Oyster broodstock structures in offshore wind farms

TU Delft

Van Oord
Marine ingenuity

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December 2020

On the design of oyster broodstock structures for nature enhancement in offshore wind farms

by

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to obtain the degree of

Master of Science

in

Hydraulic Engineering

at the

Delft University of Technology

to be defended publicly on 17-12-2020

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Project duration:	February 2, 2020 – December 17, 2020	
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Executive summary

Countering the effects of climate change has become an increasingly important topic for governments and societies around the world. As a part of this effort, replacing energy generation methods that use fossil fuels with those based on renewable energy sources has become a key focus. Since offshore wind is seen as one of the major renewable energy sources, the Dutch Continental Shelf (DCS) has seen the erection of multiple wind farms over the past decades. The majority of these sites, use scour protection to protect monopile foundations from scour holes. The construction of these scour protections impacts the seabed environment of these appointed sites, replacing a sediment-based environment by placing of rock material, thus ousting some of the benthic species that inhabit these areas. However, while the insertion of hard substrate (widespread around each monopile) on the seabed changes the habitat, the newly constructed habitat can be enhanced for nature. By means of ecological enhancement, these scour protections are to become sites on which marine life can live in harmony with offshore wind industry. The Dutch government has been increasingly stimulating the offshore industry to apply ecological enhancement to offshore constructions, by imposing more stringent requirements to permit holders. This will aid the Dutch government in their goal to restore and maintain the marine ecosystem of the North Sea.
Creating new oyster reefs is one of the ecological enhancement methods that is of interest for nature-inclusive offshore wind farm scour protections. In order to enable oyster reefs to form in an area without oysters present, a broodstock population is required in the vicinity of the targeted area, such as a scour protection. The abundance of hard substrate available in these zones, as well as the shelter these sites provide from fishing activities makes them interesting areas for developing such reefs (Lengkeek et al., 2017). In spite of the favourable conditions found in an offshore wind farm, previous experiments have concluded that the currently available methods for ecological enhancement through oyster reefs were not successful in harbouring an oyster population, as the broodstock structures holding the oysters were unstable or did not provide the right habitat for the oysters (Bouma, Belze, et al., 2013; Stokes et al., 2012). This research explores the criteria for a successful design and produces such a design of an oyster broodstock structure for offshore wind parks, and applies this knowledge in Project Ecoscour. Project Ecoscour is part of the innovation site Borssele V and is a research project of the Royal Dutch Institute of Marine Research (NIOZ), Wageningen Marine Research (WMR), Hogeschool Zeeland (HZ), Bureau Waardenburg (BuWa) and Van Oord, with the goal to increase understanding of oyster restoration and provide guidance for oyster restoration projects. The goal of this study is:

Design stable and structurally robust flat oyster broodstock structures for nature enhancement in offshore wind farms.

This thesis follows the five-step design methodology by de Vriend et al. (2015)::

- Understand the system;
- Identify alternatives;
- Evaluate qualities of alternatives & select a solution;
- Fine-tune the selected solution;
- Prepare the solution for implementation.

Understand the system: flat oyster habitat & Borssele V site

Using the habitat criteria for flat oysters, four categories of design criteria were conceived. In a brainstorm with the partners in Project Ecoscour, design criteria were defined and were divided in the four categories:

Ecology	**Structural integrity**
Space for the oyster	Stability
Permeability structure	Durability structure
Protection against predation	Modularity
Protection against burial	Certifiability
Composition broodstock population	
Commissioning & construction	**Monitoring**
Costs	Liftability structure
Oyster accommodating surface	Sensing
Complexity of structure	Data transfer

Table 1: Design criteria for oyster enhancing structure

Identify alternatives

Together with experts from Royal Dutch Institute of Marine Research (NIOZ), Wageningen Marine Research (WMR), Hogeschool Zeeland (HZ), Bureau Waardenburg and Van Oord, eight structural design concepts were conceived by means of a brainstorm, following the design criteria.

Evaluate qualities of alternatives & select a solution

The terraced concept and tripod tree were selected as the best concepts following a SWOT analysis of the concepts, using the design criteria in Table 1.

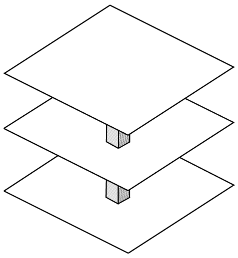

Figure 1: Terraced concept

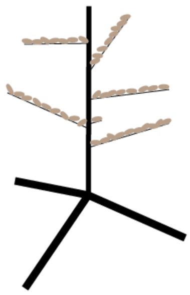

Figure 2: Tripod tree concept

Fine-tune the selected solution

In order to rapidly assess a structure for strength and stability, an open source tool was developed named Econstruct. This is an Object-Oriented Programme, in which geometries can easily be evaluated under various wave heights, wave periods, tidal currents and water depths, taking into account the effect of marine fouling on a structure. This could then be used for quick iterations to investigate loads, stability and structural integrity. Econstruct can be used for any structure that can be decomposed into cylindrical shapes or cuboid shapes. The model was validated and analysed for sensitivity for the input parameters, of which the input radius and current velocity had the highest influence on stability, following a One-At-a-Time sensitivity analysis.
By making use of unit testing, the Econstruct design tool was validated for the calculation of forces and moments on a structure composed of a cylindrical- or block shaped building block, in a submarine environment. Using the environmental input parameters that hold for the Borssele V wind farm, the following design was proposed:

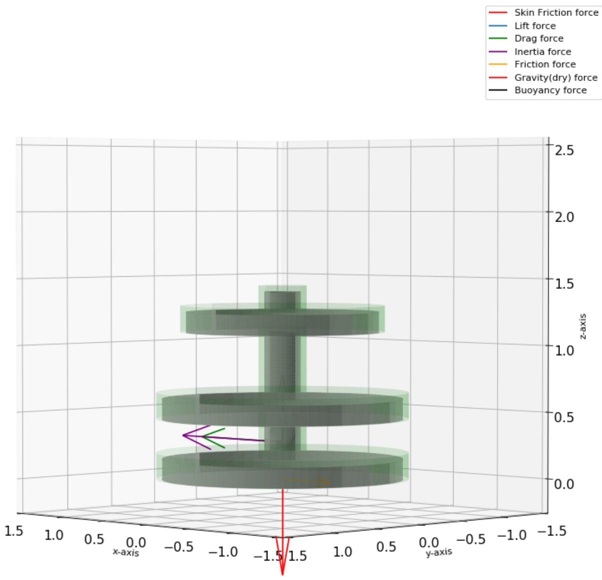

Figure 3: 3D render of Terraced concept in Econstruct

Prepare the solution for implementation

Due to manufacturing limitations, the design was altered by D & M engineers which resulted in the structure in Figure 4.
This alteration was tested later on and evaluated using the Econstruct design tool. The 3D render is shown in Figure 5. The structure was calculated to have a maximum inclination of 9° before failing due to sliding. It is expected that a the maximum wave in a storm with a return period of 50 years could subject the structure to critical loads causing it to slide. The probability for a wave to exceed the height of such a wave is $3.2 * 10^{-}4$, during its lifetime. It is therefore advised to inspect the structure after such an event and potentially increase the weight of the structure.

Figure 4: Altered terraced design by DM engineers

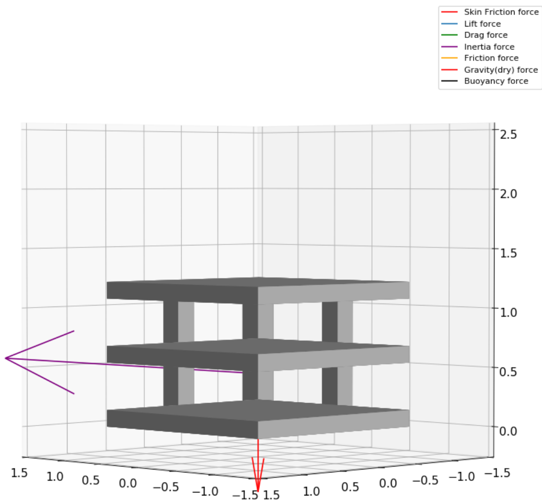

Figure 5: Altered terraced design run through the Econstruct tool

Conclusions & Recommendations

By studying the characteristics of a flat oyster habitat, design criteria for a broodstock structure were set together with experts in Project Ecoscour as a part of the conceptual framework. Various concepts were conceived, analysed and two were selected. Of one of the concepts, the terraced concept, a detailed design was made for the Borssele V site. A versatile rapid assessment tool was developed named Econstruct and for Project Ecoscour, a structure was designed. In total, four structures were manufactured and placed on site at Borssele V, as can be seen in Fig. 6. The manufacturing was done by D & M engineers, after which the structures were placed in October 2020 by Van Oord. These structures were assessed using Econstruct for safety. A number of recommendations have been made, such a monitoring plan and further research was recommended in geotechnical aspects and hydrodynamics.

Figure 6: The designed structures awaiting placement in the sun

Preface

Having started my time at the Delft University of Technology at the faculty of Aerospace Engineering, little did I know eight years later I was to finish my thesis on a subject in the domain of eco-enhancement engineering, designing an oyster enhancement structure.

The world of oyster enhancement and eco-engineering drew me from before I started this research, combining knowledge of two different disciplines and being able to consult a knowledgeable panel of oyster experts challenged me to think and design for in a multidisciplinary way. I was stimulated to develop software in Python, a language I could not work with before this project, which can now be helped designers in this field. I have learned a lot in the realisation phase of the project, involving manufacturers to check whether something cannot be built, is in hindsight a pretty big hurdle for designers at times. In the end, I believe I have contributed to the field of oyster enhancement and nature-inclusive design of offshore wind by mixing practical engineering thinking with ecological knowledge. I hope my legacy will carry on and more students and academics continue my work.

I would like to thank some people, not only for guidance in this project but also in everyday life, without whom this endeavour would have been much harder. Firstly, I want to thank Prof. dr. ir. Mark van Koningsveld for the insightful, patient and stimulating Python sessions we had over Teams, which sometimes exceeded 7pm. You stimulated my, in your words 'pioneering', work by being critical and supportive. Thanks also go out to ir. Tim Raaijmakers, whose interesting stories about offshore wind developments and models inspired me. You have given me plenty of ideas to add to my research, which I really appreciated. Thanks also go out to Prof. dr. Peter Herman, whose reaction to my first slide during the kick-off made me realise I entered a world where different powers were present than I knew existed. Many thanks for this experience, it has trained me to remain critical for different views and lines of thought in a new context.

Remment ter Hofstede and Willemijn Foursoff were instrumental for my work here, as my closest supervisors. Willemijn, thanks a lot for the those couple weeks in the end of July, where we worked under high pressure to deliver a practical design. Those weeks taught me a lot about the 'real deal'. Remment, you instilled in me the feeling of ownership about the project and reassured me about the path to take. I hope to work together with the both of you in the future!

Last but not least, I want to thank my family, Eric, Ella and Laura for their unconditional support and belief throughout my entire period as a student at the Delft University of Technology. You have stimulated to get the most out of my abilities and kept me close to myself. Thanks also go out to my friends and neighbours for making my period in Delft and Rotterdam as enjoyable as it was.

My next step will be to work at Van Oord as a Production Engineer, which means my journey that started with rockets has now evolved to studying and optimising processes for sediment on the seabed. Things do sometimes take quite a turn.

I have worked on this research with enthusiasm, I hope this piece will leave you just the same after reading.

Victor Alexander van Rie
Rotterdam, December 17, 2020

Abstract

Over the recent years, the Dutch Continental Shelf has seen the erection of various wind farms in an effort to counter climate change by replacing fossil-based power plants. Since the majority of these sites use scour protections which have a substantial impact on the surroundings, the Dutch government increasingly stimulates and requires ecological enhancement of such structures in order to restore the natural habitat and maintain the marine ecosystem of the North Sea. Oyster enhancement has been one of the methods used for the ecological enhancement of offshore wind farm scour protections. However, studies report that a successful structure for the harbouring of an oyster population is yet to be developed. Existing structures were found to be unstable or unable to provide a suitable habitat for the oysters (Bouma, Belze, et al., 2013; Stokes et al., 2012). The study at hand aims to develop a successful design for oyster broodstock structures for nature enhancement in offshore wind farms. It was conducted for Van Oord as part of project Ecoscour. To establish design criteria for the oyster broodstock structures, oyster habitats and the Borssele V site were analysed and a brainstorm session with partners from project Ecoscour was set up. The final criteria concerned: ecology; structural integrity; commissioning & construction; and monitoring. The design criteria were used to develop several viable structure designs. In order to rapidly assess the strength and stability of potential designs, a Python-based open source tool was built named Econstruct. With this tool, geometries can easily be evaluated under various influences, accounting for the effect of marine fouling. This could be used for quick investigations of loads, stability and structural integrity. The Econstruct tool was validated and analysed for sensitivity for the input parameters, of which the input radius and current velocity had the highest influence on stability. Using the environmental input parameters that hold for the Borssele V wind farm, a terraced design was proposed. After consultation with the manufacturer of the structure, D & M engineers, this proposal was altered to account for manufacturing limitations. The definitive design was evaluated using the Econstruct tool and found to be stable. It was then manufactured, and ultimately placed in Borssele V in October 2020. Several recommendations are made for future research and the design of ecological enhancement structures for offshore wind farms. Most importantly, the Econstruct open source tool can be used in the future for the design of structures for other ecological enhancement projects such as coral reef restorations.

Contents

List of Figures

List of Tables

List of Abbreviations

BuWa Bureau Waardenburg. iii, 8, 19

DCS Dutch Continental Shelf. iii, 3, 18

HZ Hogeschool Zeeland. iii, iv, 8, 17, 19

ICCP Impressed Current Cathodic Protection. 8

LAT Lowest Astronomical Tide. 34, 39

LCoE Levelised Cost of Energy. 8

MP Monopile. xix, 4, 34, 41, 96, 105

NAP Normaal Amsterdams Peil. 14, 56

NIOZ Koninklijk Nederlands Instituut voor Onderzoek der Zee. iii, iv, 8, 15, 17, 19

OAT One-at-a-time method. 49

OWF Offshore Wind Farm. 3, 13, 15, 17, 55–57, 103

ROV Remotely Operated Vessel. xvii, 7

TSA Thermal Sprayed Aluminum. 8

WMR Wageningen Marine Research. iii, iv, 7, 8, 19

WTG Wind Turbine Generator. xvii, xx, 3, 8, 15, 132

List of Symbols

ε	Plate roughness
ρ_w	Density of water
α_{cc}	Factor taking into account long term effects on the compressive strength
η	Surface elevation
γ_c	Partial safety factor for concrete
$\hat{p}_{wave}$	Wave pressure amplitude
$\hat{u}_x$	Amplitude of the velocity in the x direction
ω	Wave frequency
ω	Wave frequency, determined from the ratio $\frac{2\pi}{T_{peak}}$
ρ_f	Density of marine fouling
ρ_l	Reinforcing ratio
ρ_s	Density of concrete
C_A	Added mass coefficient
C_D	Drag coefficient
C_F	Skin friction coefficient
C_L	Lift coefficient
C_M	Mass coefficient
f_y	Yield strength of steel
f_{cd}	Design compressive strength of concrete
f_{ck}	Characteristic compressive strength of a concrete cylinder
$f_{ctk,0.05}$	Characteristic axial tensile strength of concrete
f_{ctm}	Maximum tensile load allowable in concrete
g	Gravitational constant (9.81 m/s^2 is used)
H_{max}	Maximum wave height
k	Wave number, determined from the ratio $\frac{2\pi}{L}$
k	Wave number
KC	Keulegan-Carpenter number
p_{wave}	Wave pressure
Re	Reynolds number
S	Wave steepness
S_n	Strouhal number

St	Strouhal number
T_{peak}	Peak wave period
u	Total current
u_c	Current velocity
u_w	Orbital velocity
u_x	Velocity in the x direction
x_c	Height concrete compressive zone
$\hat{u}$	Fluid particle acceleration (orbital motion)

Chapter 1

Introduction

Global warming has caused governments, institutions and multinationals to unite forces and aim for greenhouse-gas-emissions mitigation and adaptation. Many climate summits have been held in an attempt to achieve global consensus on the path towards a climate change-resilient world with low-carbon technologies, the latest of which is the Paris climate summit. The Paris climate summit, resulted in the Paris Agreement which has seen 195 signatories agree upon a long-term temperature increase goal of well below 2 °C (United Nations, 2015).
As global efforts to meet this sustainable energy goal are gathering momentum, it is crucial to explore low-carbon, affordable energy technologies. In their quest for new energy technologies, scientist may turn to an age-old technology that was first used by the Persians in A.D. 500-900 and later mastered by the Dutch in the 14th century to drain their lands: the wind mill (Pasqualetti et al., 2004; Shahan, 2014).
Offshore wind energy technology plays a key role in the energy transition of many states in Europe. Europe's pioneering role in this sector, the abundance of shallow waters, a favourable wind climate and the proximity of quality ports and energy consumers, makes the market for offshore wind energy a growth market. Between 2010 and 2018, the global offshore wind market grew approximately 30% per year, spurred on by rapid technology improvements. Although many projects are under construction worldwide, today's offshore wind market does not scratch the surface of the full potential of this market, with a potential of more than 420 000 TWh per year globally (Cozzi et al., 2019). Remarkably enough, one of the late adopters in the growth of

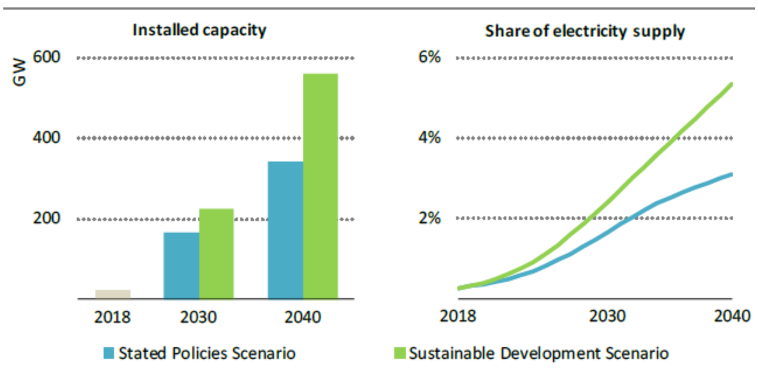

Figure 1.1: Global offshore wind installed capacity increases by fifteen-fold in the States Policies Scenario, raising its share of electricity supply to 3 % in 2040 (Cozzi et al., 2019)

offshore wind energy are the Dutch. Whilst neighbours such as the United Kingdom, Germany and Denmark are early investors in this renewable energy source, the Dutch have built two small wind farms on their shores, being Offshore Wind Farm Egmond aan Zee (OWEZ, 2006) and Princess Amalia Wind Farm (2008), although many more are under construction (RVO, 2015; Wind Europe, 2019). Large Wind Turbine Generators (WTGs) are to be constructed on selected sites on the Dutch Continental Shelf (DCS), as can be seen in Fig. 1.2. In 2019, 1 gigawatt (GW) of power was generated by readily installed offshore wind turbines, for 2023, the Energie Akkoord states that 4.5 GW is to be installed at various designated Offshore Wind Farms (OWF) along the Dutch coast (Sociaal-Economische Raad, 2013).

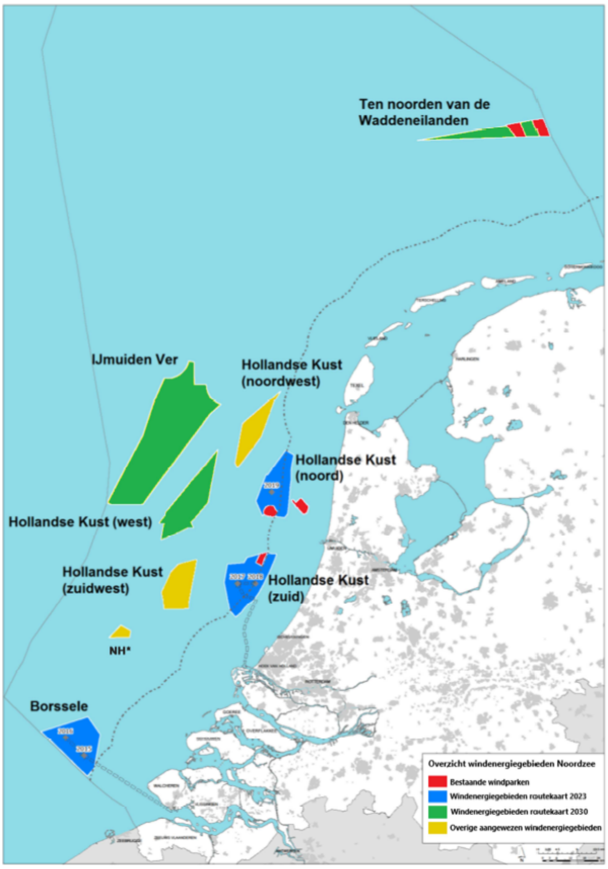

Figure 1.2: Map of the existing OWFs (red), wind energy areas designated in roadmap 2023 (blue), wind energy areas from roadmap 2030 (green), other appointed wind energy area's (yellow) Ministerie van Economische Zaken en Klimaat, 2018

Wind farms with a monopile (MP) foundation in significant flow velocities need a scour protection to keep a potential scour hole at sufficient distance from the monopile and to maintain a relatively fixed seabed level around the foundation (Raaijmakers, Roetert, and Steijn, 2017). This addition of hard substrate to the North Sea, changes the previously present (sediment rich) benthic substrate, and with that, the benthic ecosystem which was based on (fine) sediment (ICES, 2018). Given the expected future growth of offshore wind energy, it is desirable to find a nature-inclusive way of designing scour protections as to limit the impact on and disturbance of the benthic ecosystem. Working in and with the environment in a sustainable manner is also reflected in the national ambition of The Netherlands on the sea and riverine systems, embodied in the National Water Plan, which is the following:

The North Sea is a healthy and resilient marine ecosystem that can be used in a sustainable manner (Rijksoverheid, 2015a; Rijksoverheid, 2015b)

Ecological enhancement in wind farm zones

The hard substrate added to the benthic ecosystem in the North Sea at the site of the wind farm zones, can be used as a foothold for species that are used for ecological enhancement of the region. Due to the cessation of bottom fishing and the addition of hard substrate, a new habitat can be formed (Jak and Glorius, 2017). Benthic species like oysters form rigid reefs on this substrate, which in turn can function as a habitat for other species. Oysters facilitate a multitude of epibenthic flora and fauna shelter, foraging grounds and habitat. The presence of oysters helps improving water quality, as oysters filter the water column, which in turn benefits the growth of phytoplankton. This disproportionally large effect, relative to their abundance in numbers, gives them the title 'keystone species'(Mcleod et al., 2011; Rodriguez-Perez et al., 2018).

The European Flat Oyster (*O.edulis*)

For centuries, the flat oyster (*Ostrea edulis*) has populated parts of the North Sea, forming vast reefs that constituted an important habitat in the North Sea ecosystem as can be seen in Fig. 1.3. Over 25,000 km^2 of reef area used to be found on the bed of the North Sea basin, but due to exhaustive fishing, the *Bonamia* pathogen and pollution, the flat oyster population in the North Sea has reduced immensely. Flat oyster reefs are nowadays regarded as one of the most threatened marine habitats in Europe (Olssen, 1883; OSPAR, 2013; Sas et al., 2016; Smaal, Kamermans, Have, et al., 2015). The Dutch government stimulates nature enhancement, by requiring permit holders to increase the suitable habitat within offshore wind farms for species naturally occurring in the North Sea (Prusina et al., 2020). Hence, the flat oyster is the oyster of choice for this nature-inclusive design study.

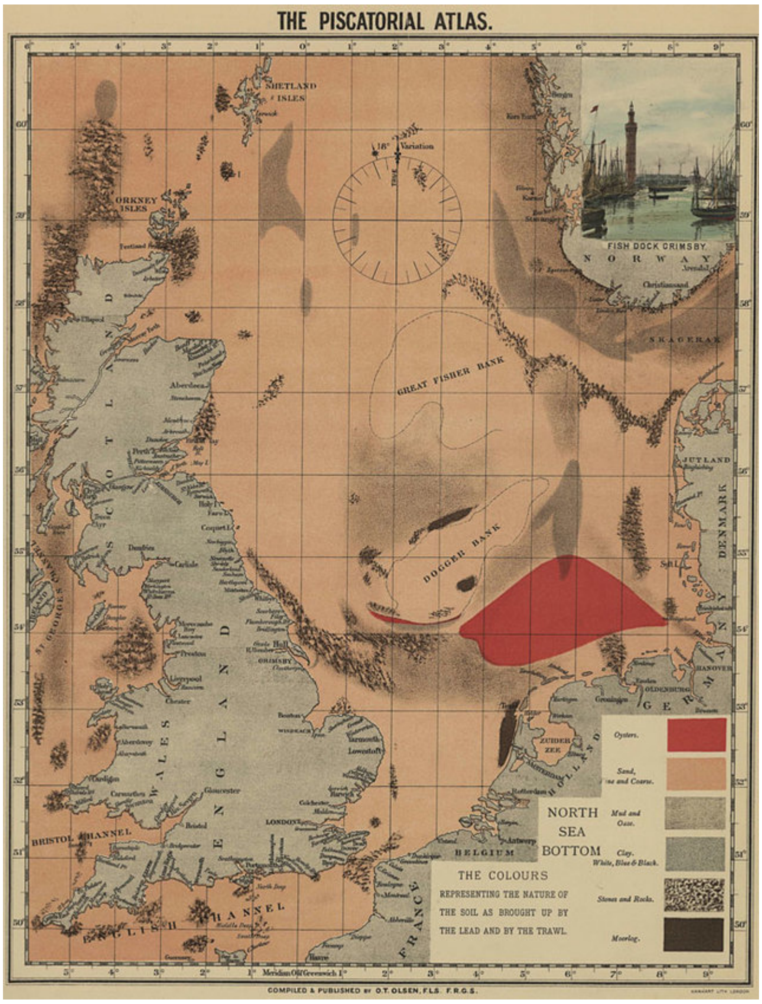

Figure 1.3: Map by Olssen, occurrence and distribution of *O. edulis* in the North Sea

1.1 Present knowledge

Oyster enhancement projects thus far have mainly focused on restoration programmes, leaving the use of oyster enhancement as nature-inclusive design project for offshore wind farms as a much less explored area. This section discusses examples of oyster reef restoration programmes completed to date, with the aim to compare different strategies for oyster enhancement structures, as well as presenting programmes of oyster placement in offshore wind farms, observing strategies and results.

1.1.1 Restoration programmes

Restoration of oyster beds by means of placing oyster shells has been common practice for a long time. The most extensive measures to support depleted wild stocks have been carried out in the UK and Ireland. In Scotland, a project by Kennedy and Roberts placed 125000 individual oysters in Strangford Lough, which led to a 10-fold increase in recruitment of new oysters in five years. With only 15% of the world's oyster reef habitat left, it is very important to initiate restoration projects to preserve a keystone species (Beck and Brumbaugh, 2014; Lotze et al., 2007).

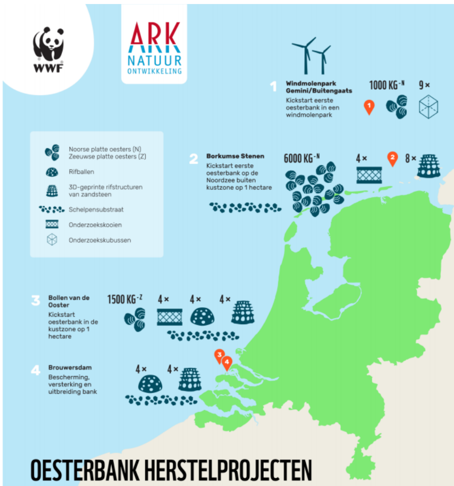

Figure 1.4: Overview of oyster recovery projects on the Dutch Continental Shelf. Oysters that are used are Nordic Flat oysters and Flat oysters cultivated in Zeeland. Adapted from (Reuchlin, 2018)

At Borkum Reef Ground, north of the Wadden islands, research racks, domes and empty mussel shells were placed on the sea bottom. The project was monitored with drop cameras, temperature loggers were used, the oyster racks were rehoistable to get quantitative results of oyster sizing. As 2 months passed, promising results were seen since at least 3 of the reef structures were standing upright in the sand and only one had sunk into the soil. Some of the oysters were still observed on the structure. However, survival rates inside the holding racks were low due to the limited space for oysters to filter feed (Didderen, Lengkeek, Bergsma, et al., 2020). It is currently unknown if survival rate is high enough to maintain the reintroduced oyster bed, or that spat will be recruited to the population.

Figure 1.5: Diver inspecting a 3D reef structure at the Borkum Reef Ground. Adapted from (Didderen, Lengkeek, Kamermans, et al., 2018)

1.1.2 Oyster enhancement in offshore wind farms

The Eneco Luchterduinen project was a joint project with Stichting De Noordzee, Natuur & Milieu, Van Oord, Eneco and ASN Bank, in collaboration with Bureau Waardenburg, Wageningen Marine Research (WMR) and Sascon. One of the aims of the project was to get insight in the key success factors of active flat oyster restoration. This was done by placing racks with different substrates, domes and racks with oysters of different age classes between the monopiles on the Luchterduinen OWF. The racks were found tilted on the seabed and were partly buried. The domes were partially covered in the sand for 10-20 cm. Little corrosion was found on the racks, but plenty of fouling was found covering large parts of the infrastructure. The oysters inside the racks showed growth, since 10 out of 12 baskets had oysters that showed growth edges. Bonamia infection was not found in the adult flat oysters. Also, larvae production was detected, showing the highest concentrations detected thus far in the Dutch North Sea (Didderen, Bergsma, et al., 2019).

