms (e.g., fatigue, corrosion, wear) in detail. Therefore, the following sections focus primarily on assessing the structural strength (ultimate limit state) to determine whether the system is capable of withstanding the design loads.
- The internal connections are single-point failures, which makes them critical for overall structural integrity. The proposed hinges allow moments only around the x-axis, while restricting moments about the y- and z-axes (this is a design choice). Note that the restrained moments can reach considerable magnitudes, making the hinges a critical component in the system. Possible alternatives for the hinge instead of restricting the moments about the y- and z-axis are as follows.
 - Releasing the moment around the z-axis, releasing the moment around the y-axis, or releasing the moments around both the z- and y-axes. However, this could lead to large displacements in the horizontal plane (in the x and y directions);
 - Adding a rotational spring around the y-axis, adding a rotational spring around the z-axis, or adding rotational springs around both the y- and z-axes. The rotational spring resists rotation and, therefore, displacements in the horizontal plane, as it generates a moment that depends on the rotation angle;
 - Combinations of these alternatives.

So, for the hinges, possible alternatives are available to make the component less critical. Therefore, the strength of the hinges is not individually assessed in the following sections, but their function is evaluated in the sensitivity analysis (section 5.5).

In conclusion, in the structural static and dynamic analysis, the focus will lie on the stability of the pontoon structure and the strength of the mooring arms.

Environmental conditions

The governing design condition is defined as a load or load combination that determines the design under normal design conditions: conditions the system can be expected to encounter regularly or predictably throughout its lifetime (i.e. environmental conditions). In addition, basic events are mainly caused by environmental conditions. This means that of all failures, the environment acts on a large part of the sub failures. For this reason, in the next section, a more in-depth investigation on the environmental conditions is performed to obtain the governing environmental design conditions.

Fault tree review conclusion

It should be noted that the conclusions drawn in this assessment are based on the information provided in the study and the expertise of the reviewer regarding both the system considered and the fault tree methodology. In addition, although the focus of the fault tree is on logical correctness and completeness, the relative contribution of the individual components has not been considered. For example, the mooring arm is identified as a critical element on the basis of qualitative justification. However, uncertainty remains that quantitative analysis may show that it is less critical or critical with respect to a different failure mechanism.

In conclusion, this study performs initial evaluations to determine the critical components and loading conditions that the structure may experience. Therefore, the following sections on structural static and dynamic analysis present more detailed calculations focusing on the stability of the pontoon structure and the strength of the mooring arms, as these are the failure mechanisms of interest. Before these analysis are performed, the design loads are established in the next section by examining the relevant environmental conditions.

5.2. Determination of the design loads and conditions

The goal of this section is to identify and quantify all relevant loads and load cases that can act on the structure under normal design conditions, ensuring that the structure can be analyzed in a reliable and consistent way. Normal design conditions are conditions the system can be expected to encounter regularly or predictably throughout its lifetime, i.e., self-weight, environmental conditions, and high/low water level conditions.

The method used to determine the design loads consists of the following steps. First, the relevant loads were identified in section 2.5. Next, the critical load cases are defined and the corresponding load magnitudes are determined. Finally, these loads are converted into design values by applying appropriate safety factors. The resulting design loads serve as input for the subsequent structural analyzes (van Baars et al., 2009).

5.2.1. Self-weight

The self-weight is often the most important load acting on a structure, as it typically represents the largest contribution to the overall load. For the pontoon structure, the self-weight provides a primary resistance against overturning and uplift. In addition, self-weight is a permanent load that must be included in the evaluation of bending moments, shear forces, normal forces, stresses, and deflections (Voorendt, 2023). In this section, the self-weight of the pontoon structure and the self-weight of the mooring arm are determined.

Self-weight pontoon structure

Two contributions to self-weight of the pontoon structure need to be considered:

- G1: permanent self-weight including structure and equipment
- G2: variable self-weight due to marine growth and water absorbed by structure (and permanent ballast)

Permanent self-weight includes:

- Weight of the mooring arms
- Weight of the pontoons and structural elements
- Weight of the ballast
- Weight of permanent data center equipment

Variable self-weight includes:

- Weight of marine growth
- Weight of water absorbed by concrete structure
- Snow and ice

For permanently submerged concrete, a weight increase of 1.0% of the initial concrete weight is assumed for water absorption. Buoyancy is determined on the basis of MSL water level and the most unfavorable value for the specific weight of water. Buoyancy calculations are based on net structural dimensions without marine growth. In order to cover tolerances in permanent weight and buoyancy, ΔG is assumed to be 3% of the permanent self-weight G1. The buoyancy is determined using a specific weight of water of 1015 kg/m³ (brackish water condition). This value is assumed constant, but in reality that is not the case. Therefore, in further research, more detailed calculations of buoyancy are required.

The self-weight of the pontoon structure is calculated in Appendix D. The following loads are found: a maximum self-weight (G_{max}) of 32074 kN/m and a minimum self-weight (G_{min}) of 30058 kN/m. The draft Figure 4.8 is selected to be 8 meters to ensure that the structure is neutrally buoyant, which means that the maximum self-weight equals the buoyancy. In addition, a ballast system will be incorporated to accommodate vertical load variations for the minimum self-weight. The structure is designed to provide space for 1 m high ballast compartments at the bottom of the pontoon structure. With a length of 350 m, a width of 250 m, and a height of 1 m, there is sufficient volume to ballast with water and to accommodate the vertical load variations between the minimum and maximum self-weight.

Self-weight mooring arm

Subsequently, the self-weight of the mooring is evaluated to exclude the possibility of second-order effects. For the calculation, the loading condition has been simplified so that a hand calculation can be performed, see Figure 5.6.

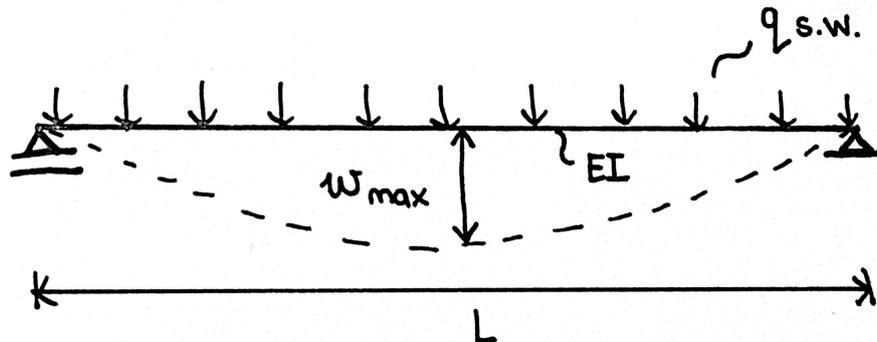


Figure 5.6: Schematization of a simple supported beam under uniformly distributed load (self-weight) showing the deflection curve

The following 'vergeet-me-nietje' applies to the maximum vertical deflection.

$$w_{max} = \frac{5}{384} \cdot \frac{q_{s.w.} \cdot L^4}{EI}$$

Where:

- $q_{s.w.}$: uniform load of the permanent self-weight of the mooring arm (the specific weight of steel S450 is 77 kN/m^3)
- L: beam span (length of the mooring arm)
- EI: bending stiffness of the mooring arm

This results in a maximum vertical deflection of $w_{max} = 16.91 \text{ m}$. The deflection limit guideline in slender steel structures is often between $L/500$ and $L/800$ (Rijkswaterstaat, 2017). For the mooring arm the maximum vertical deflection is $16.91 \gg \frac{250}{800} \approx 0.3125 \text{ m}$, which does not satisfy the requirement.

Although the mooring arm experiences excessive deflection, this is not its primary function. The arm is primarily intended to transfer loads. Deflection remains a relevant second-order effect that must be optimized in a later design phase. Iterating towards the triple-tube (3D) configuration (see chapter 4), would provide a stiffer system and is expected to significantly reduce deflection. However, the proposed mooring arm (double tube with crossings) is used for further analysis so that the overall performance, load transfer, and system interaction can first be established. A subsequent design phase can then verify whether a stiffer configuration, such as the triple tube (3D), is required to meet the deflection criteria.

5.2.2. Wind conditions

Determining the wind conditions is essential for structural analysis because the wind represents one of the dominant external loads on the floating data center. Wind loading arises from airflow around the structure, generating horizontal forces, suction effects, and the associated bending moments and shear forces within the structural components. Wind is a stochastic variable consisting of a mean component and a fluctuating component (turbulence). This variability leads to (i) rapidly varying loads on short time scales and (ii) dynamic effects such as vibrations induced by vortex shedding or gust loading (Voorendt, 2023). In this section, the horizontal wind force is first determined, followed by an assessment of wind set-up, wind gusts, and vortex shedding.

Horizontal wind load

In this section, the horizontal wind load is determined. To avoid over-dimensioning, an extreme value analysis is performed to characterize peak wind conditions, while the accompanying static analysis addresses long-term (quasi-steady) behavior. For reliability modeling, hourly ERA5 reanalysis winds at 10 m (single level) from Copernicus (C3S, 2025) are used. Wind data is extracted at the Delta21 site (51.54° N, 3.54° E; Google Earth, 2025); see Figure 5.7. The data set comprises 3-hourly wind-speed records spanning the past six years, which are used to fit the wind reliability model and derive design extremes. The choice for this data set is based on the following considerations: (i) 3-hourly data are generally sufficient to capture storm peaks (although the very highest short-duration peaks can be missed and are therefore discussed separately in Table 5.2.2), (ii) the data set contains approximately $8 \cdot 365 \cdot 6 \simeq 17500$ data points, which is adequate to characterize the general wind climate, and (iii) the design is currently in the conceptual design phase, for which this choice provides a suitable first indication and order-of-magnitude estimate of extreme wind loads.

The, the Weibull distribution provides the best fit for this data set Table D. According to the Weibull fit, the 100-year return wind speed is estimated at 24.95 m/s.

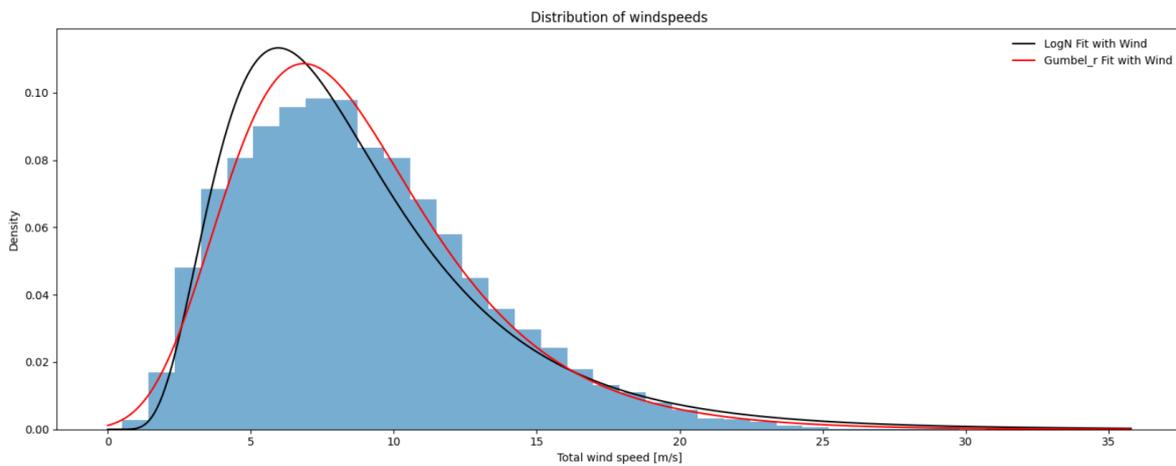


Figure 5.7: Distribution wind speed

Using the following formula defined in section 2.5, the horizontal wind force for south-west wind direction and wind speed of 24.95 m/s is 1519 kN.

$$F_w = C_d q S \sin(\alpha)$$

In this global formulation, the contributions of pressure and suction are included in the drag coefficient (C_D), yielding only the resultant force. Local suction effects, moments, and detailed distribution of pressure and suction over the structure are not captured. However, for an initial assessment of wind loads and their influence on the global behavior of the floating data center system in a static analysis, the approach is considered adequate.

Wind setup

Next, the wind setup corresponding to the determined wind speed is evaluated. The formula of wind setup from Figure 2.5.2 is applied to the two considered water level conditions, see Table 5.1.

Water level	Water surface slope [-]	Wind setup [m]
NAP -28 m	$7.50 \cdot 10^{-5}$	0.750
NAP -3 m	$1.25 \cdot 10^{-5}$	0.125

Table 5.1: Wind induced setup at site

It is not the tilt caused by the wind setup (for the initial width of 250 m of the data center, the maximum tilt of the data center is 18.75 mm), but the water-level difference that governs the response. For a water level at NAP -3 m and for a wind speed of 24.95 m/s, a surface slope can develop that displaces the data center in the positive z-direction (upward) by 0.125 m. In this case, the pontoon structure and the mooring system are not aligned. The same effect occurs when the data center moves in the negative z-direction (downward) and is included in both static and dynamic analyzes, since the difference in water level is a governing design condition. In conclusion, it should be noted that the wind setup in itself will therefore not have a direct impact, as the mooring arms are designed to accommodate vertical displacements.

Wind gusts

In conceptual designs, wind gusts are typically not explicitly considered. Instead, they are taken into account through standardized design approaches. Therefore, it can be assumed that the wind load for a 100 year return period, as determined above, already includes gustiness through statistical modeling. Although gusts are not treated explicitly at this conceptual phase, it is important to note that a gust is a short-duration dynamic load with high temporal variability. It behaves as a transient load that can induce vibrations in the system. Therefore, it is of interest to examine in the dynamic analysis whether the natural frequencies of the system are excited by wind gusts. However, a gust is a highly stochastic (random) process. Therefore, its frequencies cannot be exactly determined. Only an estimated order of magnitude of 0.3 Hz based on meteorological definitions (KNMI, 2000) can be used.

Vortex shedding

A structure that has been placed in a stationary flow can start to vibrate. For the floating data center structure, the effect of wind on the topside can cause potential vortex induced vibrations. Large flat roof structures are atypical cases for which the standard procedures prescribed in NEN-EN 1991-1-4 are not directly applicable, therefore, wind tunnel tests should be performed or specialist advice should be sought (NEN-EN, 2023). Consequently, no reliable assessment can be made regarding the likelihood of system instability caused by vortex induced vibrations.

5.2.3. Wind generated waves

Determining wind-generated waves is essential for the stability and dynamic analysis of floating structures. In this study, no measurements are available because Delta21 has not yet been constructed. Therefore, empirical wind-wave models form the basis for a first-stage design in this section.

Frequencies of wind generated waves

First, significant wave heights and peak periods are determined for the extreme wind speed and for wind speeds under normal conditions for the governing water level conditions. Subsequently, the corresponding frequencies ($f = \frac{1}{T_p}$) and angular frequencies ($\omega = \frac{2\pi}{T_p}$) can be calculated. Extreme wind speeds and wind speeds under normal conditions are analyzed to obtain a more explicit understanding of the impact of wind-generated waves on the system.

For the same wind speed, fetch length, and wind duration, wind generated waves in deep water will be higher than in shallow water, since limited depth restricts wave growth and causes additional dissipation (Tissier, 2023). Only wind waves from the South West direction are considered, since the fetch length for this direction is large (see Figure 5.8). A fetch length of 10 km is assumed for the different water levels. This is conservative since the effective fetch length will be shorter due to the sheltering of the dunes.



Figure 5.8: Fetch length of 10 km for South West wind direction

The wind generated waves for a 100 year return period are calculated using formulas from section 2.5, the results are shown in Table 5.3. Here 24.95 m/s is used for the extreme wind speed and 7.5 m/s for the wind speeds under normal conditions (as taken from Figure 5.7).

	Water depth D [m]	H_s [m]	T_p [s]	f [Hz]	ω [rad/s]
Extreme wind speeds	30	1.84	4.30	0.23	1.46
	5	1.38	3.91	0.26	1.61
Normal wind speeds	30	0.42	2.55	0.39	2.46
	5	0.39	2.38	0.42	2.64

Table 5.2: Significant wave height, peak period, frequency, and angular frequency for two water depths and extreme wind speeds (24.95 m/s) and normal wind speeds (7.5 m/s)

Finally, the frequencies of interest identified for the wind-generated waves can be evaluated in dynamic analysis.

Horizontal load of wind generated waves

Second, to select an appropriate hydrodynamic force model, the force regime is evaluated using two dimensionless parameters: the Keulegan-Carpenter number ($\frac{H}{D}$) and the diffraction parameter ($\frac{\pi D}{\lambda}$). Where:

- For shallow water the wave length is $\lambda = \frac{gT_p^2}{2\pi}$
- The characteristic diameter is $D = \sqrt{L^2 + B^2}$

The resulting Keulegan-Carpenter number is $3.6 \cdot 10^{-3}$ and the resulting diffraction parameter is 52.8. For these parameters and following the linear trend of the hydrodynamic force model (Figure 5.9), the structure is placed in the diffraction region. This is expected since the structure is large compared to the wave length. It implies that the Morison equation (for slender structures) is no longer applicable. Instead, linear diffraction theory (potential-flow) must be applied with frequency-dependent added mass and radiation damping.

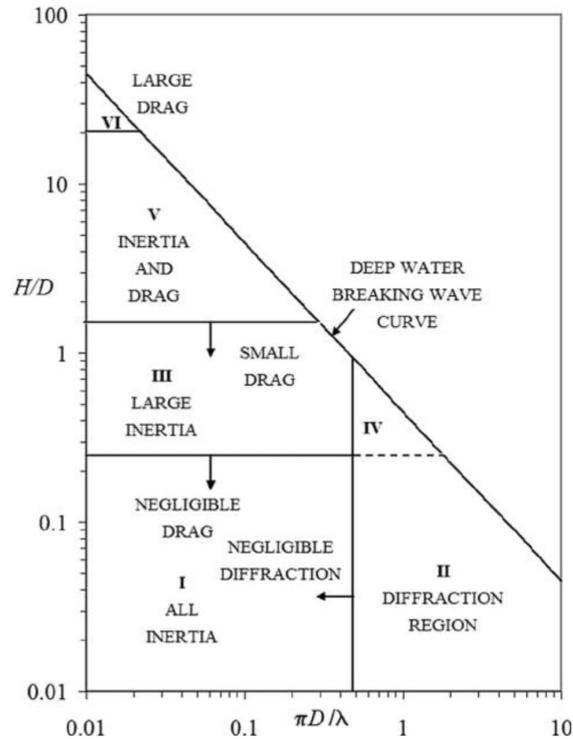


Figure 5.9: Hydrodynamic force regimes

The hydrodynamic forcing is computed by approximating the horizontal load resulting from wave-induced currents.

$$F_D \simeq \frac{1}{2} \rho C_D A_{\perp} u^2$$

This formulation is applicable when the mean Lagrangian current induced by a progressive wave (Stokes drift) is present. The assumption holds as long as the waves do not break, which is consistent with the assumptions of linear wave theory.

The wave number (k) is obtained by solving the linear wave dispersion relation:

$$\omega^2 = g \cdot k \cdot \tanh(kh)$$

The Stokes-drift at depth z is obtained by using the following formula:

$$U_s(z) = \frac{\omega k a^2}{2} \cdot \frac{\cosh(2kh)}{\sinh^2(kh)}$$

Where:

- $\omega = \frac{2\pi}{T}$
- $a = \frac{H}{2}$
- h : water depth

(Tissier, 2023)

Calculations are performed for extreme winds on the water surface ($z=0$) for both water level conditions, see Table 5.3. Only extreme winds are considered because they transfer the highest amount of energy into the water compared to lower wind speeds, resulting in waves with significantly higher heights and loads.

Water depth D [m]	H_s [m]	T_p [s]	$U_s(0)$ [m/s]
30	1.84	4.30	0.23
5	1.38	3.91	0.22

Table 5.3: Significant wave height, peak period and angular frequency for different water depths

Finally, the horizontal load can be estimated from the wave-induced current formula. Because the computed current velocity is very small and contributes quadratically to the resulting horizontal wind generated wave load, the associated hydrodynamic force is orders of magnitude lower than the wind force. Therefore, it does not contribute significantly to the overall static structural response.

5.2.4. Turbine generated waves

In section 2.5 it was concluded that turbine-generated waves must be examined especially under low-water conditions. The translation wave that develops when the Delta21 energy storage lake is filled is a long wave and is therefore expected to be fully reflected at the boundaries (Tissier, 2023). As a result, the waves travel back and forth during the filling process, causing the water levels to vary significantly. Consequently, the structure must accommodate large rises in water level over short periods, which can cause stability problems for the floating structure.

First, the instantaneous free-surface elevation (η) caused by the turbines is determined relative to the mean water level. The following simplified formula is used to calculate the free-surface elevation, to give first estimates of the effect of translation waves on the system (Tissier, 2023).

$$H_0 \simeq \frac{\Delta Q}{B \cdot c}$$

Where:

- $c_0 = \sqrt{g \cdot h_0}$: wave celerity for non-dispersive waves in m/s and h_0 is the minimum water depth
- $Q = 20000 \text{ m}^3/\text{s}$: maximum discharge for 100 pump/turbines
- $B = 2500 \text{ m}$: length over which the pump turbines are installed

As a result, this yields a free-surface elevation of $\eta = 1.14$ m. Reflection at the boundary results in a doubling of the free-surface elevation, i.e. $\eta = 2.28$ m, see Figure 5.10. In addition, interference will arise between waves that reflect off the structure, travel around it, and propagate beneath it, resulting in a complex wave pattern. This effect has not yet been investigated in Delta21 studies and can have a significant influence on the structure. Detailed calculations on this phenomenon are beyond the scope of this study. Therefore, follow-up research is recommended to examine this effect.

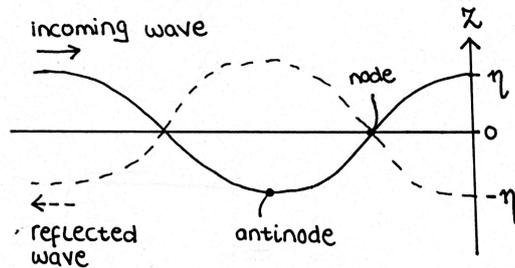


Figure 5.10: Increase of the free-surface elevation at the boundary caused by wave reflection

However, the effect can be mitigated by gradually increasing the discharge outflow of the turbines. Therefore, a rough estimate of the allowable discharge that does not exceed the serviceability limit states (this limit state is used because this is a frequently occurring operational condition) of the data center is provided. According to (NTA8111, 2011), the serviceability limit state requirements for rotations about the x- and y-axes is 0.5° . For these requirements, two possible configurations for the slope of the data center are considered, see Figure 5.11.

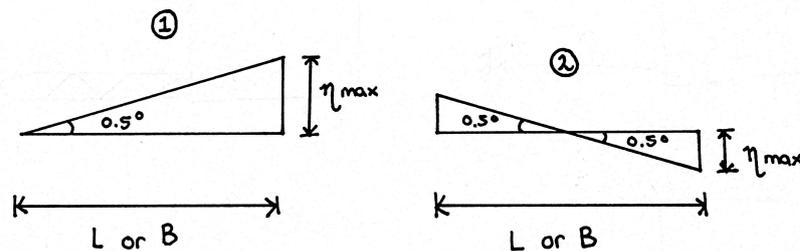


Figure 5.11: Two situations for vertical displacement of the floating data center, given a rotational service limit state of 0.5°

This results in a critical minimum value of $\eta_{max} = 1.09$ m for rotations about the x-axis for situation 2. This free-surface elevation consists of the incoming wave and the reflected wave and therefore corresponds to twice the single-wave free-surface elevation. Substituting $\frac{\eta_{max}}{2}$ into the expression produces a maximum discharge of $Q = 9542$ m³/s.

In conclusion, this study assumed that a maximum discharge of 20000 m³/s can flow through the turbines. However, the pump-turbines themselves require a start-up period and cannot operate at full capacity instantaneously. According to (Delta21, 2024a), the design discharge for the turbines for an energy storage lake with a water depth of 5 meters is 60 m³/s per turbine. As a result, the stability requirements for the floating data center are met. This design discharge for low water level conditions must also be maintained during extreme storm events in which Delta21 operates as a flood protection system, to prevent dynamic and stability problems for the floating data center. As recommended earlier, a more detailed investigation into turbine-generated waves is therefore advised.

5.2.5. Currents

Currents can affect the structure. Therefore, this section examines whether currents can occur that are relevant for the loading or stability of the structure. There are no tides in the energy storage lake. However, the water level can vary between NAP -28 m to NAP -3 m due to the pump/turbines. The maximum flow rate of 100 pumps for an efficiency of 0.85 is 20000 m³/s (Delta21, 2024a).

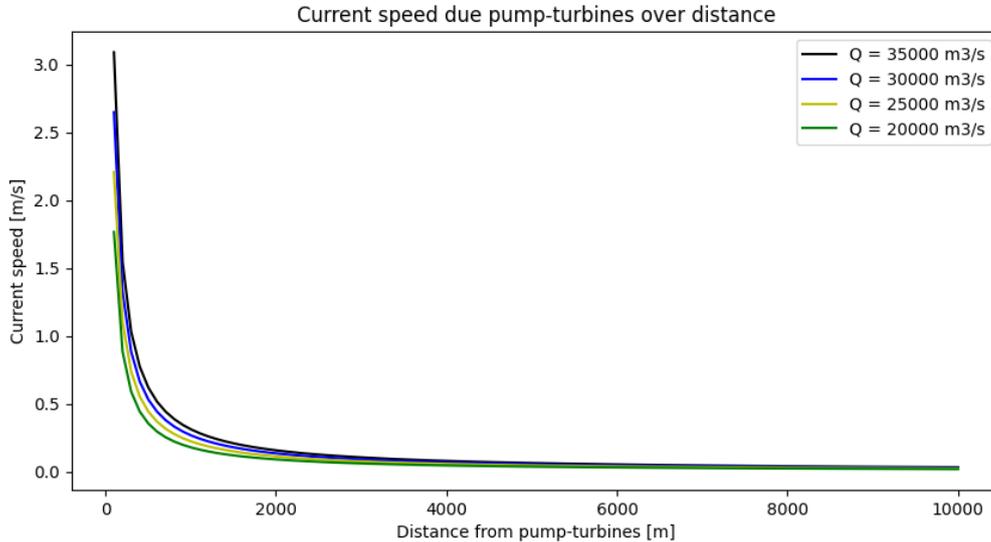


Figure 5.12: Currents generated by the pump-turbines over distance

In Figure 5.12 it can be seen that the current is locally strong but decreases with distance due to friction losses, increasing cross-sectional area, and energy dispersion. Due to the choice of location for the floating data center (which is at approximately 8000 m), the currents acting on the structure are approximately 0 and therefore not significant. In Figure 5.12 it is also shown that an increase in discharge does not influence the current generated by the pump/turbines at the floating data center site.

Vortex induced vibration due to currents only

Vortex shedding occurs if the flow is separated from the surface. This flow separation creates a vortex which causes a local increase in rotational velocity. Higher flow velocity results in a reduction in dynamic pressure, which creates an attraction force by the vortex on the structure. Determine if there is a possibility for vortex induced vibration by checking the reduced velocities range: $5 < V_r < 11$.

$$V_r = \frac{V_{current}}{D \cdot f_n}$$

In conclusion, there is no continuous current along the structure, so this effect is not significant for the possibility of vortex induced vibration.

Wake induced vibrations

The possibility of wake induced vibrations is not significant because there is no continuous current along the structure.

5.2.6. Conclusion determination of the design loads

In this section, the design load conditions have been quantified to identify which loads govern strength, stability, and safety in extreme conditions. The governing design conditions found in this section are summarized below.

In the static analysis, two design conditions are evaluated for the strength of the mooring arm and the stability of the pontoon structure.

- The horizontal wind load from the south-west direction for a 100-year return period for high water level conditions;
- The horizontal wind load from the south-west direction for a 100-year return period for low water level conditions.

However, significant extreme conditions do not necessarily coincide with extreme loads (Viré, 2023). Therefore, a sensitivity analysis is performed in which changes in wind direction and return period are evaluated for high and low water level conditions, see section 5.5.

In the dynamic analysis, three design conditions are evaluated for the stability of the pontoon structure.

- The wind generated wave frequency of extreme wind speeds from the south-west direction for a 100-year return period for high and low water level conditions;
- The wind generated wave frequency from the south-west direction for a 100-year return period for low water level conditions;
- The gust frequency from meteorological definitions.

To evaluate this section, the determination of the design loads is performed to the extent that is feasible at this stage of the design. The results should therefore be regarded as estimates that still contain a degree of uncertainty. In addition, not all effects could be quantified. For example, vortex-induced vibrations caused by the wind acting on the top side of the structure could not be determined.

In conclusion, the findings in this section demonstrate that wind pressure is the significant condition for static analysis in evaluating structural safety for strength and stability. In addition, wind generated waves are the significant condition for dynamic analysis in evaluating structural safety for stability. These analyzes are carried out in the following sections.

5.3. Static structural analysis of strength and stability

The primary goal of a static structural analysis is to verify that the floating data center structure can safely and reliably withstand all design loads without exceeding the limits of material strength or losing global or local stability (van Baars et al., 2009). In this section, a structural design is performed that includes a linear approach to the design of the floating data center using partial safety factors for the ultimate limit state. Two verifications are performed: (i) strength verification of the mooring arm including checks for tension, compression, bending, shear, and global buckling, and (ii) stability verification of the pontoon structure including checks for rotations and vertical displacements. Other structural verification checks could be performed, e.g., local stability, fatigue. However, these require a higher level of design detail that is not yet available in this design phase. In this structural analysis, first the model schematization and the static structural checks are defined. Then, the model input is explained. Finally, results are made and conclusions drawn.

5.3.1. Static structural analysis definition

This section outlines the linear matrix-based frame-model (Matrix Structural Analysis) of the designed floating data center structure for the response to wind pressure. For this analysis, the pontoon is schematized as a rigid body to estimate internal forces and moments, and displacements. Given its dimensions ($350 \times 250 \times 15$ m) and the resulting high stiffness, this assumption is justified for first-order evaluation. The primary quantities of interest are the responses of the mooring arm ($F_x, F_y, F_z, M_x, M_y, M_z$) governing global strength and the degrees of freedom motions of the pontoon (x, y, z , roll ϕ , pitch θ , yaw ψ , see Figure 5.13) governing global stability. Local structural deflections are expected to be small relative to global hydrostatic/hydrodynamic motions but should be verified in subsequent detailed design analyzes.

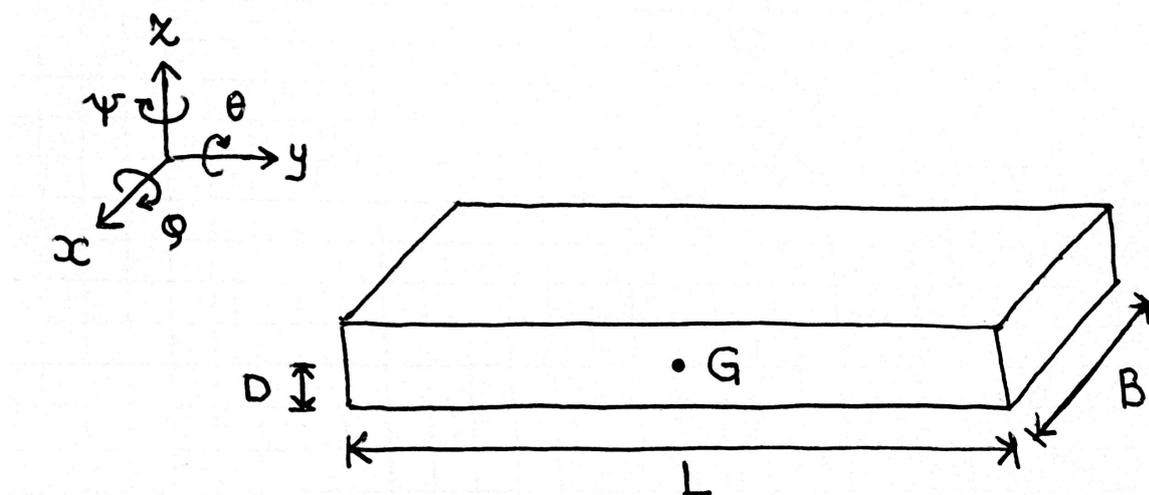


Figure 5.13: Overview global motions of the structure with a length (L), width (B), center of gravity (G) and draft (D)

Next, to model the hydrostatic conditions of the system, a linear spring system is developed. The structure derives its stability in water from its shape and weight (Kamerling, 2005). The vertical stiffness (K_{FZ}) of the pontoon is described with the following formula:

$$K_{FZ} = \rho_w g A$$

The horizontal stiffness of the water is neglected. The accuracy is sufficient in this stage, as the pontoons can be designed with prescribed stiffness.

The roll (ϕ) and pitch (θ) stiffness of the pontoon under hydrostatic conditions, can be described with the meta centric height (GM). To ensure static stability, the meta centric height must be greater than 0.25 m (NTA8111, 2011).

Linear spring stiffness for respectively roll (transverse direction T) and pitch (longitudinal direction L) are formulated as follows.

$$K_{\phi}^{hydro} = \Delta GM_T$$

$$K_{\theta}^{hydro} = \Delta GM_L$$

Where:

- $\Delta = \rho g \nabla$, with the displaced volume $\nabla = L \cdot B \cdot D$
- The vertical distance between the center of gravity (G) and the metacentric point (M):

$$GM_T = KB + BM_T - KG$$

$$GM_L = KB + BM_L - KG$$

With:

- $KB = D/2$
- $KG = h/2$ (assumption)
- $BM_T = \frac{I_x}{\nabla}$, with $I_x = \frac{LB^3}{12}$
- $BM_L = \frac{I_y}{\nabla}$, with $I_y = \frac{L^3B}{12}$

In addition, the combination of the design load used in the analysis of the static ultimate limit state applies a safety factor of 1.35 to the wind action (Fjeld, 2012).

$$LoadCombination = G + 1.35 \cdot Q_{wind}$$

Finally, the results are reported for two still-water conditions: high water (NAP -3 m) and low water (NAP -28 m). For the low-water case, no correction is applied for near-surface wind speed reduction due to coastal dunes. Designing for this condition is therefore intentionally conservative. The output variables considered in this static analysis are (i) the six degrees of freedom (translations x, y, z and rotations R_x, R_y, R_z), (ii) the forces in three directions (F_x, F_y, F_z), (iii) the moments in three directions (M_x, M_y, M_z), and (iv) the stresses (σ, τ_y, τ_z).

The mooring arm shall be verified against the following checks:

- Unity check (NEN-EN, 2023):

$$\frac{N_{Ed}}{N_{Rd}} + \frac{M_{y,Ed}}{M_{y,Rd}} + \frac{M_{z,Ed}}{M_{z,Rd}} \leq 1.0$$

Where:

- $N_{Rd} = \frac{kAf_y}{\gamma_m}$, with $k = 0.9$ for structures subjected to fatigue
- $M_{y,Rd} = \frac{W_{y,el}f_y}{\gamma_m}$
- $M_{z,Rd} = \frac{W_{z,el}f_y}{\gamma_m}$
- The material factor: $\gamma_m = 1.0$

- Buckling check (NEN-EN, 2023):

$$N_{b,Rd} = \chi \cdot \frac{Af_y}{\gamma_m}$$

- Huber-Henkey check:

$$\sigma_{HH} = \max(\sqrt{\sigma_{x;i}^2 + 3\tau_{y;i}^2 + 3\tau_{z;i}^2}) \leq f_y, \text{ where the governing equivalent (von Mises) stresses are verified at each characteristic point of the cross-section (MatrixFrame, 2025)}$$

The pontoon structure shall be verified against the following offsets:

- Rotations: $|R_x|, |R_y| \leq 0.5^\circ$ (NTA8111, 2011)
- Freeboard: $z \leq 150mm$ (NTA8111, 2011)

5.3.2. MatrixFrame Model

MatrixFrame is selected as the software tool because it is designed for efficient analysis of structures under static loading. A student version is available, allowing access to most of the software's functions. For an initial strength and stability assessment, as performed in this study, it provides a fast, clearly interpretable, and reproducible workflow. However, the software is not validated for the specific loading conditions associated with floating constructions and can not perform a realistic dynamic analysis of the entire floating system. Nevertheless, given the scope of this study, its efficiency and simplicity were considered to be more important than its limitations.

MatrixFrame 6.2

The static analysis is performed with MatrixFrame version 6.2. The software's modeling assumptions and solution procedures are documented in the vendor's manual (MatrixSoftware, 2024).

Input parameters

A 3D-Frame model is created, the input parameters are listed in Table 5.4. The pontoon is made rigid by a three-layer space frame with an in-plane grid spacing of 50x50m and a vertical separation of 5m between the layers. Cross-bracing is applied in the top and bottom layers to suppress (shear) deformation. The resulting triangulation provides geometric stiffness. The elements have been assigned a large cross-sectional area ($A = 10^9$) and large moments of inertia ($I_x, I_y = 10^{12}$). In addition, all connections within the rigid-body assembly are defined as fixed.

The linear spring model and the external loads are applied at the center of mass, as the pontoon is modeled as a rigid body. The center of mass is located at ($x=175, y=125, z=7.5$). The self-weight is included with a unity factor (1.0), assuming hydrostatic equilibrium and static stability of the pontoon in conditions without external loads.

The support allows rotation only around the x-axis, accommodating vertical displacement resulting from the water level variation in the Delta21 energy storage lake, see Figure 5.14.

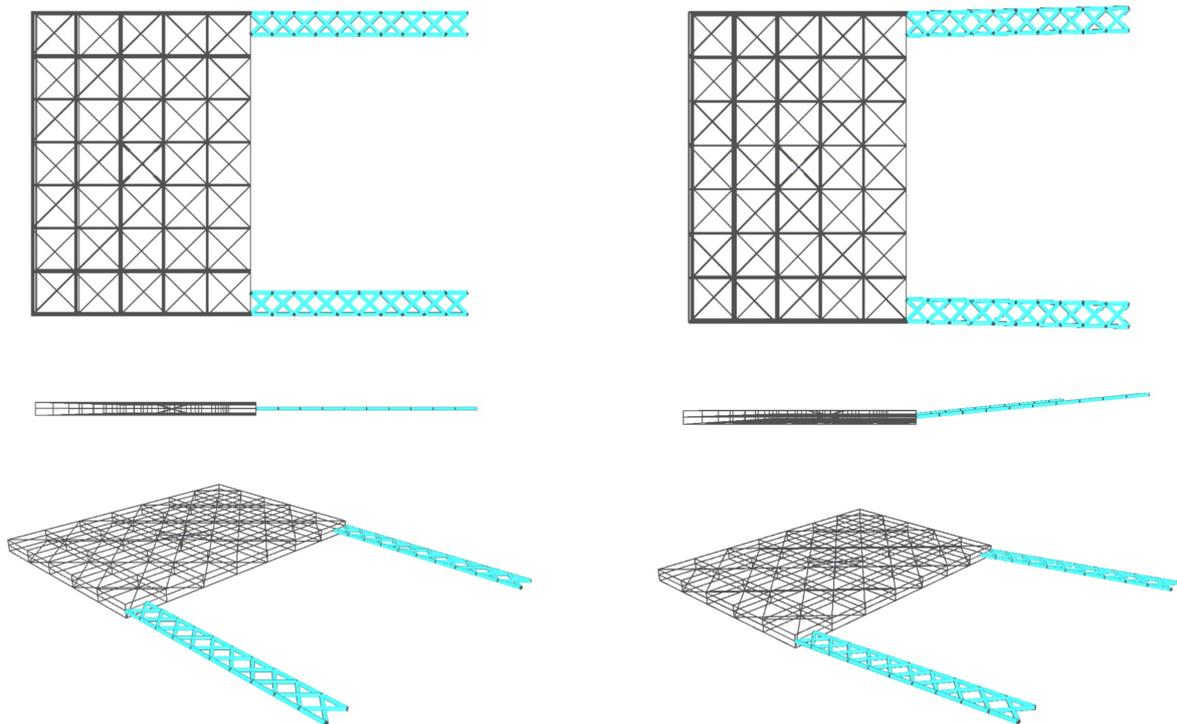


Figure 5.14: Top view, side view, 3D view MatrixFrame model for high water level (left) and low water level (right)

Input overview:

Input variable	Input MatrixFrame	Explanation
Pontoon dimensions	350 x 250 x 15 m	L x B x h
Vertical spring stiffness	$K_z = 8.71 \cdot 10^5$ kN/m	
Pitch spring stiffness	$X_r = 4.51 \cdot 10^9$ kNm/rad	
Roll spring stiffness	$Y_r = 8.87 \cdot 10^9$ kNm/rad	
Support	X'_r	
Draft	$z = 8.0$ m	
Center of mass	$x = 175, y = 125, z = 7.5$ m	Assume $KG = h/2$
Mooring arm connection height	$z = 7.0$ m	Positive z-axis downward
Mooring arm dimensions	250x25m	L x B (c/c)
Mooring arm parameters	S450, $t = 30$ mm, $D = 3$ m	Choose S450
Wind load	$F_y = 1376$ kN, $F_x = -642$ kN	$F = SF \cdot C_D \cdot \frac{1}{2} \rho_{air} g A \cdot u_{10m}^2$ Where $SF = 1.35$, $C_D = 1.05$, $\rho_{air} = 1.25 \text{ kg/m}^3$, $A = 423 \cdot 7 \text{ m}^2$, $u_{10m} = 24.06 \text{ m/s}$

Table 5.4: Input parameters MatrixFrame model overview

5.3.3. Results and conclusion static structural analysis of strength and stiffness

In Appendix E, the results from MatrixFrame of the static model and the verification checks for mooring strength and pontoon stability are presented. Maximum member bending moments, axial forces, and stresses remain below the design capacities, see Table 5.5. However, rotations about the x- and y-axes exceed the allowable limits ($|\phi| < 0.005 \text{ rad}$ and $|\theta| < 0.005 \text{ rad}$). Due to the asymmetric loading introduced by the self-weight of the mooring arms, the pontoon does not satisfy the stability requirements, see Table 5.6.

Quantity	Value	Requirement	Satisfies	Element
Unity Check	0.0464	≤ 1.0	Yes	S582
Huber-Henkey check	0.0396	≤ 1.0	Yes	S582
Buckling check	0.0119	≤ 1.0	Yes	S623

Table 5.5: Check results: the mooring arm satisfies the requirements for the significant low water level condition

Quantity	Value	Requirement	Satisfies	Node
$ R_{x,\max} $	1.458	≤ 0.005	No	K3
$ R_{y,\max} $	$1 \cdot 10^{-6}$	≤ 0.005	Yes	K1
z_{\max} [mm]	242.6	≤ 150	No	K6
z_{\min} [mm]	-122.2	≥ -150	Yes	K37

Table 5.6: Rotation and z checks: the pontoon does not satisfies the requirements for the significant low water level condition

To ensure compliance, an asymmetric ballast system is required. In subsequent calculations, it is therefore assumed that an asymmetric ballast system is provided and that the pontoon is neutrally buoyant.

At this stage, it can be concluded that the mooring arm is heavily over-dimensioned in strength for the applied horizontal wind loads (see the checks in Appendix E). Note that this static analysis considered only the 100-year wind load from the south-west direction, so before making design modifications, the full design-cycle step must first be completed to demonstrate that the design is sufficiently robust to meet the requirements under other conditions as well. Therefore, the next section investigates the effect of wind-generated waves on the structure.

5.4. Dynamic structural analysis of stability

The goal of dynamic structural analysis of stability is to ensure that the floating data center structure remains safe under time-varying actions. In this dynamic analysis, only the natural frequency of the structure is compared with a dynamic wave spectrum to provide a first-order estimate of the risk of resonance. This is an essential step, even in an early design stage, because it can indicate with minimal information whether the structure may exhibit potentially unsafe behavior (van Baars et al., 2009). At this stage of the design, a detailed dynamic analysis is not yet feasible due to the lack of geometric and structural detail, while hand calculations or simplified models offer too little engineering value because they cannot capture the relevant mass and stiffness distribution of the designed structure. Therefore, the natural frequency is determined using a finite element method using the global mass, global stiffness, and global dimensions of the structure. In this dynamic analysis, first the model is defined. Then the numerical method is explained. Finally, results and conclusions are made.

5.4.1. Physical model definition

This section outlines the numerical modeling approach for the natural frequency and corresponding mode shapes of the designed floating data center structure. The model is defined within the Finite Element Method framework, which allows for computation of complex geometrical shapes. The model uses 3D beam elements with 6 degrees of freedom per node.

The model developed in this study is linear-elastic and geometrically linear, meaning that second-order effects (such as large rotations and nonlinear changes in hydrostatic stiffness) are not captured. In addition, the mooring arms are modeled as linear elements, whereas their real behavior is likely to be nonlinear. Nevertheless, the model provides a useful first-order estimate of the global modal properties of the floating data center, which is the intended goal of this section.

Governing Equations

The system consists of the mooring arm design and the pontoon schematized as a large rigid beam. Six equations are applied: three for translational motions and three for rotational motions. Each mooring arm consists of two tubes connected with diagonals, all governed by the same six equations. All connections within the mooring arms are rigid. Equation 1 describes the axial deformation. Equations 2 and 3 describe bending in two directions of the beam. Equation 4 describes torsional deformation of the beam. Equations 5 and 6 describe bending rotations of the beam. The positive directions were already identified in Figure 5.13. These equations form the basis of the Finite Element Method analysis.

$$\rho A \frac{\partial^2 u(x, t)}{\partial t^2} - EA \frac{\partial^2 u(x, t)}{\partial x^2} = q_u(x, t), \quad x \in (0, L) \quad (1)$$

$$\rho A \frac{\partial^2 w(x, t)}{\partial t^2} + EI_w \frac{\partial^4 w(x, t)}{\partial x^4} = q_w(x, t), \quad x \in (0, L) \quad (2)$$

$$\rho A \frac{\partial^2 v(x, t)}{\partial t^2} + EI_v \frac{\partial^4 v(x, t)}{\partial x^4} = q_v(x, t), \quad x \in (0, L) \quad (3)$$

$$I_m \frac{\partial^2 \theta_x(x, t)}{\partial t^2} - GJ \frac{\partial^2 \theta_x(x, t)}{\partial x^2} = q_{\theta_x}(x, t), \quad x \in (0, L). \quad (4)$$

$$I_m \frac{\partial^2 \theta_y(x, t)}{\partial t^2} - GJ \frac{\partial^2 \theta_y(x, t)}{\partial x^2} = q_{\theta_y}(x, t), \quad x \in (0, L). \quad (5)$$

$$I_m \frac{\partial^2 \theta_z(x, t)}{\partial t^2} - GJ \frac{\partial^2 \theta_z(x, t)}{\partial x^2} = q_{\theta_z}(x, t), \quad x \in (0, L). \quad (6)$$

The mooring arm system is solved within the model, so boundary constraints must be specified. The mooring arms are supported with a hinged support that allows rotation around the x-axis. From Equations 1 to 6 it is concluded that 16 boundary conditions are required (corresponding to the 16 derivatives with respect to x) to fully define and solve the system. The boundary conditions with respect to x are described as follows.

For x at $0, L_1, L_2$ and L :

$$u(x, t) = 0, \quad v(x, t) = 0, \quad w(x, t) = 0, \quad (\text{fixed translations})$$

$$EI_v v''(x, t) = 0, \quad EI_w w''(x, t) = 0, \quad (\text{zero bending moments})$$

$$GJ \theta'_x(x, t) = 0 \quad (\text{zero bending moments})$$

Boundary constraints that must be specified as well are the four internal hinges that connect the rigid pontoon with the mooring arms. This is done by creating 4 rigid elements between the nodes of the rigid beam and mooring arms and prescribe interface conditions for the degrees of freedom. The interface conditions for an internal hinge between node m_i of the mooring and node p_i of the pontoon are described as follows.

For x at $0, L_1, L_2$ and L :

$$u_m(x, t) = u_p(x, t), \quad v_m(x, t) = v_p(x, t), \quad w_m(x, t) = w_p(x, t),$$

$$\theta_{y,m}(x, t) = \theta_{y,p}(x, t), \quad \theta_{z,m}(x, t) = \theta_{z,p}(x, t),$$

Neumann-conditions: :

$$M_{x,m}(x, t) = 0, \quad M_{x,p}(x, t) = 0$$

$$\text{with } M_x = GJ \frac{\partial \theta_x}{\partial x}$$

Used parameters

Parameters that are used in the governing equations are shown in Table F.1.

Parameter	Symbol	Value pontoon	Value mooring tubes	Value diagonals	Unit
Mass per meter	m	1.17×10^4	2.2×10^3	7.18×10^2	kg/m
Bending stiffness	EI	1.0×10^{18}	6.49×10^{10}	2.26×10^9	N m ²
Axial stiffness	EA	1.0×10^{18}	5.88×10^{10}	1.92×10^{10}	N
Torsional stiffness	GJ	1.0×10^{18}	4.99×10^{10}	1.74×10^9	N m ²
Torsional inertia	I_m	5.54×10^7	4.85×10^3	1.69×10^2	kg · m

Table 5.7: Material and cross-section parameters used in the Finite Element Method

5.4.2. Numerical Method

This section uses the Finite Element Method to solve the Partial Differential Equations (PDEs).

First, the domain of the system is discretized, see Figure 5.15. Exact dimensions of the floating data center are mentioned in section 5.3

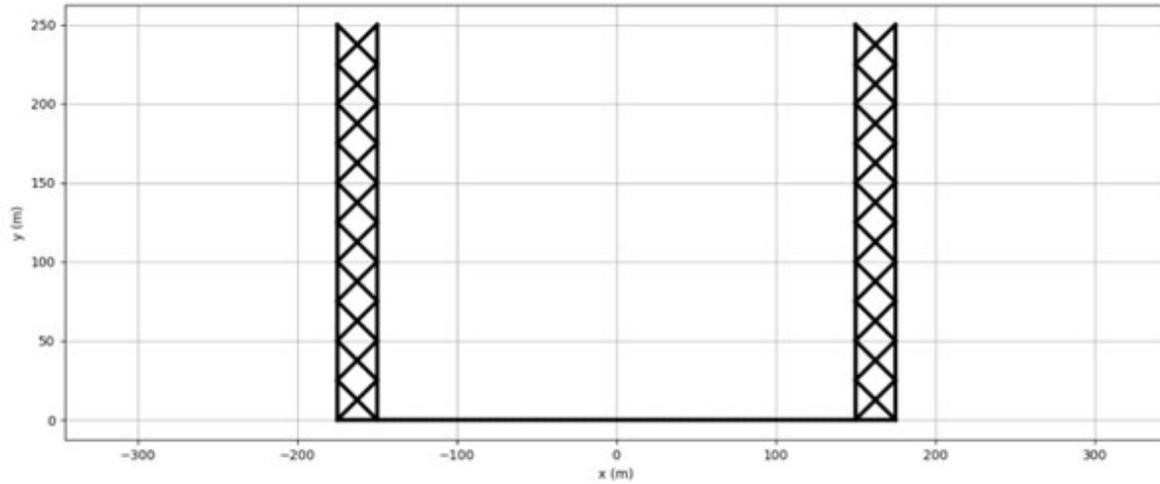


Figure 5.15: Discretized domain of the mooring arm system

All geometry is defined relative to the global coordinate system. Consequently, the distance between the center of gravity and the center of the beam is modeled as a fixed offset of 0.5 meters in the z-direction.

Shape functions

The solutions to the PDEs describing the system is computed in the nodes. The solutions in the elements are approximated using shape functions. Shape functions interpolate the solution between two nodus, creating a continuous solution across the domain. The order of the shape function should match the highest-order term in the weak form of the PDE. Linear shape functions are sufficient for governing equations 1, 4, 5 and 6.

$$N_1 = 1 - \frac{x - x_i}{h}$$

$$N_2 = \frac{x - x_i}{h}$$

For governing equations 2 and 3, cubic shape functions are used.

$$N_1 = 1 - 3\frac{(x - x_i)^2}{dx^2} + 2\frac{(x - x_i)^3}{h^3}$$

$$N_2 = x - 2\frac{(x - x_i)^2}{dx^2} + \frac{(x - x_i)^3}{h^3}$$

$$N_3 = 3\frac{(x - x_i)^2}{dx^2} - 2\frac{(x - x_i)^3}{h^3}$$

$$N_4 = -\frac{(x - x_i)^2}{dx^2} + \frac{(x - x_i)^3}{h^3}$$

Where:

- x : coordinate in the element from x_i to x_{i+1}
- h : length of an element

To ensure that interpolation will not return irrational values, the sum of the shape functions should equal 1 at every location in the element.

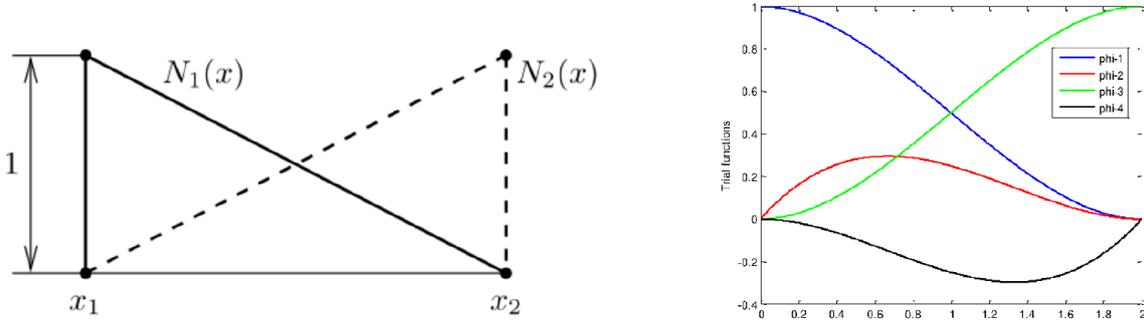


Figure 5.16: Linear shape functions (left) and cubic shape functions (right)

Define weak form

To reduce the order of the spatial derivatives, the governing equations introduced above, are rewritten in their weak form. The weak form is derived by multiplying the original (strong) form of the equation by a test function.

1. Multiply the strong form by the test function $k(x)$ and integrate over an element;
2. Apply integration by parts.

The next step is the derivation of the discretized elemental form by choosing $k(x)$ to be the shape functions ($k(x) = N_i(x)$ for $i = 1, \dots, n$). For an element k bounded by nodes a and b , only the corresponding shape functions $N_a(x)$ and $N_b(x)$ are then non-zero. This substitution is also made for the forcing to express the loading directly at the nodal points.

Combined Elemental Matrices

The general form of the combined elemental matrices system:

$$M_{ij}^k \ddot{u}_j^k + K_{ij}^k u_j^k = Q_j^k q$$

Where:

- M_{ij}^k : elemental mass matrix
- K_{ij}^k : elemental stiffness matrix
- Q_j^k : elemental external forcing matrix
- q : hydrodynamic force vector

The construction of the elemental matrices system for the combined rod and beam elements is done by computing the individual elemental matrices first and assembling them into the combined elemental matrix. The combined 12 DOFs elemental matrices then include the contributions in local coordinates of all different types of deformation in each element.

Hydraulic stiffness

The hydraulic stiffness of the pontoon is also included in the analysis. The stiffnesses (heave k_z , roll k_ϕ , pitch k_θ) were already defined in section 5.3. These stiffnesses are added directly to the stiffness matrix and are applied at the center of mass of the rigid beam (which represents the pontoon).

Added mass

To account for the radiation effect, added mass in heave, roll and pitch (since these directions are the most interesting for this study) is also included in the analysis. A simplification for calculating the added mass is used. First the displaced mass is determined.

$$m_a = \rho \nabla$$

Where ∇ is the submerged volume $L \cdot B \cdot D$. The added mass is then calculated as follows.

$$A_z(\omega) = a_{33} \cdot m_a$$

$$A_\phi(\omega) = a_{44} \cdot m_a \cdot \frac{B^2}{12}$$

$$A_\theta(\omega) = a_{55} \cdot m_a \cdot \frac{L^2}{12}$$

Here a_{33}, a_{44}, a_{55} are coefficients used to estimate the added mass in heave, roll and pitch. Ideally, these coefficients are obtained from a potential-flow tool or calibrated so that the computed natural periods match reference data/experience. For a simplified analysis, the coefficients can be chosen so that the eigen periods fall either inside or outside the high-energy frequency band (see JONSWAP ??). The worst case scenario arises when the eigen period lies within the high-energy frequency band. The goal in this analysis is to obtain the mode shapes. The added mass coefficients are then selected ($a_{33} = 1.0, a_{44} = 0.1, a_{55} = 0.1$) for which the eigen periods lie outside the high-energy frequency band. For further research a sensitivity sweep of these coefficients is recommended (or determine them with a potential-flow solver and/or calibration against experimental data to match the natural periods).

The added masses are added directly to the mass matrix and are applied at the center of mass of the rigid beam.