Figure 1.6: Remotely Operated Vessel (ROV) inspected the placed oyster racks at the Eneco Luchterduinen OWF. The racks show displacement happened and a lot of accretion. Adapted from (Didderen, Bergsma, et al., 2019)

Figure 1.7: Flat oysters (*O.edulis*) in a cage, part of a rehabilitation programme at Luchterduinen run by (Van Oord, 2018a)

1.2 Application of study

Of the areas marked for offshore wind energy exploitation, the Borssele OWF has been earmarked as a potent site for oyster enhancement. Bos et al., 2019 found the location to be amongst the best suited for flat oyster restoration. The government has designated a part of the Borssele site for innovations, namely Borssele V, which can be seen in Fig. 1.9. The tender for this area has been won by the Two Towers consortium, consisting of Van Oord, Investri Offshore and Green Giraffe Holding. Five innovations are tested at this site with the aim to lower the Levelised Cost of Energy (LCoE):

1. Slip joint: the installation of a WTG without using grout or bolts
2. Impressed Current Cathodic Protection (ICCP) optimisation: anti-corrosion system
3. TSA coating: Thermal Sprayed Aluminum (TSA) innovative aluminum-based protection coating
4. Oval cable entry hole: optimisation in the cable protection system
5. Eco-friendly scour: nature- inclusive design of the scour protection to improve biodiversity and natural habitat of marine life

One of the innovations tested at this site are eco-friendly designs for scour protection, in the Project Ecoscour (Van Oord, 2018b). This project will provide guidance on practices for oyster restoration offshore, by testing oyster spat settlement on substrates, selecting suitable outplacement methods which are applied at the research location and monitoring the locations to determine the efficiency of the methods. The method for designing a structure useful for ecological enhancement developed in this study will be applied to create a broodstock structure design for project Ecoscour, in collaboration with Van Oord, Wageningen Marine Research (WMR), Royal Netherlands Institute for Sea Research (NIOZ), Hogeschool Zeeland (HZ) and Bureau Waardenburg (BuWa).

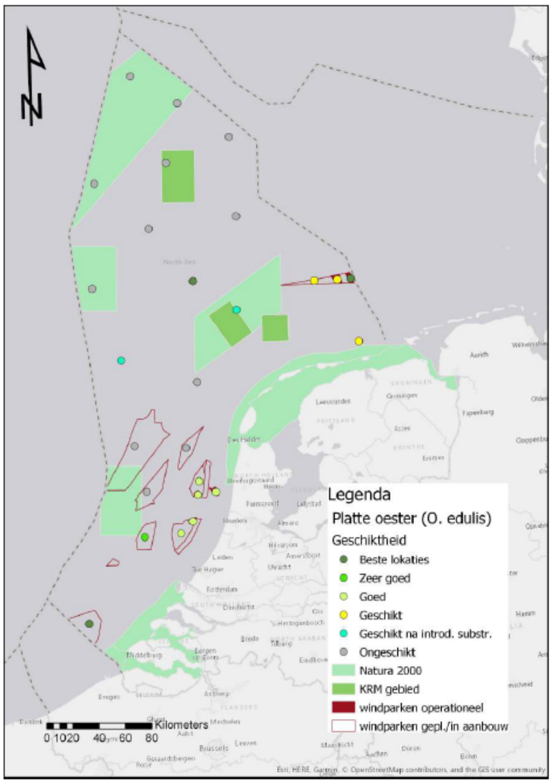

Figure 1.8: Suitability of the DCS for the *Ostrea Edulis*, the Borssele site is a prime location for a *O. Edulis* habitat. Adapted from (Bos et al., 2019)

Figure 1.9: Wind farm sites at the Borssele Wind Farm Zone

1.3 Research objectives

The challenge of oyster enhancement for offshore wind farms is that a broodstock element is required to supply larvae to the target substrate, in order to kick start oyster reef growth. A broodstock element is a structure that inhabits adult oysters that serves as a source of oyster larvae. More research on the design of such elements is required, as no in-depth research on the design of such elements has yet been done (Bouma, Belze, et al., 2013; Didderen, Lengkeek, Kamermans, et al., 2018; Kamermans et al., 2018; Lengkeek et al., 2017; Smaal, Kamermans, Have, et al., 2015; Smaal, Kamermans, Kleissen, et al., 2017; Stokes et al., 2012; Tonk et al., 2020).

1.3.1 Objective

The next step in successfully bolstering the oyster reef development to enhance nature-inclusive design efforts for offshore wind farms is to design functioning broodstock elements. The objective of the research is therefore formulated as:

Design stable and structurally robust flat oyster broodstock structures for nature enhancement in offshore wind farms

1.3.2 Research questions

To achieve this objective, a main research question is used with accompanying sub-questions, that serve to seek answers to more specific questions that support the main research question.

Main research question

"How to design an oyster broodstock structure for offshore wind farms, that remains structurally robust and stable under prevailing environmental conditions?"

Sub-question 1: Which design criteria and concepts can be identified to determine a flat oyster broodstock structure?
Underlying questions:

- What are design criteria for a structure to host a flat oyster broodstock population?
- What are concepts for such a structure, in order to inhabit flat oysters?
- How to systematically compare concepts for oyster broodstock structures?

Sub-question 2: Which environmental processes that occur in an offshore wind farm should be included in the design of an oyster broodstock structure?
Underlying questions:

- What are the relevant environmental parameters for the design of an oyster broodstock structure in offshore wind farms?
- How do these parameters influence the design of such a structure over time?

Sub-question 3: What is a systematic method to assess the structural integrity and stability of an oyster broodstock structure?
Underlying questions:

- What are the relevant forces acting upon an oyster broodstock structure in an offshore wind farm?
- What is a method to carry out rapid iterations for all forces while designing and evaluating such a structure?

1.4 Methodology

By finding the answers to the sub-questions, the research question can be answered which will amount to accomplishment of the research objective. The research is conducted in two phases;

1.4.1 Design methods

As a design methodology, the conceptual Five Step design methodology of de Vriend et al. is used to ensure an inclusive design is obtained, which prescribes the following step-by-step procedure:

- **Step 1**: Understanding the system;
- **Step 2**: Identify realistic alternatives that use/and or provide ecosystem services;
- **Step 3**: Evaluate the qualities of each alternative and preselect an integral solution;
- **Step 4**: Fine-tune the selected solution (practical restriction in the governance context);
- **Step 5**: Prepare the solution for implementation in the next project phase

Therefore, through gaining an understanding of the general system by means of a literature review and studying the habitat of the flat oyster, knowledge is gathered about the ecological requirements for the conceptual design of an oyster broodstock structure.
Firstly, a literature review is done to study the habitat of the flat oyster, which is used to set design criteria categories. Secondly, a brainstorm session is hosted with the knowledge parters in Project Ecoscour in order to determine the design criteria and conceive several concepts for

broodstock structure. Thirdly, an analysis of these concepts is conducted to select the best alternatives for further design efforts. Fourthly, a method is developed to iterate design calculations for a broodstock structure, which is used in the design of a structure for Project Ecoscour to be placed at the site of Borssele V. Fiftly, the structure that is constructed by the manufacturer will be evaluated with the design method and analysed for stability and potential failure.

1.4.2 Validation methods

In validating the model that is created, basic geometries have been used as a unit test to check whether the tool's calculations are valid. Also, a sensitivity analysis of key input parameters has been carried out to check the model.

1.5 Research scope

To make the results of this thesis specific and relevant to the North Sea environment, a scope is required for this study. This section presents the scope chosen for this research.

- Flat oysters - Oysters
  This study focuses on flat oysters as broodstock population species, and does not concern oysters in general.

- North Sea - Continental shelf seas in general
  As this study concerns a specific species and is conducted in light of the Project Ecoscour, the North Sea is selected as area to retain relevance for other potential wind farm zones.

- Scour protection - Bottom of the sea in general
  The structure will be placed at the scour protection. Settlements and erosion induced failure of the structure are avoided in the project Ecoscour by placing on top of the scour protection, and as such will be taken as a baseline for this study.

- Preliminary design study - Fully certified design
  Due to limited time, the design is made following a desk study and as such, the realised designs are prototypes without scale testing.

- Costs
  Costs are not made part of this design.

- Compliance
  Legislative matters are not covered in this technical design study.

1.6 Reader's guide

This reader's guide serves the purpose to guide one through this document. In **Chapter 1**, an introduction is offered to the subject, offering context about the study. The knowledge gaps are highlighted, the objective of this study is stated as well as the research questions and the scope of the research. **Chapter 2**, the design requirements are presented, concepts are conceived and analysed which results in the selected concepts for design. In **Chapter 3** contains the theoretical framework for the explorative design tool Econstruct, it describes the inputs, calculations occurring in the tool and the outputs. It also covers the validation of the design tool, by means of unit testing and a sensitivity analysis. **Chapter 4** describes the application of the design method for Project Ecoscour, studying environmental characteristics and environmental processes, carrying out a first design iteration and an evaluation of the structure that is placed. **Chapter 5** presents the conclusions and discussion. In **Chapter 6**, recommendations are made for further research and practical advice for oyster enhancement projects is given.

Chapter 2

Methodology - conceptual framework

This chapter elaborates on the conceptual framework for the design of an oyster broodstock structure. Firstly, the environmental conditions that are relevant for a flat oyster habitat are studied. Some of these conditions are relevant for the design of an oyster broodstock structure, some are more relevant to investigate the suitability of an OWF for nature enhancement by placing oyster broodstock. Secondly, these conditions give insight in what criteria are to be considered in designing an oyster broodstock structure. Thirdly, these design criteria are used to generate a variety of concepts. Fourthly, the concepts are analysed and compared leading to the selection of concepts. Finally, the selected concepts are . These four parts together form the conceptual framework for the conceptual design of an oyster broodstock structure and serve to provide a structural concept for further design of such structures later in the study.

2.1 Environmental conditions for a flat oyster habitat

In this first section, the habitat conditions for flat oysters are presented, based on a literature review. It is useful to know these conditions in order to define what characterises a functioning oyster habitat. The parameters that are studied in the literature study are given in Table 2.1.

Location 2.1.1
Water depth Morphological Target substrate composition Predation
Hydrodynamics 2.1.2
Bottom shear stress Currents
Water quality 2.1.3
Turbidity Water temperature Salinity Oxygen content Food concentration
Critical mass 2.1.4

Table 2.1: Habitat conditions reviewed and presented in this chapter. Selection adopted from (Smaal, Kamermans, Kleissen, et al., 2017).

In this first subsection, the environmental conditions relevant for a habitat of a flat oyster population are studied, such as the position in the water column, morphological features, the composition of the substrate and the predators present. Subsequently, the hydrodynamics at the site of a flat oyster habitat are studied, by investigating the bottom shear stress and currents in the North Sea.

Thirdly, the water quality required for an oyster population is studied. Finally, required critical mass for a reproductive oyster broodstock population is discussed.

2.1.1 Location

This subsection presents the conditions at the location of an oyster habitat, discussing water depth at the site, morphological features in the area, the substrate present and predators for oysters.

Water depth

Being a filter feeder, the *Ostrea edulis* requires submersion for feeding. Since this sets the upper limit to the water depth, supertidal areas are off-limits, and intertidal areas are suited if the time spent out of the water is not too long. Although flat oysters found in estuarine areas were found at -1m Normaal Amsterdams Peil (NAP), the maximum depth for flat oysters is limited by both the food supply as the oxygen content in the water, which is potentially critical in deeper water zones (Montes et al., 1991). Hayward and Ryland (1998) determined the lower limit to be -80m below NAP. As Fig. 2.1 shows, the seabed of the Dutch Continental Shelf is generally within the posed limits and therefore suitable for reef development. The seabed is generally flat, with a general slope of max. 1:1000, where the southern part is characterised by sand waves with a wave height from 6m in the south to 2m in the Den Helder coastal region. The water depth has a large influence on the flow velocity as a consequence of waves that occur during extreme weather events. In shallow waters, a bottom founded structure will experience higher flow velocities from waves than is experienced in deep water (Holthuijsen, 2009).

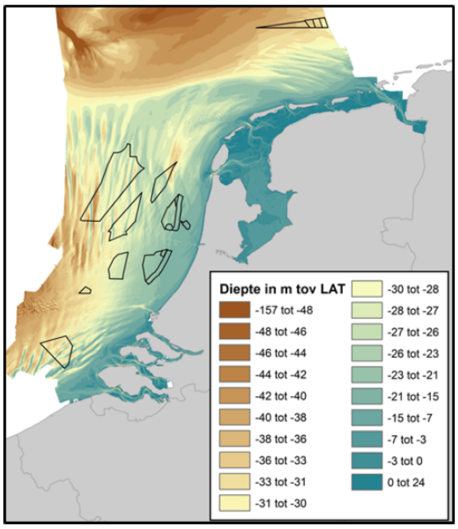

Figure 2.1: Water depths of the Dutch Continental Shelf area, marked are the areas that are designated for wind energy exploitation. Adopted from Smaal, Kamermans, Kleissen, et al. (2017).

Morphological features

Within the North Sea, various morphological features exist, of which the types are given in Table 2.2:

Feature	***Migration rate***	**Unit length**	**Unit height**
Sand banks	stationary	kilometers	10s of meters
Sand waves	several meters per year	100s of meters	meters
Megaripples	fast	10s of meters	decimeters
Ripples	fast	centimetres	centimeters

Table 2.2: Morphological features in the North Sea bed. Orders of magnitude adapted from (Raaijmakers, Roetert, Riezebos, et al., 2016)

These features are generated by the complex interaction between hydrodynamics, sediment transport and existing morphology (Hasselaar et al., 2015; Raaijmakers, Roetert, Riezebos, et al., 2016). Ripples are the smallest occurring phenomenon, also being the fastest migrating seabed feature. These elements have an influence on the bed roughness and sediment transport in the area. Megaripples are somewhat larger, slower versions of regular ripples. Sand waves and sand banks are the largest features on the sea bed, and have a large impact on subsea construction of scour protection at offshore structures, as they define the North Sea bathymetry (Hasselaar et al., 2015; Raaijmakers, Roetert, Riezebos, et al., 2016). Sand waves can move several meters per year across the seabed, while sand banks are more or less stationary for decades. As a result, sand waves are the most important elements for reef construction, since the structure will most likely be affected by migrating sand waves. The position of the sea bed can vary due to sand waves. These morphological features are dependent on bottom shear stress as they determine the entrainment of sediment. For the area of the pilot study, research by Hasselaar et al. (2015), Raaijmakers, Roetert, Riezebos, et al. (2016), and Riezebos, Hasselaar, et al. (2014) has shown a highly dynamic morphology, with large shore-parallel sand banks and medium shore-perpendicular sand waves. In (Riezebos, Hasselaar, et al., 2014), it is stated that for stability reasons, the partial burial of the scour protection is expected, but not further studied as this does not threaten the stability of the scour protection material.
For the design of broodstock structures for nature enhancement with flat oysters, these sand waves can be fatal. Flat oysters cannot survive prolonged periods deprived of oxygen, hence burial is a serious threat, as was seen at the Eneco Luchterduinen pilot (Didderen, Bergsma, et al., 2019). It is therefore important to study the morphological dynamics of the site on a local scale, in order to determine the threat of morphological features to ecological enhancement campaigns. Since sand waves move at slow speeds, it is difficult to design a structure that will protect the oysters from burial, without creating a tall structure that will remain emerged above bypassing sand waves. This process is relevant for the selection of oyster restoration sites in the planning phase of an OWF.

Substrate composition

The composition of the sediment is important for attracting oyster larvae, which is often referred to as the recruitment of oyster larvae. Due to the gregarious nature of the flat oyster, it prefers settlement on existing oyster reefs and oyster shell material. The flat oyster thrives on locations where it can avoid burial by fine sediments. Work by Liang et al. (2005) has demonstrated that a soft sediment deposition between 1-2mm on a hard substrate is a barrier to settlement. Broodstock structures support flat oysters that are reproductive, which means the oysters are artificially placed upon the structure. For the placement of oysters on the artificial reef, some sort of connection between (adult-)oysters and the substrate of the structure is required. Experiments have been conducted by NIOZ within Project Ecoscour in 2020, testing different glues on various substrates testing on the toxicity of the glues, the durability of the attachment and the survival rates of the oysters. Polyurethane glue showed to be the best alternative.

Figure 2.2: Example of a scour protection at a monopile foundation of a WTG. Adapted from (Van Oord, 2018a)

In Tonk et al. (2020), the settlement preferences of the flat oyster were studied. This study showed that mussel shell material was succesfull in spat collection per cm^2, whereas granite also showed promising results. Concrete, being a common construction material, also gave good results for settling of oyster spat. This information about the flat oyster gives insight in what materials are most suited for the construction of an oyster broodstock structure. Concrete is shown to be an material that can both work well with oysters whilst also being a potent construction material.

Predation

Knowledge of predators of the flat oyster helps in designing an oyster broodstock structure upon which the oysters will stay alive longer. The natural enemies of the flat oyster are:

- Starfish(*Asteria rubens*);
- Whelk (*Buccinum undatum*);
- Dog whelk (*Nucella lapillus*);
- Littoral crab (*Carcinus maenas*);
- Brown crab (*Cancer pagurus*);
- European sting winkel (*Ocenebra erinaceus*);
- Eastern oyster drill (*Urosalpinx cinerea*);
- Japanese oyster drill (*Ocinebrellus inornatus*)

Of the above mentioned, the mobile ones such as the crabs and the snails, rely on chemical cues to find their prey (Dale F. Leavitt, 2013). According to Dale F. Leavitt, the mobile species follow the track of the cue until the desired prey is found, which means the predators will actively have to be removed, or a barrier between predator and prey should be created, like a fence or suspending the prey in the water column. By developing a barrier between the broodstock population and benthic predators, the structure improves the survival rates of the oyster broodstock population.

2.1.2 Hydrodynamics

This subsection discusses the conditions as a consequence of the hydrodynamics on site that are of relevance to oyster populations. The influence of bottom shear stress and currents on an oyster population are discussed.

Bottom shear stress

Bottom shear stress is induced by currents and orbital velocities of waves, which in turn can cause entrainment of particles (e.g. silt, sand or oyster larvae). No studies have been conducted on the tolerance of flat oysters with respect to bottom shear stress, however, this study uses the relation between the historic appearance of the flat oyster (as seen in Fig. 1.3) and the modelled bottom shear stress maps of the North Sea in Fig. 2.3. Concluding from this comparative analysis, a qualitative threshold value was put at 1 N/m^2 (Smaal, Kamermans, Kleissen, et al., 2017). This information is relevant for selecting sites for oyster enhancing projects.

Currents

Oysters require flowing water to refresh oxygen and for the supply of new nutrients, however under certain circumstances the flow velocities become too large and will prevent settlement on substrate. For a soft substrate the limiting current velocity is found at 0.25 m/s, ideally 0.03 m/s. This is mainly due to the preferred limited dispersal of the larvae of the oysters in their phelagic phase (Drinkwaard, 1961). On hard substrate, oysters have been observed to handle 0.25-0.6 m/s, where higher velocities are detrimental to the settlement of larvae and lower current velocities are not

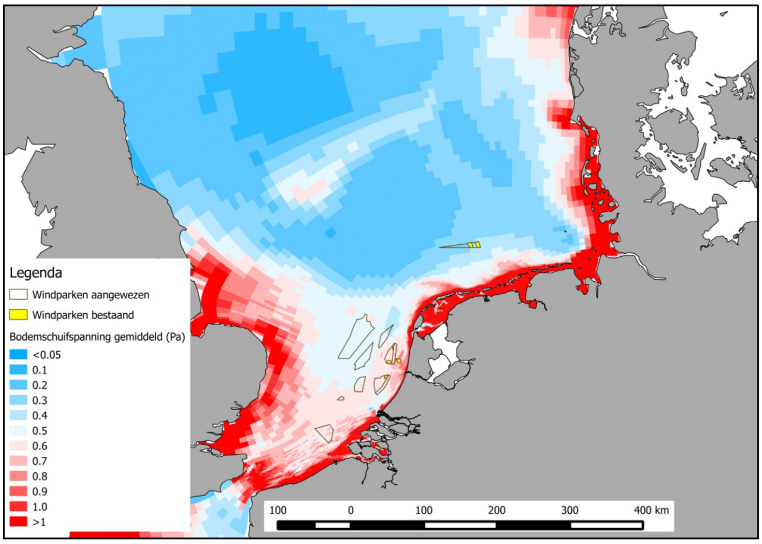

Figure 2.3: Overview of designated wind energy locations, modelled for the maximum bed shear stress due to waves and currents. Adapted from (Smaal, Kamermans, Kleissen, et al., 2017)

desired as oysters will have to deal with a higher sedimentation rate of silt (Gercken and Schmidt, 2014).
Some space around the oyster has to be reserved for the growth of the oyster and the flow of the water. In experiments conducted by the NIOZ, flat oysters of the size of 6-8cm were tested on a variety of materials with various adhesives. In designing the experiment, oysters were expected to grow twice as large (Belsen, 2020, May 5). As the oysters placed on the broodstock element that is designed in this study will have to be of reproductive age, Spencer states that flat oysters have a shell length of 65mm, and can grow beyond 160mm in size as they grow older. This information is relevant for the design of oyster broodstock structures, whilst also being important in the selection of oyster enhancement sites. The velocities found in this study will be exceeded in offshore wind farms due to tidal flows and waves, and as such a metocean study on hydrodynamics will be required to study the stability of the structure.

2.1.3 Water quality

The water quality at the site where an oyster broodstock structure cannot be influenced by the structure. It is however important to study these characteristics to analyse the potential for oyster enhancement on site.

Turbidity

Turbidity influences the ability of oysters to grow, as oysters are filter feeders, they rely on phytoplankton that is in the water. With flat oysters being filter feeders, the presence of other suspended materials that are indigestible for the oysters is disadvantageous for an oyster population. Experimentally, Barillé determined that above 90 mg/l, the growth of flat oysters is significantly reduced based on annual averages. The areas in which this most often happens is the shallow coastal zone.
In a study conducted by NIOZ & HZ, the effects of burial have been studied, and showed that vertical burial leads to total death by asphyxiation, whereas horizontal burial beneath ground results in few deaths by asphyxiation (Oosterwal and Belzen, in prep). Turbidity is difficult to mitigate for a structure, and is a relevant process for the monitoring of the environment of the OWF, as it is detrimental for marine life in general.

Water temperature

The development of the reproductive organs of the oyster broodstock population is very important. This development is optimal between 7- 14 °C, and spawning of reproductive cells is observed at temperatures larger than 18.5 °C. Survival requires a temperature of at least 3 °C, and reduces above 30 °C (Lubet, 1976). For the North Sea, these values are within range, as for the Borssele Wind Farm the temperature range is modelled between 3 to 20 °C annually in (Smaal, Kamermans, Kleissen, et al., 2017). The water temperature should be studied before an attempt is made to enhance offshore wind farms with oysters.

Salinity

In saline waters, a salinity of 25-30 is optimal for the survival of oyster larvae. If salinity concentration reaches below 20 , the waters are not hospitable for oyster larvae (Davis and Ansell, 1962). The salinity of the North Sea waters is favourable for the entire Dutch Continental Shelf, as can be seen in Fig. 2.4. Salinity could change in the future due to alterations in fresh water discharges from the Rhine/Meuse into the North Sea and increased evaporation on the water surface, however in recent years no trend is observed and large uncertainties surround long-term changes (Holliday et al., 2010). This factor is relevant for the selection of oyster enhancement sites, and should be examined before attempting enhancement projects involving oysters.

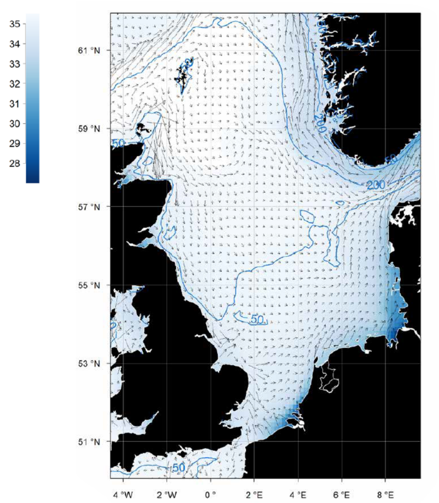

Figure 2.4: Averaged direction of flow & salinity of the North Sea. Adapted from (Herman et al., 2015)

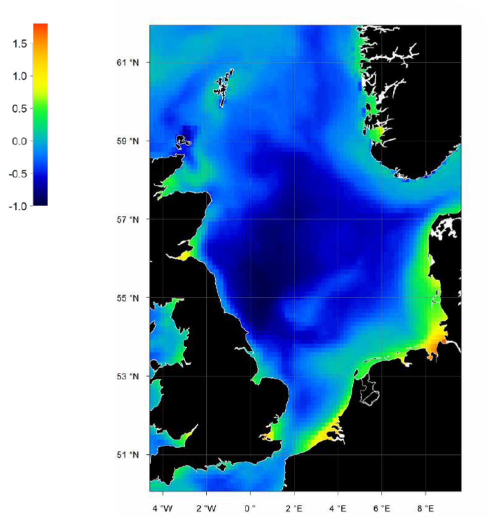

Figure 2.5: Long-term averaged chlorophyll content of the toplayer (10m), logarithmic scale, 0 = 1 μm, 1 = 10 μm. Adapted from (Herman et al., 2015)

Oxygen content

Bivalves can survive some time in oxygen-deprived water for their ability for anoxic respiration, which is an adaptation to the situation where the oyster is out of the water, when it closes its valve. The oyster can survive like this for several days (Smaal, Kamermans, Kleissen, et al., 2017). As the flat oyster is a subtidal species, no trigger to close the valve is given. This reduces the time for survival significantly when buried. However, in the case that the oyster is not buried, no reason for an oxygen deficit is known as the water in the North Sea is generally well-mixed, particularly in the relatively shallow areas with strong tides (Dutch Ministry of Transport, Public Works and Water Management), 1986). The design of the structure can aid in the oxygen supply to the oyster, by supplying the oyster with ample renewed water, which can be achieved by improving the permeability.

Food concentration

Flat oysters grow through feeding off phytoplankton in the water. The presence of phytoplankton can be measured by measuring chlorophyll, the pigment that captures sunlight to be able to use photosynthesis. In Fig. 2.5 one can see, the shallower waters of the DCS appear to be promising premises for flat oysters.

2.1.4 Critical mass

A substantial reproduction is required for an oyster broodstock structure to be successful in starting up a self-sustaining flat oyster population. A successful system of flat oyster broodstock elements consists of a total population of 1000 individuals (Kamermans, 2020, April 9; Lengkeek et al., 2017). This is a relevant parameter for the design of the structure, as it determines the size of the structure.

2.2 Conceptual framework

The previous sections serve the purpose to describe the influence of environmental conditions influence the performance of an oyster enhancing element. In the following section, various design aspects of the broodstock structure are discussed. As previous experiments with structures inhabiting oysters have yet to yield structurally positive results, a thorough design process is followed. By using expert knowledge of the flat oyster, flat oyster habitats and hydraulic engineering design principles this process is carried out step-by-step. The first step is gathering expert opinions on the design criteria, and using these to develop conceptual models of an oyster broodstock element. In a brainstorm session hosted for the partners in Project Ecoscour (WMR, BuWa, HZ, NIOZ and Van Oord), design criteria were discussed and determined. This information is then used to conceive various alternative concepts. These concepts are analysed for strengths and weaknesses and combinations are made to improve the selected concepts potential concepts.

2.2.1 Design criteria

Having design criteria gives a framework to conceive concepts in. These criteria are best determined in consultation with experts in the field of oyster restoration and nature enhancement with oysters. Four categories which were determined in preparation of the brainstorm session with Project Ecoscour knowledge partners. The brainstorm was conducted on April 9th 2020 via Microsoft Teams and Miro board, and is covered in Appendix A. The design criteria have been divided into four categories:

- Ecology;
- Structural integrity;
- Commissioning & construction;
- Monitoring

The criteria will be discussed per category in the paragraphs below.

Ecology

This category of criteria concerns the way the structure interacts with the flat oysters that are supported by the structure, and how the structure can contribute to a thriving flat oyster broodstock population.
The design criteria in the category Ecology were determined to be:

1. **Space for the oyster**
   This criterium has the aim to enable the flat oyster to filter feed and grow. In oyster outplacement pilots, oysters have been attached to the carrier structure either by putting them in a basket, or by attaching them using some adhesive. In this criterion, the desired structure will make efficient use of its shape to hold the oysters.

2. **Permeability structure**
   The permeability of the structure is crucial in enabling the flow of water through the structure and around the flat oysters with fresh water containing oxygen and supply of new nutrients. Concepts will be rated high on this criterion when the structure does not enclose the oyster or provide the possibility for biofouling to block the flow.

3. **Protection against predation**
The North Sea environment inhabits many predators that can threaten the flat oyster. Even though it is not desirable nor possible to negate the threat of the predators as described in Section 2.1.1 completely, placing the oysters on an elevated surface with respect to the sea bed, will reduce the predation. Structures that have such a barrier in place will do well on this criterion.

4. **Burial protection**
The flat oyster cannot survive prolonged periods of burial by sediments. The structure must ensure that the flat oysters remain clear of this phenomenon. This can be caused by sand accretion in the structure or morphological phenomena. Distance off the seabed, exposure to a flow of water and general avoidance of stagnating flow around the structure are key to score well on this criterion.

5. **Composition of population**
This criterium covers the oyster population that will be placed upon the structure. In order to achieve the goal of becoming a source of flat oyster larvae, enough oysters of reproductive age and a good variation in sex. This criterion, being key to the success of a broodstock population, does not influence the structure and is as such equal for all concepts.

Structural integrity

This category of criteria contains important structural aspects that need to be considered in the design of a broodstock structure.
The design criteria in the category Structural integrity were determined to be:

1. **Stability**
The stability of the structure is paramount to ensure a safe structure for the oysters and surroundings. This criterium will focus on ensuring no significant movement of the structure under extreme circumstances. As this criterion is dependent on the dimensions and composition of the structure, which are the result of the engineering design process later, the concepts will be judged on stability by shape and weight.

2. **Durability structure**
The structure has to remain in place for the lifetime of the wind park. In order to retain structural integrity, the structure has to remain intact. Structures that have the aim to be retractable have to be designed more rigid than ones that are intended to disintegrate on the seabed, and will as such score better on this criterion.

3. **Modularity**
The surface upon which the structure is placed is important for the design of the bottom of the structure. For a soft surface, such as sand, the support of the structure has to be designed for a low bearing capacity. If the structure is placed on rocks, an uneven surface should be accommodated for. For this criterion, the base of the structure that transfers the load onto the subsoil should be flexible to be changed if the surroundings change for the project.

4. **Certifiability**
This criterium is not crucial for the performance of the structure, however, it is could be desirable to certify the structure, in order to be actively used in oyster outplacement projects. It is expected that placement on the scour protection while interlocking with the infrastructure will provide difficulties for certifying institutions due to the risk of damaging the construction, however, a very heavy structure could also threaten the integrity of the infrastructure beneath it.

Commissioning & construction

The category Commissioning & construction represents the criteria related to the commissioning of the structure, such as the construction, transport, installation and removal of the structure.
The design criteria in the category Commissioning & construction were determined to be:

1. **Costs**
The time and equipment needed to install the construction whilst offshore are crucial for the costs of the operation. The structure should therefore be simple to install and should not require auxiliary equipment to be lifted and lowered. The concept has to be suitable for lifting and should be controllable during placement. The structure should be cost efficient in use of materials.

2. **Oyster accommodating surface**
The flat oysters have to be attached to the surface of the structure in some way, the surface has to be able to accommodate oysters, ideally with some indentations on a rough surface. The concept that meets this requirement will have surfaces that can be designed with indentations.

3. **Complexity of structure**
During construction and installation, the complexity of the structure can limit productivity. Simple shapes are easily constructed and robust structures that can handle external conditions during installation are characteristics of a concept that meets this criterion.

Monitoring

In the category Monitoring, the criteria related to the monitoring aspects of the structure. Monitoring of the broodstock element is focused on monitoring the performance of the structure and the condition of the oysters.
The design criteria in the category Monitoring were determined to be:

1. **Liftability structure**
In order to inspect the structure and study the oysters, the structure has to be lifted from the seabed. As with the criterion 'Fast placement on site', some kind of lifting hook is required on the structure, as well as allowing a partial or complete retrieval of the structure from the seabed for inspection.

2. **Sensing**
In order to study the performance of the structure under extreme events such as storms, sensors have to be attached to the structure that can measure the stability of the structure. For this design study, the aim is to provide data for analysis in the field of oyster outplacement, and as such the designed structure will contain sensors regardless of the concept. This criterion is therefore not used in the selection procedure.

3. **Data transfer**
The data generated by the sensors should be transferred to the mainland, either remotely or by retrieval. Just like the criterion above, this is required for all concepts and thus not taken into consideration in this selection.

Using the research conducted in the literature review, some of the design criteria can be specified.

2.2.2 Concepts

Using these criteria, the participants of the brainstorm proceeded to make a sketch of a viable concept. These sketches can be found in Appendix A. The concepts are presented below and analysed for strengths, weaknesses, opportunities and threats.

Pyramid concept

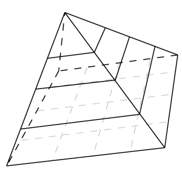

Figure 2.6: Pyramid concept

A reinforcing bar construction with the core principle of being able to roll over and still remain stable, due to its shape. Oysters could be fitted in baskets inside or glued to the structure. Large permeability, should be designed to corrode completely in time. The concept can be seen in Fig. 2.6.
Strength: Permeability structure, stability, liftability.

Weakness: Complex shape, protection against predation, protection against burial.
Opportunity: Roughness on surfaces for oyster attachment, temporary oyster seeding structure providing some shelter. Could be fitted with terraces to provide this rough surface and barrier against predation.
Threat: Decay structure threatens structural integrity, fouling in structure could clog structure and hamper flow, rolling of structure not desirable for flat oysters (Kamermans, 2020, April 9).

Terraced concept

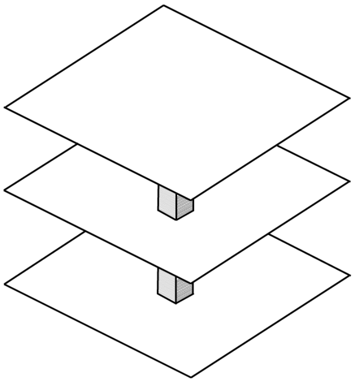

Figure 2.7: Terraced concept

A multi-layered structure with horizontal terraces upon which the flat oysters are glued or placed. Spacious for the oysters and the flow of water around them, supporting base can be changed to accommodate different soils. The concept can be seen in Fig. 2.7.
Strength: Spacious for the flat oysters, permeable for flow, elevation protects from predation and burial events, stability due to wide base, modular, oyster friendly surface.
Weakness: Possibility of sand accretion on terraces, can be come top-side heavy.
Opportunity: Add profile in the surfaces to accommodate oyster attachment and spat settlement, use mesh materials for terraces to decrease weight, drag, lift forces. The terraces could be placed in a tapered fashion, in order to provide the lower layers with a larger volume of fresh water that can pass, where the top platform could be a removable platform for oyster inspection.
Threat: Initial placement could induce a tilt to the structure, which can influence the drag and lift coefficients. Oysters that are placed high in the water column could see their larvae be dispersed beyond target substrate.

Tripod tree

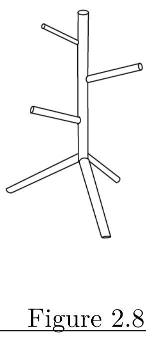

Figure 2.8: Tripod concept

A slender construction that anchors itself using a tripod, in the subsoil or scour protection. Flat oysters are attached to the slender structure, where they are always in contact with a body of flowing water to obtain nutrients and oxygen. The concept can be seen in Fig. 2.8.
Strength: Permeability structure, stability, liftability
Weakness: Predation
Opportunity: Use a rough surface to enhance oyster attachment, the tripod base can be replaced with a flat base if intrusion into the infrastructure is not permitted.
Threat: Relies on interlocking with subsoil for stability, might have problems in certification.

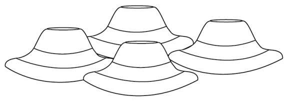

Figure 2.9: Hat concept

Hat

A ribbled concrete convex structure that tapers to the top that is placed on the seabed, providing attachment space for the flat oysters on the ribbles. The structure is stable due to its wide base and mass, and has cavities that can accommodate marine life. The hat concept is best placed in multitude and can be supplemented with loose oysters. The concept can be seen in Fig. 2.9.
Strength: Stability, room for other marine life,
Weakness: Predation, large structure required, burial
Opportunity: Placement of loose oysters or shell material
Threat: Sedimentation, predation

Bowl

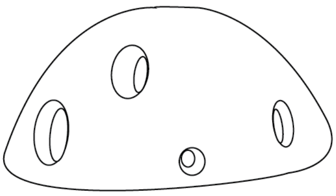

Figure 2.10: Bowl concept

Concave structure with orifices to accommodate flow of water through the structure and around the oysters. Stability is found in the wide base and mass, while the concave outer edge of the structure provides ample opportunity for oysters to be attached. The concept can be seen in Fig. 2.10.
Strength Stability, simple shape, oyster friendly surface
Weakness: Permeability, predation protection, burial protection
Opportunity: Oyster friendly surfaces, sheltered place to put loose shell or oysters, space for other marine life
Threat: Predation, sedimentation could threaten retractability, survival of oysters

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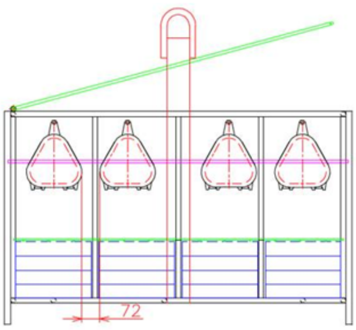

Figure 2.11: Oyster cage by W. Bakker

'Bakker' oyster cage

The cage used for Eneco Luchterduinen resembles the Bakker model oyster cage well. It consists of a framework in which baskets of loosely placed oysters are kept (Van Oord, 2019a) . This concept has retrievable baskets for oyster inspection and retains stability on the basis of gravity. Unlike the Bakker cages placed near Eneco Luchterduinen wind park, this concept supports itself on pads to decrease the pressure on the subsoil. The concept can be seen in Fig. 2.11.
Strength: Known design, fast placement, modularity.
Weakness: Settlement, instability, protection against predation, protection against burial.
Opportunity: Can be recycled, can detach one unit for oyster inspection.
Threat: Fouling can threaten permeability.

Egg container

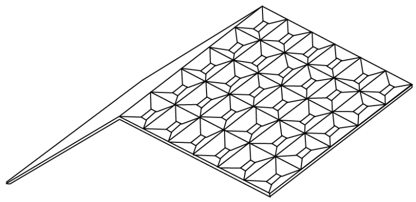

Figure 2.12: Egg container concept

A concept that revolves around permeability, a hollow structure with cavities that can contain oysters, while allowing water to flow freely. Like the pyramid concept, this structure is corroded in time. Due to the hollow shape, it can trap some of the larvae and accommodates marine life. The concept can be seen in Fig. 2.12.
Strength: Permeability, space for oysters, larvae retainment
Weakness: Predation protection, protection against burial, complex shape, deterioration structure
Opportunity: Placement of shell material and oysters
Threat: Fouling could lead to clogging

Donut

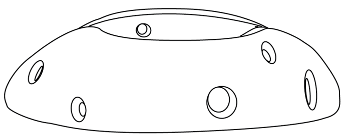

Figure 2.13: Donut concept

A circular shape that tapers to the top, with a hole in the centre. The structure has a rough exterior to provide attachment opportunities for the flat oysters. It has many cavities and has space for shell material in the centre. Stability is gravity based. The concept can be seen in Fig. 2.13.
Strength: Stability by mass, space for oysters, porosity for marine life
Weakness: Large structure, complex shape,
Opportunity: Space for oyster material
Threat: Accretion, fouling clogging the pores, sinking, predation

---

The original concepts can be seen in Appendix A.

2.2.3 Concept selection

While acknowledging there are more options to the design of a broodstock element, the concepts presented are seen as viable options proposed by experts in the field of flat oysters.
Firstly, the optimal concept is presented per design criteria. Secondly, all concepts are rated qualitatively on each of the design criteria In order to converge to one or two concepts that can be designed in depth, strengths of different solutions can be used to combine the concepts into an optimal concept. First, the concepts are rated per requirement in a relative sense.

Ecology

- Space for the oyster
  With regard to the space provided for the oysters placed on the structure, the flat concept offers the most efficient use of volume to place oysters, similarly to the pyramid concept.

- Permeability structure
  The tripod tree structure offers the most free space for the oysters for water to flow past them, followed by the pyramid concept and the terraced concept.

- Predation protection
  The flat concept has an offset with respect to the seabed, creating a barrier for benthic predators to prey on the oysters, whereas the tripod tree has a vertical offset as well.

- Protection against burial
  The tripod tree has a slender stem that will locally increase flow velocities that will prevent significant sediment accretion, as well as providing an offset for the oysters with respect to the sea floor. No stagnant zones are present that can accumulate sediment. The flat concept can accumulate sediment on the terraces, but due to its offset from the seabed it can avoid burial by morphological features and thus rates well.

- Composition of population
  Is disregarded in this selection, the composition of the population is determined by other partners in project.

Structural integrity

- Stability
  This criterion is heavily reliant on the exact design and material choices, but is critical to the success of the broodstock element. Any selected structure will therefore be designed to maintain a stable position on the seabed. Rating these concepts is therefore an analysis of the geometric properties like centre of mass and area. In terms of stability, the Donut concept has the lowest centre of mass while its mass ensures stability on the bed. While the hat, bowl and terraced concepts are also stable due to the mass being made of concrete.

- Durability structure
  All concepts that are not intentionally decaying are suitable, which means: Terraced concept, tripod concept, Hat, bowl, donut and 'Bakker' concept.

- Modular base
  Terraced concept and 'Bakker' cage provide the option to change the base shape.

- Certifiability
  Concepts that protrude into existing infrastructure will have to undergo extensive checks to ensure stability of the infrastructure in place, hence, a structure like the tripod tree can provide difficulties. However, if a structure is too heavy, the infrastructure could exceed the bearing capacity of the underlying soil, leading to failure. In this conceptual design, this criterion is therefore disregarded in the selection procedure.

Commissioning

- Fast placement offshore
  Nearly all concepts score well on this criterion, except for the Donut structure, which is eccentric with respect to the centre of gravity and will thus require more complex lifting equipment.

- Oyster friendly surface
  The Hat, bowl, terraced concept, Donut and eggbox concept all have oyster accommodating flat or slightly sloping surfaces which can be fitted with oysters

- Simple shape
  Being able to make the structure from standard shapes and elements will decrease costs and construction time. Many of the concepts are one-of-a-kind, and will need extra attention in the construction process, except for the known concepts of the 'Bakker' cage and the Bowl structure, which have been used in previous oyster outplacement projects.

Monitoring

- Liftability structure
  Structures that have a separate element that is liftable for oyster inspection will do well in this category and as such, the 'Bakker' cage scores the best.

- Sensing
  All of the concepts can be fitted with sensors, so this criterion does not help to distinguish between concepts and will be disregarded in this phase.

- Data transfer
  The data transfer is organised within the structure, and just like the sensors can be fitted to any of the structures, and will also not be regarded in this selection.

	Pyramid	Terraced	Tripod	Hat	Bowl	'Bakker' cage	Egg container	Donut
Space for the oyster	++	++	+	+/-	+/-	-	+/-	+/-
Permeability structure	+	+	++	-	-	-	+/-	-
Protection from predation	+/-	++	+	-	-	++	-	-
Protection from burial	+/-	+	++	-	-	-	-	-
Composition of population	+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-
Stability	−	+	+	+	+	+/-	+	+
Durability structure	−	+	+	+	+	+/-	−	+
Modular base	+/-	+	-	−	−	+/-	−	−
Certifiability	+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-
Costs	+/-	+	+	+	+	+	+/-	-
Oyster accommodating surface	-	+	+/-	+	+	++	+/-	+/-
Complexity structure	-	-	-	+	+	+	-	-
Liftability structure	+/-	+	+	+	+	++	-	-
Sensing	+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-
Data transfer	+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-
Total	0	13	8	0	0	2	-7	-6

Table 2.3: Relative rating of the concepts with respect to the design criteria

Table 2.3 shows the scoring of each concept with respect to the design criteria. The terraced concept and tripod tree concepts are found to be the most promising concepts, scoring well on the design criteria in general.

2.2.4 Combining concepts

Looking at the SWOT analysis of the concepts in Table 2.3, aspects of various concepts can be used to complement structures and improve their performance. This is done in Table 2.4, by combining the 8 proposed concepts with the two best concepts by looking at their strengths to form new concepts.

	Terraced	Tripod
Pyramid	Tapered terraced structure	Christmas tree
Terraced	x	Stem with mesh terraces
Tripod tree	Terraced tripod	x
Hat	Terraced hat	Convex hedgehog
Bowl	Ridged bowl	Concave hedgehog
'Bakker' cage	Retrievable terrace for monitoring	Retrievable basket branches
Egg container	Profiled hat concept with terraces	Profiled tripod
Donut	Terraced donut	Spiked donut

Table 2.4: Mixing concepts

These combinations provide solutions to weaknesses of the terraced and tripod structures:

Terraced concept

1. **Tapered terraced structure**:
   By having a large lower terrace and a small top terrace with incrementally larger terraces moving downwards, the oysters are given more space, more free flow of water. This mix of concepts increases the permeability and space for the oyster whilst lowering the centre of gravity for the structure.

2. **Terraced tripod**:
   Using meshed terraces, the permeability of the structure can be greatly increased, whilst providing the opportunity for larvae to move between the levels of the structure. Using a protruding foundation, stability can be enhanced at the cost of threatening the infrastructure and increasing the difficulty of certification. Recognising the threat of a tilt, which could set the terraces at an angle with respect to the average flow direction and thereby increasing the frontal area and with that the drag force, replacing the solid terraces with a meshed material will reduce this area and the drag force. Also, the increased flow and meshed terraces will prevent sediment accretion on the terraces and reduce bio fouling due to a limited amount of surface to grow on.

3. **Terraced hat**:
   The Hat with terraces combination offers extra mass to the terraced concept, increasing stability.

4. **Ridged bowl**:
   The same effect occurs for the Bowl with terraces as with the Hat combination.

5. **Retrievable terraces for monitoring**:
   The combination 'Bakker' cage and the Terraced concept could see the top level of the Terraced concept to be retrievable from the seabed for oyster inspection. This element would also contain the sensors or data storage unit to monitor the performance of the structure. Also, the placement of oysters in the baskets is a quick operation, while attaching each oyster individually using adhesive on the terraces is labour intensive. By shaping the terraces in such a way that the oysters are contained by their own weight in cavities on the terraces, preparation could be less time intensive.

6. **Profiled hat with terraces**:
   An interesting feature of the Egg container is the profile of the plate in which the oysters are placed, this profile could be combined with the Terraced concept to keep the oysters within the confines of the structure.

7. **Terraced donut**:
   The Donut concept can be combined with terraces to form a similar concept like the Hat and Bowl mixtures.

Tripod tree

1. **Christmas tree**:
   Combining the Pyramid concept with the Tripod tree can result in a structure with branches that decrease in size from bottom upwards, resembling a Christmas tree. The structure would be more stable due to a lower centre of gravity.

2. **Stem with mesh terraces**:
   The two best concepts, the Terraced concept and the Tripod tree concept, together would give a promising concept. By introducing terraces made of mesh material at the lower stages of the tree, space would be created for the oyster, reducing the amount of branches required, and thereby the difficulty in construction. Also, these terraces would form a barrier for benthic predators roaming the area. The tripod tree with terraces can also be fitted with a different base to accommodate for different subsoils.

3. **Convex hedgehog, concave hedgehog, spiked donut**:
   The Hat, Bowl & Donut concepts are gathered in this space: all concepts in their combination would gain branches on top of their superstructure, leading to a variety of hedgehog-like structures to provide the oysters with more fresh water and increased space for oysters to be placed on

4. **Retrievable basket branches**:
   The Tripod tree and 'Bakker' cage combination results in a modular base for the Tripod tree dependent on the subsoil, while some branches are designed for retrieval for inspection.

5. **Profiled tripod**:
   The Egg container's oyster cavities can be implemented on the Tripod tree's surface, creating leaves on the tree for oysters to be placed on. Due to the increase in drag force that this will cause, the base has to be strengthened to provide stability.

2.2.5 Conclusion conceptual analysis

Using the brainstorm to determine design criteria, and using expert insight into viable concepts for an oyster broodstock element, the concepts have been rated and studied for strengths, weaknesses, opportunities and threats, relatively. Table 2.3 shows the relative, qualitative rating of the concepts as described above. This has shown that the two best concepts are the Terraced concept and the Tripod tree concept. By combining other concepts, variations can be used which can be applied in detailed design for project-specific goals. Concluding, this chapter has presented an overview of the relevant environmental conditions for an oyster broodstock structure, discussed design criteria and brought forward several viable broodstock structure concepts, which can be used in future design research for oyster broodstock structures.

Chapter 3

Methodology - modelling

A structure that is constructed for offshore conditions, faces several challenges in engineering design. In order to quickly understand the performance of a concept structure, a tool is developed called Econstruct. An overview of the structure of the tool is given in Fig. 3.1. Firstly, the relevant input parameters and processes are discussed. Secondly, these inputs are used to calculate the forces and moments by first combining the objects and then subjecting them to the environmental loads. Thirdly, the third section presents output generated. This contains what forces act upon the structure, the magnitude of the crucial loads for structural integrity, gives safety factors for stability and creates a 3D render of the structure. Fourthly, the tool is validated by means of unit testing. Finally, an uncertainty analysis is conducted in the fifth section, containing a sensitivity analysis.

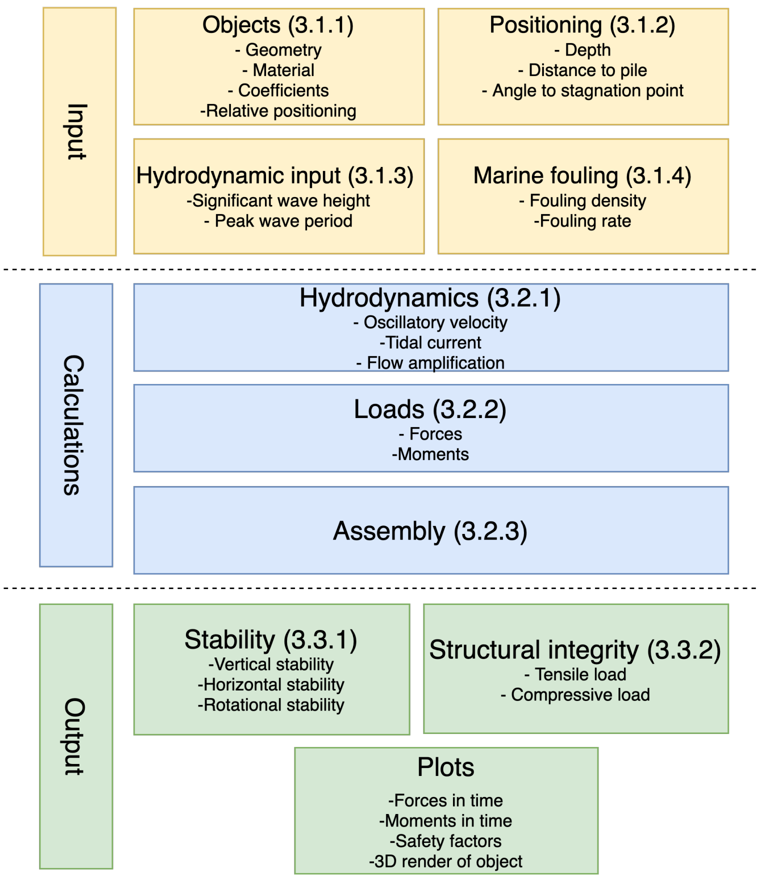

Figure 3.1: Flow chart of the contents of the Econstruct tool as discussed in this chapter

3.1 Input parameters

In order to be able to evaluate various designs, it should be possible to alter the input variables. The input of Econstruct consists of four elements:

- Positioning of the structure with respect to the seabed;
- Object geometries;
- Hydrodynamic inputs: wave height and wave period;
- Marine fouling

These parameters are discussed in the following sections.

3.1.1 Objects

In order to translate a conceptual idea of a structure to a model that can be used in Econstruct, or transforming an existing structure to be assessed by the Econstruct tool, one is required to decompose the structure in basic geometries as a cylinder or a block, as can be observed in Fig. 3.2.

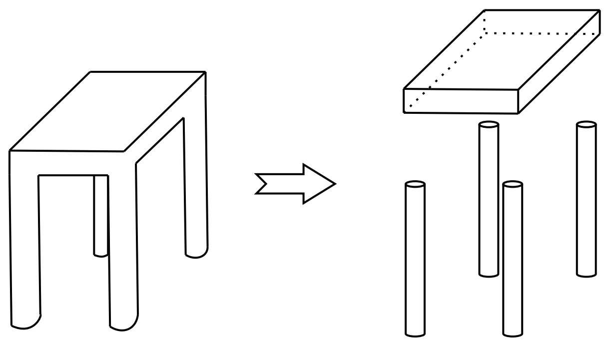

Figure 3.2: Any object that can be decomposed in cuboid or cylindrical shapes can be modelled in the Econstruct tool, by splitting the object in these shapes. The shapes are analysed individually and are then assembled together to analyse the complete structure.

The core of the Econstruct tool is found in three Python classes:

1. Block
2. Disk
3. Structure

In the first two classes, a three dimensional object can be defined: in 'Block' a cuboid object, with a variable width, length and height can be conceived. In 'Disk', a cylindrical shape with radius R and a user-defined height can be created. These objects independently contain information about their geometrical proportions, positioning with respect to the axis system, fouling, hydrodynamic loading, density of material used and location with respect to the seabed. The values for these inputs are defined by the user. The objects also contain coefficients used in the calculations of the loads, and are described in the following paragraphs. When these objects have been created, have a mass and forces due to environmental parameters inserted by the user, the objects are combined together to form a structure. This is done in the class 'Structure'. In this class, the loads of the objects are combined, the centre of gravity of the structure is calculated, as well as the moments within the structure. This is used to determine the resultant forces in horizontal and vertical sense, as well as the total rotational moment about a user defined point. To provide the designer with insight on the structure, a 3D render is created to enable the designer to verify whether the structure that is modelled is the same structure as one had in mind. To see whether the structure is stable and structurally robust, the 'Structure' class provides the user with figures of the moments and forces in time, as well as the safety factors in time. These figures can be used to evaluate the structure for stability. These outputs are discussed in Section 3.3. The code can be viewed using the QR code in Appendix F.

Coefficients

The objects that are defined above perturbate the flow of water around, leading to loads on the structure. These loads will be covered in Section 3.2.2, where coefficients related to the objects are required. These coefficients are the drag coefficient, the skin friction coefficient, the bottom friction coefficient and the added mass coefficient.

Drag coefficient

The drag coefficient C_d is a number that is used to model complex dependencies of shape, inclination and flow conditions on drag. In the calculations, the elements of the structures are simplified to obtain a coefficient. When designing these structures, stability is key and as such a worst-case approximation of the element provides a safe estimation of the drag coefficient. With marine fouling being a large factor in the long-term stability, a filled up shape should be used in worst-case design of the structure, mimicking a structure filled with marine fouling.
For the terraced concept, the space between the terraces can be filled up to form a solid shape, in this case, a cylindrical shape is used, which gives a drag coefficient of approximately 0.7 (Ikhwan and Ruck, 2004).
The tripod tree will be simplified as a solid cylinder, which has a drag coefficient of 0.7.

Skin friction coefficient

Skin friction coefficient C_f is defined for various shapes. For the terraced concept, the flat plate idiom will be used. The drag force on the stem of the terraced concept will be dominated by the pressure drag rather than the skin friction (Lin, 1980). For C_f for a plate, the relation below is used (White, 2011):

$$C_f = 2.87 + 1.58 log\left(\frac{L}{\varepsilon}\right)^{-2.5} \tag{3.1}$$

- L = Length of the plate in the direction of the flow;
- ε = Roughness on the plate, which is in this case assumed as the length of marine fouling

Lift coefficient

The lift coefficient is used to convert properties of the structure and the flow parameters to the lift force. For an irregular shape as is designed in this this study, we will use simplifications to make an accurate estimation of the lift force. To optimise stability, the worst case situation is selected for the determination of the lift coefficient. For the terraced concept this means simplifying the structure to a vertical array of flat plates without marine growth. In time, both the bottom and top side of the plate will experience less lift due to the growth of fouling and plants (Khor and Xiao, 2011). The lift coefficient is coupled to the aspect ratio of the plate with respect to the incoming flow. For the terraced concept with square plates, the aspect ratio is 1, giving a lift coefficient of 0.01 (Ortiz et al., 2015).
The tripod tree was simplified as a composite structure before, of flat plates, an ellipse and a cylinder. The flat plates have an aspect ratio of 8 and 0.13, depending on their orientation with respect to the flow, which results in a lift coefficient of 0 to 0.3 and 0 to 0.5 respectively, for an angle of attack in the range of 0 to 15 degrees.

Bottom friction coefficient

The structure is made of concrete and placed on the scour protection around the monopile. This gives a friction coefficient of 0.6 for contact between concrete and granite under water(Young, 2018), which was also the result of a study conducted by Eiksund et al. for concrete pipelines in rock berms (μ=0.62). It is assumed that the structure is fully in contact with the scour protection, although in reality the rocky scour protection will have many point contacts with the bottom of the structure. CIRIA and Voorend and Molenaar recommend that tests be conducted on large or full scale to establish more confident values of the friction factor.
Also, the structure will settle a little into the scour protection, dependent of the rock grading and weight of the structure, and the protruding elements will form point contacts with the structure. This is a complex process unique to the composition of the bed below the structure, and is not

studied in this research. This scope of research is not conducted in this study, it will however be taken into consideration in Chapter 4 whilst assessing the manufactured structure.

Added mass coefficient

The added mass coefficient required for the calculation of the inertia force describes the mass of the fluid surrounding the structure. For a cylindrical object or radius R, length L accelerating at a rate $\dot{U}$. The hydrodynamic force is in this case perpendicular to length L. This results in a counteractive force exerted by the body, which is captured in the added mass m_a variable. For the cylindrical object this is found by the relation (Techet, 2005):

$$m_a = \rho \pi R^2 L \tag{3.2}$$

Where the density ρ is the density of the surrounding fluid. Combined with the relation for the added mass coefficient as found in Recommended Practise C205 (DNV-GL, 2010):

$$C_a = \frac{m_a}{\rho * A} \tag{3.3}$$

This can be used to experimentally determine the added mass coefficient. In practise, the structure will be simplified to a certain geometry to approximate the added mass coefficient. In Recommended Practise C205 DNV-GL, 2010, various methods are presented to find the mass coefficient C_M, which relates to the added mass coefficient as follows:

$$C_M = 1 + C_a \tag{3.4}$$

If the Keulegan-Carpenter (KC) number of a structure is larger than 3, the cylinder is in unbounded fluid, far from the surface and seabed, the following formulae can be used for the mass coefficient:

$$C_M = max[2.0 - 0.044(KC - 0.3); 1.6 - (C_D - 0.65)] \tag{3.5}$$

For which the KC number should be calculated. This is done by means of the equation below:

$$KC = v_m \frac{T_{peak}}{D} \tag{3.6}$$

Where:

- v_m = the maximum acceleration of a fluid particle, resulting from the hydrodynamic analysis;
- D = the horizontal equivalent parameter, in this case, the diameter.