Global system

To assemble the elemental matrices into a global system, a transformation matrix T is introduced.

$$K = T \cdot K \cdot T^T$$

$$M = T \cdot M \cdot T^T$$

$$Q = T \cdot Q \cdot T^T$$

The elemental matrices are transposed so that they can be superimposed on the global system. This result in the global matrix equation:

$$M\ddot{u} + Ku = Qq$$

The vectors $\ddot{\mathbf{u}}$ and \mathbf{u} are:

$$\ddot{\mathbf{u}} = \begin{bmatrix} \ddot{u}_1 \\ \ddot{v}_1 \\ \ddot{v}'_1 \\ \ddot{w}_1 \\ \ddot{w}'_1 \\ \ddot{\theta}_{x1} \\ \ddot{\theta}_{y1} \\ \ddot{\theta}_{z1} \\ \vdots \\ \ddot{u}_N \\ \ddot{v}_N \\ \ddot{v}'_N \\ \ddot{w}_N \\ \ddot{w}'_N \\ \ddot{\theta}_{xN} \\ \ddot{\theta}_{yN} \\ \ddot{\theta}_{zN} \end{bmatrix} ; \quad \mathbf{u} = \begin{bmatrix} u_1 \\ v_1 \\ v'_1 \\ w_1 \\ w'_1 \\ \theta_{x1} \\ \theta_{y1} \\ \theta_{z1} \\ \vdots \\ u_N \\ v_N \\ v'_N \\ w_N \\ w'_N \\ \theta_{xN} \\ \theta_{yN} \\ \theta_{zN} \end{bmatrix}$$

Modal analysis

To understand the natural vibration of the structure, a modal analysis is performed to determine the eigen frequencies and mode shapes of the structure. These outputs are used to predict resonance and for designing for dynamic loads (i.e. wind generated waves, data center equipment vibrations).

First, the external force is set to zero (i.e. $Q = 0$) to analyze the dynamic deformation modes that can exist in the structure without external loading. This is in the absence of damping. Therefore, a harmonic solution of the form $a(t) = \phi \cos(\omega t - \theta)$ is assumed and substituted into the system. The resulting eigenvalue problem is:

$$(K_{FF} - \omega^2 M_{FF})\phi = 0$$

Where:

- ω : the angular natural frequencies;
- ϕ : eigenvectors of the system corresponding to the angular natural frequencies;
- $_{FF}$: denotes the matrices restricted to free DOFs.

Every single DOF has its own natural frequency, described by a corresponding eigenvector or modal shape. The natural frequencies of interest lie within the range of the loading frequencies. For the floating data center the frequencies that correspond to the wind waves are analyzed. The Finite Element Method model generates a number vibration modes equal to the number of DOFs in the system. However, only modes with natural frequencies within the loading frequency range (e.g. from 0 Hz up to the peak frequency) are relevant to analyze for the structural response. Modes with natural frequencies above the peak frequency are not excited by the wave loading and can therefore be disregarded.

5.4.3. Results and conclusion dynamic structural analysis of stability

Results modal analysis

In this section, the modal analysis for the system is performed following the steps above in Python (see Appendix F). The following results were obtained. In Figure 5.17 and Figure 5.18, the first 20 modes and their corresponding natural frequencies are illustrated for the high water and low water conditions, respectively. In this analysis, a global eigenvalue problem is solved ($(K_{FF} - \omega^2 M_{FF})\phi = 0$). Therefore, the resulting modes include a combination of heave, pitch, and roll motions, rather than each mode representing a pure single degree of freedom. The roll behavior of the pontoon structure cannot be observed in the figures because the pontoon is represented as a rigid beam. The first 20 modes are plotted because the low frequencies of the system correspond to its global motions. Higher frequencies correspond to local deformations, which are outside the scope of this study. Note that the plots should be read from left to right, whereas the legend should be read from top to bottom.

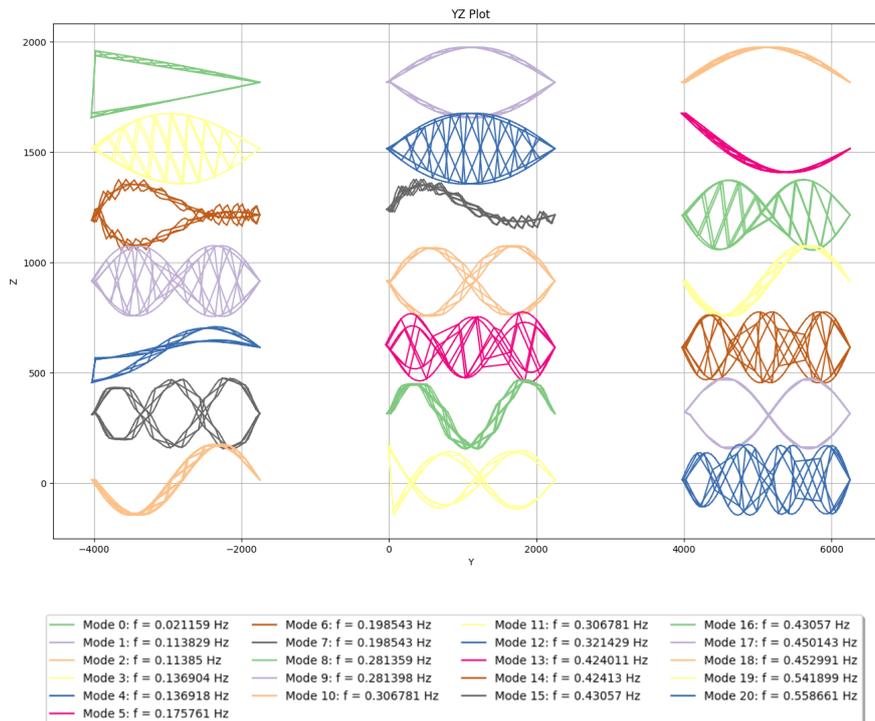


Figure 5.17: Modal shapes in YZ-plane for high water condition

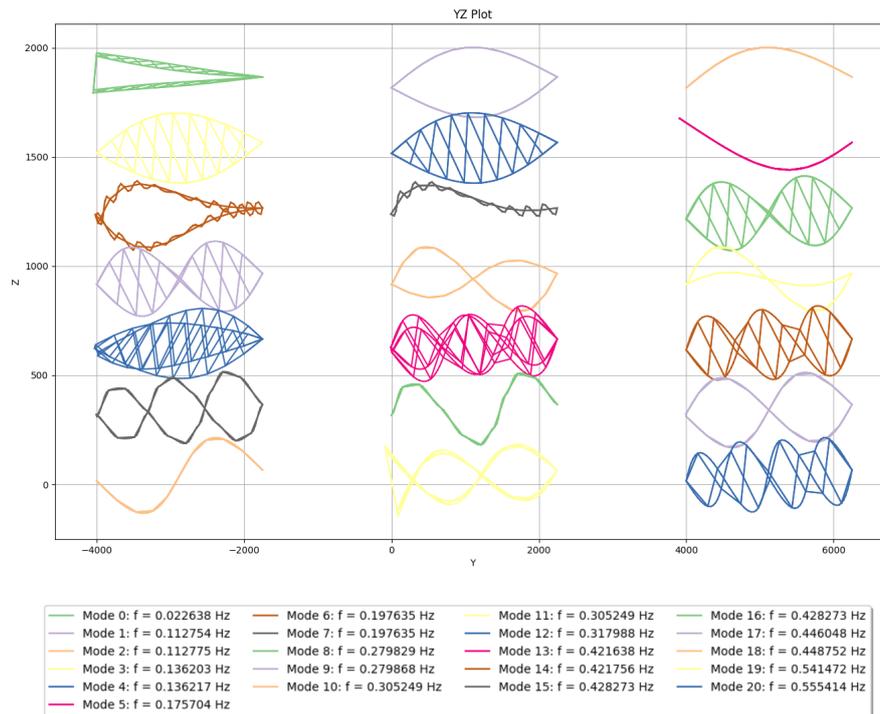


Figure 5.18: Modal shapes in XZ-plane for low water condition

In the results, pairs can be seen in the modal response, these confirm the symmetry in the model. A fully symmetric system yields modal doublets: pairs of modes with the same natural frequency but different symmetry.

- Symmetric mode: both mooring arms deform in phase;
- Asymmetric mode: both mooring arms deform in anti-phase.

This effect is evident in Figure 5.17 and Figure 5.18, for example in modes 1 and 2.

Finally, small numerical differences may give the impression that the two mooring arms deform differently. For example, the difference of 0.000024 between the natural frequency $f=0.112754$ Hz for mode 1 and $f=0.112775$ Hz for mode 2. This is because the numerical finite element method is an approximation method, so perfect symmetry is not preserved. In Appendix F, a convergence study was performed to verify the model. From this it is concluded that the model is fully converged. Therefore, the results are considered reasonable.

Evaluating the dynamic results

Next, the natural frequencies of the structure are compared with the frequencies of interest obtained in section 5.2. If the frequencies of interest are equal to the natural frequencies of the system, i.e. $f_{interest} \simeq f_{system}$, the corresponding modes of the structure can then be excited and could induce significant dynamic responses (resonance). If $f_{interest} \leq f_{system}$ or $f_{interest} \geq f_{system}$ no resonance can occur, because the structure is not excited at its natural frequency. The frequencies of interest are as follows.

1. The frequencies of the wind generated waves, see Table 5.3;
2. The frequency for wind gusts, which is 0.3 Hz;
3. The frequencies of the data center equipment, which is in range of 20 - 250 Hz, see chapter 3.

It can be observed, by comparing the frequencies of interest with the natural frequencies of the system, that the following modes of the structure can be excited and could induce resonance in the system.

- $f = 0.42$ Hz: generated by wind waves of normal wind speeds for low water level conditions. For which it is possible that mode 13 and mode 14 will be excited;
- $f = 0.3$ Hz: generated by wind gusts for high and low water level conditions. For which it is possible that mode 10, mode 11, and mode 12 will be excited.

Then, the observations are evaluated for each frequency of interest.

1. The possible resonance generated by wind waves of normal wind speeds is analyzed for low water level conditions. The spatial variability of the environment can be assessed by comparing the characteristic length (L) with the intrinsic oscillation of the waves, represented by the wavenumber (k). When $kL \gg 1$ the spatial variations are small relative to the wavelength. On the other hand, $kL \ll 1$ indicates a large spatial disturbance or reflection. For the structure considered, the wave number was determined from the dispersion relation ($k = 0.712$ rad/m) and the characteristic length is 250 m, so $kL = 178 \gg 1$, satisfying the fact that pressure fluctuations average spatially across the pontoon. However, shorter waves can locally induce bending, shear, and stresses even when the global motions are small. In conclusion, structural excitation will likely remain limited.
2. The gust effects need to be taken into account, but definitive conclusions cannot be formulated, as the assumption of resonance due to wind gusts involves significant uncertainty. Further research is required to assess the influence of gusts on the system.
3. The structural requirements are evaluated for housing the sensitive data center equipment. First, the vibrations induced in the equipment due to excitation of the global system response are assessed. As shown in this dynamic analysis, low frequencies are associated with the pitch, roll, and heave motions of the floating system. The equipment experiences these as slow global movements. As long as the resulting accelerations remain low, these motions do not pose a problem (IBM, 2025). Second, the vibrations transmitted to the structure generated by the data center equipment are considered. Since the equipment does not produce low-frequency vibrations, it cannot excite the global modes of the floating system. The equipment typically generates vibrations on the order of approximately 20–250 Hz. As noted earlier, these frequencies correspond to the higher structural modes, which represent local deformations rather than global motion.

Conclusion dynamic structural analysis of stability

In conclusion, the modal analysis (an undamped free-vibration analysis) does not account for damping or external excitation. As a result, it provides a theoretical response that is sensitive to resonance. When damping and wave excitation are included, the dynamic response will be reduced and more realistic. Therefore, it is recommended to include forcing time series and damping in subsequent research. The current results indicate a potentially critical frequency range rather than actual instability, aligning with the goal of this section to obtain a first feeling of the dynamic behavior of the system.

This first feeling of the dynamic behavior of the system for the effects assessed under the governing failure mechanism is concluded as follows. In detailed designs, the dynamic effects induced by wind gusts must be analyzed, as they can excite the natural modes of the system. In addition, the dynamic effects due to wind generated waves are less likely to occur due to the small spatial variations relative to the characteristic length of the structure. However, they should not be neglected because their frequencies are within the range of the natural frequencies of the floating system. Finally, the frequencies generated by the data center equipment can most likely only induce local resonance within the structure.

5.5. Sensitivity analysis

The goal of a sensitivity analysis is to evaluate how variations and uncertainties in key geotechnical parameters, such as environmental loads and assumed geometry, affect the determined factor of safety and the structural behavior of the system. This provides information on the robustness and reliability of the floating data center structure. To indicate the sensitivity of the system to uncertain parameters, a quantitative analysis is used for variations in the wind load, and a qualitative analysis is used for variations in the design parameters.

5.5.1. Sensitivity analysis definition

In a sensitivity analysis, each input variable is examined to determine to what extent deviations from the base case influence the resulting output variables (Yukio et al., 2017). Since dynamic stability is satisfied at this stage of the design, this section examines the sensitivity of the structure at system level to variations in strength and stability in static conditions. Local sensitivity of the mooring arm and pontoon justifies additional design refinement.

In addition, robustness with respect to the basic events (see section 5.1) depends on the load effect (S) and the resistance (R). The load effects are subject to uncertainties arising from modeling assumptions and input factors, while the structural resistance is governed by design choices. First, the influence of the environmental wind loading is examined. Subsequently, it is assessed how modifications to the design parameters affect the structural response.

5.5.2. Sensitivity of the system to environmental wind load variation

In section 5.3 a design was performed using safety factors for the ultimate limit state. However, there are no standards for a floating data center as designed in this study. Therefore, system failure and robustness can be evaluated using push-over analysis. This will be carried out in this section.

Base case and input variables

Although the section on wind conditions (subsection 5.2.2) determined that a rough first-order estimate of the wind load would be sufficient, this analysis investigates how variations in the selected wind load parameters influence the system, with the goal of providing information of its overall robustness. The wind-induced drag force action on floating structures can be evaluated, in general, by applying the fundamental equation of drag force in aerodynamics (Jang & Jyh-Shinn, 2009). This was also mentioned in subsection 2.5.2.

$$F_D = \frac{1}{2} \rho C_D A(u)^2$$

This equation consists of the following input variables:

- u : constant wind speed depending on the height above the sea level
- ρ : air density
- C_D : drag coefficient
- A : projected area of a structure

In this analysis, the density of air is taken as constant ($\rho_{air} = 1.25 \text{ kg/m}^3$). Therefore, the sensitivity analysis will take into account the following input variables that affect the output variables: (i) wind speed, (ii) drag coefficient, and (iii) projected area (i.e., wind direction). The base case was performed in section 5.3.

Sensitivity analysis approach for each input variable

The sensitivity analysis is performed by a process of recalculating the system to obtain new static load conditions. In each iteration, all variables are kept fixed except the input variable of interest, assuming that the variables are independent (Sørensen, 2004). The same verification checks as defined in section 5.3 are used to compare the input variable with the base case variable.

The first analysis quantifies the effect of the magnitude of the wind speed (base case: 100 year return period for extreme environmental events, $u = 24.95$ m/s). Wind speeds are scaled using values associated with progressively larger return periods: for abnormal environmental events and accidental events (ISO19900, 2019). Extreme Value Analysis is conducted for return periods of 100, 1000, 10000, 100000, and 1000000 years to estimate extreme winds in the dominant south-west direction.

The second analysis investigates the influence of wind direction (base case: south-west). The directions considered are: south (S), south-west (SW), west (W), north-west (NW), north (N), north-east (NE), east (E), and south-east (SE). The orientation of the floating data center at the selected site is used to derive the corresponding approach angles and the wind-exposed (effective) length for each direction. Directional effects are quantified by the ratio of the maximum wind speed for each direction to the base case, defined by the extreme wind in the dominant SW direction.

The third analysis assesses the influence of the drag coefficient C_D (base case: $C_D = 1.05$ (NEN-EN, 2023)). In wind-load formulation, the drag coefficient is linear dependent to the applied load. Although the drag coefficient is typically obtained from wind-tunnel testing, no reference data are available for the intended data center geometry and scale. Therefore, the drag coefficient is treated as an uncertain parameter and a sensitivity sweep is conducted for the range [0.9, 2.4] (NEN-EN, 2023).

To identify the influence of the sensitivity parameters, a sensitivity factor is introduced. With this factor the checks are normalized with respect to a base case (Yukio et al., 2017).

$$SF = \frac{response}{basecase}$$

Where:

- $SF = 1.0$: the system behaves exactly like the base case;
- $SF > 1.0$: the load effects or stresses have increased;
- $SF < 1.0$: the load effects or stresses have decreased.

Influence of the return period

The 100 year return period was selected for structural requirements based on industry practice and (ISO19900, 2019), but this choice is supported by the following consideration. There exist two uncertainties within the partial safety factors: aleatory uncertainty and epistemic uncertainty. Epistemic uncertainty can be reduced with knowledge about the floating data center structure (determined through strength values and lab tests). The aleatory uncertainty can be reduced with a strong basis. Therefore, the reference value is the 100 year maximum stress resulting from the 100 year environmental condition to provide static certainty (Ummels & Lange, 2025). For designing based on a 10^6 year return period, the associated uncertainty becomes very large because the relative short-term statistics must then be extrapolated far beyond the range for which they are reliable. Therefore, in this section, this uncertainty is reduced to a value (the sensitivity factor).

First, extreme wind speeds are estimated using Extreme Value Analysis for five return periods (using the same data set as in subsection 5.2.2). For each case, the Weibull distribution provides the best fit. The resulting estimates are summarized in Table 5.8 the corresponding wind loads can be found in Appendix G.

Return period	RT = 100 [y]	RT = 1000 [y]	RT = 10000 [y]	RT = 100000 [y]	RT 1000000 [y]
Wind speed [m/s]	24.95	27.31	30.40	33.35	36.20

Table 5.8: Wind sensitivity for return period based on 3-hour wind speed data from (C3S, 2025)

All checks for the mooring arm and pontoon structure are performed and satisfied, see Appendix G. The sensitivity factors for the strength and stability checks for low water level are significant and are shown in Figure 5.19 and Figure 5.20, respectively.

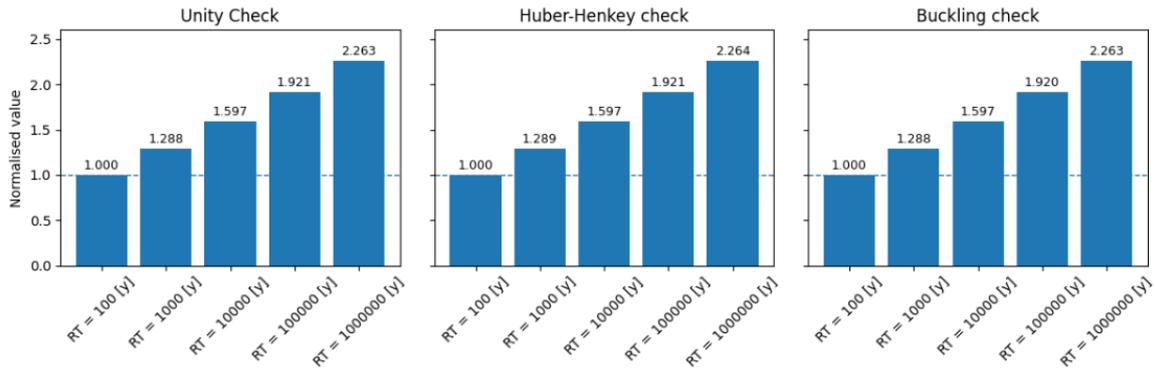


Figure 5.19: Influence of increasing return period on mooring arm strength for low water level

Figure 5.19 shows a linear relationship between load parameters and structural response, a logical result within the linear modeling framework. The direct proportionality observed confirms that the current approach primarily captures elastic linear behavior. This limits predictive capability at higher load levels, where plastic deformation, instability, or fatigue may become significant.

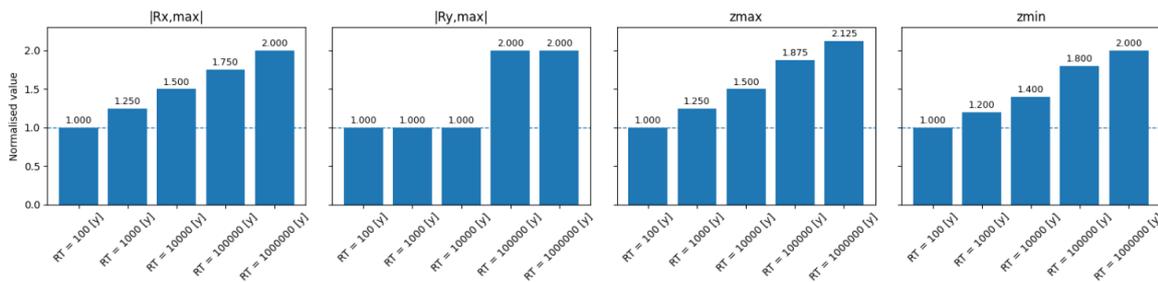


Figure 5.20: Influence of increasing return period on pontoon stability for low water level

Finally, a notable deviation is observed in Figure 5.20. At low wind loads, the stability check for $R_{y,max}$ remained nearly zero, followed by a sudden increase at the 10^5 year return period. This behavior suggests a shift in stiffness characteristics, possibly caused by geometric nonlinearities or changing interactions between the pontoon and mooring arms. Although such effects were not explicitly modeled, they indicate that the system is unlikely to behave fully linearly in reality.

In conclusion, for the increasing return period, the structural strength and stress levels in the mooring arm scale almost linearly with the load magnitude. The highest sensitivity factor is found for a 10^6 year return period, where the von Mises stresses increase by a factor of 2.26 relative to the base case. This difference is primarily due to statistical extrapolation rather than to physically realistic conditions. This implies that for such extremely long return periods the uncertainty becomes more dominant than the load itself. As a result, it is not meaningful to dimension a structure based on these values, whereas the 100-year load level is based on reliable environmental data and therefore defensible. Finally, the structure in this analysis has effectively been evaluated under extreme loading, demonstrating that it is robust with respect to higher wind speeds from the south-west direction.

Influence of member break down with increasing return period

To assess structural robustness under increasing return periods, a member check has been performed. Therefore, the critical components of the mooring arm are identified and systematically removed. The critical component is determined based on the verification checks, selecting the element that scores the highest (i.e., the most critical) in these evaluations. Subsequently, the load factor between the 100 year return period and the 10^6 year return period is calculated.

Then, progressive failure analysis shows that three members fail before the system becomes statically indeterminate. The structural response under high and low water level conditions is qualitatively similar for the mooring arm strength, but for the pontoon stability the low water level condition is more significant (Appendix G). As illustrated in Figure 5.21, three members fail before the system becomes statically undefined. The failed members are S581, S590, and S601, followed by S600, at which point the system loses static determinacy. Despite these local failures of the mooring arm members, the system remains within the required strength limits, indicating no global failure. This is shown in Appendix F.

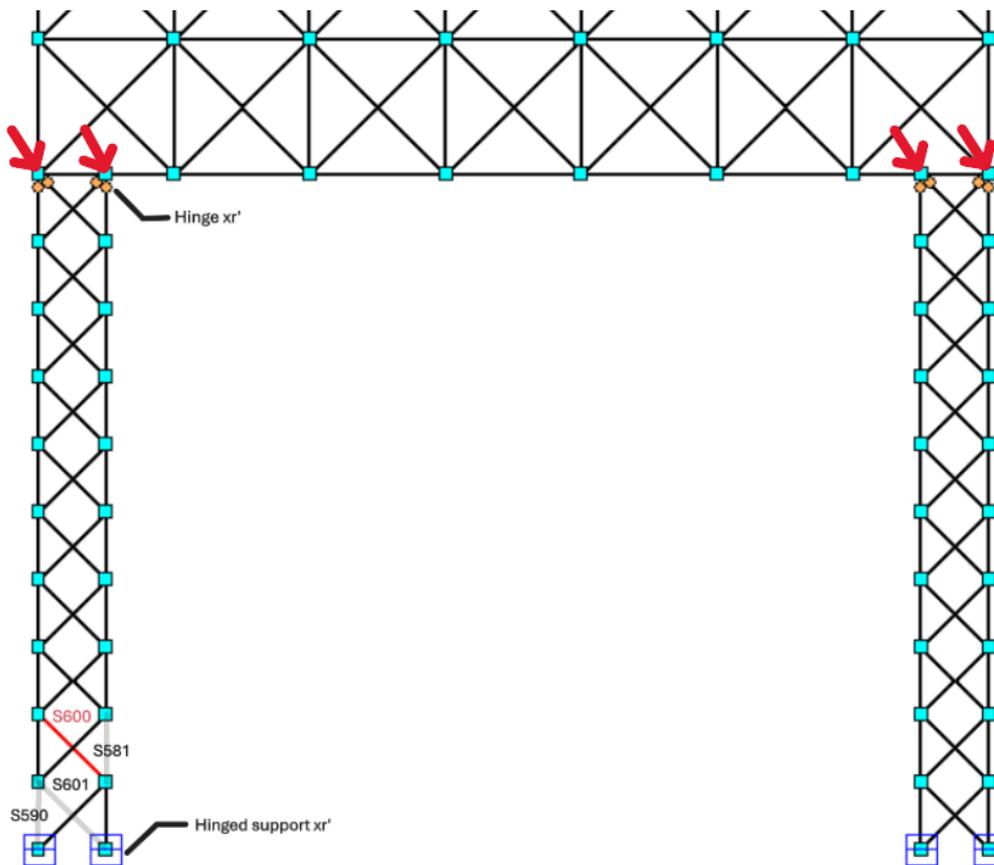


Figure 5.21: Influence of increasing return period on member break down of mooring arm for high and low water level (in red the loads applied)

For this member breakdown assessment, not only the member checks normalized with respect to the base case are considered, but the displacement of the pontoon is also included as a reference, see the formula below. This approach ensures that the impact of a member failure is considered on the entire system, rather than assessing the affected individual members.

$$SF = \frac{F_i \cdot u_i}{F_{basecase} \cdot u_{basecase}}$$

Where:

- F_i : the value of the check corresponding to the return period under consideration
- u_i : the displacement of point K6 corresponding to the return period under consideration
- $F_{basecase}$: the value of the check for the base case
- $u_{basecase}$: the displacement of point K6 for the base case

Then the values are normalized to the base case using the formula of the sensitivity factor. In Figure 5.22 and Figure 5.23 the results are shown. It is observed that for a 10^5 year return period, the unity check increases more rapidly once two members have failed.

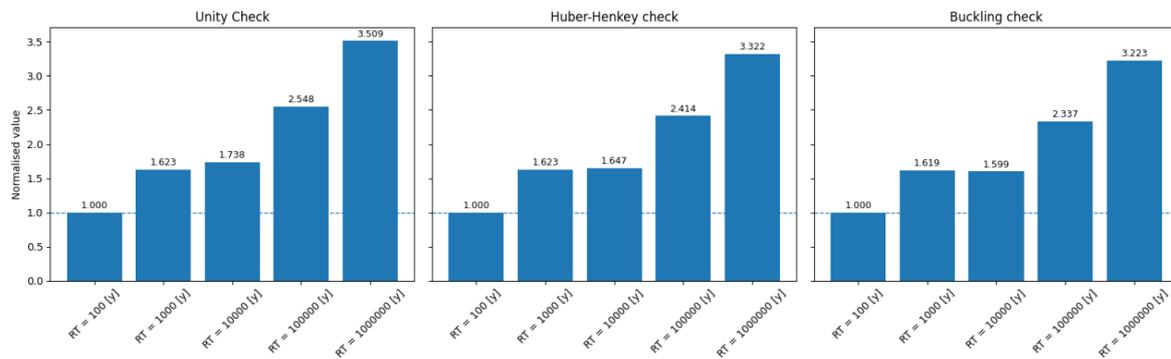


Figure 5.22: Trend of mooring checks per return period for member break down for high water level conditions

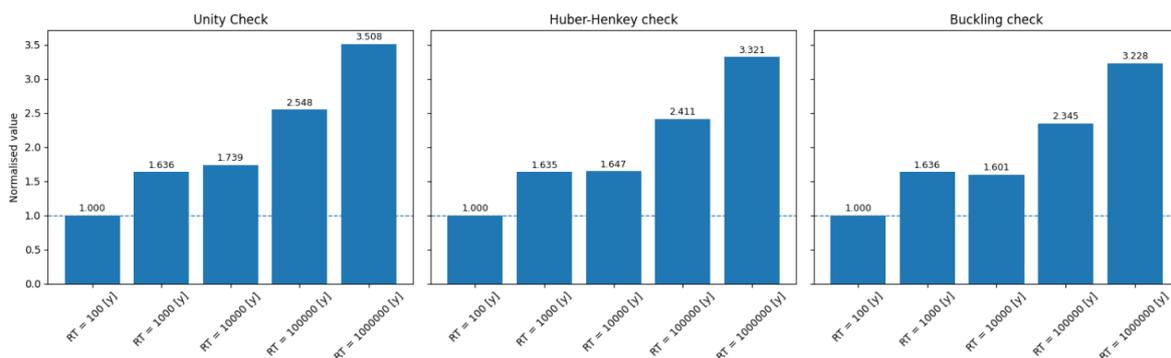


Figure 5.23: Trend of mooring checks per return period for member break down for low water level conditions

In conclusion, progressive member break down study confirms that local member failure does not immediately lead to global losses. After the failure of two members, the resistance of the structure against structural strength, von Mises stresses, and buckling decreases dramatically (sensitivity factors in the range of 3.2 - 3.5). The first two components to fail are tube members. This highlights that the diagonals provide sufficient redundancy against buckling and that tube member in this case govern the ultimate strength behavior.