As the assumptions for this approximation are not valid for the structure in design, as it is placed on the bottom of the seabed, the field will be bounded and it will be on the seabed. This means the approximation above serves as a guideline. In conversation with R. Luiken (pers. comm), it was convened that a factor C_M of approximately 1.3 would suffice (van Rie, 2020).

3.1.2 Position of structure

In the analysis of stability of the structure, the position of the structure with respect to the seabed is crucial for the hydrodynamics and fouling. This study limits the positioning of the structure to the scour protection around a monopile foundation within an offshore wind farm. The positioning with respect to the MP is of effect on the flow velocity. The closer the structure is placed to the MP, the more turbulence is of effect on the structure. The complexity of this turbulence is not regarded in this study, i.e. the wake of the MP and the vortex shedding occurring due to the presence of the MP. Flow amplification due to the presence of the MP is however taken into account in the Section **??** . The angle with respect to the vertical axis and the rotational angle are expressed as ϕ and α in the model. The positioning of the structure is defined as presented in Figure 3.3. The position of the structure with respect to the water column is expressed in the water depth, which is the distance between the top of the structure and the Lowest Astronomical Tide (LAT), in order to maximise the velocities and have a conservative measure of placement to determine fouling species.

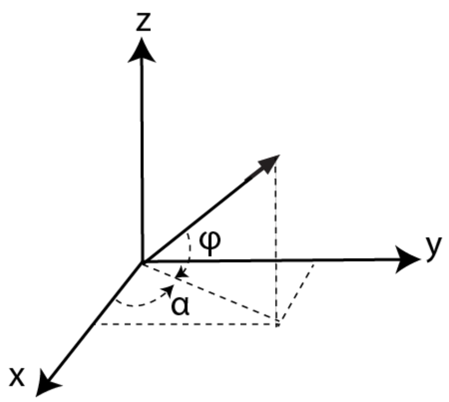

Figure 3.3: The axis system used in the Econstruct tool

3.1.3 Hydrodynamic inputs

The structure will be placed on the scour protection of an offshore wind farm, hence it is paramount to account for the hydrodynamics. The loading due to currents is a result of this but also wave pressures on the structure that can impair structural integrity. The inputs required to carry out the calculations are presented in this section. Local currents are composed of many components, like density driven currents, tidal currents and wave-induced currents. On a local scale, the differences in density will not be large to have an influence on the stability of the structure.
Linear wave theory assumes irrotational, inviscid and incompressible fluid characteristics and is a basic though powerful approximation of the propagation of waves in oceanic waters, where the only external force is the gravitational force (Holthuijsen, 2009). This means, wind forcing and bottom friction are amongst the forces that are neglected, and both have an influence on the structure. As offshore wind parks are inherently located on windy locations and as such experience significant wind forcing, this is relevant to consider. Also, the broodstock element is located on the scour protection, close to the bed. This makes the bottom friction relevant. Through this theory, the maximum wave height and peak wave period can be translated to a velocity profile for the water column. Using the following relation for a progressive monochromatic wave:

$$\hat{u}_x = \omega a \frac{cosh[k(d+z)]}{sinh(kd)} \tag{3.7}$$

With k being the wave number, d the water depth and z the depth of interest. This gives the amplitude of the velocity at depth z. This amplitude is used to determine the particle velocity u_x:

$$u_x = \hat{u_x} sin(\omega t - kx) \tag{3.8}$$

This can be used for the design of a structure, as it provides the flow velocity at the depth of the structure, however, non-linear wave effects are to be considered at smaller scales, for example for marine structures (Holthuijsen, 2009).

Maximum wave height

In order to evaluate the structure for strength and stability, the maximum load case is required. This is found for the maximum wave (H_{max}). The maximum wave height is calculated from the significant wave height using the following equation from (Holthuijsen, 2009):

$$H_{max} = 1.86 \cdot H_s \tag{3.9}$$

Peak wave period

The peak wave period is determined by means of the significant wave height, the average zero crossing period for an extreme storm and the significant wave steepness S.

$$T_z = \sqrt{\frac{2\pi H_s}{gS}} \tag{3.10}$$

$$T_{peak} = 1.29 \cdot T_z \tag{3.11}$$

This wave has a wave frequency of 0.885 rad/s.

3.1.4 Marine growth

Marine growth, or biofouling, is the attachment of organisms to a man-made surface within an aquatic environment (Cooksey and Wigglesworth-Cooksey, 1995). The extensive growth of marine organisms on man-made structures has implications on the performance of structures placed in marine environments. Marine growth influences the mass, the geometry, and the surface texture of a structure placed in aqueous environment. Effects of fouling on loading to cylindrical structures and flow regime are the following (Zeinoddini et al., 2016):

- Increase in cylinder diameter, increased drag and inertia forces due to increase in projected area, displaced volume and changes to the hydrodynamic coefficients;
- Shedding frequency of the cylinder decreases, has direct effects on the vibration, lock-in and synchronization;
- Additional mass on the structure, decreases natural frequencies of the structure, which can bring the natural frequency closer to the shedding frequency, possibly increases the likelihood for the structure to start resonating;
- Increased flow instability due to increase in effective diameter;
- Complicates damage assessment;
- Surface roughness is increased;
- Roughness density plays a role on mean forces and pressures;
- Surface skewness affects the lift/drag coefficients;
- Increased Strouhal number:

  $$S_n = \frac{D_e f}{v} \tag{3.12}$$

  D_e is effective diameter, f is vortex shedding frequency, v is flow velocity;

It is therefore an important parameter to include in designing marine structures (Loxton et al., 2017). The composition of the fouling is important in order to derive the fouling parameter that is required for the Econstruct tool. The effects of marine fouling are hard to quantify, due to the bio-variety of marine growth, season conditioning, natural cleaning or death of species, severe competition leading to replacement of some species and of course local hydrodynamic conditions(Schoefs, 2018). In the following section, an overview is presented of the fouling species, which species are most relevant for modelling fouling and how this alters the fouling parameter.

Fouling species

Marine growth is broadly divided into three classes, that occur along the water column as shown in Fig. 3.4:

1. “Hard” fouling (generally animals such as mussels and barnacles);
2. “Soft” fouling (algae, sponges);
3. Long kelp

The main ”hard” fouling species, are the following(Schoefs, 2018):

- Mussels;
- Oysters;
- Tubeworms;
- Barnacles;
- Kelps

The main "soft" fouling species, are the following (Schoefs, 2018):

- Soft coral;
- Anemones;
- Hydroids;
- Sea squirt;

Kelp consists of a holdfast for attachment, a flexible stipe and a blade (Tiron et al., 2013).
In practice, the influence of marine fouling upon fluid loading in underestimated. This is particularly so, for flexible (soft) forms of fouling such as kelp, which are not easily characterized by a single parameter like roughness (Zeinoddini et al., 2016).

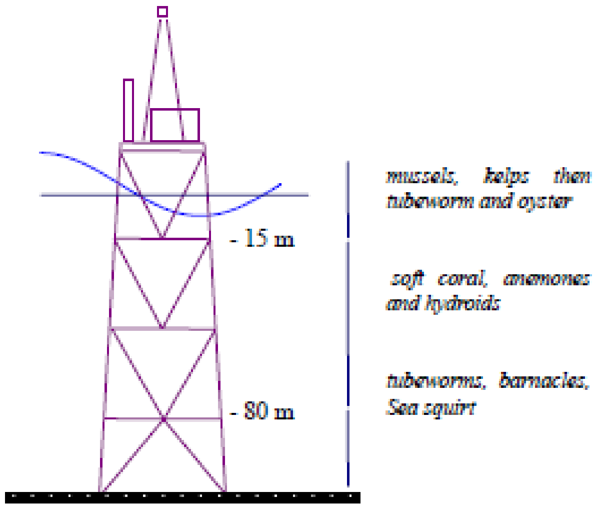

Figure 3.4: The main layers of colonization, generalising 29 vegetal species and 60 animal species

Growth of biofouling

After placing a structure in the sea, a biofilm of bacteria starts to stick to the surface (this is called micro-fouling), upon which primary colonizers (uni-cellular organisms) attach themselves quickly(Tiron et al., 2013). Secondary colonizers such as hard and soft foulers can then attach to the structure nutrition to these species (Vinagre et al., 2020) . Fouling organisms generally colonize a structure soon after installation but the growth tapers off after a few years (Jusoh and Wolfram, 1996). The growth rates are highly susceptible to water temperature variations, flow patterns, biodiversity, salinity and variation in substrate type (Yebra et al., 2004). Marine fouling also tends to form a thicker layer higher up in the water column, decreasing in species abundance and decreased thickness of marine growth. Main species of fouling in the North Sea can be seen in Fig. 3.5.

Usual name	Colonization process	Life time	Maximal size
0 to -20 m			
Bivalve mussel (R)	bed established after 2 years		l < 9 ; t > 15 (1) to 20 (2)
Barnacle (R)	thickness more than 3 cm	18 to 24 month but shell still attached → new support	d< 3 ; h < 4
Sea-squirt (S)	horizontal components protected / agitation		l = 3 to 6
-30 to –100 m			
Anemone (S)	After 1 year : density more than 300 / m²		l = 20
Soft coral (S)	Density more than 500 / m²	35 weeks for the grub	d = 8 to 10 ; h > 20
-30 to –210 m			
Barnacle (R)	adult at 7 years		d < 5 ; h < 5
0 to bottom			
Tubeworms (R)	Solitary specie	18 month but the tube keeps attached on the component	d = 5 ; l < 10
Hydroids (S)	at the beginning ; survive after for deepness more than 100 meters		l < 15
0 to –300 m			
Sea-squirt (S)	horizontal components protected / agitation	//	l = 3 to 6
-60 to –550 m			
Tubeworms (R)	d = 30 to 50 ; h < 20	fragile	d > 0,1 ; l > 5
-200 to -500 m			
Rigid coral (R)	Slow growth	Great life time	d = 8 to 10 ; h > 20

Figure 3.5: Main species of fouling animals in the North Sea. All dimensions in centimeters (Schoefs, 2018).

Quantifying the fouling parameter

In modelling the fouling layer, a scope of the fouling species is applied to investigate the temporal effect of the growth on the loading on the structure. Hard fouling species have a large, predictive influence on drag and skin friction on the structure, while the influence of soft fouling species is more difficult to predict, as species as seagrass can also contribute to reducing the drag on the boundary layer (Bouma, Vries, et al., 2005). For this reason, a hard fouling species is chosen for the quantification of the fouling parameter. Whilst mussels rapidly add weight to the structure, mussels also greatly increase the surface diameter and surface roughness of submersed structures (Riezebos, de Graaff, et al., 2015; Vinagre et al., 2020). Mussels form a hard crust around the structure, which will protrude into the flowing body around the structure in time. Mussels will take some time to grow to this size. This will give the fouling parameter a sense of temporal differentiation in the composition of the fouling layer and mass. From the Table 3.5, the maximum dimensions of the species can be seen.

The mussel (*Mytilus edulis*)

The mussel, or *Mytilus edulis*, has been studied to show 5cm shell length growth from settlement in 5 years, for UK waters to 5cm in 18 months in waters near South Africa and New Zealand

(Bayne and Worrall, 1980; Berry, 1978). Since the UK waters in which Berry (1978) conducted their research also include the North sea, the growth rate of 5cm in 5 years will be adopted. This leads to a useable fouling parameter of 1cm per year. This is of course a rough estimation, it is recommended to do more in depth research on this parameter than is currently known. The rate that will be used is 1cm per year, until the 5 year mark, when 5cm thickness of the layer is reached. This meets the prediction of the growth of biofouling by Deltares and DNV-GL, which amounts to 50mm for the zone below -7m LAT for the Borssele OWF (Riezebos, de Graaff, et al., 2015).

3.2 Calculations

The Econstruct tool uses the input discussed in Section 3.1 to evaluate a proposed design of a broodstock structure or to assess one. The calculations done with the inputs are discussed in this section.

3.2.1 Hydrodynamics

The hydrodynamic input from Section 3.1.3 are processed to be useful in calculations of forces and loads. The processing is done in this section, by calculating the tidal current velocity, the oscillatory velocity component due to waves and the flow enhancement due to the presence of the monopile.

Wave length

Firstly, the Econstruct tool calculates the wave length. This is required for the calculation of the wave number k, which is used in many expressions further on. The wave length is determined for intermediate waters, using the relation from Holthuijsen (2009):

$$L = \frac{g \cdot T_{peak}^2}{2\pi \cdot tanh(2\pi \frac{Depth}{L_0})} \tag{3.13}$$

Where L_0 is the default value inserted in the hydrodynamics module in the Econstruct tool, which is used to iterate to the wave length used in further calculations, as the relation is implicit.

Wave pressure

The hydrodynamics cause the loading on the structure, by means of wave pressures due to an elevated water level and flow velocities on- and around the structure. The module that is integrated in the tool is based on the following theoretical notions:

$$\eta = asin(\omega t - kx) \tag{3.14}$$

$$u_x = sin(\omega t - kx) \tag{3.15}$$

$$\hat{u}_x = \omega a \frac{cosh[k(d+z)]}{sinh(kd)} \tag{3.16}$$

$$\hat{p}_{wave} = pga \frac{cosh[k(d+z)]}{cosh(kd)} \tag{3.17}$$

$$p_{wave} = p_{\hat{wave}} sin(\omega t - kx) \tag{3.18}$$

The Econstruct tool uses Eq. 3.18 to determine the wave induced pressure.

Tidal current velocity

In order to translate the tidal currents as measured from the surface the 1/7th power law is used, derived from shelf-sea oceanographic research by Soulsby and Humphery (1990) and Chant (2005). This relation is widely used in offshore engineering.

$$U_z = \left(\frac{z}{h}\right)^{\frac{1}{\alpha}} \bar{U} \tag{3.19}$$

Where the following parameters are:

- z = height of the structure
- h = water depth
- α = 7 for 1/7th power law
- $\bar{U}$ = averaged flow velocity at the surface

Oscillatory velocity component

When waves are too steep or the water is too shallow, linear wave theory is no longer valid. The degree of non-linearity of waves is often quantified with the Ursell number, which acts as a dividing line between Airy and Stokes' wave theories (Stokes et al., 2012).

$$N_{Ursell} = \frac{steepness}{(\text{relative depth})^3} = \frac{\frac{H}{L}}{\frac{d}{L^3}} = \frac{H \cdot L^2}{d^3} \tag{3.20}$$

Which, using the environmental parameters for Borssele V, results in $7 \cdot 173^2/32^3 = 5.95$. This means Stokes' theory is applicable (Holthuijsen, 2009).

The nonlinear equations are obtained by adding corrections to the harmonic wave profile. In Stokes' theory, the corrections are successive, by correcting on the basis of previously obtained lower-order corrections. The theory of Stokes is formulated in terms of the velocity potential. It is not suited for calculations in shallow water. The Stokes' theory adds a harmonic component to the basic harmonic component. The amount of harmonic components that are to be added to the basic harmonic is determined by the order of the Stokes wave, which can be read from Fig. 3.6.

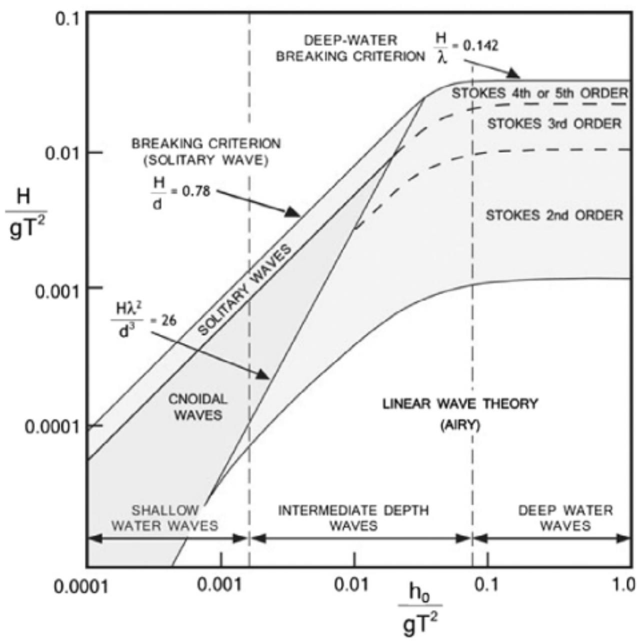

Figure 3.6: The various ranges of wave theories, by Le Mehaute, 1976

For a wave height of 6.96m, peak wave period of 11.6s and a water depth of 32m, a second-order Stokes wave approximation is used. These parameters are drawn from the application study conducted in Chapter 4. Being a second-order wave, the wave steepness will be raised to the second power. The resulting formula for the second order Stokes waves is shown in Eq. 3.21.

$$\eta(x,t) = acos(\omega t - kx) + ka^2 \frac{cosh(kd)}{4sinh^3(kd)}[2 + cosh(2kd)]cos[2(\omega t - kx)] \tag{3.21}$$

The velocity components and surface profile are written in terms of a series of harmonics, but are solved with the stream function ψ.

$$\Psi(x,z,t) = a\frac{\omega}{k}\frac{1}{sinh(kh)}xcosh(k(z+h))sin\theta + ka\frac{3cosh(2k(z+h))}{8sinh^3(kh)}sin2\theta - (ka)^2\frac{1}{2sinh(2kh)}\frac{gt}{k} + O((ka)^3) \tag{3.22}$$

Komar (1976) gives the second-order approximation for the horizontal component of the water particle velocity u at time t and at a point (x,z) where z is positive upward from MSL (Horn and Hardisty, 1990).

$$u(x,z,t) = \frac{\pi * H}{T}\frac{cosh[k(z+h)]}{sinh(kh)}cos(kx-\sigma t) + \frac{3}{4}(\frac{\pi H}{L})^2 C\frac{cosh[2k(z+h)]}{sinh(kh)^4}cos[2(kx-\sigma t)] \tag{3.23}$$

$$c = \frac{\omega}{k} = \sqrt{\frac{g}{k}\sigma} + O((ka)^2) \tag{3.24}$$

$$\sigma = tanh(kh) \tag{3.25}$$

The Stokes equation is valid for deep- or intermediate water depth. It is assumed that the wave steepness is much smaller than one, the propagation is only under the influence of gravity, the fluid is inviscid, incompressible and irrotational. The validity of the second-order Stokes' approximation has a limit in near-bed conditions, due to the increased amplitude of the second harmonic component. The flow velocity attenuates more rapidly with depth than is described by the second-order Stokes' approximation by Horn and Hardisty (1990), and was corrected by means of experiments to the following relation for maximum flow velocity:

$$U_{in,atbed} = 0.58 * U_{in} \tag{3.26}$$

Where the velocity $U_{in,atbed}$ is the velocity measured in the experiments, and the velocity U_{in} is the velocity predicted by Eq. 3.23.

Flow enhancement & potential flow theory

As the structure will be placed on the scour protection of a MP, it will experience the presence of the large structure by the disturbance of the flow field created by complex three dimensional flow structures in the vicinity of the object. As the flow passes the cylindrical shape of the MP, they are accelerated. This is called flow enhancement and can be described by potential flow theory as conceived by Laplace. Potential flow theory describes the flow of a fluid through a space, and can be applied to study flow patterns about structure. The potential theory assumes negligible viscous effects and irrotational low-speed flows (White, 2011).

This research will not go into flow effects due to turbulence generated by the the monopile, which can extend up to 80 pile diameters downstream. Work by Miles has shown that the mean flow was reduced immediately downstream of the pile, but returned to 5% of the background levels 8.3 pile diameters from the pile center. Velocities in the wake region of the pile were much less than predicted by potential flow theory. For the oscillatory velocity component, background velocity levels were found for distances of 1.65 pile diameters to 3.5 pile diameters (Miles, 2017). Approximating the flow velocity at the broodstock structure's position with respect to the monopile is therefore conservatively estimated by means of potential flow theory, and is done by means of Equations (3.27), (3.28), (3.29). These describe the progression of flow velocities near a monopile of radius R on a location r away from the pile center, at an angle θ away from the prevailing current.

$$U_r = U_\infty\left(1 - \frac{R^2}{r^2}\right)cos\theta \tag{3.27}$$

Eq. (3.27) describes the radial velocity of a particle in the flow field around an object.

$$U_\theta = -U_\infty\left(1 + \frac{R^2}{r^2}\right)sin\theta \tag{3.28}$$

Eq. (3.28) describes the tangential velocity of a particle in the flow field around an object.

$$U = (U_r^2 + U_\theta^2)^{1/2} \tag{3.29}$$

Eq. (3.29) describes the absolute velocity magnitude of a particle in the flow field around an object.

Result

The velocity of the current and the amplitude of the oscillating velocity component are assumed to be normal to the y-plane and in the negative x direction', as defined in Section 3.1.2. The velocity used in the calculation of the loads, is determined by combining the velocity of the tidal currents with the velocity induced by the oscillatory wave component from the second-order Stokes' approximation. This is a conservative combination, as both components will in practice not always be in the same direction, due to a different direction of the wave field with respect to the dominant tidal current, or even by acknowledging the oscillations within the flow velocity, which means the current is not constantly present. However, for this study, the worst-case scenario where the load is at its maximum magnitude, is relevant for stability calculations.

3.2.2 Loads

In this section, the important forces on the structure are introduced. This section will also discuss the output of these forces that is used to evaluate stability of the structure.

Horizontal loads

For horizontal loads, the dominant factor is the current velocity, induced by storm events and tides. The forces are adapted from the Morrison equation.

Drag force

The drag force is the resulting force of an object obstructing flow of a medium in which it is placed (White, 2011). The Morrison equation for drag reads as follows:

$$F_D = \frac{1}{2}\rho C_D S(u_c + u_w sin(\omega * t))^2 \tag{3.30}$$

With:

- u_c =current velocity (tidal + wind driven) (m/s)
- u_w =orbital velocity (m/s)

To study the stability of the structure in a flow, the maximum drag force is of interest. This is obtained by taking the maximum period, which results in the following drag force equation:

$$F_D = \frac{1}{2}\rho C_D S|u|u \tag{3.31}$$

With:

- S is projected area normal to the force direction (m^2)
- u is fluid particle velocity amplitude (tidal+wave) (m/s)

Bottom friction force

The bottom friction force is found between the seabed and the lower part of the structure.

$$F_{bottomfriction} = \mu(F_{gravity} - F_{buoyancy} - F_{lift}) \tag{3.32}$$

The bottom friction force follows from vertical force components from gravity, buoyancy and lift multiplied by the friction factor μ that can be found in literature for a wide variety of material combinations and roughnesses.

Skin friction drag

This force is a component of the drag force, caused by the roughness of the surface encapsulated by the flow, in this case, by protruding mussels and oysters on the surface of the structure. The force is determined by the following relation:

$$\tau_w = \frac{1}{2}\rho u^2 C_f \tag{3.33}$$

- τ_w is the skin shear stress on a surface (N/m^2)

Which has a resulting skin friction force given by :

$$F_{skinfriction} = \frac{1}{2}S\rho_w u^2 C_f \tag{3.34}$$

Where S is the area of the structure orthogonal to the flow of water around the structure.

Inertia force

The inertia force is the resisting force of an object against movement, following Newton's first law. Taking into account the variation of the inertia force throughout the wave cycle, the inertia force is given:

$$F_{inertia} = \rho_w(1+C_A)V\bar{u} * cos(\omega t) \tag{3.35}$$

With:

- V is the displaced volume (m^3)
- û is the fluid particle acceleration amplitude (only for orbital motion) (m/s^2)

Vertical loads

The vertical loads on the structure will be dominated by the weight of the structure.

Lift force

The lift force is the force induced by the flow of a medium around an object

$$F_{lift} = \frac{1}{2}\rho_w C_L S|u|u \tag{3.36}$$

Gravitational force

The gravitational force is caused by the gravitational pull on an object.

$$F_{gravity} = mg \tag{3.37}$$

Buoyancy force

The buoyancy is, as defined by Archimedes, the upthrusting force on an object equal to the weight of the displaced water by the object.

$$F_{buoyancy} = \rho_w V g \tag{3.38}$$

Moments

The moments that are found in the structure can be calculated after having determined the forces, a point can be selected within the structure object about which the moments can be calculated. For the analysis of stability, the bottom plate's outer most edge is used for the evaluation of rotational stability.

3.2.3 Assembly

The structure element in the Econstruct tool is the engine of the design tool. This element combines all objects together, joins the forces and determines the arms between the forces and a certain point of interest for calculating moments. This is done with the parameters of the individual objects, where the positioning is important in constructing the structure. Within the ”Structure” module, the 3D render of the structure of interest is created, as well as the output generation of the forces in time plot, moments in time plot, Tension & Compression loads and the plot with the safety factor against the failure mechanisms.

3.3 Output

3.3.1 Stability

Stability is one of the most important results to check for the structure. To ensure the oyster broodstock population remains alive, the structure must remain in place and should not be at risk of failure. This section discusses the stability conditions.

Vertical equilibrium

In order to achieve stability, vertical equilibrium is required. This is obtained when the downward directed forces are larger than the upward directed forces. This must also hold during extreme weather events, as this could cause the structure to move along the vertical plane, to the detriment of the functionality of the structure. The tool will present the forces at the start of the project and at the end, making the fouling parameter more visible. Econstruct will also plot the forces in time, and the safety factor for vertical stability.

Horizontal equilibrium

Horizontal equilibrium is also required to achieve stability, which can be achieved by calculating the drag force, bottom friction force, skin friction force and the inertia force. Stability in the horizontal plane requires no movement of the structure. The tool will present the forces at the start of the project and at the end, making the fouling parameter more visible. Econstruct will also plot the forces in time, and the safety factor for horizontal stability.

Momentum equilibrium

The horizontal and vertical forces exert a momentum on the structure. The structure is considered stable (not overturning) when the momentum exerted by its resisting forces (gravitational force, bottom friction force) is greater than the combined momentum exerted by the solliciting forces (drag, inertia, buoyancy, lift, skin friction force). The tool will present the moments at the start of the project and at the end, making the fouling parameter more visible. Econstruct will also plot the moments in time, and the safety factor for rotational stability.

3.3.2 Structural integrity

In order for the structures to be placed on site, they should be checked for structural integrity. The function of the structure should not be compromised by structural failure, which can lead to the failure of the outplacement project. The structural failure of the broodstock element can also threaten infrastructural elements in the vicinity of the structure, such as inter-array cables in wind parks, other nature-inclusive stimulating structures or monopiles.
Extensive structural analysis can be done using FEM analysis software, which is not done in this design study, and is not often done for such an element in practise (Luiken, (pers. comm)). The Econstruct design tool offers some guidance in calculating and designing for structural integrity, however, this procedure is completely unique for the geometry of the structure that is to be evaluated. From the analysis conducted in Chapter 4, the most critical load cases are taken which can be integrated in the Econstruct in a way that provides insight in structures of a wide spread of geometries. The Econstruct design tool also offers to calculate the moment within the structure at a given point in the structure, which aids the designer in calculations.

Tensile forces

Tensile loading within the structure, lifting the structure off the seabed for monitoring on a vessel, is the limiting load case. The structure, fouled and perhaps covered with some sand accretion, will carry tensile loads through its structure. The Econstruct tool provides the maximum tensile load within the structure, and returns the value of required steel reinforcement to carry the load.
The nature of the enhancement project will determine how this output can be used. In a project where broodstock elements are permanently placed on the seabed and removed at the end of life, it is required to determine the required tensile capacity of the reinforcing steel to be able to remove the structure.
When a project asks for regular monitoring of the structures after placement, the lifting will cause cracking in the concrete to occur due to the elongation of the structure due to the tensile loads, as concrete is not capable of handling large tensile loads.
In the first case, for permanent placement, the Econstruct tool calculates the required area of reinforcing steel in the central spine, by using the tensile load (f_y, the maximum strain allowed in the reinforcing steel(ε and the Young's modulus (E_s).

$$A_s = \frac{f_y}{E_s * \varepsilon} \tag{3.39}$$

The ε is determined from the crack width, which is 0.3mm for exposure class XS2 (EN 1992-1-1, 2018). When a structure requires monitoring at certain time intervals, the maximum tensile loads are restricted to the size of cracks in the concrete. Increased propagation of cracks in the structure will accelerate deterioration of the structure as a consequence of corrosion when the reinforcing steel is in contact with the saline waters surrounding the structure.

The maximum tensile load for reinforced is therefore limited by the tensile strength, which is expressed as:

$$f_{ctm} = \frac{\alpha_{cc} \cdot f_{ctk,0.05}}{\gamma_c} \tag{3.40}$$

Where:

- α_{cc} is the coefficient that takes into account long term effects (=1.0)
- $f_{ctk,0.05}$ is the characteristic axial tensile strength of concrete, which is 2.2 MPa for C35/45
- γ_c is the partial safety factor for concrete (1.5 for persistent loads) (Voorend and Molenaar, 2019).

By making use of this relation, the design tensile strength is found to be 1.47 MPa.

Compressive forces

For applications in various environments, it is interesting to know what the compressive loads are on the bottom of the structure. This information can be useful to determine whether a structure will sink into the seabed, or will collapse on its own weight when lifted on the vessel.

The design compressive strength of concrete is calculated by means of the following equation:

$$f_{cd} = \frac{\alpha_{cc} \cdot f_{ck}}{\gamma_c} \tag{3.41}$$

This relation contains similar parameters used in the design tensile strength relation. The characteristic axial tensile strength is swapped out for the characteristic compressive cylinder strength of concrete, measured at 28 days since pouring, which is found at 35 MPa for C35/45 concrete. With this parameter, the design compressive strength for this concrete class is found to be 23.33 MPa.