Influence of the wind direction

The orientation of the floating data center relative to the wind directions was illustrated in Figure 4.4. The sensitivity analysis uses south-west wind as the base case condition for the sensitivity factor.

First, from the wind data (see subsection 5.2.2), the values of the minimum, maximum and mean wind speeds by wind direction are shown in Figure 5.24. Directional effects are subsequently quantified using the non-dimensional metric $\frac{u_{max,i}}{u_{max,SW}}$, where i indexes the wind direction see Table 5.9. For each wind direction the wind forces are calculated in Appendix G.

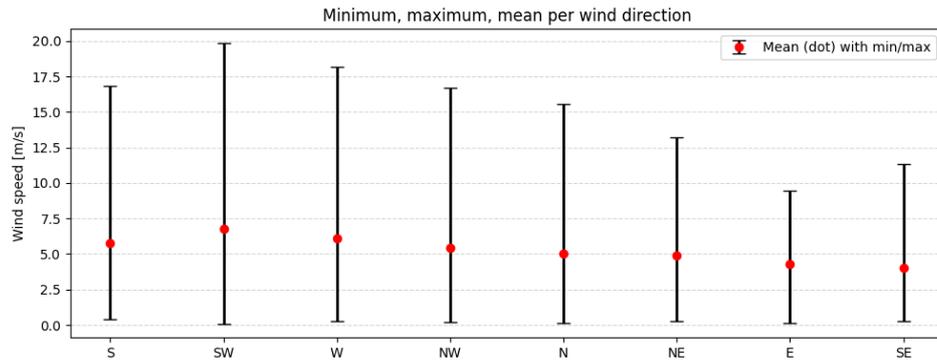


Figure 5.24: Wind speeds and wind directions

Wind direction	S	SW	W	NW	N	NE	E	SE
Ratio [-]	0.85	1.0	0.91	0.84	0.78	0.66	0.47	0.57
Angle of DC [°]	200	245	290	335	20	65	110	155
Surface length [m]	355	423	414	375	355	423	414	375

Table 5.9: Wind sensitivity for direction

Next, strength checks for the mooring system were carried out for all wind direction. Results for the significant low water level condition are shown in Figure 5.25. Under the high water level conditions, the pontoon verifications are identically zero, see Appendix G. Under the low water level conditions, the pontoon verifications remain at or below the base case envelope, see Figure 5.26.

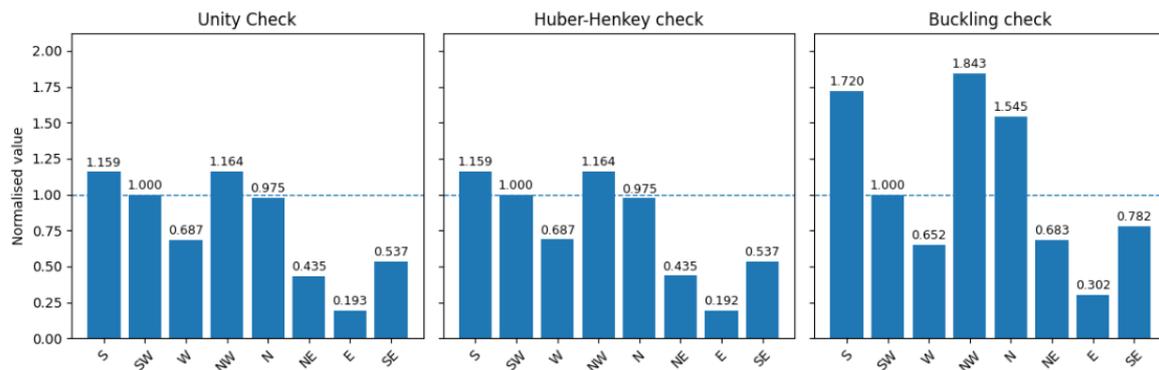


Figure 5.25: Influence of wind direction on mooring arm checks for low water level

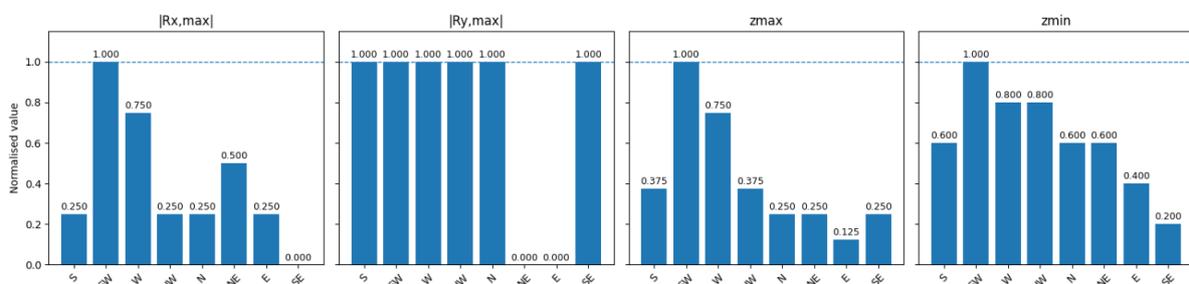


Figure 5.26: Influence of wind direction on pontoon checks for low water level

Finally, the increased sensitivity to buckling for wind directions from the south, northwest and north can be explained by the geometry and configuration of the mooring system. In these conditions, the wind load acts almost perpendicular to the main load-bearing axis of the structure, causing interaction between the pontoon and mooring arms. Because the mooring arms have a length of 250 meters, the effective buckling length is considerable, resulting in a decrease in lateral stiffness. As a result, cross-wind forces induce mainly bending and shear. The large mass of the pontoon at the end of the mooring arms amplifies this effect by increasing the moment at the connection, which increases the risk of buckling or excessive deflection.

In conclusion, the wind direction analysis shows that the south and north-west wind directions produce 16-17% higher structural strength forces, and von Mises stresses compared with the south-west base case. For south, north-west, and north directions, buckling becomes more likely to govern (55-84% more sensitive to buckling failure) due to increased lateral bending. For the pontoon checks, the south-west condition remains sufficient to capture the governing load case, as stability trends are directionally consistent and less sensitive.

Influence of drag coefficient

The drag coefficient C_D shows a similar analysis as the return period, see Appendix F.

Conclusion sensitivity of the system to environmental wind load variation

The sensitivity analysis demonstrates that the structural behavior of the floating data center is governed by strength rather than stability, and that system redundancy plays a larger role in robustness than absolute member capacity. Although all checks remain within acceptable limits, the analysis demonstrates sensitivities to variation in environmental wind load.

First, the scaling of stresses and unity checks with return period is close to linear, confirming that the load path and stiffness distribution remain unchanged up to extreme load levels. However, the rapid increase in member-level responses once two components fail indicates that the load redistribution capacity is limited.

In addition, the directional analysis shows that the assumed south-west base case indeed minimizes global load effects, but it also observed that cross-wind directions (south, north-west, north) result in a shift in the dominant failure mode: from structural strength to buckling. This implies that the buckling resistance of the mooring arms is not redundant but direction dependent. The earlier assumption that the diagonals provide sufficient buckling stiffness holds only for loading from the south-west direction. In cross-wind directions, bending and compression combine in a way that activates sensitivity to buckling.

Overall, the structure demonstrates adequate robustness under 100-year design load, but limited tolerance to local failures or asymmetric loading. The key sensitivity drivers are the following:

- Return period: controls the overall load level. Nearly linear scaling up to 10^6 years, but reduced structural safety at high extremes;
- Member loss: triggers superlinear stress growth. Redundancy is insufficient beyond two failed elements;
- Wind direction: shifts the governing failure mode from structural strength to buckling. And indicates that the south-west direction is not governing for structural strength but is governing for pontoon stability;
- Aerodynamic uncertainty (drag coefficient): linearly amplifies loads.

In conclusion, the goal of the sensitivity analysis is to reduce uncertainties in the design variables by introducing variations and evaluating their effects. Within the applied method, this has provided greater insight into the stability of the pontoon and the strength of the mooring arms. It also reduces the uncertainty in the environmental data, as different (and more extreme) environmental conditions have now been assessed.

However, no analysis was performed for the strength of the hinges and supports. These are critical components of the system and, therefore, the overall robustness of the system cannot be confirmed. Furthermore, the selected method only considered linear effects. To confirm full robustness, nonlinear effects should also be investigated.

5.5.3. Sensitivity of the system to design parameter variation

The previous subsection evaluated the sensitivity of the system to variations in environmental loading. This subsection addresses the influence of variations in design parameters on the structural response of the system. The goal is to identify the dominant design parameters based on the findings so far. The design parameters considered are: pontoon draft, pontoon dimensions, hinge attachment point, hinges, mooring arm configuration, and mooring arm dimensions.

Pontoon draft

For the current design with a draft of 8 m, the bathymetry of the Delta21 energy storage lake must be locally modified. Consequently, reducing the draft (i.e. floating the structure higher) would have a beneficial effect on the project. Reducing the draft increases pontoon rotations because the hydrostatic restoring in heave and pitch/roll is reduced. Although the previous subsection shows that the system can tolerate larger rotations under extreme loading, it remains sensitive to vertical load components that drive roll (see section 5.3). Therefore, a ballast system has been integrated to control trim and heel. Given this sensitivity and the dependence on ballast for attitude control, it is not advisable at this stage to lower the draft as a design adjustment.

Pontoon dimensions

The sensitivity analysis of the system to environmental condition variation indicate that the current pontoon dimensions provide a stable configuration for the 100-year environmental condition. Varying the pontoon dimensions directly affects both hydrostatic stiffness and global load distribution.

The governing relation is: $F_w \propto A$, where $A = L \cdot H$ or $A = B \cdot H$ dependent on the direction of the wind. In addition, the hydrostatic rotational stiffness scales with the second moment of inertia: $I_x \sim \frac{LB^3}{12}$ (roll) and $I_y \sim \frac{BL^3}{12}$ (pitch).

First, a smaller water plane area results in lower hydrostatic restoring coefficients and therefore larger vertical displacements and rotations under wind loading.

Second, changing the dimensions of the pontoon while maintaining the rectangular shape and total volume gives the following sensitivities:

- Length (L): $F_w \propto L$ the wind load increases with the length for cross-wind, $F_w \propto \frac{1}{L}$ the wind load decreases as the length increases for governing wind direction. This will result in increased cross-wind and reduced governing wind sensitivity. In addition, increasing the length improves pitch stiffness (L^3), but reduces roll stiffness. This will result in less pitch but more roll sensitivity. Next, the mooring arms are spaced along the length. Increasing the longitudinal distance between the mooring arms, increases eccentricity for off-axis wind load direction, leading to larger bending moments and stresses in the mooring arm that faces the wind.
- Width (B): $F_w \propto \frac{1}{B}$ the wind load decreases as the width increases for cross-wind, $F_w \propto B$ the wind load increases with the width for governing wind direction. This will result in reduced cross-wind and increased governing wind direction sensitivity. In addition, increasing the width improves roll stiffness (larger B^3), but reduces pitch stiffness. This will result in less roll but more pitch sensitivity.
- Height (H): $F_w \propto H$ for all wind directions, indicating a linear dependence between height and mooring arm forces and member stresses. Increasing the height will increase the force application height, raising the overturning moment. This means that the system reaches the rotation limits faster.

In conclusion, variations in the length and width of the pontoon structure shift the direction of the governing wind load rather than the failure mode itself. In addition, robustness should focus on balanced load sharing between mooring arms across all approach angles.

Hinge attachment point

The location of the internal hinge depends on the attachment point of the mooring line and the center of gravity of the pontoon. The lever arm height (h_{lever}) between these two points determines the restoring moment generated by the mooring system for a given horizontal load F_h :

$$M_{restoring} = F_h \cdot h_{lever}$$

A larger vertical offset increases the lever arm, thus amplifying the restoring moment for the same horizontal force, resulting in a greater rotational stiffness of the overall system. On the other hand, a smaller vertical offset reduces the effective lever arm, making the mooring less effective in resisting rotation but more efficient in opposing pure translational motion.

In the initial design configuration, the mooring arm is attached at the waterline, providing a balanced interaction between translational and rotational restraint. However, in future design iterations, the connection point could be raised to increase the capacity of the restoring moment. While the sensitivity analysis of the system to environmental condition variation indicates that the current mooring arms can accommodate the resulting higher internal moments without exceeding allowable stresses. This adjustment would also lead to larger displacements under high water level conditions. This occurs because, in high water level conditions, the mooring arm and pontoon structure are more geometrically aligned, resulting in reduced moment coupling and reduced rotational coupling. As observed in the sensitivity analysis of the system to environmental condition variation, the low water level condition consistently governs the structural response, as it induces greater interaction between the mooring system and the pontoon structure.

Hinges

The hinges are a critical component of the system (see section 5.1). A detailed design of the hinges must be carried out at a later stage by a mechanical engineer. However, at this stage of the design, it is already possible to assess the maximum forces that can occur in the hinges (given the constraints that have been set for the hinges as a design choice). Two situations are considered that govern the forces that can occur in a single hinge: (i) the extreme support reactions for a return period of 10^6 for wind loads from the south-west under low water level conditions, and (ii) the extreme support reactions that occur under normal extreme conditions for wind loads from the south under low water level conditions, see Table 5.10.

Support load	Fx [kN]	Fy [kN]	Fz [kN]	Mx [kNm]	My [kNm]	Mz [kNm]
Wind from south	-245.667	-2.563.286	256.291	-0.000	-43.619	-443.677
Return period 10^6	459.104	-4.952.316	495.109	-0.000	75.929	770.868

Table 5.10: Support loads for two sensitivity cases for low water conditions

From Table 5.10 it can be seen that the normal forces are the largest. For high water level conditions, this horizontal force is directly resisted by the mooring arms, because in this condition the pontoon structure and the mooring arms are aligned. For low water level conditions, this horizontal force causes interaction between the pontoon and the mooring arms because in this condition the pontoon structure and the mooring arms are not aligned, resulting in extreme conditions for the hinges.

In addition, the design choice for the hinges (allowing rotation about the x-axis and fix rotation about the y- and z-axes) means that the hinges must resist shear forces and moments. If further analysis shows that the selected hinges cannot withstand these forces and interactions, alternatives must be considered, such as a spherical hinge (as already mentioned in section 5.1). Other design choices can then be made to accommodate for shear and moments. By placing the arms as far apart as possible (which has already been done in this design), shear is carried through tension and compression in the system. The mooring arms can also be locally placed farther apart to carry shear through tension and compression.

Note that in this analysis only the forces generated by the wind have been considered. Forces arising from the movement of the structure are expected to be more critical to the design of the hinge. Therefore, calculations must be performed to evaluate the second-order effects of the system, and a detailed design of the hinges must be developed.

Mooring arm configuration

The mooring arm configuration considered in this section consists of two arms connected at the ends of the pontoon. Reducing the configuration from two mooring arms to a single arm will induce an asymmetric structural response: stresses and buckling utilization increase rapidly (see Figure 5.5.2). In addition, maintaining two-arm redundancy is essential to ensure robustness in partial failure scenarios.

Then, variation can be applied to the attachment point of the mooring arms. When the mooring arms are moved closer together, the following effects occur:

- The moment arm of the outer sections increases, resulting in greater bending;
- The overall structural stiffness decreases;
- The natural frequency becomes lower, as the system becomes more flexible;
- Higher stresses will develop at the supports.

In this design, the attachment pints are positioned at the ends of the pontoons, following common practice in the maritime industry (where the vessels are moored on the quay, as seen in Figure C.1). However, reducing the spacing between the mooring arms could be considered as a potential approach to dynamic tuning. Since the dynamic analysis performed in this study indicated that no critical conditions are expected with respect to the natural frequencies within the applied boundaries and the simplified model, this distance cannot be further optimized in this design phase.

Next, the distance between the two tubes of one mooring arm is determined by the weld angle that can still be achieved between the tubes and the diagonals. When this distance increases, the length of the diagonals also increases. When the distance decreases, more diagonals need to be added. Otherwise, the angels become too sharp and can no longer be welded properly. Design considerations for the distance between the mooring tubes are based on:

- Sufficient stiffness;
- Natural frequencies;
- Fabrication feasibility;
- Mass and CO₂ costs.

Sensitivity analysis showed that the current mooring arm design provides sufficient stiffness. In addition, a more slender mooring arm exhibits lower natural frequencies due to its increased flexibility, while a larger distance between the tubes has greater stiffness and therefore higher natural frequencies. Since the dynamic analysis performed in this study indicated that no critical conditions are expected with respect to the natural frequencies within the applied boundaries and the simplified model, this distance cannot be further optimized in this design phase. Fabrication is feasible for the current mooring arm dimensions. The mass and CO₂ costs are evaluated in the following section: mooring arm dimensions.

Mooring arm dimensions

The mooring arm considered in this section consists of two tubes of 250 meters connected by horizontal bracing. Next, the stiffness and cross-sectional properties of the mooring arms have a direct influence on global load distribution and failure mode. Two changes can be made to the cross section.

1. Decrease wall thickness at constant diameter. For circular hollow section, the following relations hold for decrease in wall thickness with x%: $A \propto t$, $I \propto t$, $Z \propto t$.

Expected impact:

Member strength: $N_{Rd} \propto Af_y$, $M_{Rd} \propto Zf_y$ Buckling: $N_{cr} \propto EI$ For both, member strength and buckling, expect 1/x times higher ratios.

The system remains globally strength-governed, but becomes locally more brittle as wall thickness decreases. Because the mooring arms contribute to the global equilibrium, weaker tubes (lower EI) provides less rotational restraint, allowing larger rotations.

2. Decrease diameter at constant wall thickness. For circular hollow section, the following relations hold for decrease with x%: $A \propto D$, $I \propto D^3$, $Z \propto D^2$.

Expected impact:

Member strength: $N_{Rd} \propto Af_y$, $M_{Rd} \propto Zf_y$ Buckling: $N_{cr} \propto EI$ For member strength the axial forces 1/(1-x) times higher ratio and for bending moments 1/(1-x)² higher ratio. For buckling strength, expect a 1/(1-x)³ higher ratio.

Reducing the diameter decreases D/t (making local buckling less critical), but introduces a large loss of global stiffness/capacity. A drop in the moment of inertia makes the mooring arm more prone to global buckling, increases bending stresses, and reduces the rotational restraint of the mooring arm.

In conclusion, the structure is governed by member strength rather than the stability, which means that cross-sectional optimization of the mooring arms offers the potential for material and cost reduction without compromising global safety. To ensure structural safety and robustness, consider thickness reductions over diameter reductions. Such optimization should preserve redundancy and maintain a balance between axial strength and buckling resistance. Redundancy can be maintained by implementing periodic inspection.

Conclusion sensitivity of the system to design parameter variation

In conclusion, the following sensitivities are found: (i) reducing the pontoon draft decreases hydrostatic stiffness and increases rotations. A ballast system remains essential for trim and heel control, (ii) modifying the hinge attachment point changes the restoring lever arm and introduces asymmetric stiffness effects. Current positioning offers a balanced response, and (iii) mooring arm cross-sections can be optimized (wall thickness reduction) while maintaining redundancy and buckling safety through proper inspection strategies.

5.6. Conclusion and evaluation structural design

In this design, the focus is on analytical evaluation and system dimensioning. To make conclusions for this section, the structural requirements are first verified. Then, the structure is evaluated on its performance. Finally, conclusions can be drawn.

Verification of the structural requirements

The following structural requirements were identified in chapter 3 and are verified in this section.

- *The structure shall be designed to allow safe, practical, and cost-efficient fabrication, transport, installation, and inspection.*

Functional design addressed the fabrication, transport, and installation criteria. However, the structural design did not explicitly evaluate the transport and installation loads. The components that have been analyzed in this structural design comply with the relevant guidelines. In addition, a ballast system is included in the design, which turned out to be essential for the structural stability of the floating platform.

- *The structure shall maintain global and local stability during all design stages and in all relevant load combinations.*

The analysis shows that the maximum vertical velocity resulting from the inflow and outflow of the energy storage lake does not pose a critical issue for the structure. This vertical motion is very slow, allowing the pontoon to follow it without difficulty, while the hinges prevent any internal system motions that could resist this movement. Instead, translation waves generated during the filling of the lake can disturb the stability of the system. Particularly at the selected site of the data center, where these waves reflect against the boundary. First-order estimates indicate that gradually filling the lake can limit these effects.

From the static analysis it follows that the structure can withstand the assumed wind loads corresponding to a 100-year return period, with the governing wind direction from the southwest, for both the mooring arm strength and pontoon stability. Also the wind setup was evaluated and it was concluded that the pontoon can follow the resulting vertical displacements. It does not pose a serviceability problem, as the induced slopes remain within the required limits.

In addition, wind generated waves corresponding to a 100-year return period from the southwest direction (for which the fetch length is sufficiently large) were assessed for their static and dynamic contribution. The static forces induced by these waves are not significant compared to horizontal wind loads. However, the frequencies associated with wind generated waves fall within the natural frequency range in which global motion of the floating system can occur and require further attention in subsequent studies.

Finally, uniformly distributed loads due to snow, ice, and marine growth were included for the calculation of the vertical loads.

- *The structure shall withstand all applied loads without exceeding the allowable stress limits, in accordance with the governing design standards and safety factors.*

The structure can withstand the applied loads identified in this study without exceeding the allowable stress limits according to the governing design standards. However, uncertainties remain, particularly regarding the dynamic effects of wind gusts and potential vortex-induced vibrations generated by wind acting on the topside of the structure.

Whether the design is structurally safe cannot be concluded from this analysis, since a reliability-based design method, required to ensure that the target reliability of the data center is met (and therefore the safety factor is verified), has not yet been applied.

- *The structure shall exhibit sufficient stiffness to ensure that deformations, rotations, and dynamic responses remain within the required serviceability limits.*

The system has been designed to be very stiff. Consequently, the static and sensitivity analysis show that, under horizontal wind loads, the structure remains within the required serviceability limits. Dynamic loads were not included in the response calculations, so conclusions cannot be drawn about the deformations and rotations of the system due to dynamic loads.

The natural frequencies of the system are outside the range of vibrations induced by the data center equipment, meaning that the global modes of the floating structure will not be excited by the equipment. The natural frequencies of the system fall within the critical range associated with wind gusts and wind-generated waves, and further analyzes are required to verify whether the resulting motions remain within the required serviceability limits.

Evaluation of the structural design

The structural concept of the floating data center has been developed as a very rigid system. The static and sensitivity analyzes show that, for horizontal wind loads, the structure remains within the required serviceability limits. In particular, the mooring arms appear robust in terms of strength, no critical utilization was found in the member checks within the considered load cases. However, second-order effects still need to be assessed to confirm the strength capacity of the mooring arms under large deformations and dynamic loading.

A key functional requirement is that the pontoon must follow the daily water level variations of the energy storage lake. This vertical motion is very slow and can be treated as quasi-static. The pontoon can accommodate this movement as long as there are no rigid constraints that oppose the vertical displacement. The hinges are therefore a crucial component and must be properly maintained. In the proposed design, the hinges are restrained about the y- and z-axes. The sensitivity analysis indicates that the structure is relatively sensitive in strength to cross-loads. Under such a loading, the restricted hinges can deform and stop functioning as intended.

It may therefore be beneficial to investigate whether a spherical hinge would perform better than the current configuration. In addition, adjustments can be made so that the mooring system, rather than the hinges alone, contributes more to resisting rotations and shear. Possible design adaptations include: (i) iterating towards the triple tube (3D) mooring arm configuration, so that rotations about the y-axis can be supported by the arms, and (ii) locally widening the arms so that shear due to cross-loads is better resisted through tension and compression in the system. After such a design iteration, the system must be rechecked in terms of strength and stability.

With respect to stability, the sensitivity analysis provides limited additional insight into the robustness of pontoon stability. The pontoon derives most of its rotational stability from hydrodynamic stiffness due to the large water plane area. Stability issues, for example those introduced by the self-weight of the mooring arms, must be compensated by the ballast system. At the same time, a draft of approximately 8 m was already required to achieve neutral buoyancy, which implies that the Delta21 energy storage lake must be significantly deepened locally. The vertical stability of the pontoon is therefore a critical aspect. Although the sensitivity analysis suggests that the pontoon structure is not sensitive to stability within the applied load ranges, observations throughout the study indicate that several mechanisms and environmental conditions can have a significant influence on the stability of the pontoon.

In summary, the current structural design appears robust with respect to the strength of the mooring arms and the static response under horizontal wind loads, but remains sensitive to hinge behavior and vertical stability. These aspects should be examined in more detail in subsequent design stages, including second-order analyzes.

Conclusion of the structural design

In conclusion, the fault tree provided an overview of the failure mechanisms and allowed the identification of critical components. Subsequently, all relevant loads and load combinations acting on the structure under normal design conditions were determined. However, because not all loads could be assessed at this stage of the design, the structure was analyzed statically and dynamically only for the design conditions identified. As a result, structural reliability cannot yet be guaranteed, and uncertainty remains regarding the overall structural safety of the system. These uncertainties were further explored through the sensitivity analysis, in which both variation in loading and the influence of design choices were examined. This analysis provided insight into the robustness of the system and supported possible adjustments to design decisions that would improve the system's performance. Finally, extensive analytical evaluation contributed to developing a better understanding of the structural dimensioning.

Whether the design is structurally safe cannot be concluded from this analysis, since a reliability-based design method, required to ensure that the target reliability of the data center is met, has not yet been applied.

6

Discussion

The development of the functional and structural design of a floating hyperscale data center provides early-stage information on feasibility, several assumptions, simplifications, and uncertainties. This section discusses the limitations and outlines their implications for the interpretation of the findings.

Limitations in environmental loading and statistical modeling

The environmental loads were determined using empirical formulations for wind-generated waves and statistical extreme value analysis for wind speeds. Although these approaches are appropriate for a conceptual design, they introduce several important uncertainties.

- Limited measurement record: extreme value analysis was based on approximately six years of wind observations. This is very short in relation to a 100-year return period and implies that only 6% of relevant events are observed. Consequently, the tail of the extreme value distribution is almost entirely extrapolated, making the estimate highly sensitive to individual storm years. For critical infrastructure, a more defensible estimate would require 20–30 years of data. However, the resulting wind speeds in this study do not deviate drastically from fundamental basic wind speed from the Eurocode for Maasvlakte 2, i.e. 27 m/s.
- Linear wave theory and empirical models: wind-generated waves were computed using linear wave theory and empirical relationships. The application of linear wave models to a very large, shallow-draft floating structure may lead to inaccuracies. Non-linear effects and depth-limited wave growth have not been evaluated.
- Operational effects related to filling and emptying of the lake, such as vertical flow velocities and long translation waves, were determined. Although the vertical velocity itself appears too small to cause problems, the associated long waves can induce significant water-level gradients around the platform.

Governing load combinations

Another limitation is that the governing load combinations were not established at the start of the design process, but rather inferred after analyzing the individual load cases. Extreme conditions do not necessarily coincide with the governing design combination, and ideally, a systematic identification of critical scenarios should be performed earlier in the design process. This affects the confidence level of the selected design loads and the resulting conclusions on structural performance.

As a result, in the static analysis, wind generated waves were not combined with the maximum wind load, even though both occur simultaneously in reality. This separation has led to a partial underestimation of the static structural behavior analyzed due to only wind loads. At the same time, several assumptions are highly conservative: the wind load is based on the 10 m wind speed, while the structure extends only about 7 m above the water surface. In addition, the shielding effects of the surrounding dikes were neglected. Finally, the fact that this interaction was not explicitly included limits the accuracy of the static assessment, although its influence is partly reflected in the variation of the results for increasing return periods.

Structural modeling and optimization

Several structural simplifications influenced the accuracy of the static and dynamic results.