3.4 Validation design tool

The goal in validating the tool is to check whether the tool is accurate in making calculations of geometrical shapes in a submarine environment, given a rate of marine fouling.
In order to verify whether the model performs correctly, both the disk module and the object module are tested by checking the outcomes of the tool with manual calculations.

3.4.1 Unit testing

In order to evaluate the validity of the model, unit testing can be applied. Whereas in software development, this technique aims to analyse the source code by analysing on a brick-by-brick base, small pieces of code at a time. For an Object-Oriented Programme, this technique can also be applied to verify calculations of a complex shape by checking the outputs for a simple shape.
In this study, two of these tests are carried out, the unit disk test and the assembly test. Both have the aim to verify a block of code. This will be done by inserting the inputs into the equations named in Section 3.2.2, and comparing the outcomes with the results from the tool. Using this method of validation, the tool was deemed applicable for the design of an oyster broodstock element. Appendix E contains the input tables and output tables that are referred to in this section.

3.4.2 Unit test

This section validates the functioning of the objects in the tool, the disk and object modules, that can be used to create any structure. The input and output tables are situated in Appendix E.

Unit Disk

A unit disk is a cylindrical object that can easily prove the validity of the tool.

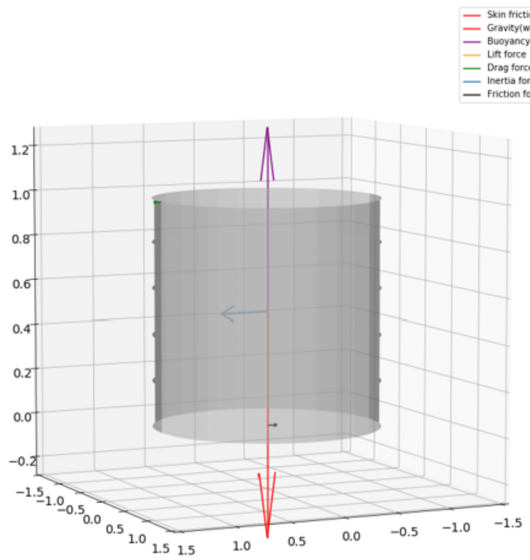

Figure 3.7: Unit disk used as input for validation

Using the input given in Table 1, and the equations presented in Section 3.2.2, calculations by hand result in the forces presented in Table E.24. This same procedure is followed for determining the moments. These results can be compared to the output in Table E.25. The outcomes are the same, thus the unit disk module is validated.

Unit block

Similarly to the unit testing done by means of the insertion of a unit disk, a unit block is inserted into the tool. The input and output tables are situated in Appendix E.

The unit block is portrayed in Figure 3.8. The parameters used as input are presented in Table 2, the results are given in Table E.26 and are compared with Table E.27. The results are equal, so the Econstruct tool is validated for the unit block.

3.4.3 Assembly test

The assembly test serves to test whether the tool can successfully unify two objects and transfer and accumulate the loadings on the unified blocks, or structure.

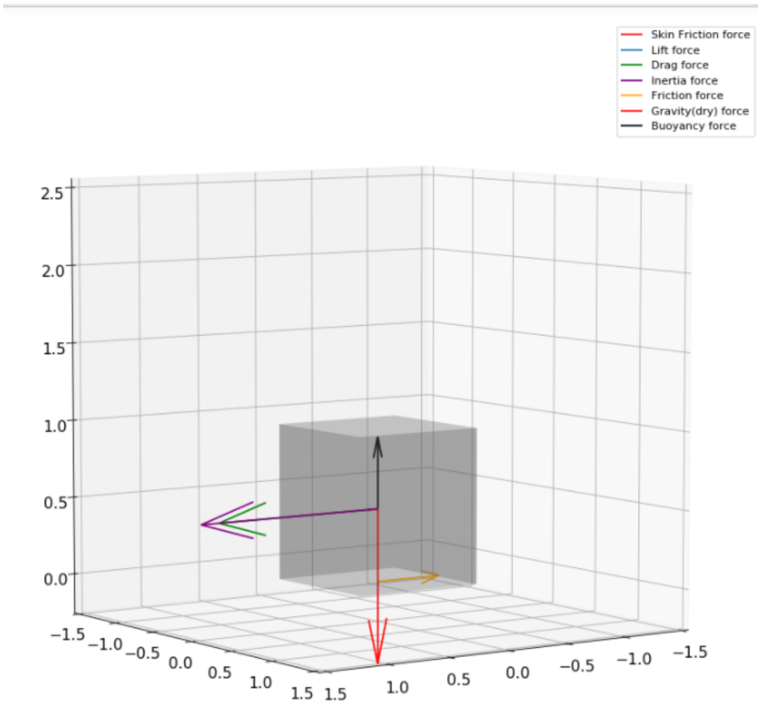

Figure 3.8: Unit block used as input for validation

Disk assembly

In this test, the block of code that assembles objects together is tested. In this case, two disk objects are joined together, and are calculated with the model. The 3D render can be seen in Figure 3.9. The input and output tables are situated in Appendix E. Joining the two disks, using

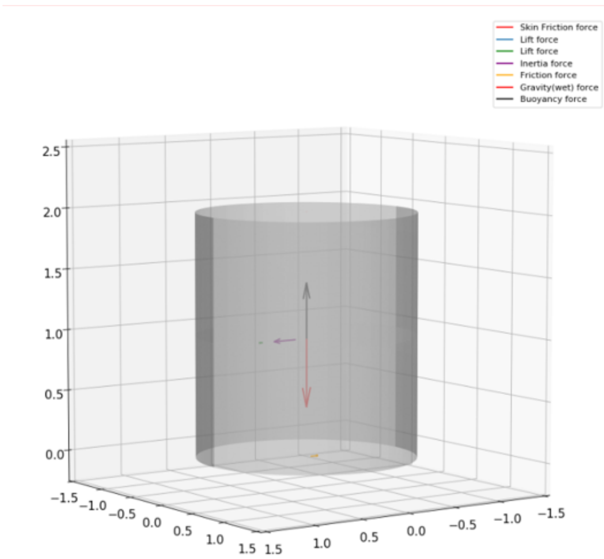

Figure 3.9: Assembly of two unit disks used for validation

the input stated in Table 3, the results of the manual calculation and Econstruct calculations can be compared using Tables E.28 and E.29. It can be observed that the results are the same, hence the Econstruct design tool is validated for the assembly of the unit disks.

Block assembly

The block assembly test serves to prove the validity of the Econstruct tool to assemble two unit blocks and keep track of the load on the structure. The input and output tables are situated in Appendix E.

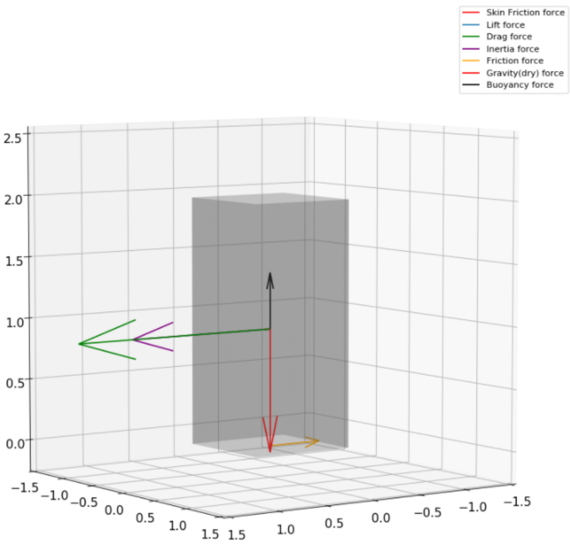

Figure 3.10: Assembly of two unit blocks used for validation

The input used in this unit test is listed in Table 4, which is used in manual calculations and as input for the Econstruct tool, and results can be compared in Tables E.30 and E.31. The results are equal, so the Econstruct tool can assemble unit blocks succesfully.

3.5 Uncertainty analysis

An uncertainty analysis covers the following elements:

1. Parameter uncertainty
   Aims to determine the relative support for different parameter values across the distribution of the parameter.
2. Model uncertainty
   Uncertainty in the completeness of the model, which could hamper the effectiveness of the model.
3. Design/data uncertainty
   Uncertainty in the data can lead to a variation in the results of the model.

3.5.1 Parameter uncertainty

In order to evaluate which parameters are important in designing structures for broodstock purposes, a sensitivity analysis (SA) is conducted. This analysis assesses the sensitivity of the output of a model with respect to changes in the inputs (Marzban, 2013). The SA gives an insight in which parameters are most important in the performance of the structure. It is therefore important to select the right parameters to evaluate in the SA. In this SA, the following input parameters are selected for examination:

- Radius of the cylinder
- Height of the cylinder
- Current velocity at the top of the cylinder
- Amplitude of the oscillatory wave component on top of the cylinder
- Rate of fouling on the surface of the cylinder

For the SA, the model is tested for a cylinder of a certain radius and a certain height, for which the parameters are explained below. The cylinder is placed in a current with a velocity, which consists of the tidal current and the oscillatory wave component. The cylinder experiences biofouling as well, which is expressed in the fouling parameter. The input parameters that are tested are listed in Table 3.1.

Parameter	Lower boundary	Upper boundary	Distribution
Radius	0.7	1.3	Uniform
Height	1	1.8	Uniform
U	2.5	4.5	Uniform
U_amp	1.5	3.5	Uniform
Foulrate	0.005	0.015	Uniform

Table 3.1: Parameters with their respective boundaries used in the sensitivity analysis

The boundaries are chosen by deviating symmetrically from the parameters found in the study of project Ecoscour. The actual parameter distributions are not taken into account, as this is not a probabilistic study. The effects of changes in the parameters on the outputs can be measured like this. The cylinder in this environment experiences a horizontal loading, vertical loading and overturning moment which are taken as the relevant output. The notion of a Sensitivity Analysis knows many methods. In this analysis, a One-At-a-Time (OAT) method is used. The OAT method studies one parameter at a time, by using a wide range of inputs in the Econstruct tool. The outputs from the Econstruct tool are the safety factors for horizontal stability, vertical stability and rotational stability. The outputs generated with these inputs are subsequently studied and compared using the method described by (Loucks and Beek, 2005; McCuen, 1973) to obtain the Sensitivity Index (SI) per input per type of output:

$$SI_{PQ} = |(Q_0 - Q_i)/(P_0 - P_i)| + |(Q_0 - Q_j)/(P_0 - P_j)|/2 \tag{3.42}$$

Input parameter	Output parameter	Sensitivity factor	Elasticity factor
Radius	Safety factor horizontal stability	0.036	0.30
Radius	Safety factor vertical stability	0.069	0.055
Radius	Safety factor rotational stability	0.47	0.65
Height	Safety factor horizontal stability	0.0159	0.185
Height	Safety factor vertical stability	0.033	0.037
Height	Safety factor rotational stability	0.11	0.21
U	Safety factor horizontal stability	0.015	0.43
U	Safety factor vertical stability	0.0012	0.003
U	Safety factor rotational stability	0.06	0.31
U_{amp}	Safety factor horizontal stability	0.02	0.425
U_{amp}	Safety factor vertical stability	1.11e-16	2.21e-16
U_{amp}	Safety factor rotational stability	0.05	0.18
Foulrate	Safety factor horizontal stability	3.93	0.34
Foulrate	Safety factor vertical stability	8.31	0.066
Foulrate	Safety factor rotational stability	9.31	0.13

Table 3.2: Results of the sensitivity analysis for the five selected parameters. The sensitivity index and the elasticity index are presented in this Table.

Where Q is the output variable as a consequence of input P, where P_0 is the base value of the input variable, the parameter with index i represents a decreased deviation and j represents an increased deviation in parameter value from its base value P_0 (Loucks and Beek, 2005). The magnitude of this number indicates the effect of an absolute change of the input parameter on the output of the model. Another result is the elasticity index (EI), that measures the proportional change in output parameter Q for a relative change in the input parameter P and is defined as:

$$EI_{PQ} = \frac{P_0}{Q(P_0)} SI_{PQ} \tag{3.43}$$

The results are found in Table 3.2. *Note: it is not the exact number that is important in such an analysis, it is important to look at the relative magnitude of the results. This tells the user something about the impact of an alteration in the input parameter*

Analysis sensitivity analysis

The results presented in Table 3.2 are analysed in this paragraph. By examining the results for each output parameter, the respective influence of the input parameters is shown. Below, the general findings:

- The SI for foulrate shows a large number, which means the spread is enormous when the upper and lower boundaries are touched. This means that the parameter has a significant influence, however, the range is much larger in a relative sense than the other parameters, which shows the uncertainty in this parameter.
- The radius generally has a large influence on all forces and moments. This was to be expected, as a wide base in general increases stability, and also increases the mass significantly.
- The elasticity factor shows that the radius has a very large influence on the overturning moment, showing that this parameter could perform as a tuning button for future designs, by adding horizontal braces to increase the 'radius' and reducing overturning threat.
- The amplitude of the oscillatory velocity component does not influence the vertical stability. This makes sense, as the lift force is the only component that is influenced by the velocity, and is very small.
- The current is important for the horizontal stability and rotational stability. This is shown in the elasticity factor. It is therefore crucial to have a good understanding of the hydrodynamics, and this also shows other phenomena like the influence of surroundings of the structure have to be investigated further, as they can have a potentially unfavourable influence on the performance of the structure.

- The height of the structure is less effective an instrument to tune stability factors with than the radius. Work in the horizontal plane to attain higher levels of safety, rather than go up in the water column.

3.5.2 Model uncertainty

The model contains the prevalent forces for a structure under water, however, it is a simplification of reality and by no means a tool that can offer a very detailed overview of the effects of hydrodynamic conditions on a structure. Effects like vorticity of flow which can increase the risk of toppling are not taken into account. The interaction between the structure and the scour protection is also not considered in this design, and could prove problematic when designing for softer beds than the armor layer of a monopile, such as sediment-rich seabeds.

3.5.3 Design/data uncertainty

This study aims to fill the gap in oyster restoration projects and nature enhancement of offshore wind where broodstock structures have not been subjected to thorough engineering research. It is therefore likely that there are more optimal solutions in shaping the objects, as the experts in the field have largely influenced the concepts that were analysed in Chapter 2. The data that is required for designing a structure, apart from the iterative geometric parameters, is obtained from site investigations regarding the hydrodynamics of the area of interest, and the information known about the fouling species dominant in the region, with their respective growing characteristics.

Chapter 4

Application: Project Ecoscour

4.1 Introduction

After defining the methodology for designing an oyster broodstock structure for ecofriendly scour protection in offshore wind, the method is applied to the Borssele OWF. The design is carried out in collaboration in Project Ecoscour. Firstly, the environmental characteristics of the site will be studied, which also entails the ecology, hydrodynamics, water quality and morphology. Also, the scour protection and MP are discussed as part of the environment of the structure. After the environmental characteristics are known, the inputs can be deducted and used for the design of the structure. The design is reviewed in collaboration with structural engineers at Van Oord and finally manufactured and placed at Borssele V OWF. The final design is assessed with the Econstruct tool.

4.2 Borssele Offshore Wind Farm

The Borssele Wind Farm zone is found in the southern North Sea area. It is divided in 5 areas as shown in Figure 1.9 and its position with respect to the Dutch Continental Shelf is depicted in Figure 4.1.

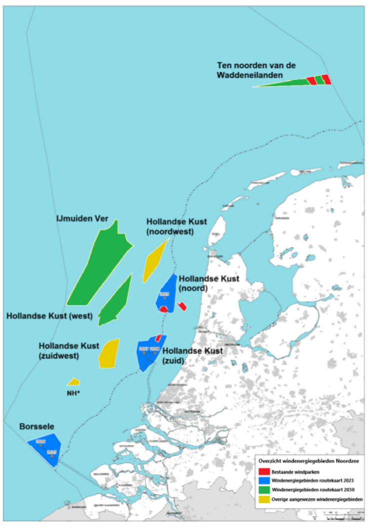

Figure 4.1: Map of the existing OWFs (red), OWF areas from in Roadmap 2023 (blue), OWF areas from Roadmap 2040 (green) and other OWF areas (yellow) (Ministerie van Economische Zaken en Klimaat, 2018).

Figure 4.2: Wind farm sites at the Borssele Offshore Wind Farm

4.3 Environmental characteristics

In this section, the environmental characteristics for a general oyster broodstock structure for flat oysters are discussed, as well as specific conditions at the Borssele V OWF.

4.3.1 Seabed composition

The Borssele area before the construction of the wind farm, used to be a sediment-rich environment, as can be seen in Figure 4.3. Due to the construction of the offshore wind farm, this sediment-rich environment is changed by the addition of large quantities of hard substrate.

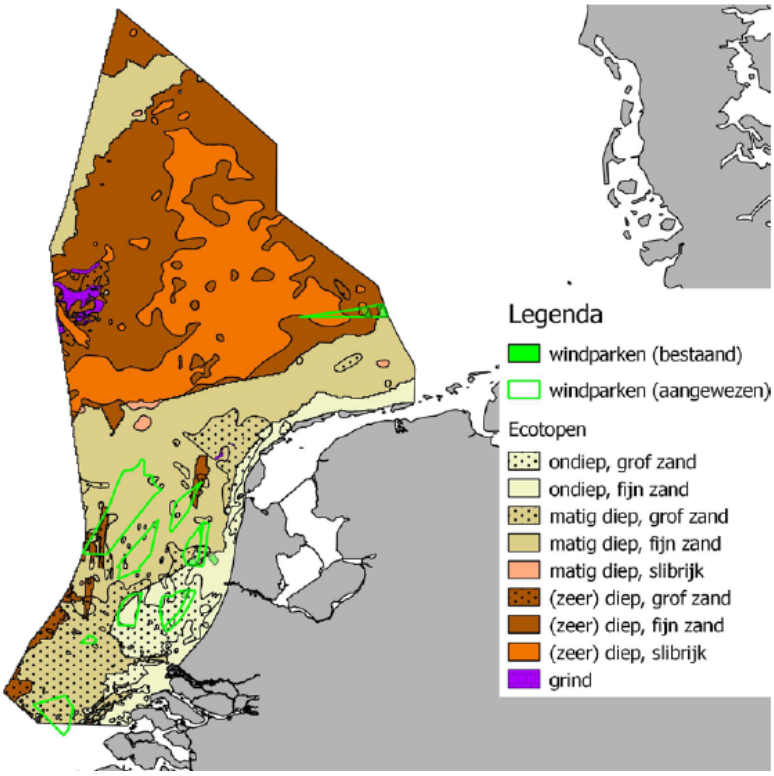

Figure 4.3: Composition of the seabed of the Dutch Continental Shelf (Smaal, Kamermans, Kleissen, et al., 2017)

4.3.2 Morphological features

Sand banks

Sand banks occur throughout the North Sea seabed, and have a length in the size of kilometers. Near Zeeland the sand banks are found at a larger depth (20-30m below NAP) than in the northern area (14-20m below NAP). The height of the banks varies between 4-20 meters, where the northern ones vary between 3 and 6 meters (Smaal, Kamermans, Kleissen, et al., 2017). Near the Borssele OWF, the bed looks as shown in Fig. 4.5.

Sand waves

A multitude of sand waves occur in the Borssele OWF, as can be seen in Fig. 4.4 and more specifically for Borssele V in Fig. 4.6. Studying the migration rates of the sand waves at the site of Borssele V, it can be observed that the waves migrate in a diverging pattern. It is therefore assumed in consultation with author Raaijmakers in Raaijmakers, Roetert, Riezebos, et al. (2016), that the sand wave migration will not significant threaten the oyster broodstock element, when placed on the scour protection.

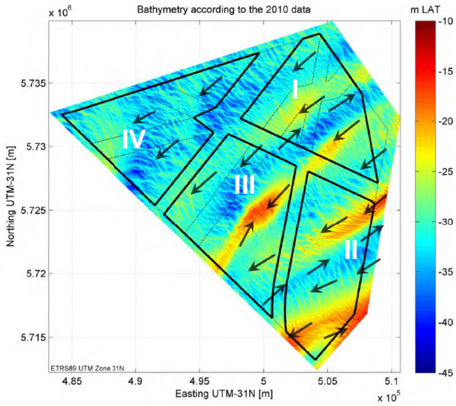

Figure 4.4: Sand waves and their directions of migration for the Borssele OWF. Adapted from (Raaijmakers, Roetert, Riezebos, et al., 2016)

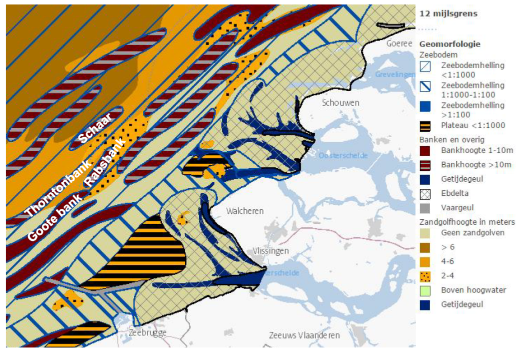

Figure 4.5: Seabed morphology in the Borssele OWF. Adapted from (Dutch Ministry of Transport, Public Works and Water Management), 1986)

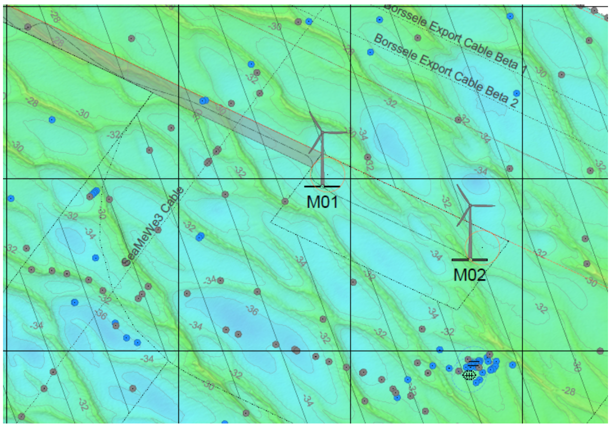

Figure 4.6: The two monopiles of the Borssele V innovation site can be clearly seen, the wavey bottom indicates the presence of many sand waves, the contour lines reveal the magnitude of these waves. Adapted from (Van Oord, 2019b)

4.3.3 Hydrodynamic & water quality conditions

Return period	1 yr	5 yr	10 yr	50 yr
H_s	4.8m	5.81m	6.21m	6.96m
T_p	8.9s	9.5s	9.7s	10.2s
$T_{p,DNV}$	10.0s	11.0s	11.4s	12.0s
Surface current speed	1.48m/s	1.61m/s	1.65 m/s	1.76 m/s
Depth-mean current speed	1.14m/s	1.19m/s	1.21m/s	1.25m/s
1.5m above seabed current speed	0.82m/s	0.83m/s	0.84m/s	0.85m/s

Table 4.1: Hydrodynamic parameters for Borssele III and IV. Obtained from (Van Oord, 2018c)

As the significant wave height (H_s) and peak period (T_p for OWF Borssele III and IV are measured, this information can be used for OWF Borssele V, as it is a piece of Borssele III OWF. Loads on the structure can be determined with this information, which requires the maximum wave height (H_{max}). This is because that one extreme wave can be enough to topple, shove or lift the structure off the bed. Using (4.1) and (4.3) from Holthuijsen (2009):

$$H_{max} = 1.86 \cdot H_s = 1.86 \cdot 6.96 = 12.96m \tag{4.1}$$

$$T_z = \sqrt{\frac{2\pi H_s}{gS}} = 10.63\sqrt{\frac{H_s}{g}} \tag{4.2}$$

With:

- T_z= average zero crossing period for extreme storm
- S = significant wave steepness for extreme storm = 1/18 (Orcina, 2020, September 8)

$$T_{peak} = 1.29 \cdot T_z = 13.7 \cdot \sqrt{\frac{H_s}{g}} = 11.5s \tag{4.3}$$

Gives a value for H_{max} of 12.95m for a H_s of 6.96m, and an accompanying peak period for such an extreme weather event of 11.5s. This results in the following oscillatory velocity component:

$$U_{stokes} = 1.77m/s \tag{4.4}$$

This result has been obtained with the Econstruct tool, by means of the following input parameters: The current as a consequence of the tidal currents can be calculated using the 1/7th power law

Parameter	Value
H_{max}	12.96m
T_{peak}	11.5s
Depth	32m
$U_{surface}$	1.76 m/s
$H_{structure}$	1.4m
L_0	100m

Table 4.2: Input parameters for the Econstruct tool

from (3.19), which gives:

$$U_{tidal} = U_z = \left(\frac{1.4}{32}\right)^{1/7} \cdot 1.76 = 1.12m/s \tag{4.5}$$

Assumed is that the velocity component as a consequence of the tidal current can be summed up, which results in the following value for the maximum current at the top of the structure

$$U_{total} = U_{tidal} + U_{Stokes} = 1.12 + 1.77 = 2.89m/s \tag{4.6}$$

This gives the total velocity that can be seen as the background velocity for the calculation with flow amplification due to the presence of the monopile.

Wave pressure

The Econstruct tool calculates the wave pressures caused by waves passing over the structure, using the parameters from Table 4.1, this gives a wave pressure of 37.4 kPa.

4.4 Stability calculations

4.4.1 Approach

In the design of the broodstock element, the concepts resulting from Chapter 2 are selected as suitable options for the Project Ecoscour.

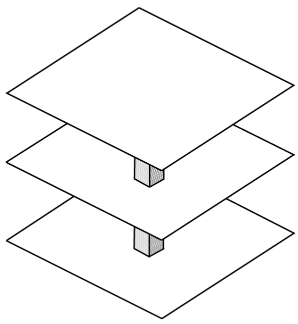

Figure 4.7: Terraced concept

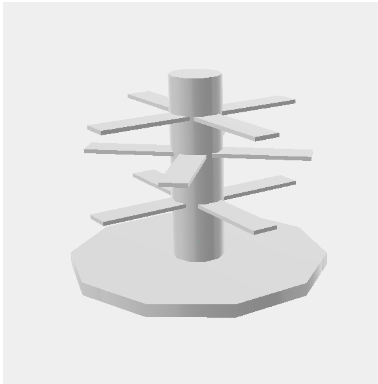

Figure 4.8: Tripod tree concept

4.4.2 Concepts

In the Figure 4.7 and Figure 4.8, both concepts can be observed. The tripod tree shows some alterations to the concept displayed in Chapter 2, in order to obtain a large enough area to support the oysters. In consultation with Van Oord's engineers, it was decided to focus on the design of the terraced concept, as the construction and corrosion protection of the tripod tree concept would be complex and costly to carry out. The elements would have to be constructed individually and assembled, which would compromise structural integrity, as bolted or welded connections in a marine environment are subjected to cyclic loads which would increase the likelihood of failure of the structure.

4.4.3 Geometry

The design iterations start from the oyster focused parameter: the oyster carrying surface area. This is the area of the elements with upward facing elements of the structures. As was determined in Chapter 2, the structure requires an oyster carrying area of $5m^2$. A fitting design for the terraced concept was iteratively found, with the following dimensions:

Part	Radius	Height	Separation
Bottom plate	1m	0.15m	0.3m
Middle plate	1m	0.15m	0.5m
Top plate	0.8m	0.15m	0.15m

Table 4.3: Dimensions of the terraced concept design, technical drawing is presented in Appendix B.

4.4.4 Input parameters

Parameter	Value	Parameter	Value
Fouling rate	0.01 m/yr	μ	0.6
H_{max}	12.96m	C_d	0.7
C_l	0.01	C_m	1.3
C_f	0.001	ρ_f	$1325 kg/m^3$
ρ_s	2500 kg/m^3	ρ_w	1025 kg/m^3
α	0	ϕ	90

Table 4.4: Inputs used in the Econstruct tool to evaluate the design for Project Ecoscour

Fouling rate

As defined in Section 3.1.4, the fouling parameter for the Borssele area is taken as 1 cm/year, based on the growth rates of mussels.

Maximum wave height

Using the information of Section 4.3.3, the maximum wave height for a 50 year return period is found to be 12.96m.

Lift coefficient

The lift coefficient is based off the flat plate assumption, giving a lift coefficient of 0.01, which was studied in Section 3.1.2.

Skin friction coefficient

The skin friction coefficient was studied in 3.1.2, and can be calculated for various surface roughnesses. After placement of the structure on the scour protection, organisms will swiftly start to cover the structure, causing obstructions for the flow on the surface of the structure. The dominant fouling species is thus taken as a measure of the skin friction, which gives a skin friction factor $C_f = 0.0077$ for a stem element, $C_f = 0.0129$ for a plate element at the start of the placement. After 5 years of growth, the friction factor grows to $C_f = 0.0145$ for stem elements and $C_f = 0.0261$ for plate elements.

Density concrete

The density of concrete is found to be 2500 kg/m^3 for concrete class C35/45 (Eurocode applied, 2010).

Inclination with respect to the x axis: α

The inclination with respect to the x axis is taken to be 0. In order to test stability due to tilted placement, the inclination with respect to the z axis is tested in parameter ϕ.

Bottom friction coefficient

The bottom friction coefficient is assumed to be 0.6, according to Young, as described in Section 3.1.2.

Drag coefficient

The drag coefficient of the structure is found by means of a simplification of the structure. The cylindrical shape gives the structure a C_d of 0.7, as described in Section 3.1.2.

Mass coefficient

The mass coefficient of the structure is found by means of the method in Section 3.1.2. to be approximately 1.3.

Fouling density

The density of fouling is taken as 1325 kg/m^3 (DNV-GL, 2010).

Sea water density

The density of sea water is 1025 kg/m^3.

Inclination with respect to seabed normal: ϕ

This is set normally as 90 degrees for the plate surface with respect to the z axis. An inclination of 5 $^\circ$ is used to test for stability.

4.4.5 Results

Using the input stated above, the design tool Econstruct is used to determine the loads and stability.

Mass

The structure weighs 3251kg in air and unfouled. After 5 years of fouling, reaching the maximum fouling thickness as described in Section 3.1.4, the weight increases to 4707.9kg.
As can be seen in Figure 4.9, the structure shows fouling in the green layer, is composed of three layers. The force vectors shown in the figure are not to scale and offer the user an insight the the direction of the loads.