- The behavior of the ballast system was assumed to be idealized. In the current model, the ballast system compensates for vertical load variations instantly and without inducing dynamic effects. In reality, pump activation can introduce impulses or vibrations that could be critical for the stability of the pontoon structure and the data center equipment. This interaction was not included.
- The self-weight of the mooring arm was not included in the initial structural assessment. Only after completing the full static and dynamic analyzes was the effect of the self-weight of the mooring arm evaluated, revealing that the mooring arm exceeds its allowable limits. This indicates that the design should have been iterated in an earlier design phase before proceeding with subsequent analyzes because it can govern strength and stiffness requirements and therefore influence the feasibility of the selected mooring arm configuration.
- The dynamic analysis used linear structural behavior and did not include damping or nonlinear hydrostatic effects. As a result, the response amplitudes cannot be interpreted as absolute predictions but only as indicators of sensitivity.
- Only environmental loads were considered, whereas operational loads such as equipment vibrations, heat-exchange flows, and cooling system dynamics were not included. These internal loads may contribute to fatigue or local instabilities. Also, loads corresponding to transport and installation conditions were not included in the structural design.
- Second-order effects and fatigue were not part of this study but may be governing in later stages of the design, especially for the mooring system and hinge connections.

Sensitivity analysis and design choices

The sensitivity analysis offered valuable insight into the robustness of the design, but also revealed several vulnerabilities:

- Hinge configuration: the assumed restrictions for the hinges about the y- and z-axes lead to sensitivity under cross-wind loading, making the hinges critical components in the system. When these restrictions are relaxed, the load is redistributed through the mooring system.
- Mooring arm robustness: while the arms appear significantly over-dimensioned with respect to strength, second-order effects must still be examined to confirm their resistance. The triple-tube (3D) configuration may provide improved performance against cross-loads and moments around the y-axis.
- Vertical stability: although the pontoon structure appears to be stable for the tested environmental wind conditions, the sensitivity analysis provided limited insight into how the pontoon structure behaves under operating and other environmental conditions.
- The functional design alternatives in the multi criteria analysis: double tube with diagonals and double tube with crossings showed almost similar performance. However, sensitivity analysis showed how optimization of the functional design can be performed.

Design assumptions and validation

In this study, conclusions were drawn through verification of the defined requirements and criteria. Verification of the boundary conditions shows that local modifications to the Delta21 energy storage lake, such as adjustment of depth and dike slope, would be necessary to make this design feasible. Although the client provided broad design freedom, the design has not been validated. Consequently, no answer can be given to the central validation question: “Do the realized structure and its performance comply with the user requirements?”

Finally, since this design represents one of the first large-scale floating data center concepts, no standardized design guidelines or reference projects are available. This complicates the validation of assumptions regarding loads, material properties, and interactions between the structure and its environment. The results should therefore be interpreted as an initial technical exploration rather than as definitive design values.

7

Conclusions and recommendations

7.1. Conclusion

This study presented a first functional and structural design for a floating hyperscale data center located within the Delta21 energy storage lake. Although the results establish a preliminary understanding of feasibility and structural behavior, several methodological limitations and uncertainties influence the reliability of the conclusions and must be addressed in future design phases.

Integrating the data center within the Delta21 energy storage lake enables the combination of data storage, energy storage, and water management, positioning the hyperscale data center not as a standalone asset but as a component of an integrated energy system. The elementary design cycle was adopted as the methodological framework that guides the development of both functional and structural design. The resulting functional design is illustrated in Figure 7.1 and Figure 7.2.

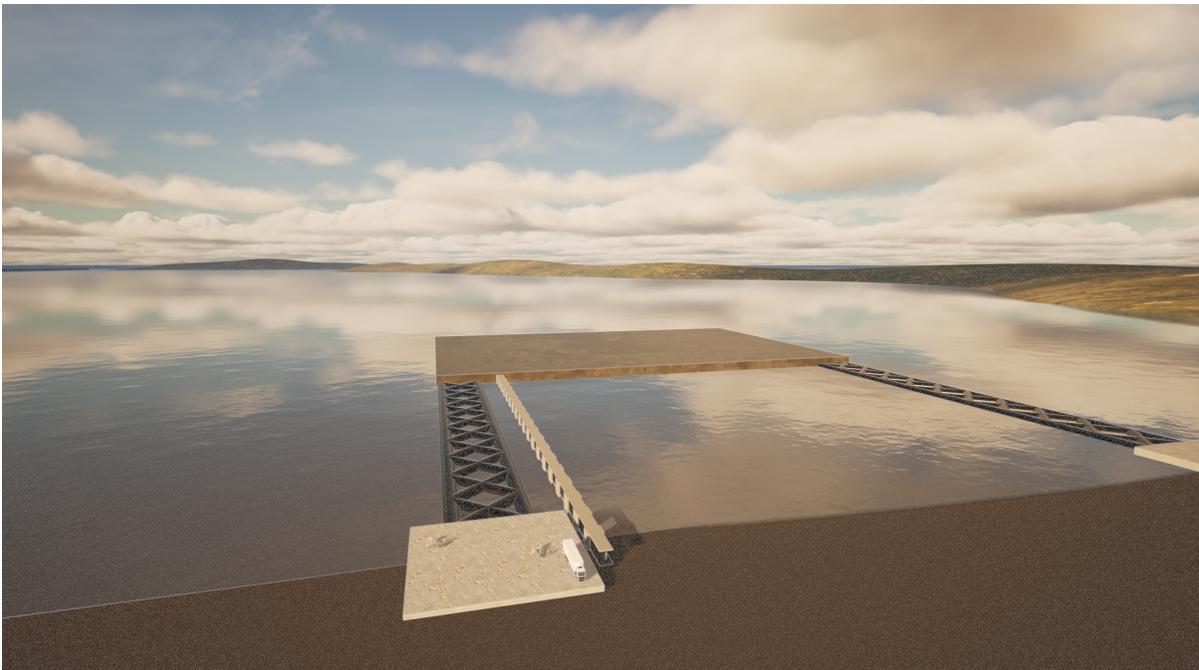


Figure 7.1: Concept design for 1 GW floating data center in high water level condition

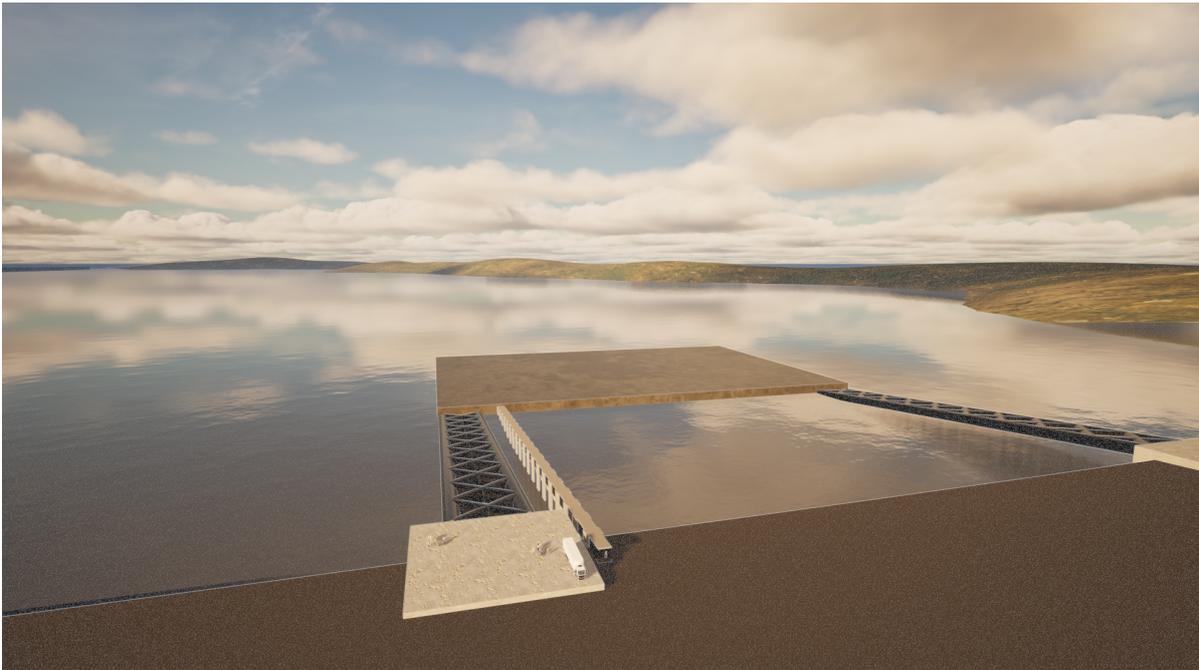


Figure 7.2: Concept design for 1 GW floating data center in low water level condition

The evaluation and verification of the functional design show that it satisfies the defined boundary conditions and meets the functional requirements and criteria, which demonstrated functional feasibility. A key requirement is that the structure must accommodate water level fluctuations of up to 25 meters, which the design achieves compliance with. However, local modifications to the Delta21 energy storage lake for water depth and dike slopes will be necessary to implement this functional design.

For the structural design, both static and dynamic analyzes were performed. A first-order static analysis of horizontal wind loads demonstrates that the structure remains within allowable limits for both mooring arm strength and pontoon stability. These findings also show that the mooring arms are significantly over-dimensioned, resulting in unnecessarily high material use. Regarding the dynamic stability of the pontoon under environmental loads, no definitive conclusions can be drawn because the analysis indicates sensitivity rather than the actual response of the system. The results suggest that the system is likely to be susceptible to resonance from wind gusts. Therefore, structural feasibility has been partly demonstrated, but structural reliability cannot yet be assessed.

In addition, a sensitivity analysis was performed to provide additional insight into possible design optimizations. This analysis shows that the hinge configuration forms a critical element in the system. Due to the assumed rotational restrictions, the system is sensitive to cross-loads. The analysis also shows how these loads are redistributed through the mooring system when the hinges are designed differently. Furthermore, the analysis indicates that the system is sensitive to vertical instability. Environmental conditions that have not yet been fully quantified, such as translation waves generated during the filling of the Delta21 energy storage lake, can challenge the design and could even undermine its performance.

Beyond the technical findings, this study also highlights the social relevance of the concept. Integrating a hyperscale data center into the Delta21 project enhances spatial efficiency and contributes to the digital autonomy of the Netherlands. The concept therefore represents an innovative solution in which spatial planning, energy integration, and sustainability are combined.

In conclusion, the study followed the elementary design cycle, an established method for the design of civil structures. Only one full iteration has been completed through the cycle. The concept developed in this study therefore serves as a foundation for subsequent design phases rather than a final structural design.

7.2. Recommendations

Throughout the design process, several additional insights have emerged that provide direction for future studies and further design development.

Structural optimization

The sensitivity analysis indicates that over-dimensioning could have been mitigated earlier through interim verification of material efficiency. Therefore, it is recommended that in the next design iteration, the structural parameters (mass, stiffness, and geometry) are systematically varied to identify the optimal balance between safety and material use. The current design is governed by strength criteria rather than stability, leaving room for cross-sectional optimization without compromising global safety.

Furthermore, the sensitivity analysis shows that the assumed hinge restrictions are a critical design choice and that cross-loads strongly influence the structural response. It is recommended to:

- Reassess the hinge concept together with a mechanical engineer, including the risk of deformation or binding under cross-loads;
- Investigate alternatives such as more flexible (e.g. spherical) hinges and design iterations in which part of the load is redistributed from the hinges into the mooring arms;
- Re-check the global response of the system after such design iterations, including strength, stiffness, and stability.

Dynamic stability and modeling

To improve the reliability of the stability assessment, the dynamic model should be refined with more detailed representations of damping, nonlinear hydrostatic and hydrodynamic effects, and variations in buoyancy. This will allow for a more accurate prediction of motions and accelerations and reduce the present uncertainty in the dynamic response.

In addition, the present study indicates that the system may be sensitive to excitation by wind gusts, and vortex-induced vibrations (caused by wind acting on the top side of the structure) have not yet been quantified. A dedicated dynamic analysis of gust loading and vortex induced vibrations due to wind should be performed to evaluate whether these phenomena can excite global modes or lead to unacceptable accelerations or fatigue in critical components.

Environmental conditions

More research is required on turbine generated waves and the resulting translation wave in the Delta21 energy storage lake, including at least the following two aspects.

- The ability of the pontoon to follow the rapid water level variations without losing stability;
- The spatial variation in the water level around the platform and the corresponding hydrodynamic forces and moments on the structure.

Special attention should be paid to possible sloshing or standing-wave effects in the Delta21 energy storage lake that can amplify local water level differences, causing potential stability problems for the pontoon structure.

Model and method refinement

The numerical verification can be further improved by:

- Separate the unity check to more clearly identify the governing failure mechanism for each component;
- Include associated wave loads under maximum wind conditions, even when their contribution appears minor;
- Adopt a range of maximum and minimum structural responses (i.e. the 95th percentile of the data) instead of the absolute minimum and maximum;
- Report the results of the sensitivity analysis in more detail, allowing a better interpretation of the trends in individual loading components.

Implementing these refinements would make the model more suitable for use in optimization studies and probabilistic reliability assessments.

In addition, iterations are required, both at the general concept level and the detailed structural level. These iterations should update the functional and structural requirements based on the refined dynamic analyzes and hinge/mooring redesign, and guide optimization towards a structurally efficient and dynamically robust final configuration.

Finally, although this study focused on the technical functional and structural design of the floating data center concept, it represents only one aspect of the overall feasibility of the project. Integration of the data center into the Delta21 energy storage lake system offers potential for further optimization, but before doing further research, design validation is recommended. Then additional studies on energy coupling, waste heat recovery, and adaptive cooling strategies would improve both the sustainability and functional reliability of the system as a whole. An integral design that considers technical, economic, environmental, and legal aspects is essential to establish the floating hyperscale data center within Delta21 not only as technically feasible, but also as socially responsible and sustainable.

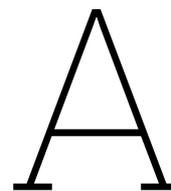
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Stakeholder analysis

This appendix focuses on the attitude of stakeholders towards the Delta21 project and is based on the stakeholder analysis of (Delta21, 2024a). It is useful because it clarifies, to some extent, the interests, power, and/or attitude of the stakeholders involved that are mentioned in the main chapters of the report.

Stakeholders Delta21

The Delta21 project aims to provide benefits for everyone and has no further interests itself. Some notable things to note when driving over the Haringvliet Dam:

- Silting of the coastline: There is now a large sandbank (hinderplaat) off the coast. Since the closure of the Haringvliet by the Delta Works, this sandbank has been steadily moving closer to the coast. If no action is taken, it will eventually contact Rockanje.
- The "kwade hoek": A Natura 2000 area on Goeree-Overflakkee. This nature reserve is expanding rapidly and pushing the Haringvliet shipping channel to the north. Currently, the shipping channel can only be kept open by permanent dredging. This is a challenging task because the channel changes continue.
- Sedimentation: The closure of Haringvliet is a contributing factor to the rapid growth of the coast. Initially, this had a positive effect on nature, but shrubs are also growing in the area.

In short, in 20 to 30 years, the entire area will be fully silted.

If the lake from the Delta21 plan is located off the coast, the sandbank will no longer be able to move closer to the coast. Sand transport from the "kwade hoek" will also cease, as the sand transport from the southwest will be blocked by the lake. In addition, sedimentation behind the lake will stabilize (Lavooij, 2024). This type of plan impacts many stakeholders; see Table A.1.

Stakeholder	Details
The Government of the Netherlands	<p>Interests: To better protect the most vulnerable, densely populated, and economically most intensive part of the Netherlands.</p> <p>Power: 200 Milliard euros to protect the Netherlands. Many parties within the government also have a responsibility for flood safety and freshwater supply.</p> <p>Attitude: The Ministry of Infrastructure and Water Management and the water boards have primarily assigned this task to the Delta Commissioner.</p>
Delta Commissioner	<p>Interests: Investigate what the long-term solutions are for safety in the event of a significant sea level rise.</p> <p>Power: The solutions developed by the Delta Commissioner will only be presented to parliament in 2026.</p> <p>Attitude: The Delta Commissioner sees the Delta21 concept as a possible and interesting (partial) solution for the effects of sea level rise in the downstream area of the Rhine and Meuse rivers.</p>
Environmentalists	<p>Interests: To urge the simultaneous optimal use of the plan for nature restoration.</p> <p>Power: If the Delta21 concept has negative consequences for nature, they must be fully and generously compensated.</p> <p>Attitude: Nature organizations would like to see more coordination and cohesion in the management of the Natura 2000 areas, possibly even an integration of these four areas. Some support for a more active nature policy. However, the nature organizations warn against false solutions and greenwashing. One environmental organization sees opportunities with aquaculture to reduce pressure in the Wadden Sea and the Oosterschelde, provided that no further damage from farming occurs in the 4 Natura 2000 areas.</p>
Watersupply (Evines)	<p>Interests: The reduction of salinization in the Haringvliet.</p> <p>Power: Need more drink water in the future. However, in combination with the low river discharge, this will be challenging.</p> <p>Attitude: Experts in freshwater supply advocate for restoring the Haringvliet as the main river outlet in the long term.</p>
Energy sector (TenneT, Stedin)	<p>Interests: The conservatively estimated value of the Energy Storage Lake for the energy sector is estimated at €8-12 billion, primarily for reducing installed renewable capacity, utilizing "surplus" electricity, as well as for price arbitrage purposes and grid management.</p> <p>Power: TenneT is a very important party within the ministry and plays a key role in decision-making, permits, and the connections of the Delta21 concept to the main grid. The vision, possible role, and position of Energie Beheer Nederland within the Dutch energy sector are also crucial for the success of the Delta21 project.</p> <p>Attitude: TenneT supports the initiatives of Delta21. Together with Stedin, TenneT closely monitors the development of the Delta21 concept, primarily for its own grid balancing, reserve purposes, and several other functions of energy storage for which these implementing organizations are responsible.</p>

Stakeholder	Details
Fishing sector	<p>Interests: The mussel and oyster farmers, as well as the algae growers, see opportunities in the energy storage lake to partially relocate or expand their activities.</p> <p>Power: There is a desire from the fishermen and the municipality of Stellendam to keep the navigation channel from Stellendam to the North Sea open via the Slijkgat, if possible without dredging.</p> <p>Attitude: The fishing sector is generally understanding and sometimes enthusiastic when it comes to reserving the tidal lake for nature purposes.</p>
Local parties	<p>Interests: Do not want to lose the charm of islands in the coastal zone. And thus wants to prevent the mouth of the Haringvliet from becoming further obstructed by sediment.</p> <p>Power: Advocating for various interests, such as an open connection from Stellendam to the North Sea via a deep, straight navigation channel that does not need to be permanently dredged.</p> <p>Attitude: There is a call for the preservation of space for peace and nature for local residents and better shielding of the industrial areas. The aim is to make the area attractive for living and recreation, but without extensive urban development, large offshore wind farms with tall turbines, and with minimal horizon pollution.</p>
Farmers and gardeners	<p>Interests: Do not want anything to change, the agriculture is growing and need more drink water to be productive. The opening of the Haringvliet will cause salinization of groundwater, which cannot be used in agriculture.</p> <p>Power: Agriculture on the former islands along the Haringvliet is among the most advanced in the Netherlands.</p> <p>Attitude: Relevant for political support and permits, for matters related to the effects on agriculture and horticulture.</p>

Table A.1: Stakeholder overview Delta21 (Delta21, 2024a)

All these different stakeholders need to be brought together by the government. The government must take the initiative, for example, by setting up a commission within the government, similar to the Zuiderzee Service. Currently, Delta21 has done a lot of outreach work to inform all parties about the plan and listen to various interests (Delta21, 2024a).

As a result of the known interests, the following concessions have already been made:

- The tidal lake will become a nature reserve where the brackish water habitat can be recovered. On the one hand, saltwater tidal flows from the North Sea and on the other hand, freshwater flows from Haringvliet. This can be achieved by adding a fish migration river;
- In the energy storage lake, there will also be the potential to cultivate mussels, seaweed, or lobsters. This could provide opportunities for the fishing industry. The fishing industry, particularly shrimp fishing, is under significant pressure because the valuable shallow areas along the coast lie within the Natura 2000 area;
- The construction of the lake requires enormous amounts of sand. A large amount of the sand extracted from the lake can be reused, but there will still be a shortage. The Delta21 plan includes a deep/wide channel of 8 kilometers long (from the mouth of the Haringvliet to Stellendam). This sand can be used for the construction of the lake, and the channel is beneficial for fishermen;
- The opportunities for Goeree-Overflakkee are that the character of the islands along the coast will not be lost (Lavooij, 2024).

Stakeholders floating data center

The Netherlands has become one of the most important data hubs in the world. The strong digital economy is essential for the country's competitive position, but fluctuating regulations and the pressure on the energy infrastructure present challenges and cause societal debates (Morri, 2023). The owner of the data center and the operations team should also be aware of the importance of stakeholder relations, as the data center and staff will be important members for a long period of time (Gillin, 2020).

Data usage will continue to grow, increasing the demand for data centers to store and process these data. Data centers consume large amounts of energy, but at the same time, new data center developments could play a role in the energy transition (Morri, 2023). However, the conflict between stakeholders arises because renewable energy is subsidized by the Dutch taxpayers. Data centers consume a large amount of the green energy produced. This means that there is less renewable energy available for residents, making it harder to meet international agreements on energy use, such as the climate goals (Ipenburg, 2024). In addition, from Table 2.1 the interests of the energy sector is in conflict with the interests of the data center sector, since they are both interested in the renewable energy from Delta21. This can cause objections.

This project is particularly appealing to hyperscalers (e.g. Microsoft), as they possess the capacity for large-scale storage. The problem with hyperscalers is that they are focused on their own business and, as a result, do not deliver as much to the Dutch economy as is promised (Morri, 2023). In addition, stakeholders cite concerns about landscape impacts and a perceived lack of local value added (Grove et al., 2023). Non-hyperscale data center companies tend to prefer land-based data centers with lower capacity in order to reduce costs (R. Rosendaal, personal communication, 04-04-2025). However, there are developments regarding the government's cloud policy. The message from the Netherlands Court of Audit and experts is that the government should tighten its cloud policy, better assess associated risks, and avoid moving everything to the cloud, especially since 80% of cloud infrastructure is owned by American companies. Moreover, there should be a stronger focus on promoting Dutch and European cloud services (Kassa, 2025). The Dutch parliament believes that the government should take more control over its digital autonomy (Monterie, 2025). There is potential for a nationally driven investment that serves Dutch interests (L. Spin, personal communication, 26-03-2025).

In conclusion, the creation of floating structures requires an understanding of the social, economic, and legal barriers. Key governance challenges include the social acceptance of large-scale floating structures. The legal frameworks and governance arrangements must enable this (de Graaf-van Dinther et al., 2024). In addition, operators should be aware of any local activism and must provide complete transparency to avoid unforeseen conflicts.

B

Evaluation mooring system designs and pontoon shapes

This appendix provides detailed analyses, comparisons, and justifications for the preselection of the concept creations of the mooring system and pontoon structure. It is placed in the appendix to keep the main report clear and readable while ensuring that the design process remains verifiable.

Mooring system preselection

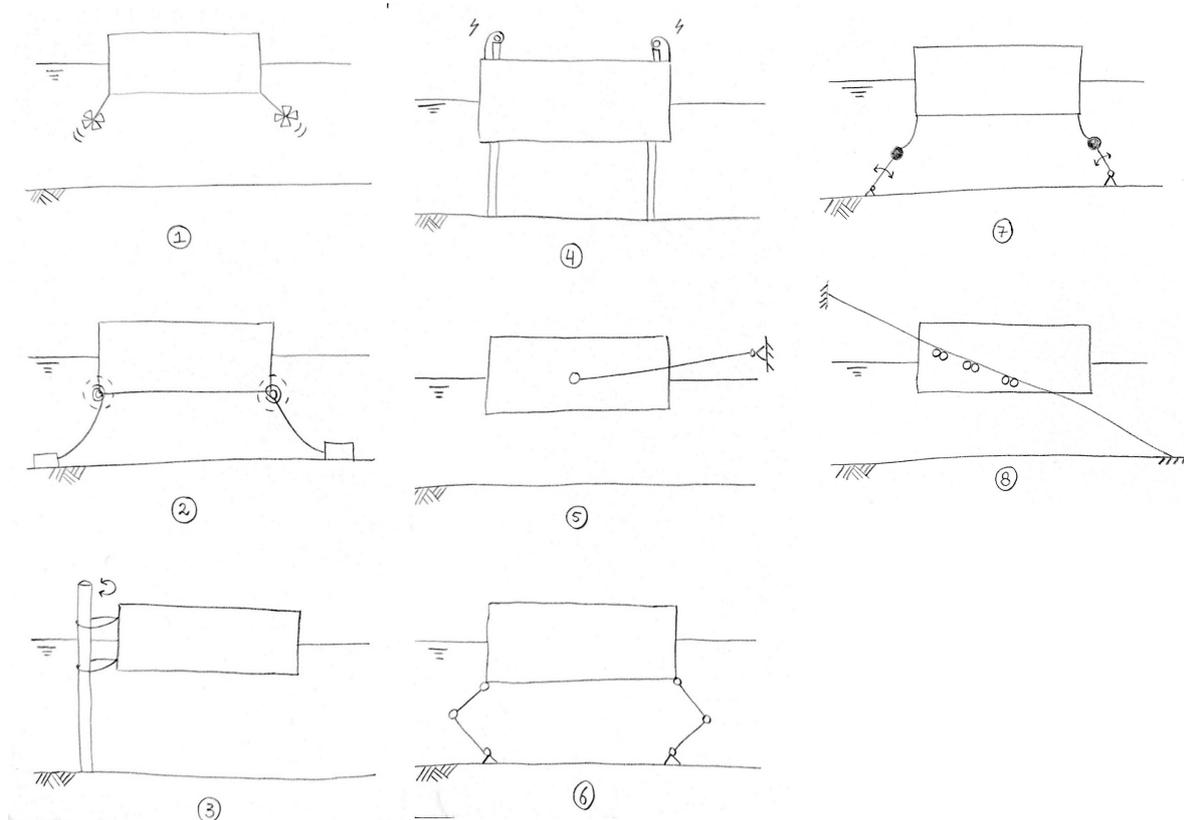


Figure B.1: Concept designs

Concept Design	Design with Nature	Flexibility	Systemic Thinking	Sustainability
1	<ul style="list-style-type: none"> + No bed disruption – Needs (green) energy – Blades are a threat to the local environment – System generates noise 	<ul style="list-style-type: none"> + Easy to move + Can be used in different water depths – Flexible system for infrastructure – Not robust, mechanical system can fail – Do not need that flexible structure, design life of 25 years 	<ul style="list-style-type: none"> + Solution to a real-world problem, because boats already exist – Not a good solution in its context 	<ul style="list-style-type: none"> +/- Does not need material for the mooring system, but does need other resources – Extra system causes higher probability of maintenance or failure – Not economical due to need for gas
2	<ul style="list-style-type: none"> + Stability in different direction for environmental conditions – Needs energy for water level adaptation system – Bed disruption 	<ul style="list-style-type: none"> + Gravity-based anchors make it possible to relocate the mooring system + The stability of the structure can be adjusted in various places – Dependent on extra adaptation system 	<ul style="list-style-type: none"> + Reference projects available: done before for smaller water level differences – Extra system for infrastructure 	<ul style="list-style-type: none"> + Economical with material – Extra system causes higher probability of maintenance or failure – Difficult to maintain
3	<ul style="list-style-type: none"> + Adapts to environmental conditions +/- Solar panels on top must also adapt to the rotation of the structure – Construction exposed to air and brackish water – Bed disruption 	<ul style="list-style-type: none"> – Flexible system for infrastructure 	<ul style="list-style-type: none"> – System is sensitive to vibrations 	<ul style="list-style-type: none"> +/- Maintainable – Degrees of freedom cause higher probability of maintenance or failure – Foundation difficult to decommission
4	<ul style="list-style-type: none"> + Generates gravity-based renewable energy + Stability in different direction for environmental conditions – Construction exposed to air and brackish water – Bed disruption 	<ul style="list-style-type: none"> – Not robust, energy generation system can fail 	<ul style="list-style-type: none"> + Multifunctional due to gravity-based energy generation system – System is sensitive to vibrations – Extra system for infrastructure 	<ul style="list-style-type: none"> +/- Maintainable – Extra system causes higher probability of maintenance or failure – Foundation difficult to decommission

Table B.1: Preselection of mooring designs based on design values (part 1)

Concept Design	Design with Nature	Flexibility	Systemic Thinking	Sustainability
5	+ No bed disruption + Construction only exposed to air	+ Can be used in different water depths	+ Multifunctional due to integration of infrastructure in mooring system – At different water levels the mooring system and structure interact due to different angle of the arm	+ Foundation at ground level, easy to construct and decommission + Easy to maintain
6	– Bed disruption	+ Stability in different direction for environmental conditions	– Extra system for infrastructure	– Dependent on several hinges, risk of failure – Foundation difficult to decommission – Difficult to maintain
7	– Bed disruption	+ Stability in different direction for environmental conditions – Multiple materials and connections between different materials, not robust	– Extra system for infrastructure – At different water levels difficult to ensure function of the mooring system	– Foundation difficult to decommission – Difficult to maintain
8	+ Mooring system can give place for local environment – Construction exposed to air and brackish water – Bed disruption	– Multiple hinges, not robust	+ Multifunctional due to integration of infrastructure in mooring system – System is sensitive to vibrations	+ Mooring system can be a meeting place for people +/- Maintainable – Foundation difficult to decommission

Table B.2: Preselection of mooring designs based on design values (part 2)

Pontoon shape evaluation

The following pontoon shapes are evaluated.



Figure B.2: Pontoon designs (top view)

In reference projects of floating data center concept designs, the following shapes are used. In the concept design for floating data centers (Stalpers, 2025) and the floating nuclear power plant (Core-Power, 2025), cylindrical structures are developed. The cylindrical shape can help reduce the impact of the wind load on the structure. On the other hand, in May 2025, Japan built a demonstration model of a floating data center that could be the first step toward offshore floating data centers cooled with seawater. This demonstration model is a rectangular structure, with a length of 80 meters and a width of 25 meters, equipped with solar panels (Stalpers, 2025).

Lessons learned about pontoon shapes from the offshore floating structures industry are the following. Pontoon design 3, with hexagonal shapes, has the added advantage of being modular and easily scalable up or down. However, it is recommended that the hexagonal modules use smooth-edged sides, as greater moment concentrations have been observed with jagged edges. For box-like structures such as pontoon designs 1 and 2, tensile stresses decrease with an increase in the thickness of the floor or wall. The presence of internal walls is beneficial for increasing bending stiffness and can therefore reduce the tensile stresses (Jiang et al., 2021). Evaluations from (Jiang et al., 2021) suggest that it is preferable to choose rectangular 2-cell modules or 6-cell hexagonal modules as a structural solution. The material costs for the hexagonal module are the lowest, but the complex configuration of the construction process is time consuming and costly.

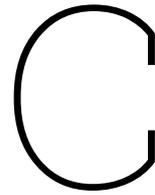
Reasoning scores of multi criteria analysis

The reasoning behind the scores assigned to each alternative in the multi criteria analysis is as follows.

- Alternative 1 scores the highest because it has the simplest geometry and requires the fewest components: consisting of only one structural arm without internal bracing. This simplicity allows for faster fabrication and easier repetition during production. However, since the outer dimension must be larger to achieve comparable stiffness and strength, manufacturing tolerances become more critical, which may complicate large-scale production. Alternative 4 scores the lowest due to its more complex internal bracing and a higher number of joints, which increases the fabrication time and assembly effort.
- Alternative 2 performs best because it combines structural redundancy with relatively low weight, improving both transportability and installation safety (its truss configuration provides stability and reduces risk of deformation during lifting). Alternative 1, although simple, is more susceptible to instability during handling due to its single-member structure, while alternatives 3 and 4 are heavier and require larger lifting capacities and more assembly steps.
- Alternative 4 scores highest because its redundant truss configuration ensures better load distribution and reduces local stress concentrations, improving fatigue and corrosion resistance. Triangular bracing reduces cyclic loading effects compared to single-member systems. Alternative 1 scores the lowest due to its single load path, resulting in higher stress amplitudes and lower fatigue resistance under dynamic environmental load.
- Alternative 4 also performs best in terms of flexibility because it provides multiple load transfer paths, allowing better adaptability to varying environmental conditions. The structural configuration can accommodate small displacements without compromising stability. Alternative 1 is the least flexible option, as its single rigid element provides limited adaptability.

- Alternative 1 achieves the highest score because its simple single-arm configuration is straightforward to analyze, fabricate, and certify. The limited number of connections and components reduces uncertainty and simplifies compliance with existing offshore design standards. Alternative 4, on the other hand, is more complex and would require additional verification steps, increasing time and effort to achieve certification.
- Alternative 4 shows the best performance with respect to structural behavior. Its multiple bracing elements and triangular geometry enhance stiffness, minimize deflections and dynamic responses, and provide torsional and overturning resistance. Alternative 1 performs worst, as it lacks redundancy and exhibits larger deflections under lateral and dynamic loads due to its single load-bearing member.
- Alternative 3 achieves the highest score because its modular truss layout allows easier access to inspect and repair individual components. The higher number of members can slightly increase inspection frequency, but redundancy of the system reduces the impact of potential failures and improves operational reliability. Alternative 1 requires the least maintenance effort in terms of frequency, but has no redundancy (meaning a single failure could lead to full system failure, which decreases overall maintainability).

In conclusion, alternatives 1 and 4 represent the two extremes of the design spectrum, each performing best in different criteria. Alternative 1 performs best in simplicity and constructability, whereas alternative 4 demonstrates better structural performance and durability. According to the multi-criteria analysis, alternative 3 provides the most balanced compromise between these extremes.



Reasoning mooring system dimensioning

This appendix includes the reasoning behind the dimensioning of the concept design. It documents the assumptions and parameter and/or configuration choices used to justify the initial dimensioning. This keeps the main report clear and readable while ensuring that the design remains transparent and traceable.

Mooring arm slope

First, an expected critical component is the fiber-optic interconnect. To avoid attenuation or fracture from over-bending, the long-term bend radius is taken as 15x the cable diameter (FOCC, 2019). For a 10 mm cable, this yields a minimum bend radius of 150 mm. Bending a 100 mm cable length over this radius corresponds to a maximum bend angle of $\theta = \frac{l_{cable}}{r_{bending}} = 0.67 \text{ rad} \simeq 38^\circ$. Verification is still required to confirm fatigue resistance under continuous vertical motions of the floating data center.

Second, from chapter 3, higher accessibility increases operational reliability and supports the 99.98+% functionality requirement (UptimeInstitute, 2025). Accordingly, the design respects a maximum stair angle of 30° , which also remains within the fiber-optic bending constraint established above.

Therefore, the governing geometric constraint becomes the embedment slopes for the Delta21 energy storage lake. The current concept uses a slope of 1:20, which implies mooring arm lengths of approximately 500 m. The dune next to the floating data center spans the Maasvlakte 2 coastline and is located inside the Delta21 energy storage lake (??). A prior study for Delta21 examined steep dunes (using a slope of 1:12.5). From this study further analysis is recommended to determine the optimal steep slope (van Dam, 2020). For the chosen floating data center site (where the dune is not the primary coastal defense), an initial design assumption of a slope of 1:10 of the mooring arm is adopted. This results in a slope of the dune $< 1:10$, for which further location-specific feasibility studies are recommended.

This assumption is consistent with environmental constraints chapter 3. Although only focusing on the functional design for the data center might allow slopes as steep as 1:2, minimizing material and cost. However, this would likely require a hard overflow structure at the land–water interface, which would impact the Natura2000 area and conflict with the project’s preservation objectives section 2.3. By contrast, a slope of 1:10 approximately halves material quantities and costs relative to 1:20, while maintaining compatibility with accessibility, cable routing, and environmental requirements.

Mooring system configuration

Rigid mooring systems can commonly be found in marinas to secure jetties and walkways. Vertical translation can be achieved by allowing rotation of one or more connection arms. If the fluctuation in water level is relatively small, then rigid moorings can be provided to the shore, which could also be used to provide access to the pontoon for operation and maintenance. However, a rigid connection to the shoreline is likely to experience high yaw moments due to the distance between the shore and an

environmental force that has a line of action parallel to the shore (Whittaker et al., 2020). To account for these expected high yaw moments, choosing two mooring arms instead of a single arm is a logical design choice, as it improves overall reliability.

In addition, from maritime industry lessons learned, an optimal mooring arrangement has been identified (Aries, 2020), see Figure C.1. This arrangement is taken as a suitable first design choice for the mooring system.



Figure C.1: Mooring of ships in maritime industry (Aries, 2020)

Based on these findings from literature and practices in the maritime industry, the following mooring configurations have been developed.

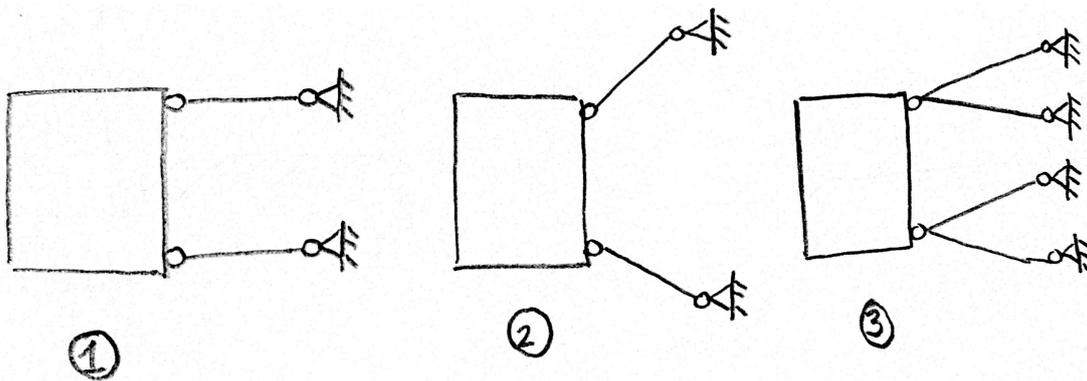


Figure C.2: Top view of possible configurations of the mooring system

Then these mooring configurations are qualitatively evaluated. With a slope of 1:10, the mooring arms reach a length of approximately 250 meters. Such long, slender structures are susceptible to buckling and therefore likely require structural enhancement through horizontal bracing.

Configuration 1 represents the simplest mooring arrangement. Compared to Configurations 2 and 3, it offers advantages in terms of material use, cost efficiency, and reduced CO₂ emissions.

In conclusion, two mooring arms are positioned perpendicular at the ends of the structure. For this configuration (1), several design alternatives for the horizontal bracing have been developed and evaluated in chapter 4.

Mooring arm diameter and wall thickness

Given the previously identified high yaw moments and the aim to steer the dynamic response favorably by providing high axial and bending stiffness (reducing resonance risk), the design assumes a tube diameter of 3 m with a wall thickness of 30 mm. These dimensions are practical from a constructability perspective. To reduce weight without compromising strength, steel grade S450 is selected. However, this choice must be validated in the detailed design, with particular attention to fatigue.

D

Calculations and results of design conditions

This appendix contains calculations and results of the design loads to demonstrate that these design decisions are technically substantiated. It presents a detailed methodology, while the main report shows only the key steps to maintain clarity and readability.

Self-weight loads

The weight of reinforced concrete is 26.5 kN/m^3 . Given the initial dimensions (section 4.4), the self-weight of the pontoon can be calculated.

		Load [kN/m]
G1	m_1 weight of pontoon	16551 (over width)
	m_2 weight of mooring arm	209 (per length/mooring arm)
	m_3 weight of relocatable ballast	–
	m_4 weight of permanent equipment	14000
G2	m_5 weight of marine growth	8
	m_6 weight of water absorption	11
	m_7 snow and ice	175
ΔG	3% of G1	911
G_{\max}	$G_1 + G_2 + \Delta G$	32074
G_{\min}	$G_1 - \Delta G$	30058
Buoyancy		32074

Table D.1: Self-Weight loads

Extreme value analysis for wind

The mean residual life plot is a graphical method that is used to select the threshold. It shows the mean excess as a function of candidate thresholds, with an approximately linear trend indicating the appropriate threshold range. For the wind data used in this report, the appropriate range is 8.5 – 9.7 m/s (see Figure D.1). Therefore, a threshold of 9.1 m/s is used for the peak-over-threshold analysis. To ensure that the peaks can be considered independently, a decoupling time of 48 hours is assumed. The decoupling time depends on the physical phenomena that drive the extreme event analyzed and the local conditions. The decoupling time for a storm can range from a few hours to 72 h. Therefore, the decoupling time should be verified (Lanzafame, 2025).

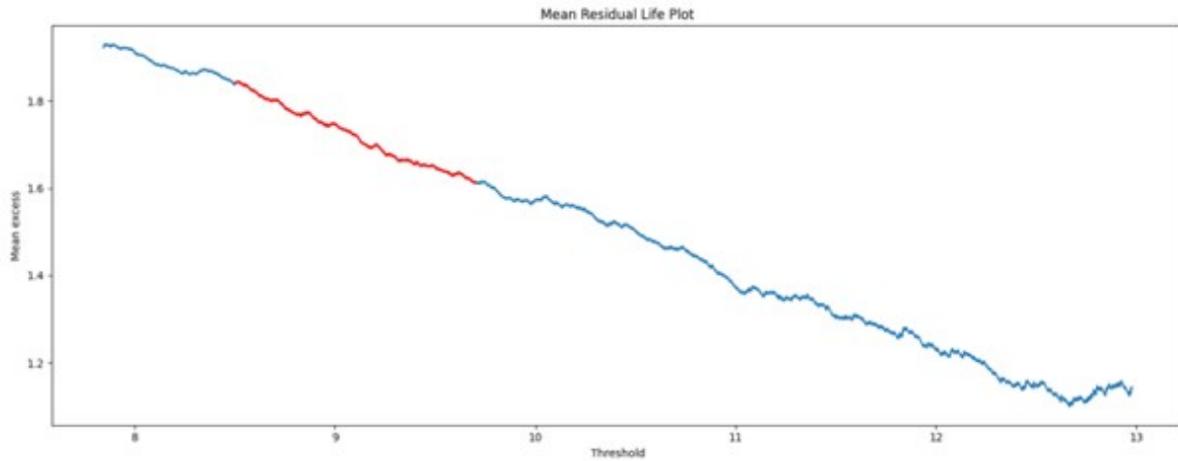


Figure D.1: Threshold analysis using MRL plot

Exceedances above the selected threshold are modeled using the peak-over-threshold method. Four candidate distributions are evaluated for the extremes: Weibull (2-parameter), Weibull (3-parameter), Gumbel, and Exponential, with parameters estimated by maximum likelihood. Based on the maximum likelihood estimate fit (see Figure D.2), the Weibull distribution provides the best match with the data. According to the Weibull fit, the 100-year return wind speed is estimated at 24.95 m/s.

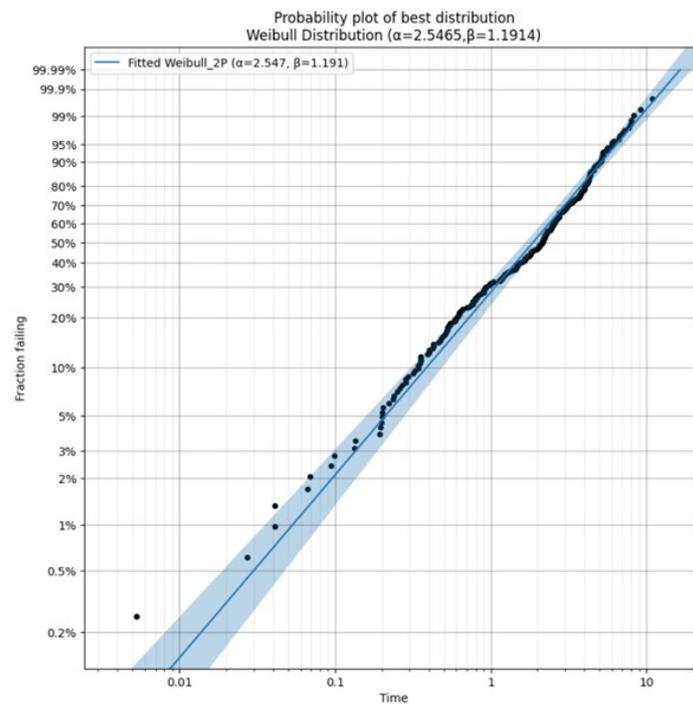


Figure D.2: Best fit wind speed

Finally, the decoupling time is evaluated using the dispersion index (DI). If $DI \simeq 1$, the decoupling time is considered plausible (Lanzafame, 2025). From Figure D.3, it is inferred that, for a threshold of 9.1 m/s, a decoupling time of 48 hours is plausible.

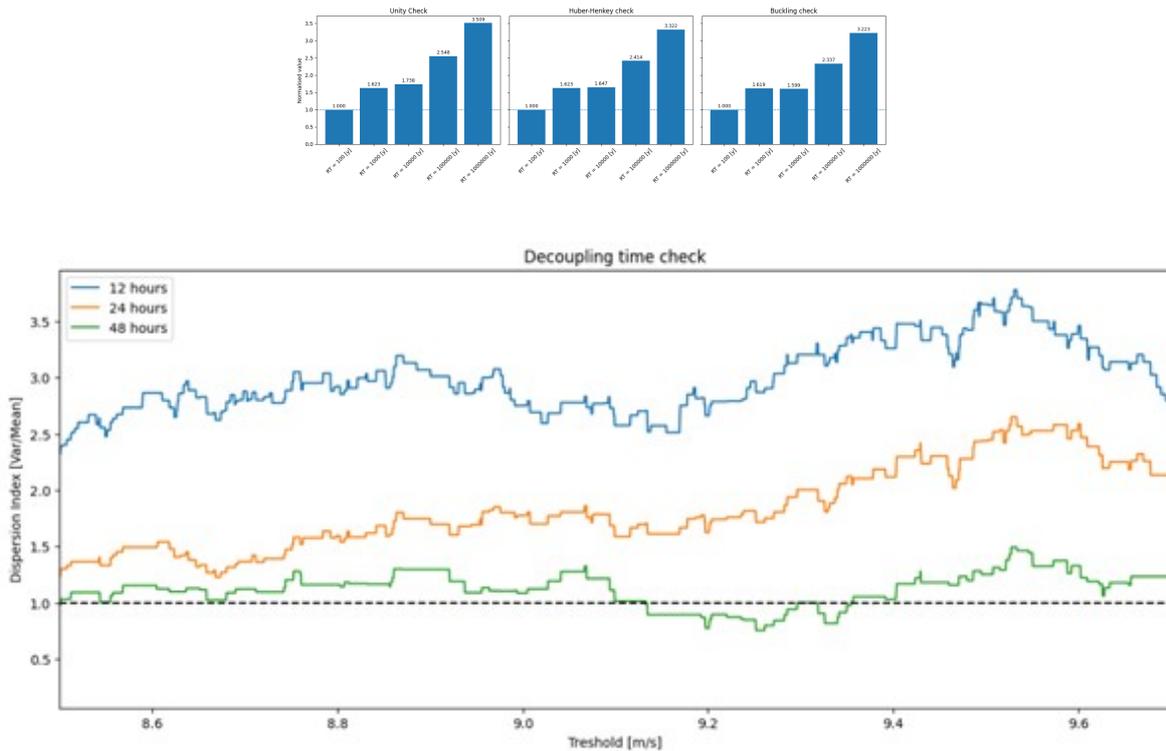


Figure D.3: Decoupling time for wind speed

Vortex shedding wind

Strouhal number for non-circular cross sections (Voorendt, 2023):

Where:

$$Re = \frac{uD}{\nu}$$

Extreme value analysis for wind generated waves

Form Copernicus data from every 3 hours from the past 6 years is collected at the location of Delta21 (longitude 51.54, latitude 3.54 according to Google Earth). The steps of section Figure 2.5.3 are used to calculate the significant wave height from this data. Note that for the calculation of the wind waves, only waves from South West direction are considered, due to the fetch length. Wind waves from other directions are assumed to be negligible at this stage of the design due to the limited fetch length.

The following procedure is used for the 3 water level conditions:

A peak over threshold analysis (POT) is performed to search for the extremes. Using the mean residual life plot method (MRL), the threshold is determined. Weibull is the best fitting distribution.

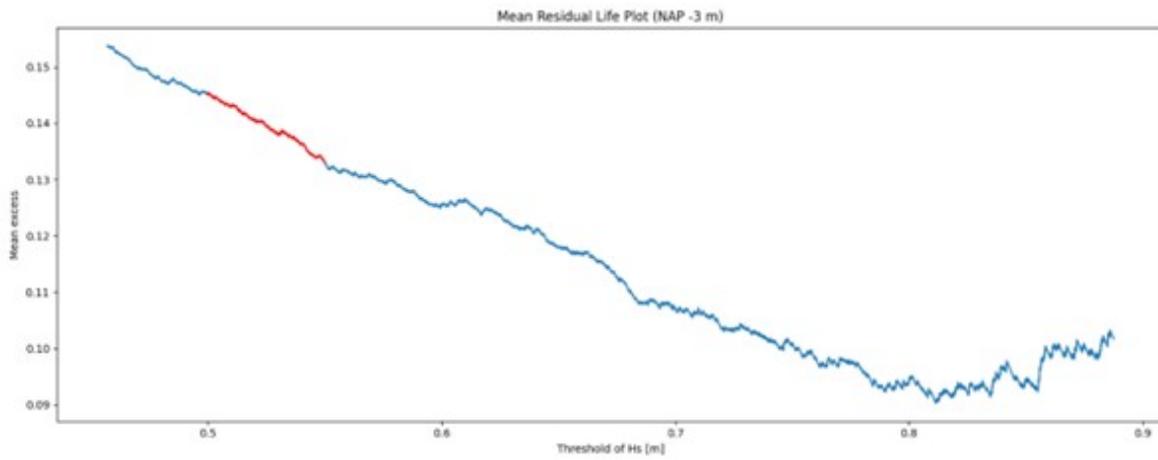


Figure D.4: MRL for water depth of 30 m: threshold = 0.53 m

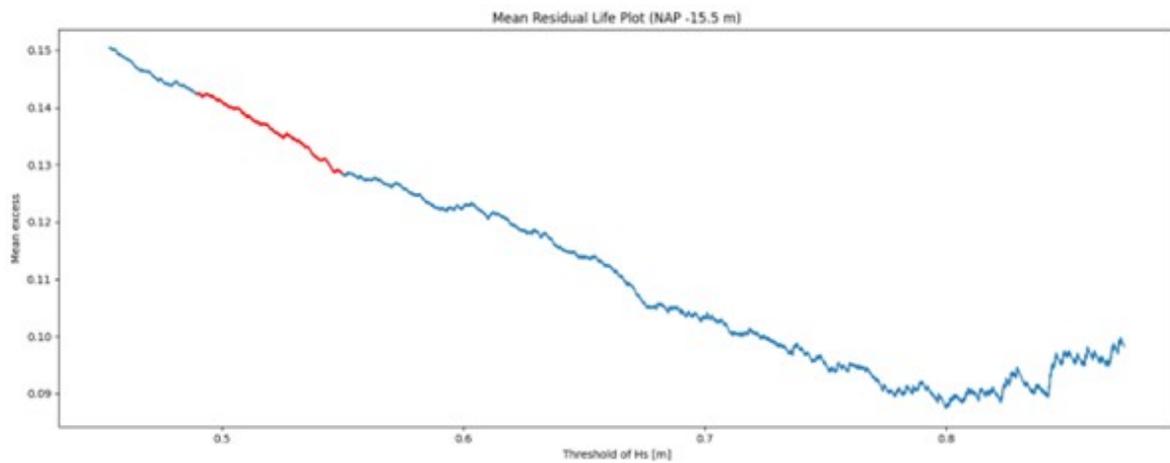


Figure D.5: MRL for water depth of 17.5 m: threshold = 0.51 m

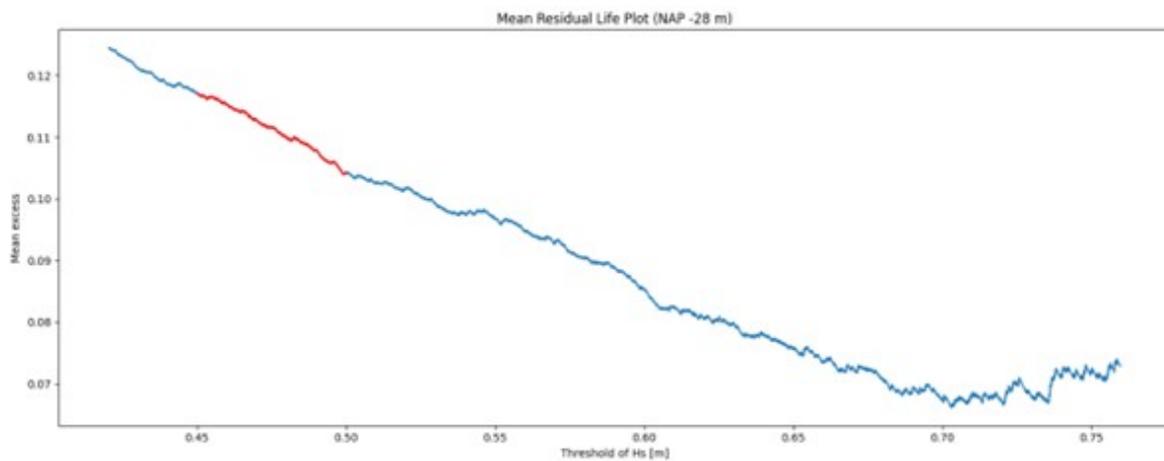


Figure D.6: MRL for water depth of 5 m: threshold = 0.47 m

From the predicted H_s for a return period of 100 year, the corresponding U_A is found to calculate the corresponding peak period (T_p), see Table D.2.

Water level	Hs [m]	Tp [s]
NAP -28 m	1.55	4.05
NAP -15.5 m	1.53	4.00
NAP -3 m	1.25	3.75

Table D.2: Wind generated waves parameters

Also, the decoupling time is checked using the dispersion index (DI). If $DI \approx 1$ then the decoupling time is assumed to be realistic. For NAP -3 m a threshold of 0.53 m with a decoupling time of 48 hours was assumed. For NAP -15.5 m a threshold of 0.51 m with a decoupling time of 48 hours was assumed. For NAP -3 m a threshold of 0.47 m with a decoupling time of 48 hours was assumed. This all seems realistic, see Figure G.2. However, for a water level of NAP -28 m it is questionable if a decoupling time of 24 hours could perform better. Because the same wind is taken into account for the different water levels, a decoupling time of 48 hours is considered reasonable (Lanzafame, 2025).

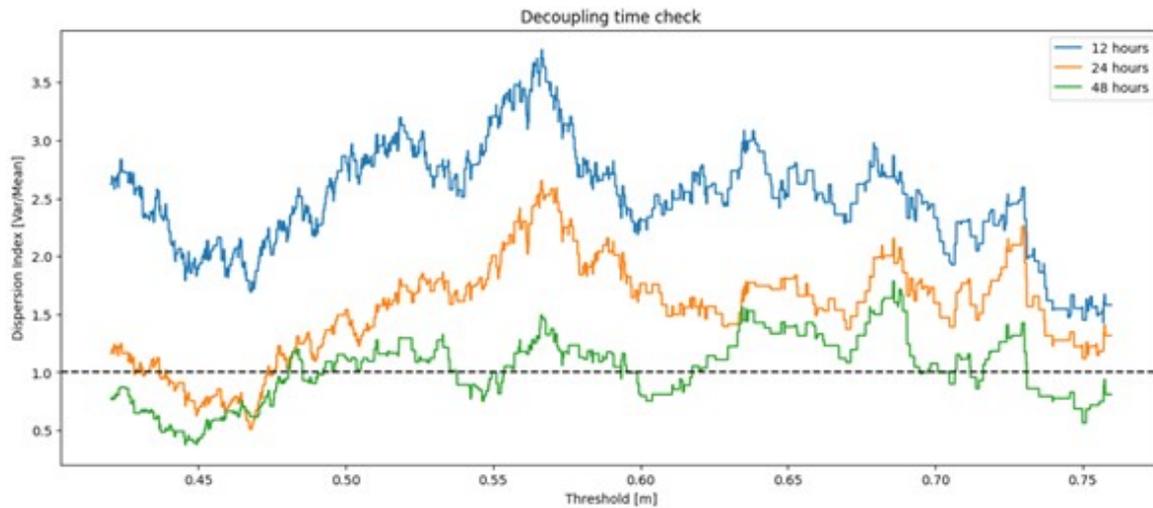
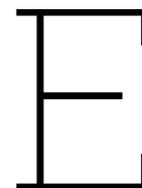


Figure D.7: Dispersion Index wind generated waves



Static structural analysis outcome

This appendix provides detailed results of the static structural analysis to substantiate the reasoning and maintain a concise and coherent main report, ensuring that the design process remains verifiable.