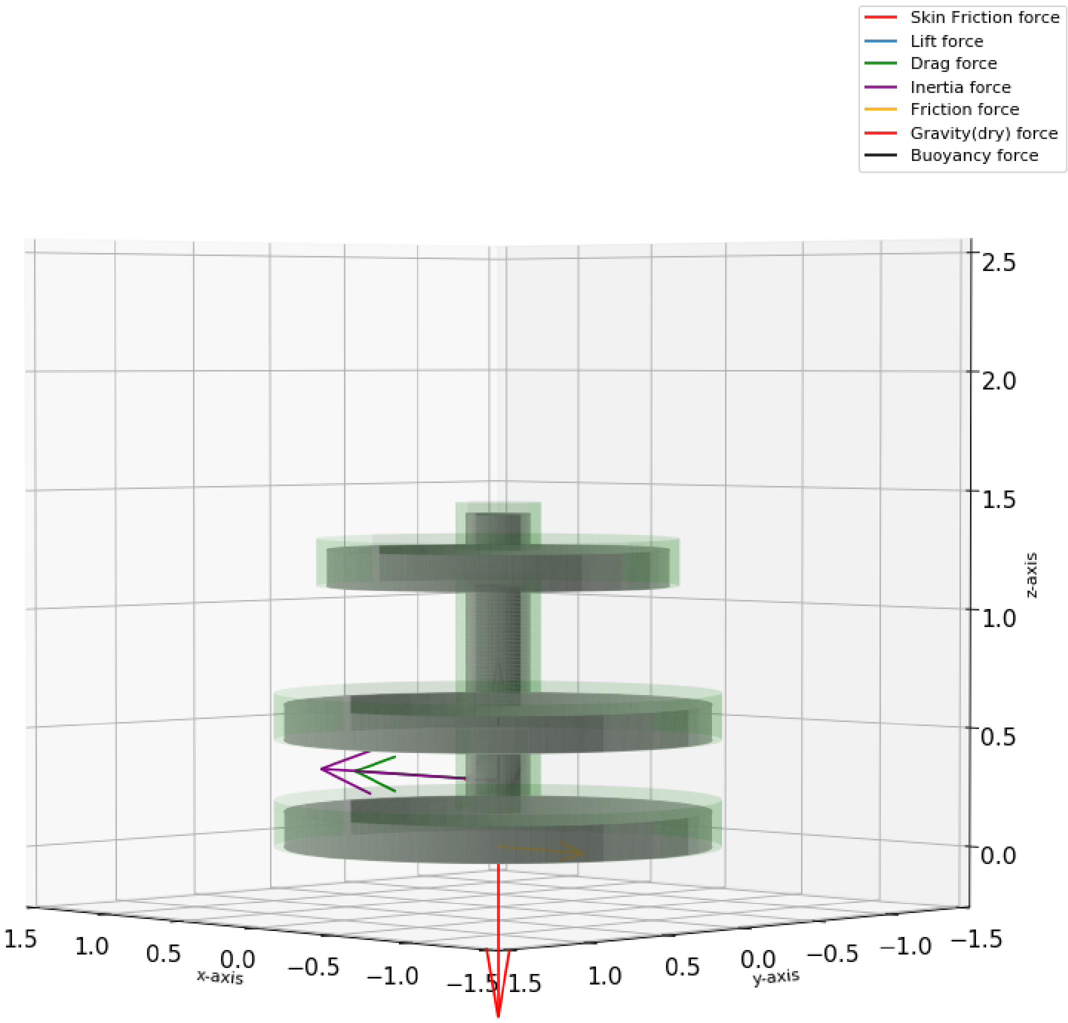

Figure 4.9: Terraced design render in Econstruct tool, showing fouling (green edge)

The 3D plot that is offered by the Econstruct tool provides the user with a view of what is designed and evaluated by the tool. For detailed drawings and renders, using a CAD software package is advised, due to the capacity of these packages to produce detailed technical drawings and can simulate loadings on the structure in a FEM module.

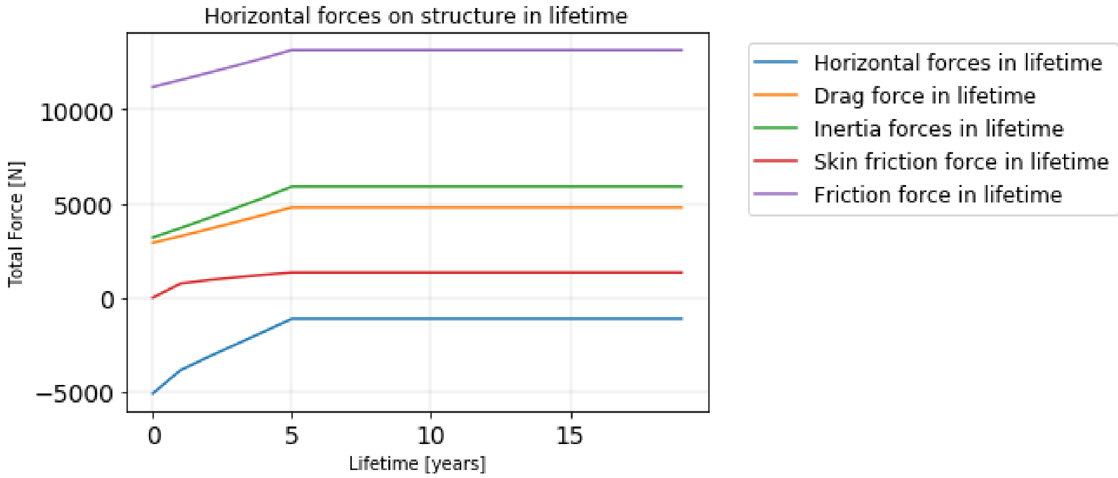

Figure 4.10: Horizontal forces in time, becoming more unstable in time due to the effect of fouling

Figure 4.10 shows the progression of the horizontal forces on the structure. The plot shows the magnitude of the forces. The weight of the structure causes a high friction force, which balances the unfavourable loads, the drag-, inertia- and skin force.
As can be seen in the figure, the fouling causes the horizontal resultant force to become more and more positive. This means, the unfavourable loads become larger in time, due to the increased profile of the structure due to fouling. The enlarged profile adds to the hydrodynamic mass being accelerated by an accelerated particle moving through the frame, increasing the inertial load. The larger profile will also cause a skin friction due to the protruding organisms off the surface of the structure. The drag force increases due to the increased dimensions of the structure, which reflects on the frontal area. The progression of the friction force can also be observed in the graph, and can be observed to increase. This is also due to the fouling, which increases the weight which adds to the friction between structure and scour protection.

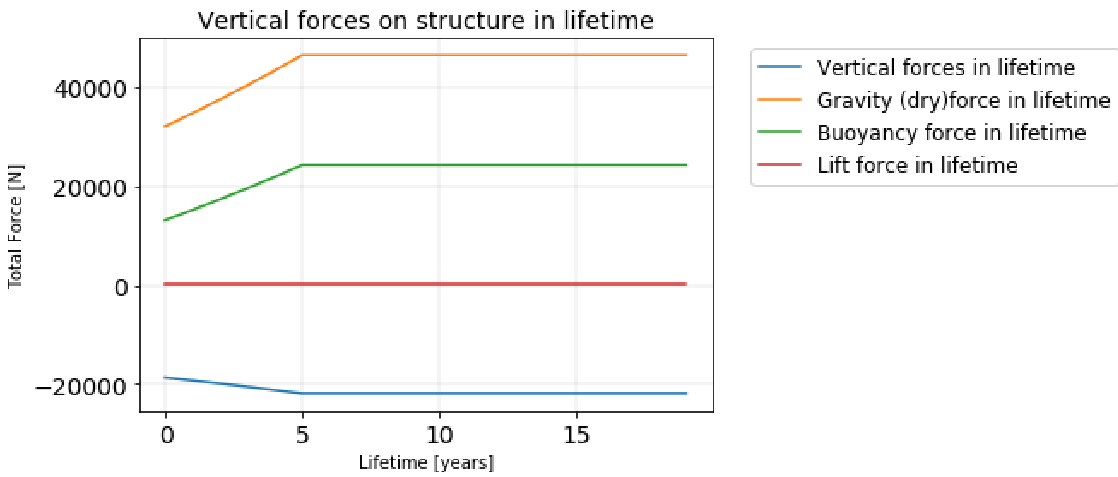

Figure 4.11: Vertical forces in time, increasing in magnitude due to growth of marine fouling layer.

The vertical forces on the structure are shown in Figure 4.11. As can be seen, the lift force is negligible in magnitude compared to the gravity force for the emerged structure. This means the resulting vertical force is downward, dominated by the gravitational force.

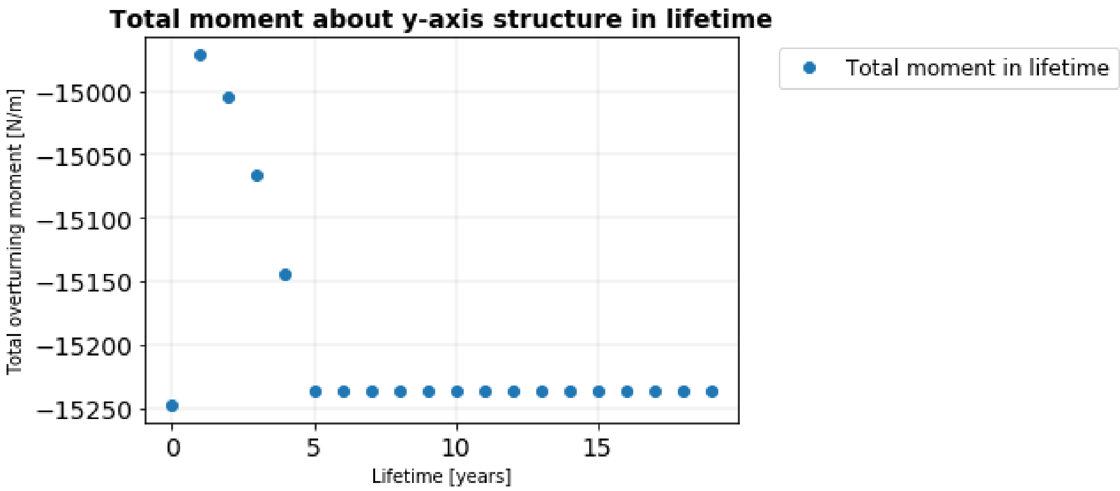

Figure 4.12: Total overturning moment of the structure with respect to the outer most edge of the bottom plate of the structure.

The progression of the total overturning moment is shown in the graph in Figure 4.12. The overturning moment is negative, which means the restoring forces due to gravity and friction outweigh the contribution of the overturning forces. The initial jump at the start of the graph is a result of the start of fouling, which initiates significant skin friction, and is also observed in Fig. 4.10. The restoring effect is dominant as the total overturning moment decreases in time. It is important to note that the moment is taken about the outer most edge of the bottom plate, which provides a large arm for the gravitational force. It is therefore important to consider the placement of the structure, as placement directly on the centre of the bottom plate will alter the balance of the structure, as the restoring moment is nullified and the structure will start to wobble. Dependent of the surrounding bed, the structure could reposition itself in a favourable manner, or the structure could become unstable due to a large inclination.

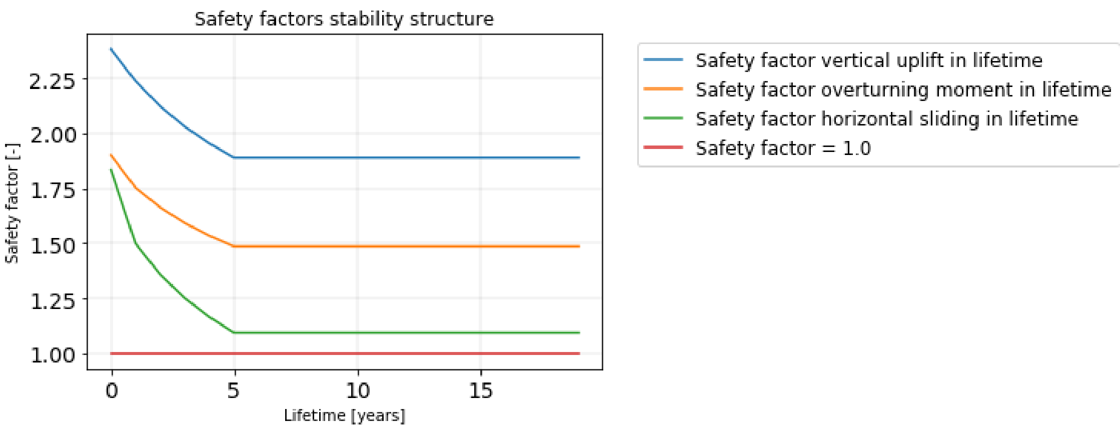

Figure 4.13: Safety factors for vertical, horizontal and rotational stability in time.

Figures 4.10, 4.11 and 4.12 give an overview of the loads the structure experiences during its lifetime. In order to give an insight in the progression of the stability of the structure in time, safety factors are drawn up by dividing the resisting forces by the soliciting forces. This is done for the vertical, horizontal and rotational stability.

$$SF_h = \frac{F_{friction}}{F_{drag} + F_{inertia} + F_{skinfriction}} \tag{4.7}$$

$$SF_v = \frac{F_{gravity}}{F_{Buoyancy} + F_{lift}} \tag{4.8}$$

$$SF_M = \frac{M_g + M_f}{M_b + M_d + M_{sf} + M_i} \tag{4.9}$$

As can be seen in Fig. 4.13, the structure remains stable during lifetime, but fouling is shown to have a negative effect on the stability.

Inclinated placement

In order to evaluate the safety of the structure, the Econstruct offers the opportunity to place the structure at an angle with respect to the seabed and incoming currents. To determine the stability of the structure in time, taking into account the dynamics of the seabed below the scour protection is important. Scour protections are usually designed using a falling apron design, which is a stack of granular material at the toe of the armour layer, that is launched when the scour protection is undermined. This will form a slope of rock material that protects the bed material from scour.

The placement of the structure upon the scour protection can also introduce an angle between

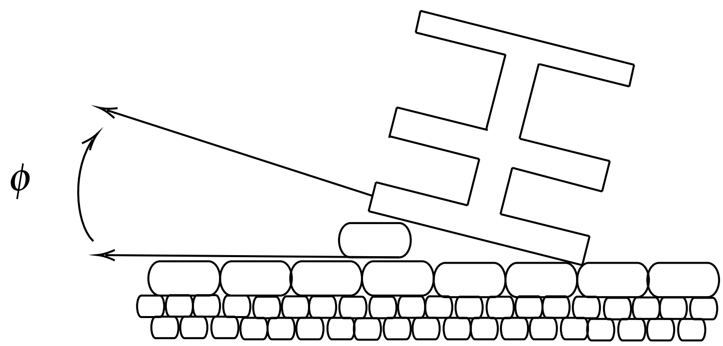

Figure 4.14: Maximum inclination of the structure is assumed to be two heights of armour block.

the structure, the bed and the currents. The inclination at which the structure is placed is based on the notion of an armour block protruding the scour protection, as shown in Fig. 4.14. This gives an angle of approximately 5 degrees, based off the D_{n50} (the nominal diameter for median armour stone size), of the armour class, and the length of the structure. The construction of the scour protection was described in Van Oord, 2019b. The rock class used for the armour layer is 5-40kg, which translates to a D_{n50} of approximately 20cm (NEN, 2015). In order to find the angle ϕ, the extrusion of the scour protection is divided by the length of the structure. Subsequently, the inverse sine is taken.

$$\phi = sin^{-1}\left(\frac{D_{n50}}{2 \cdot Radius}\right) \tag{4.10}$$

Which gives an angle ϕ of 5 degrees, for a radius of 1m.

The structure is tested for an inclination of 5 degrees in either directions, in order to take into account the negative effects of tilted placement with respect to the currents. Figure 4.15 shows the render of the structure by the Econstruct tool for an angle of 95°.

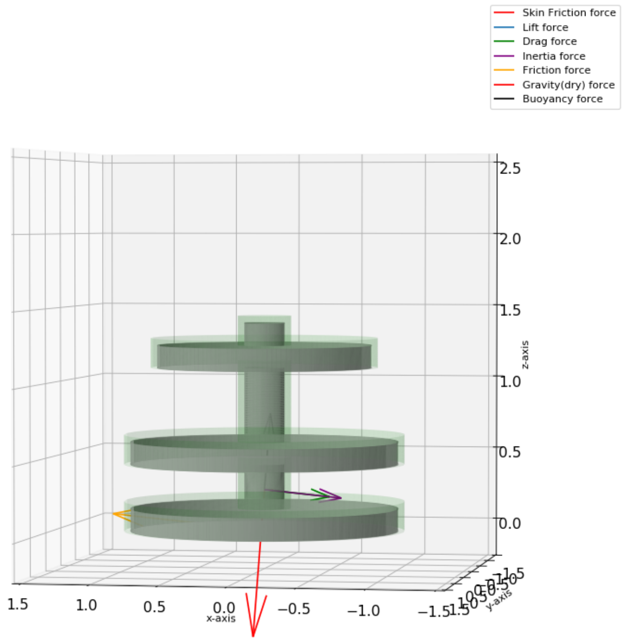

Figure 4.15: The terraced structure at an 5° angle with the horizontal plane

The horizontal forces change due to the inclination. As the structure is tilted at an angle, the frontal area of the structure changes and the profile for the drag forces is increased, the gravitational force is at an angle with the horizontal, which could cause sliding to occur. However, it is observed that the resisting horizontal forces of the structure are strong enough in Figure 4.16.

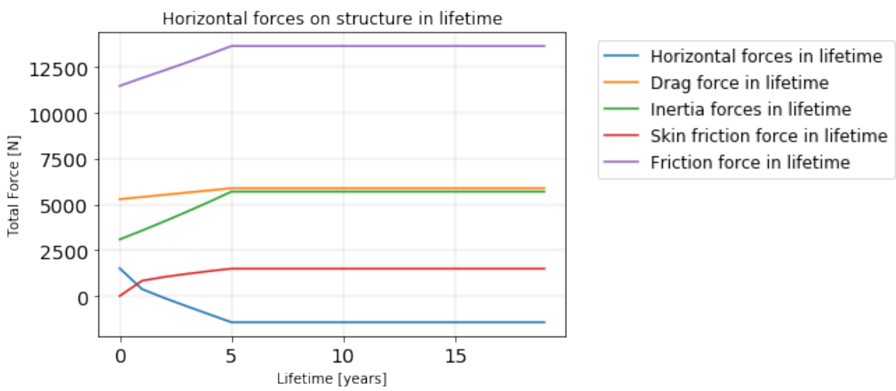

Figure 4.16: Horizontal forces for the structure at an 5° angle with the horizontal plane

The vertical forces on the structure change slightly. As the gravitational pull of the Earth is partly restored by the frictional forces, the vertical resultant force is a little less strong than at a levelled placement area.

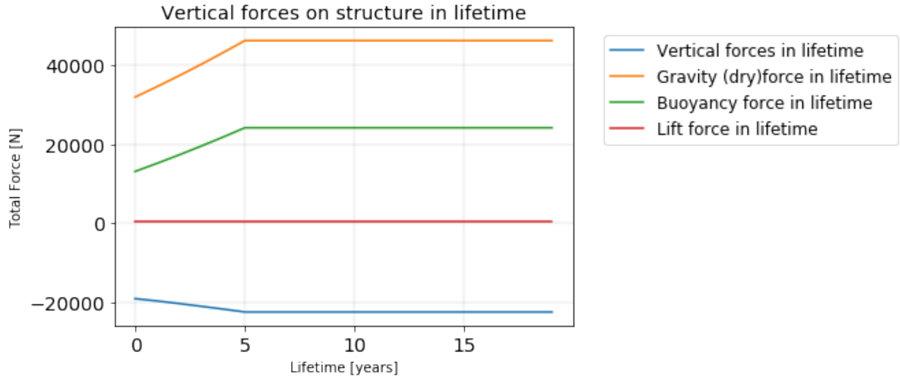

Figure 4.17: Vertical forces for the structure at an 5° angle with the horizontal plane

The overturning moments of the structure remain well in the stable region, dominated by the gravitational load.

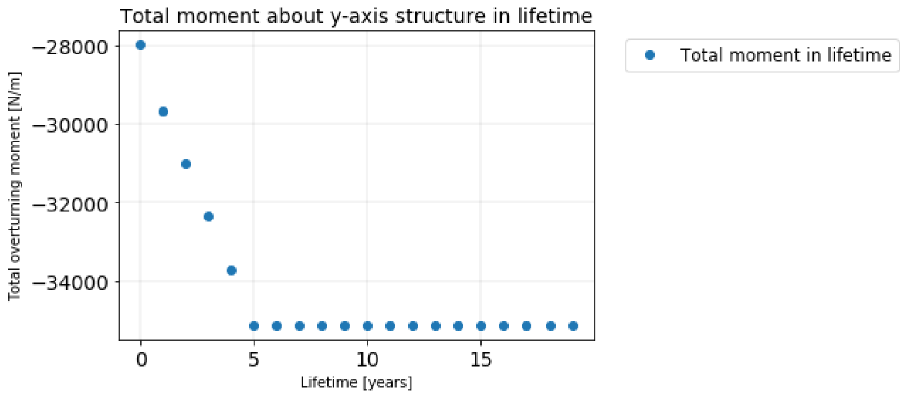

Figure 4.18: Overturning moment for the structure at an 5° angle with the horizontal plane

Looking at the safety factors for the stability of the structure, the structure remains above 1, which ensures stability. The structure only marginally stays above 1 for horizontal stability, which means the structure is safe, but that is dependent on the circumstances, such as more extreme weather events.

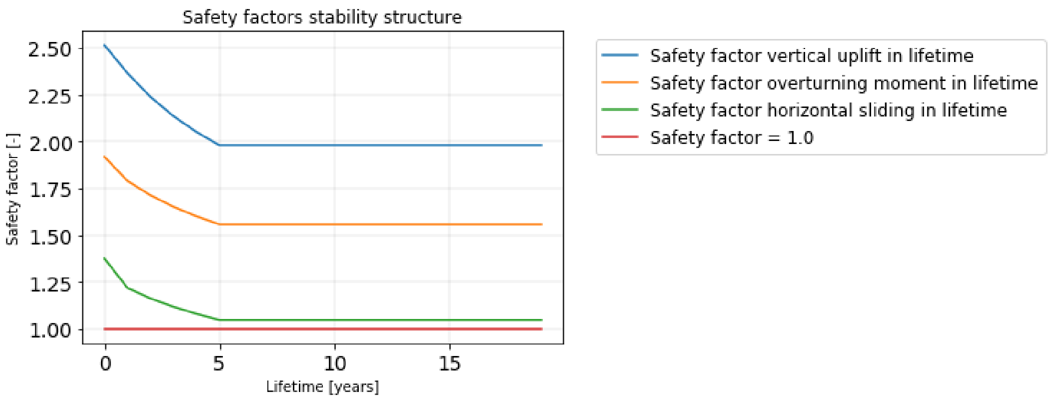

Figure 4.19: Safety factors for the structure at a 5° angle with the horizontal plane

As can be observed from the Figure 4.20, the tilt with respect to the horizontal actually becomes favourable. This is due to the fact that the horizontal unfavourable loads press down on the structure, which increases the friction force and thus horizontal stability is attained. This can be seen in Figure 4.20 and 4.24.

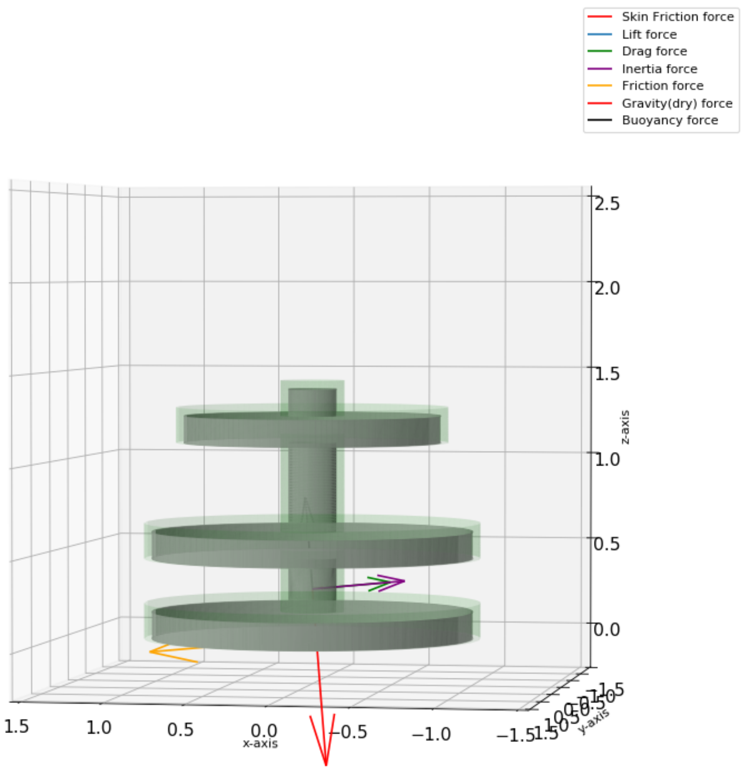

Figure 4.20: Horizontal forces for the structure at a -5° angle with the horizontal plane

The horizontal forces change due to the inclination. As the structure is tilted at an angle, the frontal area of the structure changes and the profile for the drag forces is increased, the gravitational force is at an angle with the horizontal, which could cause sliding to occur. It is however observed in the horizontal forces in Figure 4.21, that the structure's resisting horizontal forces are still strong enough, aided by the 'pushing' effect of the horizontal forces as a consequence of the currents.

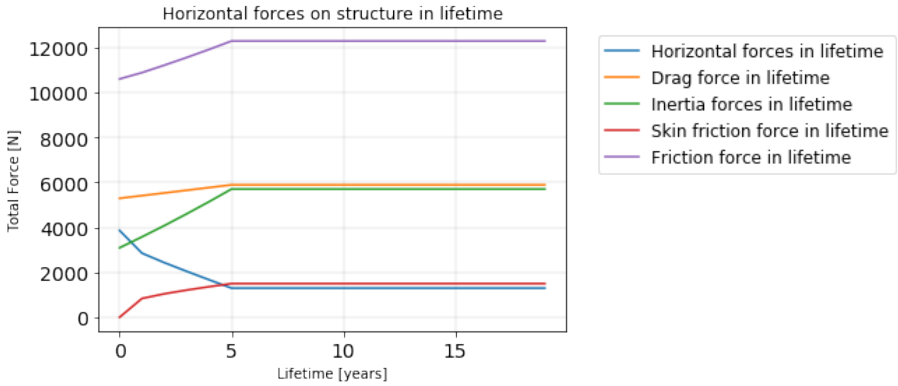

Figure 4.21: Horizontal forces for the structure at a -5° angle with the horizontal plane

The vertical forces do not show large differences with respect to flat placement.

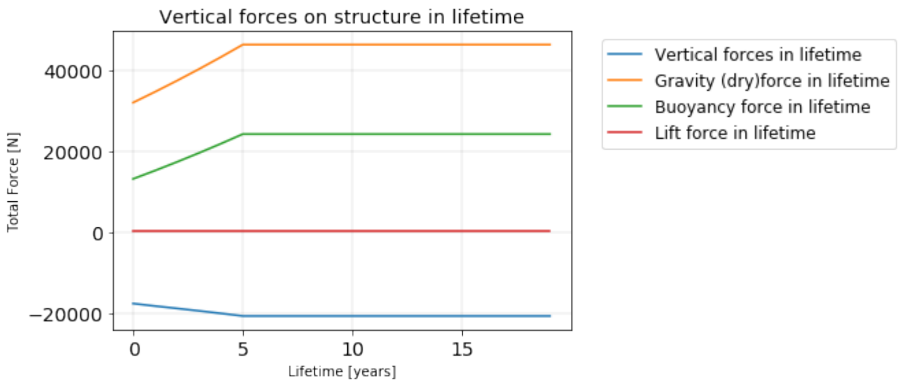

Figure 4.22: Vertical forces for the structure at an -5° angle with the horizontal plane

The resisting moment gets increases in strength as the weight of the structure increases. It will increase the gravitational force, which outweighs the effect of the overturning forces.

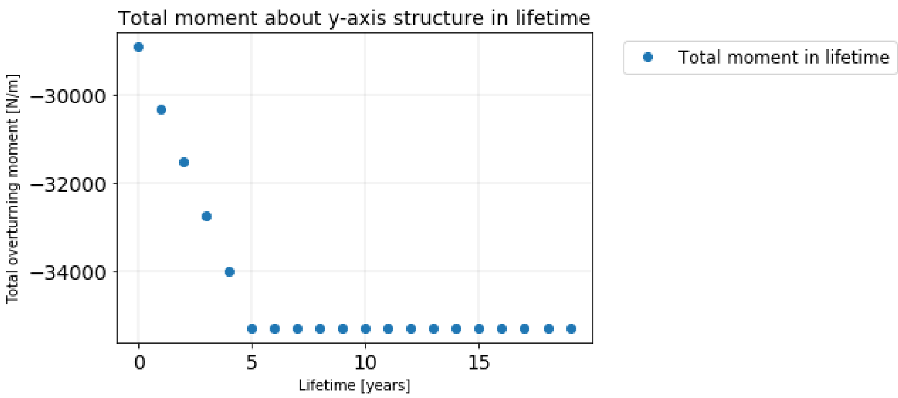

Figure 4.23: Overturning moment for the structure at a -5° angle with the horizontal plane

This positioning of the structure is also safe, as can be seen in Figure 4.24.

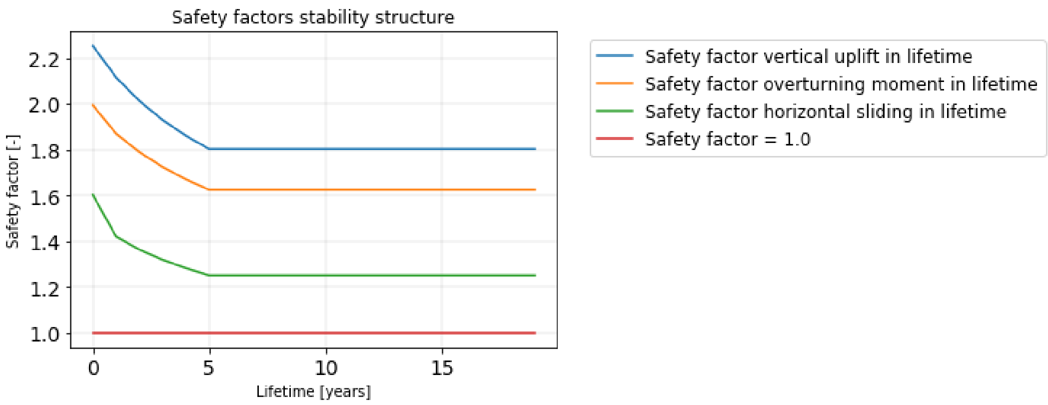

Figure 4.24: Safety factors for the structure at a -5° angle with the horizontal plane

4.5 Structural calculations

In order to evaluate the structural integrity of the concept, several loading cases are to be investigated in order to arrive to the right dimensions and composition of the structure. The structure is designed to be made from standard concrete class C35/45 and reinforcing steel FeB 500B ribbed. The following load cases are studied to design for a structurally robust structure.

- Concrete cover;
- Reinforcement percentage;
- Plate bending of the middle plate;
- Plate bending of the bottom slab;
- Compressive loads in the stem;
- Tensile loads in the stem;
- Shear force;
- Punch due to compressive loads;
- Punch due to tensile loads;
- Bending at connection stem and bottom plate due to hydrodynamics;
- Bending at the connection stem and bottom plate during lifting;
- Anchorage of reinforcing steel;
- Vibrations

4.5.1 Concrete cover

As the structure is placed on the scour protection, sufficient concrete cover is required to protect the reinforcement steel from corrosion. The amount of concrete cover is determined by the exposure classification and structural class of the structure. For the oyster broodstock element, the following classes hold:

- Exposure classification: XS2 (Seawater, persistently submerged)
- Structural Class: S4 (EN 1992-1-1, 2018)

Using the following equations, the concrete cover is determined (Voorend and Molenaar, 2019) :

$$Cover_{nominal} = Cover_{min} + C_{dev} \tag{4.11}$$

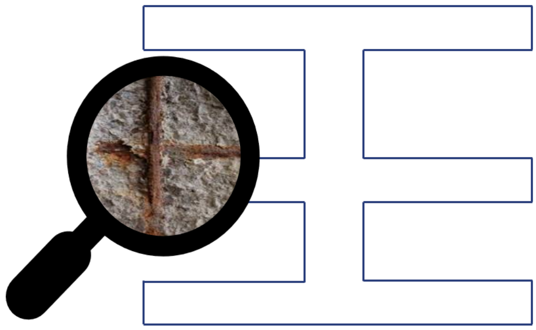

Figure 4.25: Sufficient concrete cover of a structure is required to prevent deterioration of the structure due to corrosion

- $Cover_{min}$ is the minimum thickness of the concrete cover layer, as determined by the exposure class and structural class in EN 1992-1-1 (2018). For Structural class S2 and Exposure class XS2, the structure requires a minimal concrete cover of 40mm.
- C_{dev} is the construction tolerance, which is put at 5mm for The Netherlands.

This results in a required concrete cover of:

$$Cover_{nominal} = 45mm$$

Crack width

Under tensile loads, reinforced concrete will start to crack in time. However, cracks should not grow too large to threaten the reinforcing steel. Sufficient concrete cover is required to prevent corrosion of the steel through these cracks, as corrosion of the steel will lead to a buildup of corroded steel which will push off the concrete cover. As defined in Eurocode 2, for the design of new structures 0.3mm is allowed for the exposure class XS2.

4.5.2 Reinforcement percentage

The required reinforcement is determined by satisfying the requirement that the reinforcement steel has to yield before the yield strength of concrete is reached, which means that the reinforcement percentage must be large enough to ensure no brittle failure when cracking of the concrete occurs. Brittle failure will expose reinforcement steel and accelerates corrosion of the reinforcement steel. In order to obtain a large enough reinforcement percentage a minimum reinforcement percentage of 0.21 is required for steel reinforcement bars of class FeB 500B and concrete class C35/45. As is calculated in Section 4.5.8, the reinforcing percentage is 0.21.

4.5.3 Plate bending of the middle plate

By simplifying the middle plate as a cantilevered beam with the same height, and width of the central stem, a test can be carried out for bending of the plate due to placement forces, hydrodynamics and own weight. The test is conservative, as 3D effects due to its actual geometry are unfavourable.

Geometry

Moment of inertia is determined for the simplified beam as presented in Fig. 4.27.

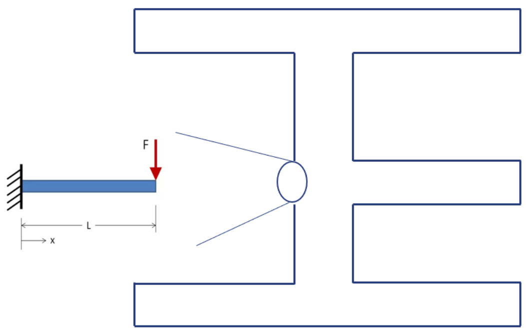

Figure 4.26: The middle plate is taken as the most unfavourable load case, whereas the plate is simplified to a beam

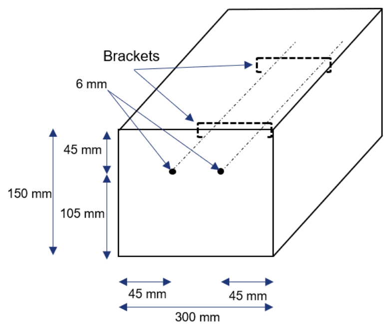

Figure 4.27: Middle plate assumed to be a beam

$I = 1/12bh^3$
$= 1/12 \cdot 300 \cdot 150^3 = 8.44 \cdot 10^7 mm^4$

Loading

The mass of one half of the middle plate is assumed to be the mass of the beam. This is a conservative assumption, as 3D resisting effects within the plate will increase the bending resistance. The mass of the entire plate is calculated to be 1099kg. Half the plate, minus the central segment which is part of the stem, weighs 525kg. This results in the distributed loading:

$Q_{ownweight} = F_g/L = 5150/0.85 = 6.1kN/m$

Combined with the wave-induced pressures on the plates, calculated in the hydrodynamic module of the Econstruct tool. The wave-induced pressure is 37.2 kN/m, and the area upon which this acts is the surface of the beam:

$Q_{wave} = P_{wavebeam} = 37.2 \cdot 0.3 = 9.96kN/m$

Using both loads, the design distributed loading is determined (Voorend and Molenaar, 2019):

$Q_d = (\gamma_c \cdot q_{ownweight} + \gamma_{cwave}) = (1.2 \cdot 6.1 + 1.5 \cdot 9.96) = 22.26kN/m$

When placing from a vessel, the heave of the vessel due to wave action must be incorporated in the maximum loading on such a structure, as accelerations of the boat's hull can, translated through the crane, cause an unfavourably accelerated load case on the structure (DNV-GL, 2018). In the guideline by DNV-GL, the accelerations are given in Table 11-7 (p. 241) and are found to be an acceleration in the Z-plane of 0.15g plus a variable acceleration of 0.017 g/m, increasing at a distance from the centre of the barge (DNV-GL, 2018). The barge that is used will be a multicat vessel, for which a beam dimension is approximated at 10m, based on available multicats from Damen (Damen, 2020). This results in the following placement acceleration:

$$0.15+(b\cdot 0.017)\cdot g = a_{placement} = 3.14m/s^2$$

Using the total mass and the acceleration, the placement force is found to be:

$$F_{placement} = 12.8kN$$

Deflection

For the calculation of the deflection, the standard construction mechanics rules with respect to bending of beams are used. The Young's modulus of concrete is 28.3 GPa, according to EN 1992-1-1, 2018, which states that the E_{cm}, the secant value between $\sigma_m = 0$ and 0.4 f_{cm} is 34 GPa, but has to be divided by γ_{CE}, for which 1.2 is the recommended value.

$$W_q = Q_d \cdot L^4/8EI = 0.6mm$$

$$W_F = FL^4/3EI = 0.93mm$$

Summing both deflections:

$$W_{tot} = W_q + W_f = 1.53mm$$

The magnitude deflection cannot exceed L/250 (EN 1992-1-1, 2018), however, this is a service limit state and is drawn up for humans. It is therefore considered to be a very conservative limit to the deflection.
This condition results in a maximum deflection of 850/250 = 3.4mm
As $w_{tot} = 1.53 < 3.4$mm, the structure remains within the boundaries for deflection of the middle plate.

4.5.4 Plate bending of the bottom slab

This case of plate bending concerns the bottom plate that rests upon the scour protection and channels the weight of the structure to the bed. Worst case loading situation is during retrieval under full loading, while being placed upon deck in rough weather conditions (H_s<4m).

Geometry

Moment of inertia is determined by:

$$I = 1/12bh^3$$
$$= 1/12\cdot 300\cdot 150^3 = 8.44\cdot 10^7 mm^4$$

Loading

The loading is determined by the weight of the structure, with maximum fouling. From the Econstruct design tool, this weight is found to be 4707.94kg when fully fouled.

$$Q_{ownweight} = F_g/L = 46184.9/0.85 = 54.4kN/m$$

$Q_{wave} = P_{wave} \cdot A_{beam} = 37.2 \cdot 0.3 = 9.96kN/m$

$Q_d = (\gamma \cdot q_{ownweight} + \gamma \cdot q_{wave}) = 1.2 \cdot 54.4 + 1.5 \cdot 9.96 = 80.22kN/m$

$F_{placement} = 12.8kN$

Deflection

For the calculation of the deflection, the basic rules with respect to bending of beams are used. For the deflection due to a distributed loading Q_d, Eq. (4.12) is used. For the deflection due to a point loading, Eq. (4.13) is used (NTHU, 2020).

$$W_q = \frac{Q_d L^3}{30EI} = 0.67mm \tag{4.12}$$

$$W_F = \frac{F * L^4}{3EI} = 0.91mm \tag{4.13}$$

Summing both deflections:
$W_{tot} = W_q + W_f = 1.58mm$
Deflection cannot exceed L/250 (EN 1992-1-1, 2018)
This condition results in a maximum deflection of 850/250 = 3.4 mm
As w_{tot} = 1.6 mm < 3.4 mm, the structure remains within the boundaries for deflection of the middle plate.

4.5.5 Compressive loads in the stem

The central stem absorbs the compressive loads caused by the gravitational force of the total structure. The critical point for compressive loads is found in the bottom plate beneath the central stem, as can be seen in Figure 4.28.

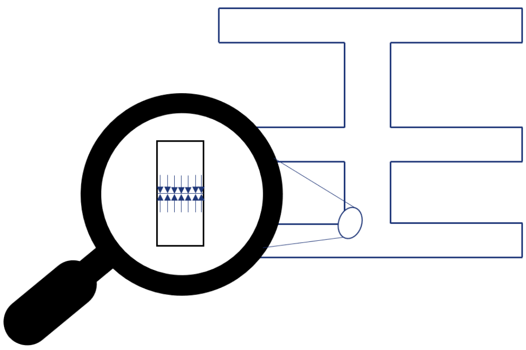

Figure 4.28: The point of maximum compressive loads is found beneath the central stem of the structure

$$f_{cd} = \frac{\alpha_{cc} \cdot f_{ck}}{\gamma_c} = \frac{1.0 \cdot 35 \cdot 10^6}{1.5} = 23.33MPa \tag{4.14}$$

With the stem radius at 0.15m, and therefore an area of 0.07 m^2, the maximum allowable compressive load can be calculated:

$$F_{compressive,max} = f_{cd\,stem} = 1.6MN \tag{4.15}$$

The mass of the structure when completely fouled:

Total mass − mass bottom slab : 4708 − 1701 = 3007 kg

The force as a result of the placement and possible accelerations has been determined before:
Placement force = 12.8 kN
Combining the two loads:
Compressive load: 29.5 + 12.8= 42.3 kN

The total compressive load is much less than the allowed compressive load, and so the structure satisfies this load case.

4.5.6 Tensile loads in the stem

Tensile forces will occur in the central stem during lifting operations, such as during placement of the structure and during lifting off the scour protection for monitoring purposes. The load case

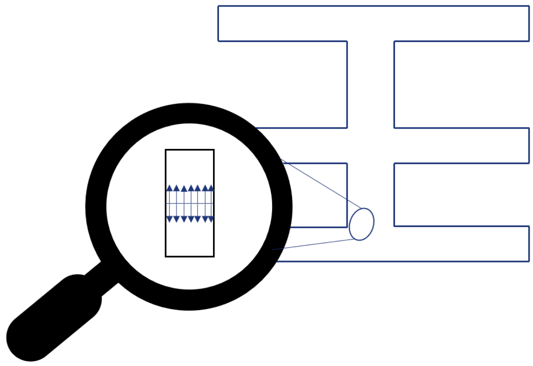

Figure 4.29: Tension in the central stem during lifting from the scour protection is a crucial load case.

used to test the structural integrity under tensile loads is for the maximum weighted structure, lifted at the end of life, where a layer of sand has accreted on the bottom plate:
Mass of the total structure is 4708 kg when fully fouled and a layer of 30 cm sand weighs 1361 kg, which combines to =6068.94 kg
Maximum load: (fouled structure) 59.5kN

Using reinforcement steel, 6 mm Ø

Which has a Young's modulus of 200 GPa and the maximum strain ε is 0.00175. This gives a maximum tension:= E·ε =350 MPa
This gives a maximum allowable tensile stress of 350 MPa
Which translates to a maximum force
$350 \cdot 10^6 \cdot 8\pi \cdot 0.003^2 = 79.2kN$
The reinforcing bars are shown in the reinforcing steel drawings in Appendix D

4.5.7 Shear force

Shearing of the plates with the central stem is calculated by calculating the shear resistance of the interface between the plates and the stem, and the shear force caused by the own weight and acceleration during placement. Critical loading for this case is defined as the shear stress between middle plate and stem. For this, the same beam simplification is used, which is conservative for this load case.
Firstly, the minimal design value for the shear stress is calculated (Braam and Lagendijk, 2011):

$$v_{Rd,c} = \frac{0.9 \cdot 0.6[1 - f_{ck}/250]f_{cd}}{cot\theta + tan\theta} \tag{4.16}$$

Where:

- $v_{Rd,c}$ is the allowable design characteristic shear stress
- f_{ck} is the characteristic axial compressive strength of concrete
- f_{cd} is the design compressive strength of concrete
- θ is the internal angle of pressure paths

Which is 3.74 N/mm^2 for concrete class C35/45 (Braam and Lagendijk, 2011). This gives an allowable shear force for the circumference of the stem of:

$V_{Rd,c} = v_{Rd,c}bd = 3.74 \cdot 300 \cdot 150 = 168300 \text{N/mm}^2$.
The shear force is caused by the weight of the plate, which is 1707 kg. This gives a shear loading of 16.7 kN, which translated to a v_{Ed} of 0.37 N/mm^2. Combined with the earlier calculated placement force due to accelerations of the crane (12.8 kN), this gives a combined load:
V_{Ed} = 16.7kN + 12.8kN= 29.5kN, which results in $v_{Ed} = 0.66$ N/mm^2 In order to check whether shear reinforcement is required, $v_{Ed} \leq v_{Rd,c}$ should hold. As 0.66 < 3.74, Eurocode 2 dictates it is not required to use shear reinforcement. However, it is advised to do so to ensure a safe design. The shear reinforcement is shown in the drawings in Appendix D. The reinforcing steel has a diameter of 6 mm. The shear reinforcement placed in the column has a spacing of 150 mm, compliant with EN 1992-1-1.

4.5.8 Punch due to compressive loads

Two relevant cases exist for punching shear failure, namely the punching shear caused by the compressive load through the stem and the punching shear caused by the tensile forces during lifting. The calculations done on the reinforcement steel are based off the drawings in Appendix D.

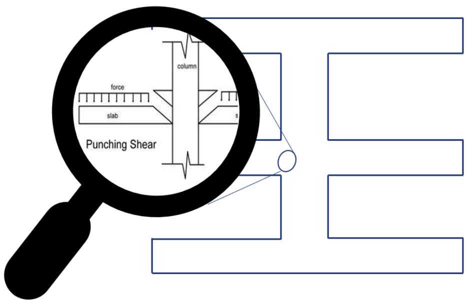

Figure 4.30: Punching is a phenomenon that can occur when a plate is axially supported by a column, where the shear forces become too large for the connection to resist (Abspoel, 2012).

Compressive punching shear failure

Following the shear calculations:
$V_{Ed} = 29.5$ kN (shear force in plate section)

The formula for the average shear stress is:
$v_{Ed} = V_{Ed}/\text{u1d} = \pi(c+4d)*d = 0.22$ N/mm^2 (Braam and Lagendijk, 2011)

For the critical value of the shearing resistance without punch reinforcement, the following relation is used:
$v_{Rd,c} = 0.12(100 \cdot \rho_l f_{ck})1/3$

With:

- k = 1 + $\sqrt{\frac{200}{d}} \leq 2.0$
- d = h - c - 0.5Ø= 150 -45 -0.5*6 = 108
- h = thickness of plate
- c = concrete cover
- Ø = diameter reinforcing steel

The ratio of reinforcement ρ_l is calculated:
ρ_l= $\sqrt{\rho_{ly}\rho_{lz}}$

Where:

- ρ_{ly} is 4, as 4 punching reinforcement bars are placed
- ρ_{lz} is 8, as 8 bars are put through the central stem

This results in the following calculation:

$=\sqrt{\frac{(1.13 \cdot 10^{-4}}{(0.3 \cdot 0.15)} \frac{(2.26 \cdot 10^{-4}}{(0.85 \cdot 0.15)}} = 0.0021.$

Filling this information into the equation for the critical value of shearing resistance:

$v_{Rd,c}$= 0.48 N/mm^2
which is used to calculate:
$V_{Rd,c}$=$v_{Rd,c} v \cdot u1 \cdot d$ =75.66 kN
Using u1 = π(c+4d) and d= 108mm (Braam and Lagendijk, 2011).
As $V_{Rd,c}$ is larger than V_{Ed}, the structure is safe against punch due to compressive loads.

Punch due to tensile loads

Following the tensile load case:
$V_{Ed} = 59.5kN$
$v_{Ed} = \frac{V_{Ed}}{u1d} = \frac{V_{Ed}}{\pi(c+4d)d} = 0.368N/mm2$
The critical value of shearing resistance was previously determined:
$v_{Rd,c}$= 0.48 N/mm^2
Hence the structure is safe against punching due to tensile loads.

4.5.9 Bending at connection stem and bottom plate due to hydrodynamics

Two bending cases are important for the bending moment in the root:

- Bending of central stem due to hydrodynamic loading
- Bending due to own weight of bottom slab during lifting

Bending due to hydrodynamics

From the Econstruct Python tool, the maximum hydrodynamic loading on the root is -5.8 kNm, because of drag, inertia, skin friction and bottom friction.
Maximum allowable bending:
$M_u = A_s f_{yd} d - \frac{1}{3}x$
With:

- A_s [m2] = total cross-sectional area of reinforcement

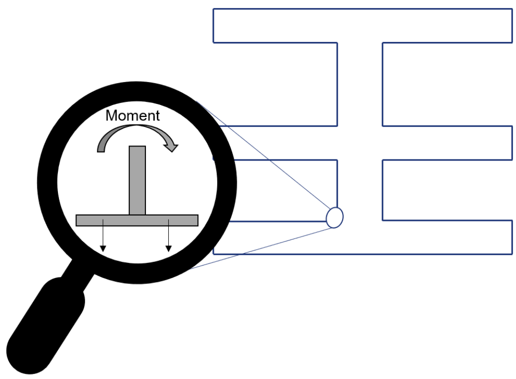

Figure 4.31: Bending of the structure at the bottom connection of the stem and the bottom plate

- f_{yd} [N/m2] = design yield strength of reinforcement
- d [mm] = effective height of the cross-section
- x_c [mm] = concrete compression zone

The variable x_c, the height of the concrete compression zone, is found by means of the following equation:
$0.5bx_c{*}\sigma_c = A_s\ f_{yd}$
For the maximum strain in the reinforced concrete, $\varepsilon = 0.000175$.
This makes $\sigma_c = f_{cd} = 13.33\ N/mm^2$.
This results in $x_c = 49.2$mm (Braam and Lagendijk, 2011).
Using these parameters, the allowable moment can be found:
$M_u = 8\pi 3^2 \cdot 435 \cdot (108 - 49.2/3)$
= 9.0 kNm
This allowable moment of 9.0 kNm is larger than the moment during extreme weather conditions (5.8 kNm). The structure is thus safe.

Bending at the connection stem and bottom plate during lifting

Using the mass of half of the bottom slab, loaded with sand and completely fouled (m = 1530.7kg) and the distance between the centre of half the slab to the centre (4r / 3π = 0.424m), the moment on the core of the bottom slab can be calculated.
M = $1615 \cdot 9.81 \cdot 0.424 = 6.7kNm$
The same formula is used for the maximum allowable bending. However, the bending moment is carried by the reinforcing steel and concrete of the bottom slab. Therefore, other parameters are inserted.
For conveniency, the situation is schematised as a beam, as has been done before.
The concrete compression zone is also different, as the reinforcing steel is now consisting of the horizontal reinforcing bars and punching shear reinforcing. Using the same relation as previously mentioned, x_c can be found:

$0.5bx_c\ \sigma_c = A_s\ f_{yd}$
$x_c = 36.2$ mm

Using x_c, the allowable moment can be found for a maximum strain of 0.000175.

$M_d = A_s\ f_{yd}$ (d-x_c/3) $= 6\pi \cdot 3^2 \cdot 435(108 - 36.9/3)$
$= 7.1kNm$
This means the allowable moment is larger than the moment on the plate, thus the structure is safe.

4.5.10 Anchorage of reinforcing steel

Pull out is tested by checking the reinforcing steel for anchorage in the concrete.
The length of required anchorage, Lb_{rqd}, is found to be 32Ø to 46Ø for C35/45 concrete, a diameter smaller than 32mm and B500 reinforcing steel. This gives a required length of anchorage of $32 \cdot 0.006$ to $46 \cdot 0.006$= 192mm to 276mm. In all elements of the construction, the reinforcing steel has this anchorage.
Shortest element: top plate (R=0.8m)
Anchorage length = 0.6m

4.5.11 Vibrations

As the structure protrudes and disturbs streamlines within a flowing medium, the flow interacts with the structure, shedding vortices. Vortex shedding can result in Vortex-Induced Vibrations (VIV), which can result in strong vibrations, that can lead to cyclic stress induced failures. In Figure 4.32, it is shown how these vibrations come to being.

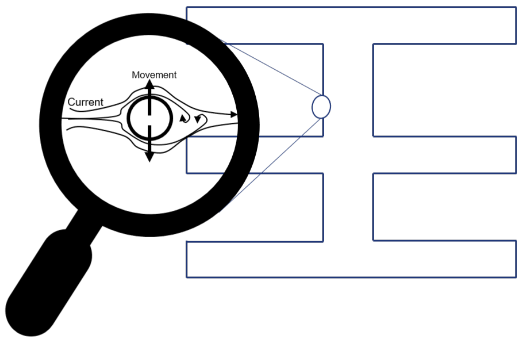

Figure 4.32: Vortex-induced vibrations

The maximum vibrations of the largest plate (radius =1m) are defined by vortex shedding frequency f_s, assuming steady flow conditions (DNV-GL, 2010):

$$f_s = \frac{S_t \cdot u}{d} \tag{4.17}$$

Where:

- St is the Strouhal number
- d is the member diameter

The Strouhal number is a dimensionless number that describes the oscillation of fluids. Assuming the structure is a smooth cylinder, the Strouhal number can be approximated using Figure 4.33.

The Reynolds number is calculated by using the parameters u = 2.89 m/s (Eq. 4.4) and d = 2m (2x radius).
Re = $uD/\nu = 2.89 \cdot 2/10^{-5} = 5.78 \cdot 10^5$
Using Fig. 4.33, the Strouhal number is approximated as 0.2.
Filling in the parameters in Eq. 4.17 gives a f_s= 0.289 Hz. If the vortex shedding frequency is close to the natural frequency of the structure, the structure will start to resonate. The natural frequency of the structure is calculated using (Kaminksi, 2011):

$$F_n = \frac{1}{2\pi}\sqrt{\frac{k}{M}} \tag{4.18}$$

With:

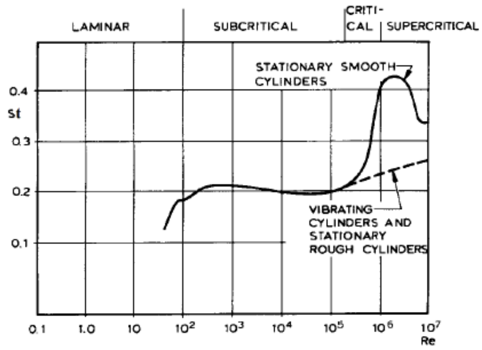

Figure 4.33: Strouhal number for a cylinder as a function of R_e. Adapted from DNV-GL (2010)

- k is the stiffness of the system
  - K is expressed as: k = $\frac{EI}{L}$
  - EI is the stiffness of the structure: EI = $0.5E_sA_sh^2 = 508.9 \cdot 10^3 Nm^2$ (Voorend and Molenaar, 2019) for E_s = 200 kN/mm^2, A_s = $8 \cdot 3^2\pi$ and h = 150mm
  - L is the characteristic length of the structure, the height of the stem (L=1.4m)
  - K = 363.5 kN/m
- M is the mass of the system

So filling in Eq. 4.18:
$F_n = 1/(2\pi)\sqrt{(363.5 \cdot 10^3/4707.92)} = 1.39Hz$

Galloping and flutter

Galloping is the occurrence of large and periodical oscillations in structure, that can potentially be catastrophic for the structure. This phenomenon is relevant for slender structures (height to width ratio is large), and as such will not be regarded in the design of this structure, as the height to weight ratio is approximately 1 (Chen et al., 2018).
Flutter does not occur in hydraulic structures in general, determined by a coupled system of equations involving lift, which is negligibly small (Kolkman and Jongeling, 1990).

4.5.12 Concluding remarks structural integrity calculations

In order to evaluate whether the terraced tructure is strong enough, unity checks are used to evaluate the structure. A unity check is carried out by evaluating the following ratio:

$$U.C. = \frac{R_d}{S_d} \tag{4.19}$$

Where R_d is the design resistance of the structure, or the allowable strength. S_d is the design solicitation, or the design load. The results of the unity checks are given in Table 4.5

In Table 4.5, can be seen that the structure is safe and strong enough to withstand the environmental conditions.

Load case	Unity check	
Concrete cover	1	✓
Reinforcing percentage	1.0	✓
Plate bending of middle plate	0.45	✓
Plate bending of bottom slab	0.47	✓
Compressive loads in the stem	0.02	✓
Tensile loads in stem	0.75	✓
Shear force	0.18	✓
Punch due to compressive loads	0.46	✓
Punch due to tensile loads	0.77	✓
Bending at connection stem and bottom plate due to hydrodynamics	0.64	✓
Bending at connection stem and bottom plate during lifting	0.94	✓
Anchorage	1	✓
Vibrations	0.21	✓

Table 4.5: Unity checks for structural integrity of the terraced design

4.6 Design: Results

Having designed the structure for stability and structural integrity, technical drawings are made for the structure. The technical drawings can be seen in Appendix B, the structural drawings can be seen in Appendix D. Fig. 4.34 shows the terraced structure that resulted from the first design iteration.

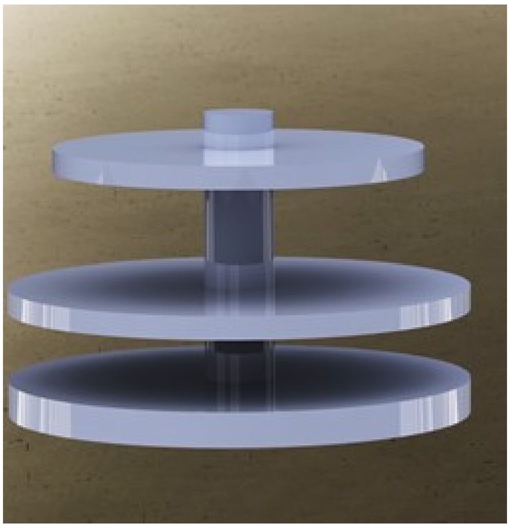

Figure 4.34: A Solidworks render of the terraced structure designed following the first design iteration

4.7 Evaluation redesign

After this design, the design was reviewed in collaboration with manufacturers. Due to time constraints, the design is simplified and manufactured as such.

4.7.1 Redesign of structure

The manufacturer D & M Engineers developed a version of the terraced design, in collaboration with this study. Two structures were developed, to simulate the two broodstock structure concepts.

- Terraced redesign
- Terraced redesign with porous plates

The terraced redesign is very similar to the terraced design that was developed using the methodology of this study, with a different central support. A steel frame supports the oyster carrying plates, whereas the terraced design, designed in this study, used a central stem constructed with reinforced concrete. The manufactured terraced redesign can be seen in Figure 4.35.
The terraced redesign with porous plates is constructed to mimic the tripod tree design. This design was discarded earlier due to manufacturing difficulties in constructing the branches and corrosion protection. The terraced redesign with porous plates is therefore conceived in order to evaluate the impact of permeability of the structure on the well-being of the oysters. The constructed terraced redesign can be seen in Figure 4.35 and 4.36. The dimensions of the structure are given in Table

Figure 4.35: Terraced redesign that is built by D & M engineers

Figure 4.36: The porous terraced design that is built by D & M engineers

4.6.