Results static analysis including mooring weight

High water level:

Support loads:

Support	x [kN]	y [kN]	z [kN]	M_x [kNm]	M_y [kNm]	M_z [kNm]
O1 (x=0 m)	202.719	-2187.918	-11.395	-0.000	19.227	340.888
O2 (x=25 m)	118.256	1008.987	-11.388	-0.000	-19.440	293.948
O3 (x=325 m)	167.569	-1697.125	-11.388	-0.000	19.468	321.372
O4 (x=350 m)	153.450	1500.053	-11.396	-0.000	-19.200	313.526

Global extremes mooring arm:

variable	value	unit	member
Mx	-747.15		S645
My	-2204.08		S614
Mz	-323.41		S581
Nx	-1992.74		S581
Vy	-14.22		S582
Vz	21.65		S602
sigmaHH	17.70		S582

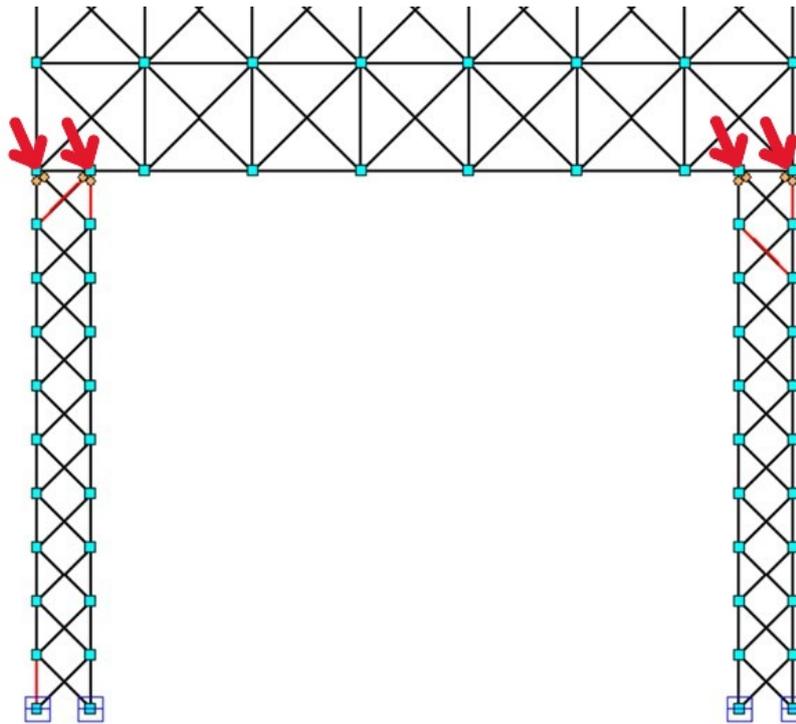


Figure E.1: In red the location of extreme moments, forces, and stress for high water level condition, also in red the forcing acting on the structure

Minimum and maximum displacement of the structure:

- $x_{min} = -26.9$ mm
- $y_{max} = 37.0$ mm
- $z_{max} = 242.5$ mm

Minimum and maximum rotations of the structure:

- $R_{x,min} = -1.46$ rad
- $R_{y,max} = 1 \cdot 10^{-6}$ rad
- $R_{z,max} = 7 \cdot 10^{-6}$ rad

Low water level:

Support loads:

Support	x [kN]	y [kN]	z [kN]	M_x [kNm]	M_y [kNm]	M_z [kNm]
O1 (x=0 m)	202.781	-2188.108	207.401	-0.000	52.668	338.673
O2 (x=25 m)	118.245	1009.171	-112.283	-0.000	9.403	295.896
O3 (x=325 m)	167.486	-1697.014	158.308	-0.000	50.941	319.157
O4 (x=350 m)	153.490	1499.948	-161.359	-0.000	11.599	315.293

Global extremes mooring arm:

Quantity	Value	Unit	member
Mx	747.23	kNm	S603
My	2200.52	kNm	S582
Mz	324.35	kNm	S581
Nx	-2001.64	kN	S581
Vy	-14.21	kN	S582
Vz	-21.47	kN	S644
sigmaHH	17.71	N/mm^2	S582

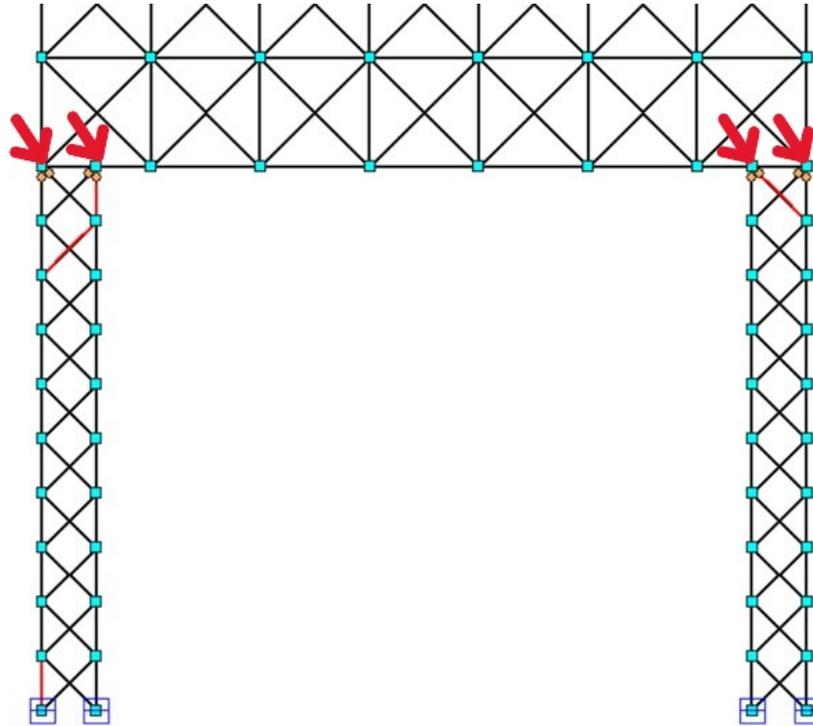


Figure E.2: In red the location of extreme moments, forces, and stress for low water level condition, also in red the forcing acting on the structure

Minimum and maximum displacement of the structure:

- $x_{min} = -26.9$ mm
- $y_{max} = 37.0$ mm
- $z_{max} = 242.5$ mm

Minimum and maximum rotation of the structure:

- $R_{x,min} = -1.46 \cdot 10^3$ rad
- $R_{y,max} = 2 \cdot 10^{-6}$ rad
- $R_{z,max} = 7 \cdot 10^{-6}$ rad

Conclusion static structural analysis including mooring weight

Highwater

The mooring arm satisfies the requirements.

Quantity	Value	Requirement	Satisfies	Element
Unity Check	0.0459	≤ 1.0	Yes	S582
Huber-Henkey check	0.0393	≤ 1.0	Yes	S582
Buckling check	0.0121	≤ 1.0	Yes	S623

Table E.1: Check results

The pontoon does not satisfies the requirements.

Quantity	Value	Requirement	Satisfies	Node
$ R_{x,max} $	1.454	≤ 0.005	No	K22
$ R_{y,max} $	0.0	≤ 0.005	Yes	K1
z_{max}	241.7	≤ 150	No	K6
z_{min}	-121.7	≥ -150	No	K1

Table E.2: Rotation and z checks per node

Low water

The mooring arm satisfies the requirements.

Quantity	Value	Requirement	Satisfies	Element
Unity Check	0.0464	≤ 1.0	Yes	S582
Huber-Henkey check	0.0396	≤ 1.0	Yes	S582
Buckling check	0.0119	≤ 1.0	Yes	S623

Table E.3: Check results

The pontoon does not satisfies the requirements.

Quantity	Value	Requirement	Satisfies	Node
$ R_{x,max} $	1.458	≤ 0.005	No	K3
$ R_{y,max} $	1.00×10^{-6}	≤ 0.005	Yes	K1
z_{max} [mm]	242.6	≤ 150	No	K6
z_{min} [mm]	-122.2	≥ -150	Yes	K37

Table E.4: Rotation and z checks per node

Conclusion static structural analysis neutral buoyant

The results for neutral buoyant structure are as follows.

High water:

The mooring arm satisfies the requirements.

Quantity	Value	Requirement	Satisfies	Element
Unity Check	0.0232	≤ 1.0	Yes	S581
Huber-Henkey check	0.0193	≤ 1.0	Yes	S581
Buckling check	0.0121	≤ 1.0	Yes	S623

The pontoon satisfies the requirements.

Quantity	Value	Requirement	Satisfies	Node
$ R_{x,max} $	0.0	≤ 0.005	Yes	K1
$ R_{y,max} $	0.0	≤ 0.005	Yes	K1
z_{max}	0.0	≤ 150	Yes	K1
z_{min}	0.0	≥ -150	Yes	K1

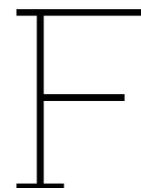
Low water:

The mooring arm satisfies the requirements.

Quantity	Value	Requirement	Satisfies	Element
Unity Check	0.0233	≤ 1.0	Yes	S581
Huber-Henkey check	0.0194	≤ 1.0	Yes	S581
Buckling check	0.0122	≤ 1.0	Yes	S623

The pontoon satisfies the requirements.

Quantity	Value	Requirement	Satisfies	Node
$ R_{x,max} $	1×10^{-6}	≤ 0.005	Yes	K1
$ R_{y,max} $	1×10^{-6}	≤ 0.005	Yes	K1
z_{max}	0.65	≤ 150	Yes	K42
z_{min}	-0.65	≥ -150	Yes	K1



Dynamic structural analysis outcome

This appendix provides the python code and detailed results of the dynamic structural analysis to substantiate the reasoning and maintain a concise and coherent main report, ensuring that the design process remains verifiable.

Python code dynamic structural analysis

First, set up the mesh:

```
Ele = []
for i in range(len(xv) - 1):
    n1 = i
    n2 = i + 1
    Ele.append([n1, n2, Pontoon_m, Pontoon_EA, Pontoon_EI, Pontoon_GJ, Pontoon_Im])
```

Figure F.1: Beam elements

```
def add_longitudinals_refined(master_idx, m, EA, EI, GJ, Im, le_target):
    for k in range(len(master_idx)-1):
        i0 = master_idx[k]
        i1 = master_idx[k+1]
        p0 = np.asarray(NodeC[i0], float)
        p1 = np.asarray(NodeC[i1], float)
        Lseg = float(np.linalg.norm(p1 - p0))
        nseg = max(1, int(np.ceil(Lseg / le_target)))
        prev = i0

        for s in range(1, nseg):
            a = s / nseg
            xyz = (1.0 - a) * p0 + a * p1
            NodeC.append([float(xyz[0]), float(xyz[1]), float(xyz[2])])
            cur = len(NodeC) - 1
            Ele.append([prev, cur, m, EA, EI, GJ, Im])
            prev = cur

    Ele.append([prev, i1, m, EA, EI, GJ, Im])
```

Figure F.2: Tube elements

```

def add_x_braces_masters(L_master, R_master, m, EA, EI, GJ, Im):
    for k in range(len(L_master)-1):
        Ele.append([L_master[k], R_master[k+1], m, EA, EI, GJ, Im])
        Ele.append([R_master[k], L_master[k+1], m, EA, EI, GJ, Im])

```

Figure F.3: Horizontal bracing elements

```

for xt in x_targets:

    i_moor = mooring_start_by_x[float(xt)]
    i_beam = beam_node_at_x(float(xt))

    xm, ym, zm = NodeC[i_moor]
    xb, yb, zb = NodeC[i_beam]
    if abs(ym - yb) < 1e-12 and abs(zm - zb) < 1e-12:
        NodeC[i_moor][2] = zm + eps

    Ele.append([i_moor, i_beam, Link_m, Link_EA, Link_EI, Link_GJ, Link_Im])

```

Figure F.4: Hinge elements

Master nodes of the mooring arm, to ensure tube/diagonal connections at the right place:

```

def append_polyline_master_nodes(x_const):
    idxs = []
    for yy, zz in zip(Yline, Zline):
        NodeC.append([x_const, yy, zz])
        idxs.append(len(NodeC)-1)
    return idxs

```

Figure F.5: Master nodes

Beam nodes, to ensure hinge connections at the right place:

```

def beam_node_at_x(x):
    cand = beam_ids
    return int(cand[np.argmin(np.abs(coords[cand, 0] - x))])

```

Figure F.6: Beam nodes

The resulting mesh is illustrated as follows:

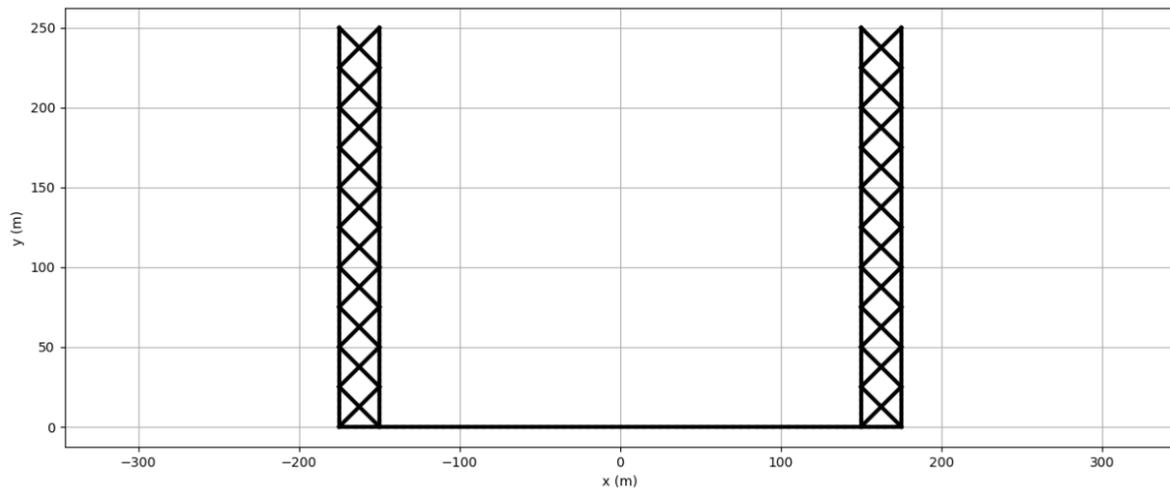


Figure F.7: Enter Caption

Second, the global matrices are assembled using the Beam3DMatrices formula:

```
Me, Ke, Qe = Beam3DMatrices(m, EA, EI, GJ, Im, (NodeC[n1], NodeC[n2]) )

indexes = np.append(n1dof, n2dof)
for i in range(0, 2*LDOF):
    for j in range(0, 2*LDOF):
        ij = indexes[i]*nDof + indexes[j]
        #print(ij)
        M[ij] = M[ij] + Me[i,j]
        K[ij] = K[ij] + Ke[i,j]
        Q[ij] = Q[ij] + Qe[i,j]
```

Figure F.8: Calculate elemental matrices and assemble global matrices

```
M = M.reshape((nDof, nDof))
K = K.reshape((nDof, nDof))
Q = Q.reshape((nDof, nDof))
```

Figure F.9: Reshape the global matrix from 1-dimensional to 2-dimensional array

Adding hydraulic stiffness, added mass, and weight to the global matrices:

```
K[i0*LDOF + Uz, i0*LDOF + Uz] += kz
K[i0*LDOF + Rx, i0*LDOF + Rx] += k_roll
K[i0*LDOF + Ry, i0*LDOF + Ry] += k_pitch

M[i0*LDOF + Uz, i0*LDOF + Uz] += A33
M[i0*LDOF + Rx, i0*LDOF + Rx] += A44
M[i0*LDOF + Ry, i0*LDOF + Ry] += A55

F[i0*LDOF + Uz] += -(mass_FDC)
```

Figure F.10: Adding hydraulic stiffness, added mass, and weight

Illustrating the mass matrix:

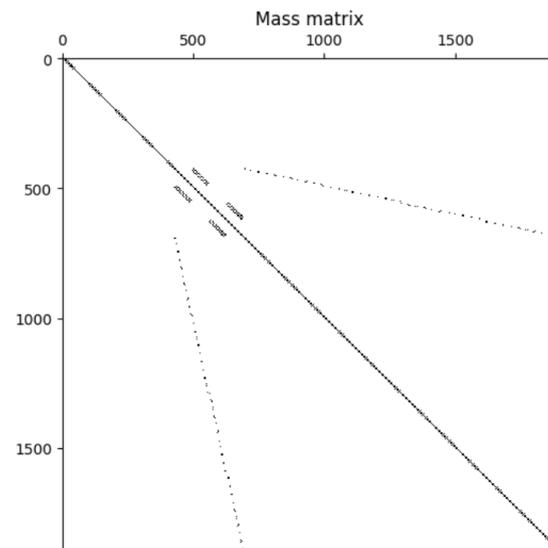


Figure F.11: Mass matrix

Illustrating the stiffness matrix:

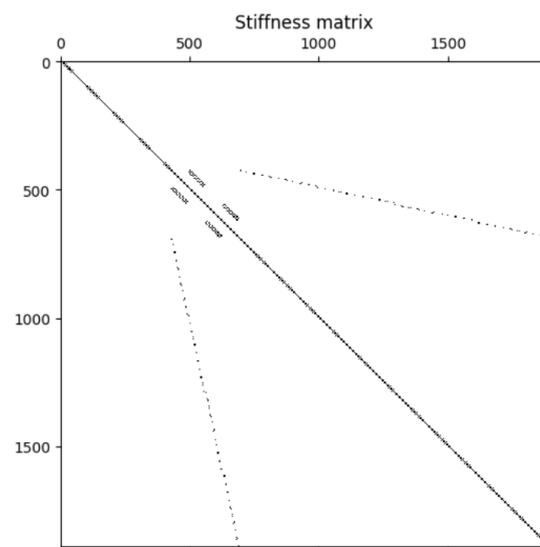


Figure F.12: Stiffness matrix

Third, apply boundary conditions:

```

support_nodes = []
for (xt, yt) in support_xy_targets:
    i = find_node_by_xy(xt, yt, y_tol=1e-6)
    support_nodes.append(i)
    print(f"Support target (x={xt:.1f}, y={yt:.1f}) -> node {i} at {coords[i]}")
support_nodes = np.unique(support_nodes)

DofsP_list = []
for n0 in support_nodes:
    base = n0 * LDOF
    DofsP_list += [base + Ux, base + Uy, base + Uz, base + Ry, base + Rz]
DofsP = np.array(sorted(set(DofsP_list)), dtype=int)

```

Figure F.13: Hinged support (Ux,Uy,Uz,Ry,Rz fixed, Rx free)

Interface conditions: To illustrate the method:

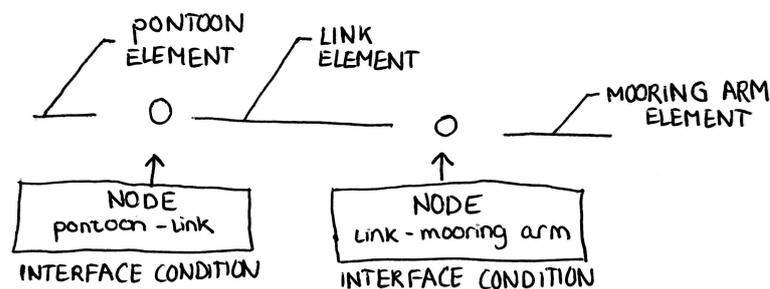


Figure F.14: Method for adding interface conditions for internal hinges explained

Parameter	Symbol	Value hinges	Unit
Mass per meter	m	1.0×10^{-18}	kg/m
Bending stiffness	EI	1.0×10^{-18}	N m ²
Axial stiffness	EA	1.0×10^{-18}	N
Torsional stiffness	GJ	1.0×10^{-18}	N m ²
Torsional inertia	I_m	1.0×10^{-18}	kg · m

Table F.1: Material and cross-section parameters for hinges used in the FEM

```

def add_penalty_tie(K, dof_i, dof_j, k_tie):
    K[dof_i, dof_i] += k_tie
    K[dof_j, dof_j] += k_tie
    K[dof_i, dof_j] -= k_tie
    K[dof_j, dof_i] -= k_tie

def hinge_tie_nodes(K, n_i, n_j, LDOF=6, k_tie=1e10):
    base_i = n_i * LDOF
    base_j = n_j * LDOF
    for dof in (Ux, Uy, Uz, Ry, Rz): # Rx vrijlaten
        add_penalty_tie(K, base_i + dof, base_j + dof, k_tie)

```

Figure F.15: Internal hinges between mooring arm and pontoon (Ux,Uy,Uz,Ry,Rz fixed, Rx free)

Assembling global matrices for free degree of freedoms:

```
M_FF = M[np.ix_(DofsF, DofsF)]
K_FF = K[np.ix_(DofsF, DofsF)]
Q_FF = Q[np.ix_(DofsF, DofsF)]
```

Figure F.16: Reduce to free degree of freedom

Finally, the modal analysis is performed:

```
mat = np.dot(np.linalg.inv(M_FF), K_FF)
w2, vr = np.linalg.eig(mat)
w = np.sqrt(w2.real)
f = w/2/np.pi
```

Figure F.17: Computing natural frequencies and mode shapes

```
idx = f.argsort()
f = f[idx]
vr = vr[:,idx]
```

Figure F.18: Sorting the natural frequencies and corresponding mode shapes

Verify with 100 year wind load from South West direction in a convergence study:

```
F = np.zeros(K.shape[0])
F[i0*LDOF + 0] += Fx
F[i0*LDOF + 1] += Fy
F_F = F[DofsF]

U_F = np.linalg.solve(K_FF, F_F)

U = np.zeros(K.shape[0])
U[DofsF] = U_F

Ux = U[i0*LDOF + 0]
Uy = U[i0*LDOF + 1]
disp_mag = np.sqrt(Ux**2 + Uy**2)

return disp_mag, len(NodeC)
```

Figure F.19: Insert wind load in global vector and extract displacements at i0 and at hinge (x=0)

```

D_values = []
N_nodes = []

for le_target in segment_lengths:
    print(f"\n=== Running FEM model with le_target = {le_target} m ===")
    try:
        D_val, nnode = build_and_solve(le_target, Fx_wind, Fy_wind)
        D_values.append(D_val)
        N_nodes.append(nnode)
        print(f"→ Displacement magnitude at i0 = {D_val:.6e} m (nodes = {nnode})")
    except Exception as e:
        print(f"→ Error at le_target={le_target}: {e}")
        continue

```

Figure F.20: Loop over meshes

For both, displacements at i0 and at hinge (x=0), the convergence study shows that the system is fully converged for the assumed nodes and elements.

```

=== Running FEM model with le_target = 25 m ===
→ Displacement magnitude at hinge (x=0) = 3.054696e-02 m (nodes = 315)

=== Running FEM model with le_target = 15 m ===
→ Displacement magnitude at hinge (x=0) = 3.054696e-02 m (nodes = 315)

=== Running FEM model with le_target = 10 m ===
→ Displacement magnitude at hinge (x=0) = 3.054696e-02 m (nodes = 315)

=== Running FEM model with le_target = 7.5 m ===
→ Displacement magnitude at hinge (x=0) = 3.054696e-02 m (nodes = 315)

=== Running FEM model with le_target = 5 m ===
→ Displacement magnitude at hinge (x=0) = 3.054696e-02 m (nodes = 315)

=== Running FEM model with le_target = 2.5 m ===
→ Displacement magnitude at hinge (x=0) = 3.054696e-02 m (nodes = 315)

```

Figure F.21: Results convergence study

Results dynamic structural analysis
High water:

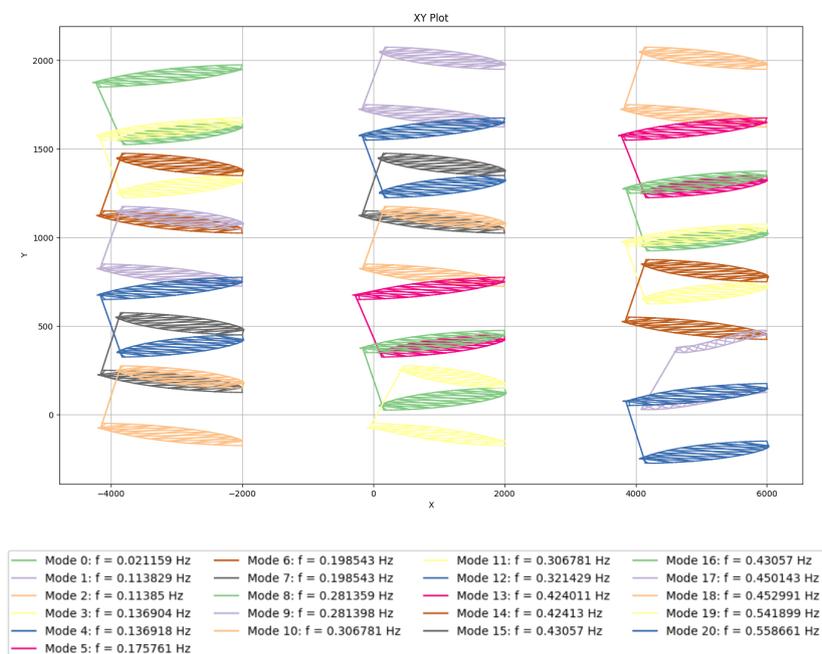


Figure F.22: Modal shapes in XY-plane

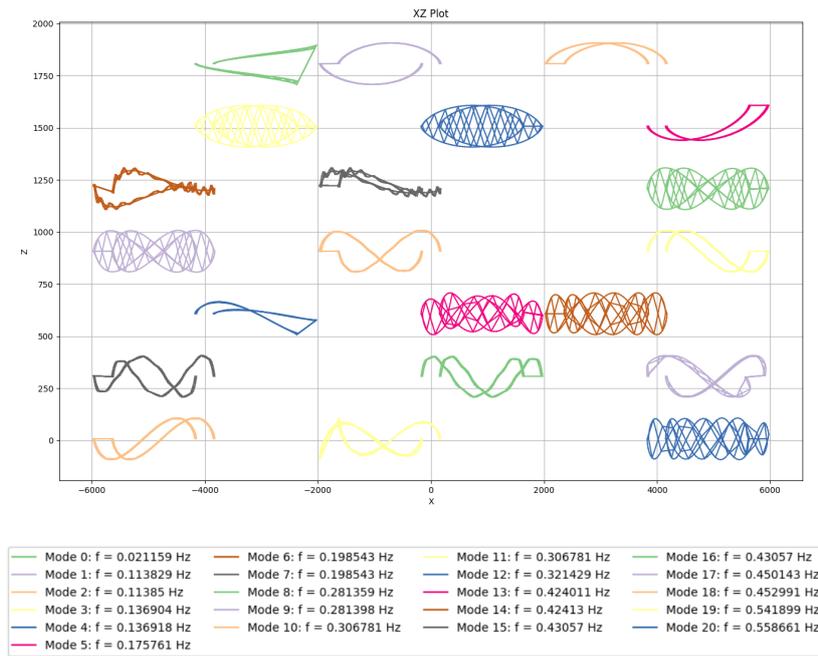


Figure F.23: Modal shapes in XZ-plane

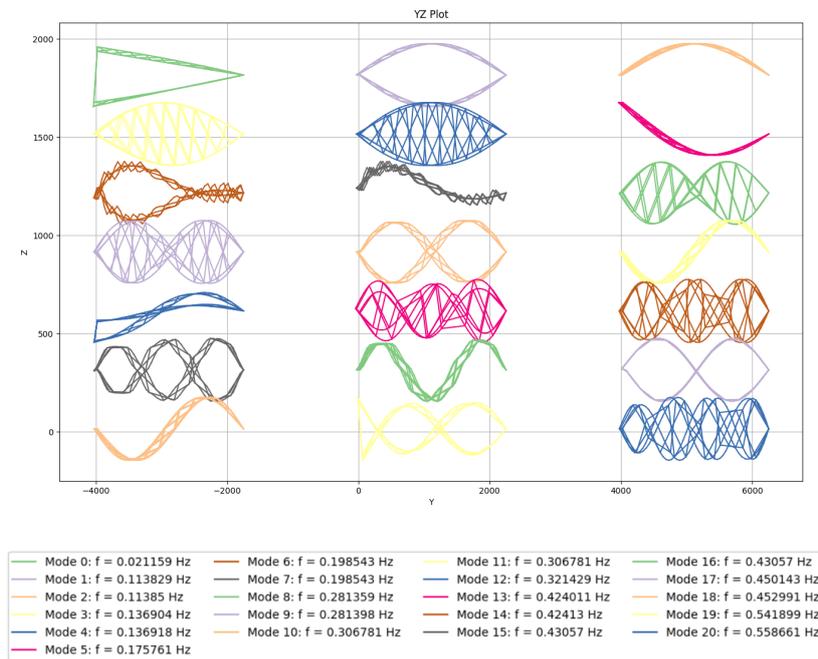


Figure F.24: Modal shapes in YZ-plane

Low water:

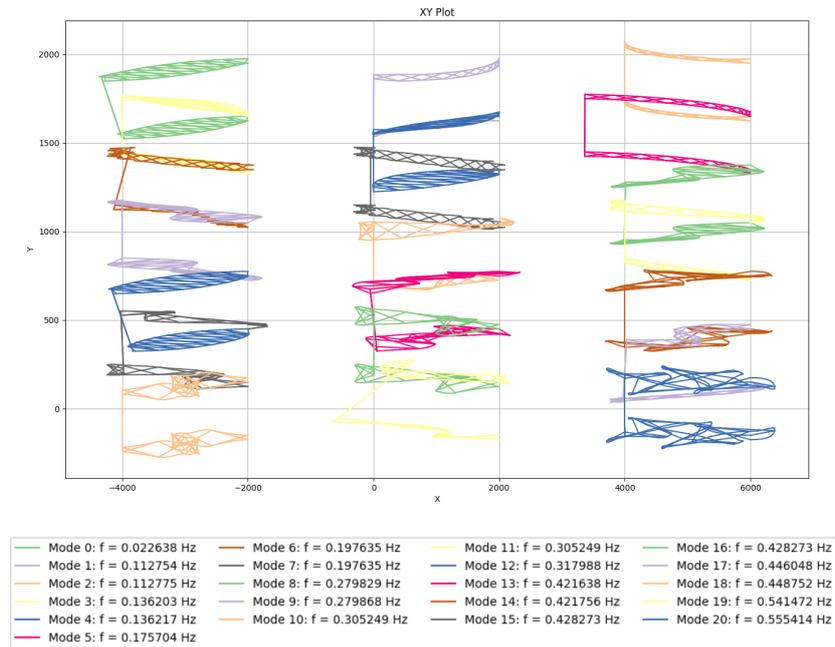


Figure F.25: Modal shapes in XY-plane

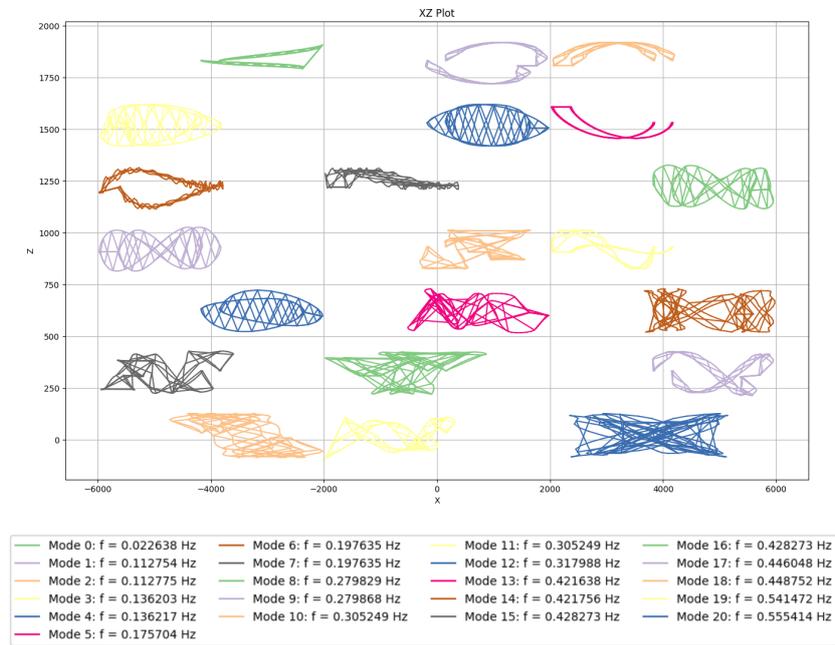


Figure F.26: Modal shapes in XZ-plane

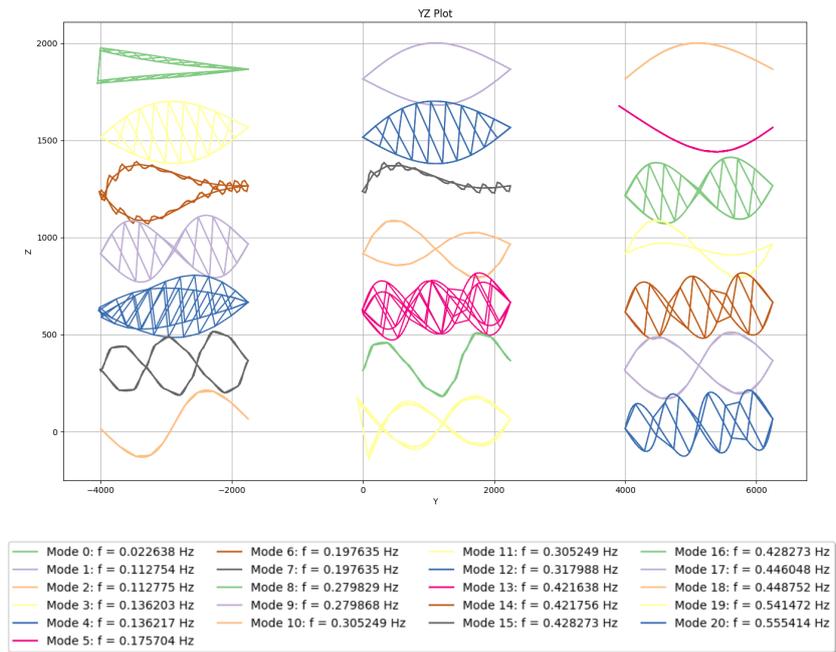


Figure F.27: Modal shapes in YZ-plane

G

Sensitivity analysis outcome

This appendix provides detailed results of the sensitivity analysis to substantiate the reasoning and maintain a concise and coherent main report, ensuring that the design process remains verifiable.

Return period sensitivity

The same model as for the static analysis is used. The axes system is defined in Figure G.1.

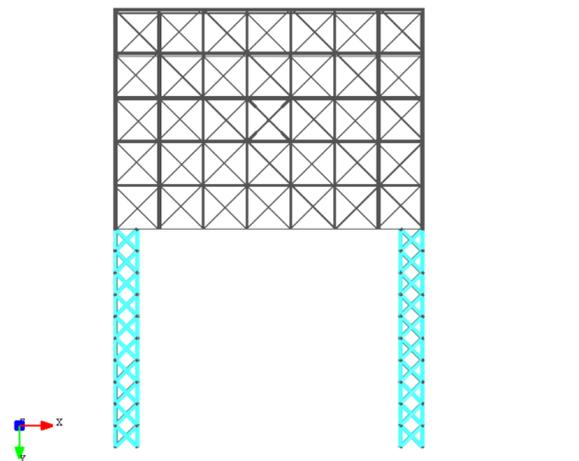


Figure G.1: Axes system sensitivity model

Input loads:

Return period	RT = 100 [y]	RT = 1000 [y]	RT = 10000 [y]	RT = 100000 [y]	RT 1000000 [y]
F_w [kN]	1519	1957	2424	2918	3438
$F_{w,x}$ [kN]	-642	-827	-1025	-1233	-1453
$F_{w,y}$ [kN]	1376	1773	2197	2644	3116

Table G.1: Wind force per return period

Results:

High water:

Return period [y]	10^2	10^3	10^4	10^5	10^6	Requirement	Satisfies	Element
Unity Check	0.0232	0.0299	0.0370	0.0445	0.0525	≤ 1.0	Yes	S581
Huber-Henkey check	0.0193	0.0249	0.0308	0.0371	0.0437	≤ 1.0	Yes	S581
Buckling check	0.0129	0.0167	0.0207	0.0249	0.0293	≤ 1.0	Yes	S623

Table G.2: Strength checks per return period high water level

Return period [y]	10^2	10^3	10^4	10^5	10^6	Requirement	Satisfies	Node
$ R_x _{\max}$	0.0	0.0	0.0	0.0	0.0	≤ 0.005	Yes	K1
$ R_y _{\max}$	0.0	0.0	0.0	0.0	0.0	≤ 0.005	Yes	K1
z_{\max}	0.0	0.0	0.0	0.0	0.1	≤ 150	Yes	K37
z_{\min}	0.0	0.0	0.0	0.0	-0.1	≥ -150	Yes	K6

Table G.3: Stability checks per return period high water level

Note that there is no change in pontoon displacements for the high water level case, except for the z_{\min} and z_{\max} displacements for a return period of 10^6 year.

Low water:

The pontoon and mooring arm satisfies the requirements for all return periods.

Return period [y]	10^2	10^3	10^4	10^5	10^6	Requirement	Satisfies	Element
Unity Check	0.0233	0.0300	0.0372	0.0447	0.0527	≤ 1.0	Yes	S581
Huber-Henkey check	0.0194	0.0250	0.0310	0.0373	0.0439	≤ 1.0	Yes	S581
Buckling check	0.0130	0.0168	0.0208	0.0250	0.0295	≤ 1.0	Yes	S623

Table G.4: Strength checks per return period low water level

Return period [y]	10^2	10^3	10^4	10^5	10^6	Requirement	Satisfies	Node
$ R_x _{\max}$	$4.0 \cdot 10^{-6}$	$5.0 \cdot 10^{-6}$	$6.0 \cdot 10^{-6}$	$7.0 \cdot 10^{-6}$	$8.0 \cdot 10^{-6}$	≤ 0.005	Yes	K1
$ R_y _{\max}$	$1.0 \cdot 10^{-6}$	$1.0 \cdot 10^{-6}$	$1.0 \cdot 10^{-6}$	$2.0 \cdot 10^{-6}$	$2.0 \cdot 10^{-6}$	≤ 0.005	Yes	K1
z_{\max}	0.8	1.0	1.2	1.5	1.7	≤ 150	Yes	K6
z_{\min}	-0.5	-0.6	-0.7	-0.9	-1.0	≥ -150	Yes	K43

Table G.5: Stability checks per return period low water level

High water return period sensitivity normalised values for the mooring arm checks.

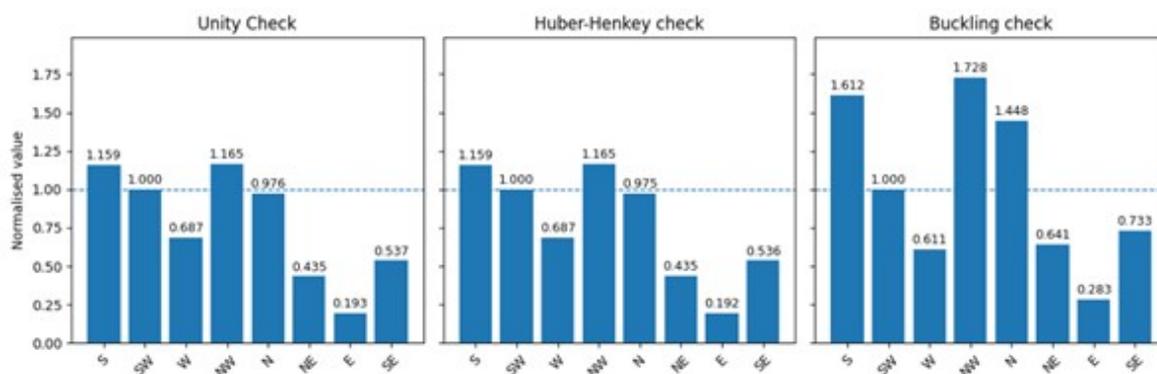


Figure G.2: MRL for water depth of 17.5 m: threshold = 0.51 m

Member break down sensitivity

In Table G.6 and Table G.7 the responses for the member checks for increasing return period conditions are shown. For each return period a member 'breaks down' and is deleted from the model.

Quantity	RT = 100 [y]	RT = 1000 [y]	RT = 10000 [y]	RT = 100000 [y]	RT = 1000000 [y]	Re
Unity Check	0.0332	0.0428	0.0370	0.0445	0.0525	
Huber-Henkey check	0.0292	0.0376	0.0308	0.0371	0.0437	
Buckling check	0.0202	0.0260	0.0207	0.0249	0.0293	

Table G.6: Member checks for increasing return period and member failure for high water level conditions

Quantity	RT = 100 [y]	RT = 1000 [y]	RT = 10000 [y]	RT = 100000 [y]	RT = 1000000 [y]	Re
Unity Check	0.033200112	0.054318592	0.057727727	0.084583783	0.116464696	
Huber-Henkey check	0.029222222	0.047780222	0.048117333	0.070468889	0.097038667	
Buckling check	0.020151235	0.032965864	0.032252945	0.047248946	0.065055846	

Table G.7: Member checks for increasing return period and member failure for low water level conditions

In Table G.8 the displacement factors are shown. To calculate this factor, one point was chosen in the model (point K6). By determining the displacements of this point for each return period and corresponding member break, the following factors were found.

Return period	RT = 100 [y]	RT = 1000 [y]	RT = 10000 [y]	RT = 100000 [y]	RT 1000000 [y]
$\frac{u_i}{u_{basecase}}$ high water level	1.0	1.26	1.56	1.90	2.22
$\frac{u_i}{u_{basecase}}$ high low level	1.0	1.27	1.56	1.90	2.22

Table G.8: Factor of displacement relative to the base case for member break down for increasing return period

Member	S581	S590	S601	S600	Member	S581	S590	S601	S600
SF_{UC}	1,00	1,43	5,17	7,40	SF_{UC}	1,00	1,44	5,53	7,92
SF_{HH}	1,00	1,51	5,61	8,04	SF_{HH}	1,00	1,52	5,62	8,07
SF_B	1,00	1,56	1,89	2,52	SF_B	1,00	1,56	1,90	2,54

Table G.9: Member break down sensitivity factors (only based on loads) for 100 year return period (left) and 10⁶ year return period (right)

Wind direction sensitivity

Forcing as a result of wind directions:

Wind direction	S	SW	W	NW	N	NE	E	SE
F_w [kN]	921	1519	1231	950	775	662	328	437
$F_{w,x}$ [kN]	865	-642	-421	-861	-728	279	112	397
$F_{w,y}$ [kN]	315	1376	1160	-402	-265	-599	-389	185

Table G.10: Wind force per direction

High water:

Direction [-]	S	SW	W	NW	N	NE	E	SE	Requirement	Satisfies	Element
Unity Check	0.0269	0.0232	0.0159	0.0270	0.0226	0.0101	0.0045	0.0124	≤ 1.0	Yes	S623
Huber-Henkey check	0.0224	0.0193	0.0133	0.0225	0.0188	0.0084	0.0037	0.0104	≤ 1.0	Yes	S623
Buckling check	0.0209	0.0129	0.0079	0.0224	0.0188	0.0083	0.0037	0.0095	≤ 1.0	Yes	S581

Table G.11: Strength checks per wind direction high water level

Direction [-]	S	SW	W	NW	N	NE	E	SE	Requirement	Satisfies
$ R_x _{\max}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	≤ 0.005	Yes
$ R_y _{\max}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	≤ 0.005	Yes
z_{\max}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	≤ 150	Yes
z_{\min}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	≥ -150	Yes

Table G.12: Stability checks per win direction high water level

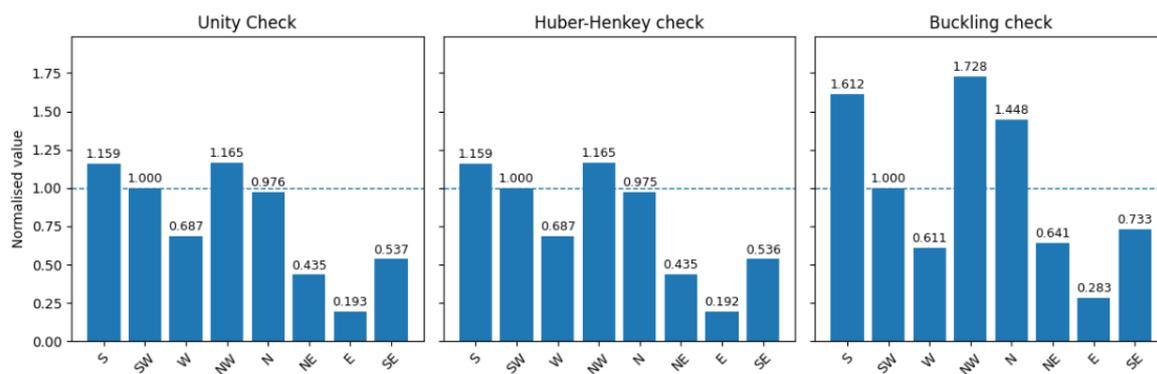


Figure G.3: Influence of wind direction on mooring arm checks for high water level

Low water:

Direction	S	SW	W	NW	N	NE	E	SE	Requirement	Satisfies	Element
Unity Check	0.0270	0.0233	0.0160	0.0271	0.0227	0.0101	0.0045	0.0125	≤ 1.0	Yes	S623
Huber-Henkey check	0.0225	0.0194	0.0133	0.0226	0.0189	0.0084	0.0037	0.0104	≤ 1.0	Yes	S623
Buckling check	0.0210	0.0122	0.0080	0.0225	0.0188	0.0083	0.0037	0.0095	≤ 1.0	Yes	S581

Table G.13: Strength checks per wind direction low water level

Direction	S	SW	W	NW	N	NE	E	SE	Requirement	Satisfies
$ R_x _{\max}$	$1.0 \cdot 10^{-6}$	$4.0 \cdot 10^{-6}$	$3.0 \cdot 10^{-6}$	$1.0 \cdot 10^{-6}$	$1.0 \cdot 10^{-6}$	$2.0 \cdot 10^{-6}$	$1.0 \cdot 10^{-6}$	0.0	≤ 0.005	Yes
$ R_y _{\max}$	$1.0 \cdot 10^{-6}$	0.0	0.0	$1.0 \cdot 10^{-6}$	≤ 0.005	Yes				
z_{\max}	0.3	0.8	0.6	0.3	0.2	0.2	0.1	0.2	≤ 150	Yes
z_{\min}	-0.3	-0.5	-0.4	-0.4	-0.3	-0.3	-0.2	-0.1	≥ -150	Yes

Table G.14: Stability checks per wind direction low water level

Influence of drag coefficient

The drag coefficient C_D is uncertain due to geometric detailing (surface roughness, edges, shape), Reynolds number, and angle of approach. Although the drag coefficient is typically obtained from wind-tunnel testing, such tests have not been performed for similar structures as the proposed floating system. Therefore, a sensitivity study is conducted in which the drag coefficient is varied around the base value over the representative range 0.9-2.4 (NEN-EN, 2023). Unlike the previous two studies (where wind speed was scaled), this analysis focuses on the aerodynamic efficiency of the wind loading

at the base case wind speed. The adopted coefficients are referenced to 10 m wind speeds, consistent with the data set in subsection 5.2.2.

Next, strength checks for the mooring system were carried out for the drag coefficient range. The significant results are for low water level conditions (see Figure G.4). Under the high water level conditions, the pontoon verifications are identically zero, see next section. For the low water level conditions, the pontoon verification results are shown in Figure G.5. It is observed that, similar to the return period sensitivity analysis, rotation about the y-axis only initiates after a critical load threshold is reached beyond which the rotation increases (it should be noted that this is an increase from $1 \cdot 10^{-6}$ to $2 \cdot 10^{-6}$). This corresponds to a change in the global stiffness of the system.

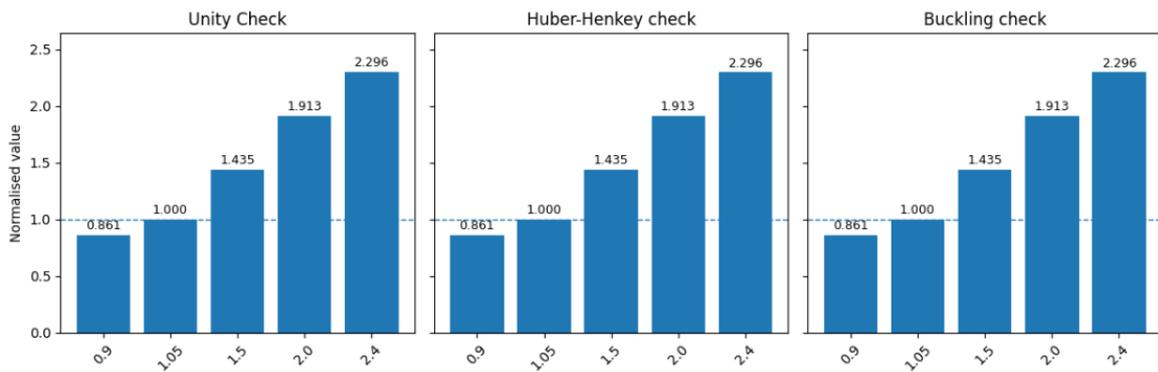


Figure G.4: Influence of Cd factor on mooring arm checks for low water level

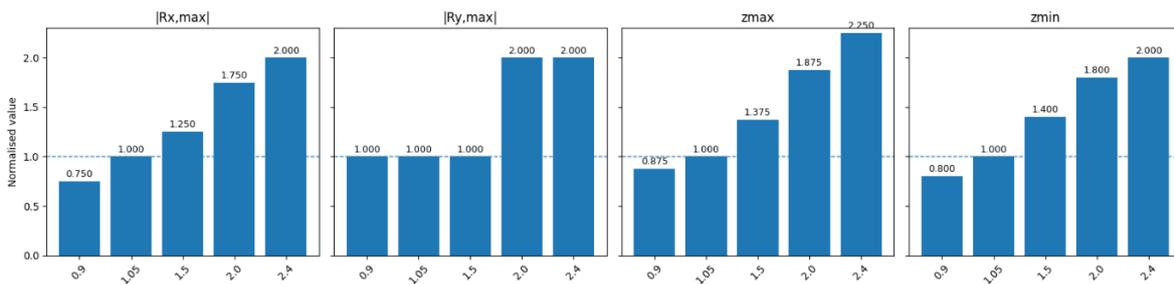


Figure G.5: Influence of Cd factor on pontoon checks for low water level

In conclusion, the drag coefficient analysis confirms a one-to-one scaling of the load effects with increasing drag coefficient. The observed increase in wind load under variations in the drag coefficient does not correspond to a physically more severe wind scenario. Instead, the increased loads arise from the linear dependence of the wind force model on the assumed drag coefficient. This indicates that the sensitivity reflects modeling uncertainty rather than a realistic physical process.

Cd factor sensitivity

Range of Cd factor from (NEN-EN, 2023):

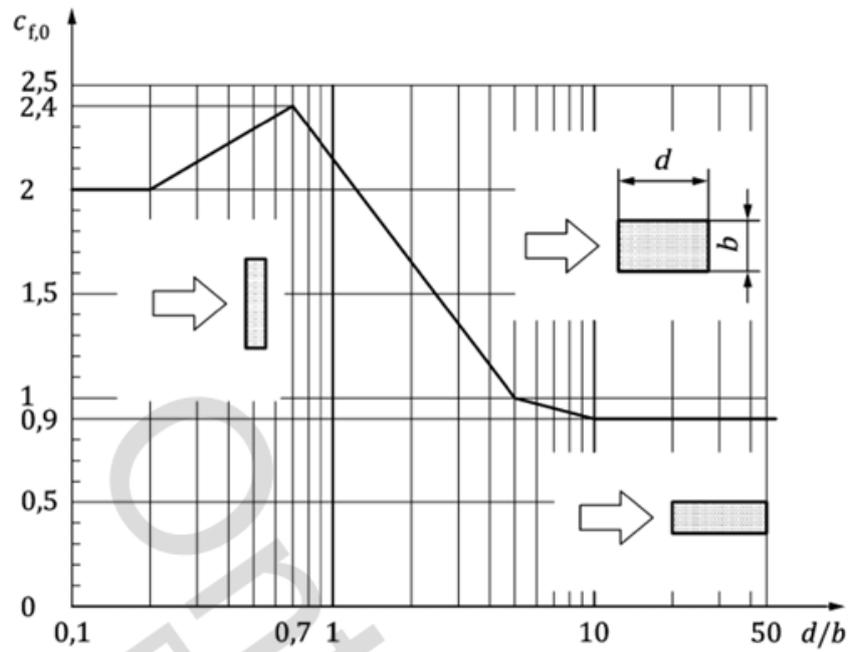


Figure G.6: Cd factors from (NEN-EN, 2023)

Wind forces as result of changing Cd factor:

Cd factor	0.9	1.05	1.5	2.0	2.4
F_w [kN]	1302	1519	2169	2893	3471
$F_{w,x}$ [kN]	-550	-642	-917	-1222	-1467
$F_{w,y}$ [kN]	1180	1376	1966	2621	3146

Table G.15: Wind force per Cd factor

Results:

High water:

Cd factor	0.9	1.05	1.5	2.0	2.4	Requirement	Satisfies	Element
Unity Check	0.0199	0.0232	0.0331	0.0441	0.0530	≤ 1.0	Yes	S581
Huber–Henkey check	0.0166	0.0193	0.0276	0.0368	0.0441	≤ 1.0	Yes	S581
Buckling check	0.0111	0.0129	0.0185	0.0246	0.0296	≤ 1.0	Yes	S623

Table G.16: Strength checks per Cd factor high water level

Cd factor	0.9	1.05	1.5	2.0	2.4	Requirement	Satisfies	Element
$ R_{x,\max} $	0.0	0.0	0.0	0.0	0.0	≤ 0.005	Yes	K1
$ R_{y,\max} $	0.0	0.0	0.0	0.0	0.0	≤ 0.005	Yes	K1
z_{\max}	0.0	0.0	0.0	0.0	0.1	≤ 150	Yes	K37
z_{\min}	0.0	0.0	0.0	0.0	-0.1	≥ -150	Yes	K6

Table G.17: Stability checks per Cd factor high water level

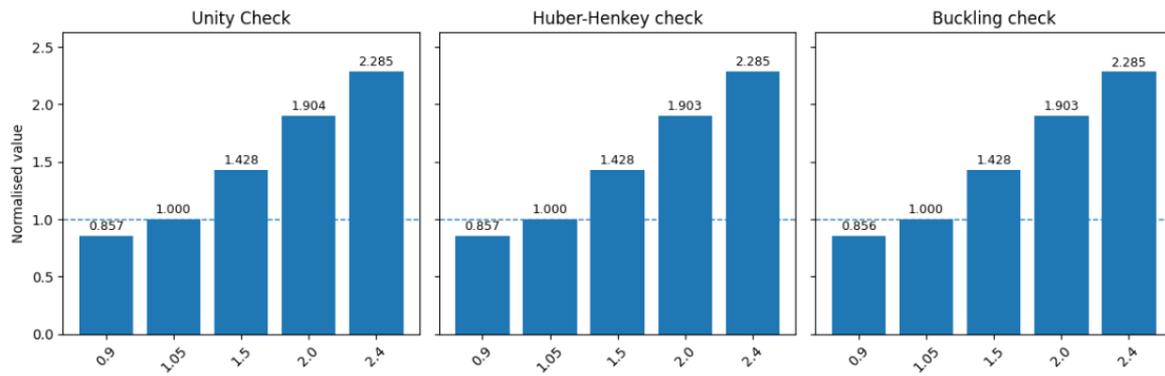


Figure G.7: Influence of Cd factor on mooring arm checks for high water level

Low water level:

Cd factor	0.9	1.05	1.5	2.0	2.4	Requirement	Satisfies	Element
Unity Check	0.0200	0.0232	0.0333	0.0443	0.0532	≤ 1.0	Yes	S581
Huber–Henkey check	0.0166	0.0193	0.0277	0.0369	0.0443	≤ 1.0	Yes	S581
Buckling check	0.0111	0.0129	0.0186	0.0248	0.0297	≤ 1.0	Yes	S623

Table G.18: Strength checks per Cd factor low water level

Cd factor	0.9	1.05	1.5	2.0	2.4	Requirement	Satisfies	Element
$ R_{x,\max} $	3.00×10^{-6}	4.00×10^{-6}	5.00×10^{-6}	7.00×10^{-6}	8.00×10^{-6}	≤ 0.005	Yes	K1
$ R_{y,\max} $	1.00×10^{-6}	1.00×10^{-6}	1.00×10^{-6}	2.00×10^{-6}	2.00×10^{-6}	≤ 0.005	Yes	K1
z_{\max}	0.7	0.8	1.1	1.5	1.8	≤ 150	Yes	K37
z_{\min}	-0.4	-0.5	-0.7	-0.9	-1.0	≥ -150	Yes	K6

Table G.19: Stability checks per Cd factor low water level