Parameter	Value
Plate	2m x 2m x 14cm
Upper frame	0.2m x 0.2m x 0.4m
Bottom frame	0.2m x 0.2m x 0.4m

Table 4.6: Dimensions of the D & M concept

4.7.2 Evaluating the D & M design

Using the Econstruct tool, the design of D & M engineers can be evaluated. This results in the render in Fig. 4.36.

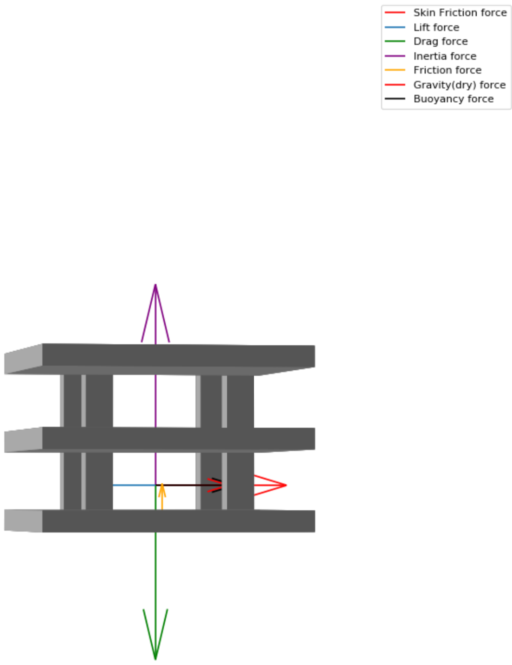

Figure 4.37: The porous terraced design that is built by D & M engineers, tested in the Econstruct tool

4.7.3 General assessment

In Figures 4.38, 4.39 and 4.40, the progression of forces and moments can be observed. Also, the safety factors are given in Fig. 4.41. The structure is stable and safe during lifetime. The dry weight of the structure without fouling is quite significant at 4520kg, fouled the structure has a weight of 6713kg. This structure is therefore 1268kg heavier at the start, and 2006kg heavier being fully fouled as described in Section 3.1.4. This increase in weight is due to the larger area of the surfaces that is fouled, increasing the amount of fouling on the structure which is reflected in the weight. The oyster carrying area of the structure is 8 m^2 whilst the terraced design had an oyster carrying area of 5.15 m^2. In practice, the oyster carrying area was even larger as oysters were placed on the downward facing sides of the plates, and on the outward facing edges.

4.7.4 Assessment of stability

Now that the positions of the structures are precisely known, the velocity can be exactly determined due to the effect of the monopile on the flow field.

Parameter	Value site 1	Value site 2	value site 3	Value site 4
r [m]	2.5D	2.5D	2.5D	2.5D
R [m]	3.85m	3.85m	3.85m	3.85m
θ[°]	116.6	93	125.5	116.6
U_∞ [m/s]	2.89	2.89	2.89	2.89

Table 4.7: Input parameters for Equations 3.27, 3.28 and 3.29 for a 50 year wave. The exact locations of the structures and the respective angles are shown in Fig. C.22 and Fig. C.23

Using the inputs given in Table 4.7, the flow velocity at the structure can be calculated. The amplification factor shows how the presence of the monopile influences the background velocity.

Parameter	Value site 1	Value site 2	Value site 3	Value site 4
U_r [m/s]	-2.78	0.87	2.72	-2.78
$U_\theta [m/s]$	1.05	2.83	0.486	1.05
U [m/s]	2.98	2.75	2.91	2.98
Amplification factor[-]	1.04	0.96	1.01	1.04

Table 4.8: The outputs of Equations 3.27, 3.28 and 3.29 for a 50 year wave, using the inputs of Table 4.7. The negative radial velocities are due to the different side of the flow converging to after passing the monopile.

With a flat placement and the maximum velocity on the structure, as given for site 1, the following graphs describe the moments, forces and safety factors for the structure.

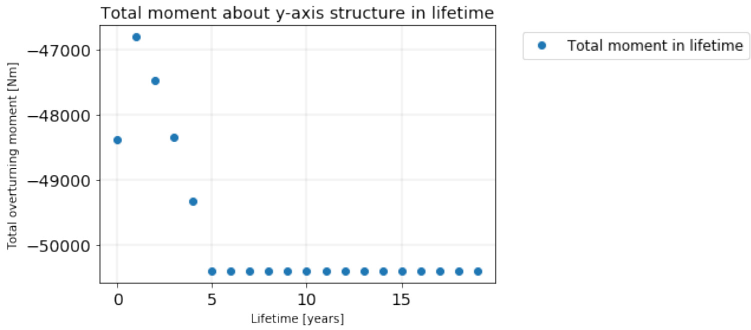

Figure 4.38: Moments about terraced redesign

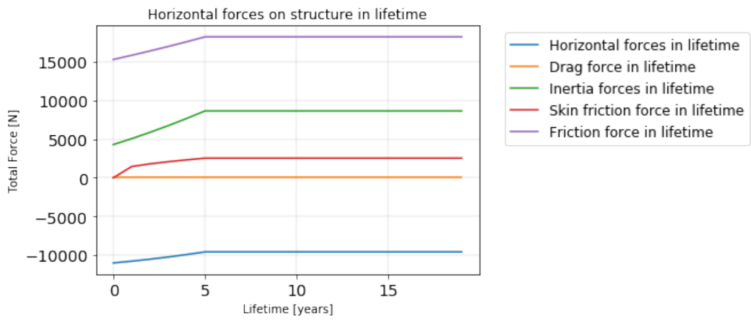

Figure 4.39: Horizontal forces on the terraced redesign

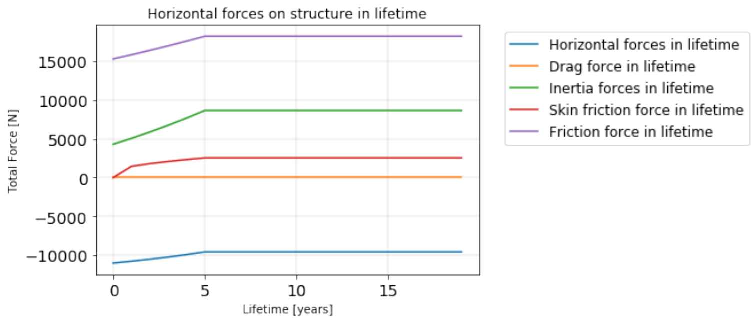

Figure 4.40: Vertical forces on the terraced redesign

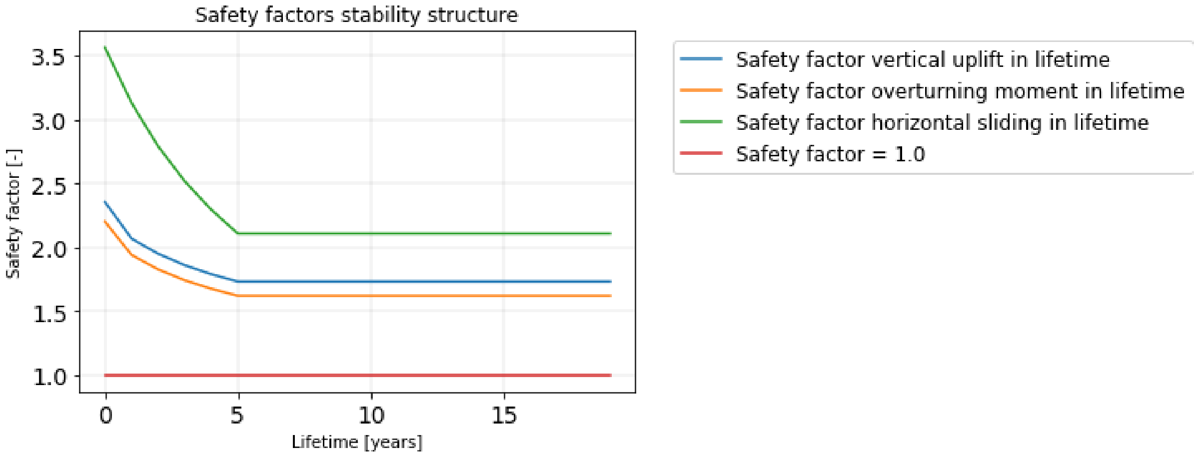

Figure 4.41: Safety factors for stability of the terraced redesign

4.7.5 Maximum inclination

Also, the maximum inclination can be tested for which the structure can be placed. Again, the structure at site 1 is of interest, due to the highest flow velocities. The maximum inclination for this structure is found to be a 9° angle.

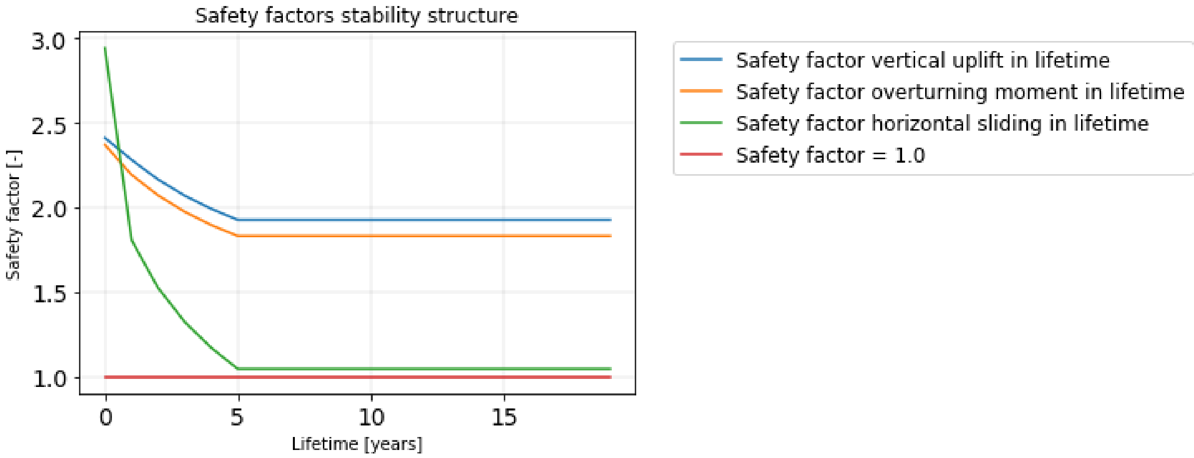

Figure 4.42: The ratio of the soliciting and resisting forces remains above 1, hence the structure remains safe. Constructed using Econstruct, for a 50 year wave.

Figure 4.42 shows the ratios of the soliciting forces and the resisting forces, as described in Chapter 3. These remain above 1, indicitating the resisting forces are larger than the soliciting forces. This means the structure is stable, but only barely, as the factor for sliding is just above 1. As indicated, this is for an angle of 9°, which would represent the critical angle.
From Fig. 4.43, the most critical failure mechanism can be observed. Sliding occurs before the other failure mechanisms, and as can be seen in Fig. 4.43, the structure becomes more unstable in harsher wave conditions. As only the 50 year wave is known from data, this is the most extreme wave that can be used in the test.

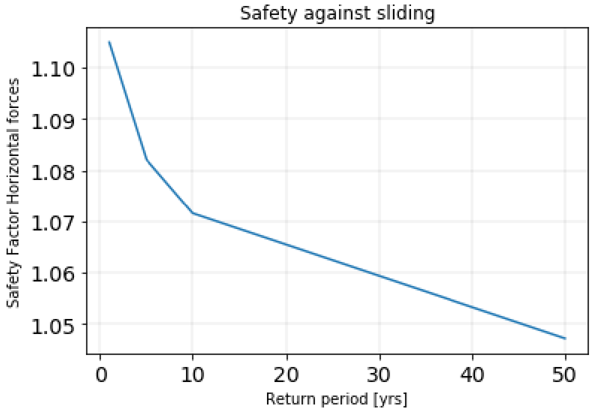

Figure 4.43: Progression of the ratio of soliciting and resisting forces for sliding with respect to the return period of a wave.

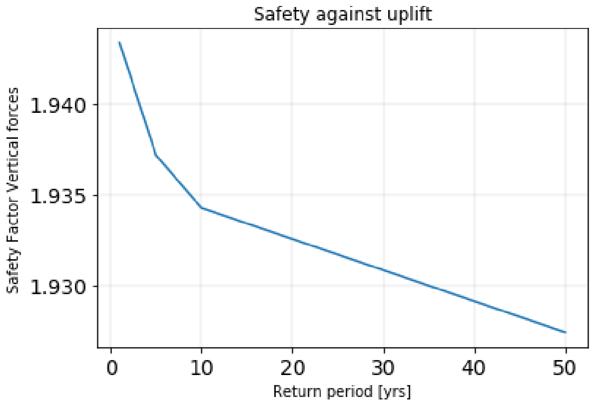

Figure 4.44: Progression of the ratio of soliciting and resisting forces for uplift with respect to the return period of a wave.

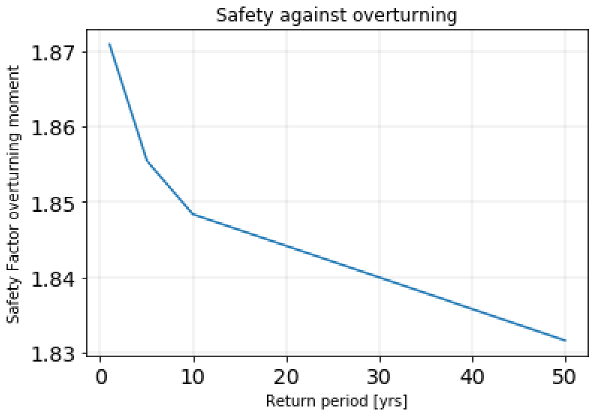

Figure 4.45: Progression of the ratio of soliciting and resisting moments with respect to the return period of a wave.

4.7.6 Friction coefficient

Also, the friction coefficient assumption can be tested for sensitivity. As stated in Chapter 3.3 Section 3, the terraced design was designed with a friction factor of 0.6, however, CIRIA advised to conducted large or full scale tests to obtain the actual value of the friction coefficient. As no large or full scale tests have been conducted on the terraced redesign that was placed, a sensitivity for lower friction coefficients can shed light on the workings of the structure. This can help aid

Van Oord and Project Ecoscour to assess the observations of the structure when revisiting the site. As the point contacts effectively means a smaller area of interfaces between the structure and the scour protection is present, a reduction in the friction factor can give insight into the behavior. As 0.6 is used, 0.5 is tested in this analysis. Firstly, the structure is tested for this lower friction coefficient for a flat placement. Then, the maximum inclination will be revisited and a new maximum inclination is presented.

Friction coefficient analysis for 0° placement

Using the lower friction factor as input in Econstruct, Figures 4.46, 4.51, 4.48, 4.49 are outputs of the Econstruct tool for a 50 year wave. As can be observed in Fig. 4.46, the structure is still safe for this friction factor. The structure's safety factor is not significantly high above 1, which does not allow for much room for error.

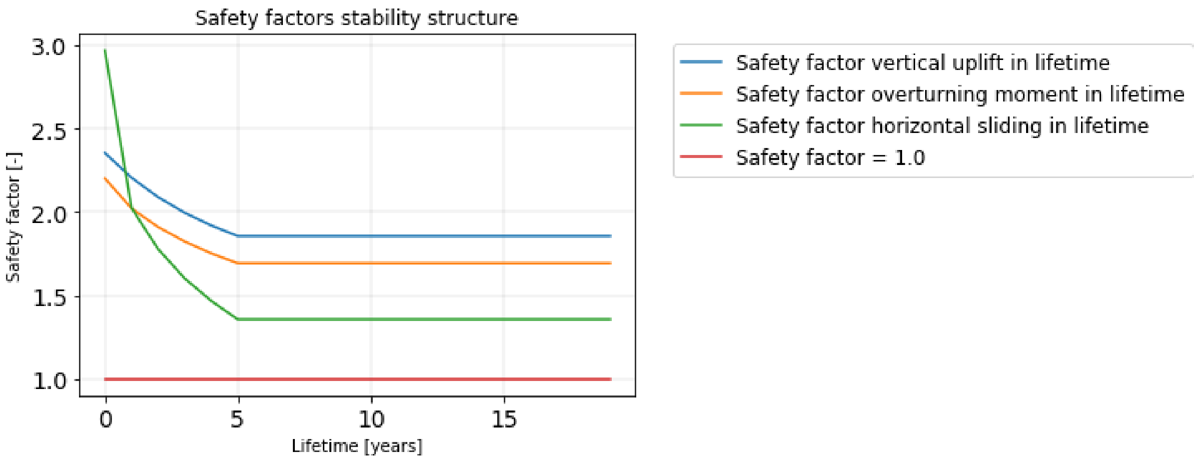

Figure 4.46: Progression of the ratio of soliciting and resisting forces for uplift with respect to the return period of a wave. Placed horizontally on the scour protection.

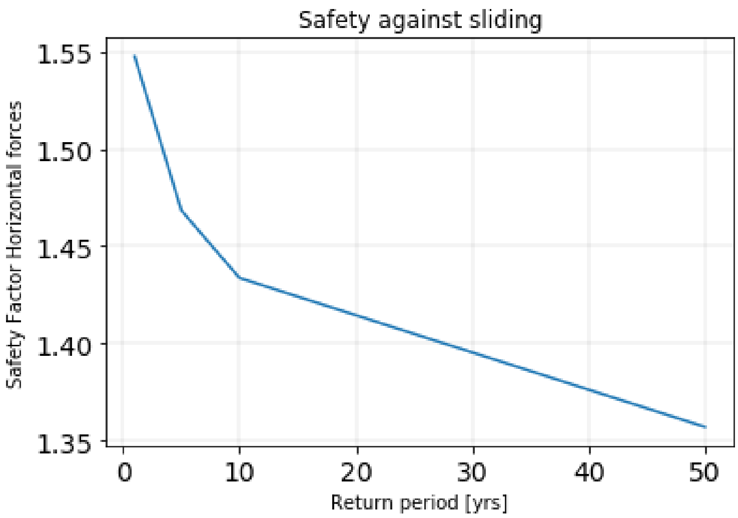

Figure 4.47: Progression of the ratio of soliciting and resisting moments for sliding with respect to the return period of a wave.

In Fig. 4.47, the sliding resistance over soliciting can be observed in the safety factors. The safety of the structure is guaranteed for a lower friction factor up until a return period of 50 years. The margin, however, is not as large as could be desired. Adding extra weight would contribute to the safety if this is desired.

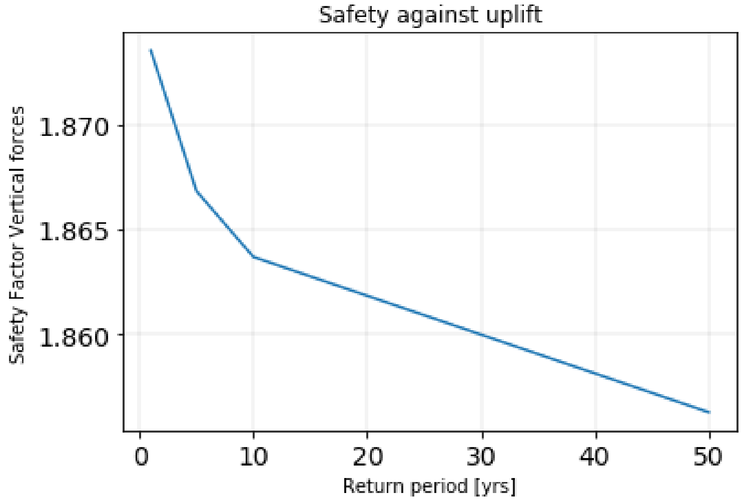

Figure 4.48: Progression of the ratio of soliciting and resisting forces for uplift with respect to the return period of a wave.

Uplifting of the structure does not seem to be an issue due to the strong gravitational force on the heavy structure. This can be observed in Fig. 4.48, and it is not surprising it is not altered due to a lower friction factor, as this does not influence the vertical forces.

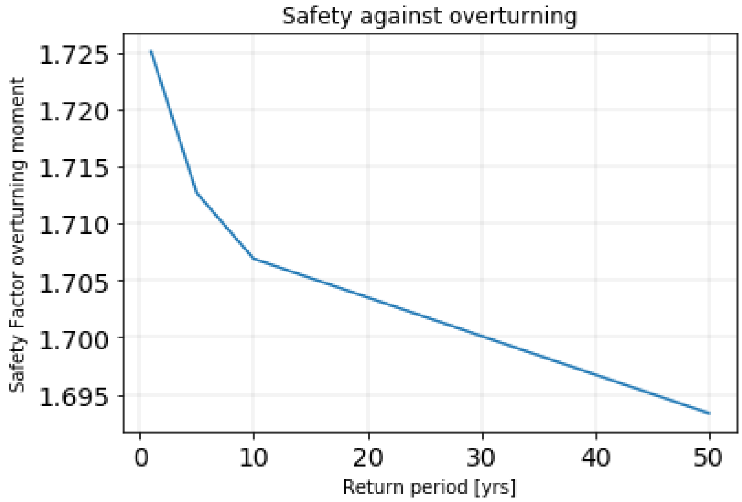

Figure 4.49: Progression of the ratio of soliciting and resisting moments with respect to the return period of a wave.

Safety against overturning does not seem to be a threat as the safety factor remains well above the 1 line and does not show significant decrease due to an increase in wave height as a consequence of a more extreme wave.

Friction coefficient analysis for 9° placement

Using this as input in Econstruct, Figures 4.50,4.51, 4.52, 4.53 show the output of Econstruct for the same structure with a lower friction factor and an inclination of 9°
As can be observed in Fig. 4.50, the structure is not safe for this inclination when a weather event generates a wave larger than the 1 year wave.
In Fig. 4.51 it can be seen that the reduced friction factor can be crucial for the instability for the structure placed at an inclination.

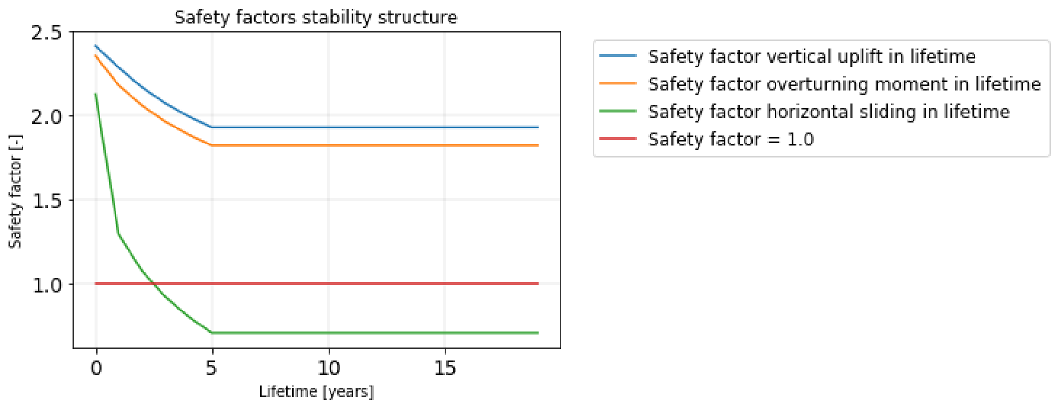

Figure 4.50: Safety factors for the redesigned structure, placed at a 9° degree angle with a reduced friction factor.

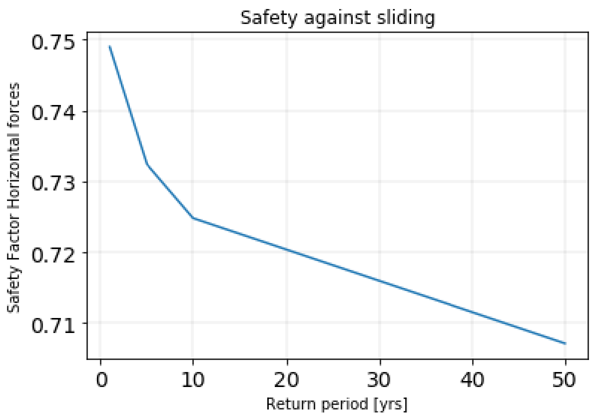

Figure 4.51: Safety factor for sliding for extreme weather events of different return periods. The soliciting forces on the structure are larger than the resisting forces, hence a factor below 1 is found.

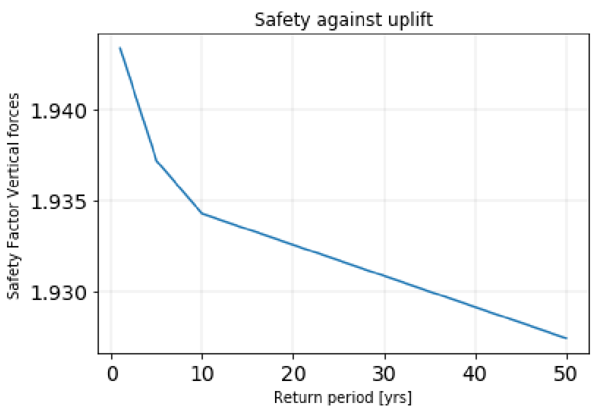

Figure 4.52: Progression of the ratio of soliciting and resisting forces for uplift with respect to the return period of a wave.

Failure is not prone to occur due to uplift or overturning, as can be observed from Figures 4.52 and 4.53.

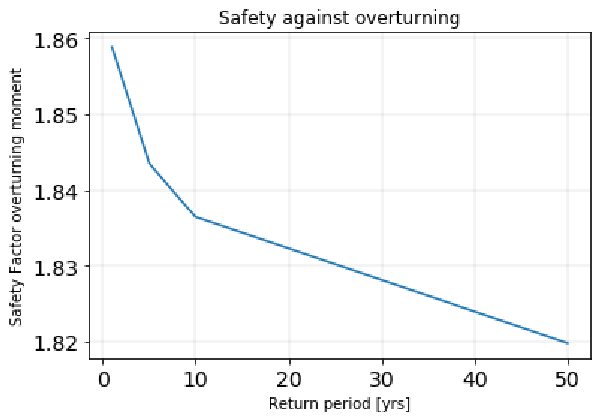

Figure 4.53: Progression of the ratio of soliciting and resisting moments with respect to the return period of a wave.

Safety analysis

After the structure has been constructed and placed, it can be of interest for the parties involved to be able to anticipate failure of the terraced redesign. Uncertainties in assumptions and weather conditions are commonplace in engineering design and as such it is paramount to conduct an analysis on the limiting conditions. In previous sections, a maximum placement inclination and a reduced friction coefficient were studied.

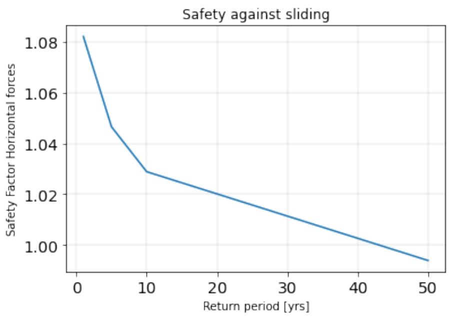

Figure 4.54: For an angle of 5°, the safety factor against sliding is shown with respect to the return period, whilst the friction coefficient is put at 0.5.

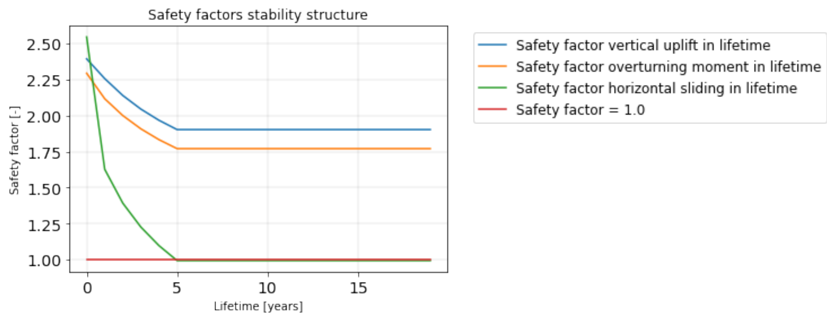

Figure 4.55: For an angle of 5°, the stability of the structure can be compromised when a 50 year wave passes

Fig. 4.55 shows the safety factors for the amplified flow as a consequence of a 50 year maximum wave height, whilst under an inclination of 5° and with a reduced friction coefficient of 0.5. The safety factor in the horizontal plane, against sliding, becomes critical when fully fouled. Looking at the extreme wave occurrence, in Fig. 4.54, it can be seen that for this critical failure mechanism the 50 year maximum wave height can be critical for the structure. It is advised to inspect the structure after such an event has occurred and if necessary fit the structure with extra weights to increase resistance against sliding.

During the lifetime of the project, which is set at 20 years, the probability of this 50 year maximum wave height to be exceeded is calculated with Eq. (4.20).

$$P(H_s > H_{s,50}) = 1 - (1-p)^n \tag{4.20}$$

Where for the return period of 50 years, the value for p is 0.02. This gives a probability of 33.2% of being exceeded during the project lifetime. The probability of occurrence holds for the occurrence of the storm, but this does not give information about the wave. Storms are typically assumed to have a duration between 6 and 12 hours (Holthuijsen, 2009). Within this storm duration, it is likely the maximum wave height occurs more than once. To give insight in this probability, a storm duration of 8 hours is taken. To calculate the amount of waves formed that are larger than the set maximum wave height of 12.96m, the following relation can be used:

$$N_{H>H_{max}} = DT_0^{-}1exp[-2(H_{max}/H_s)^2] \quad (4.21)$$

Using the maximum wave height of 12.96m, the significant wave height of 6.96m, the peak wave period of 11.5s and the storm duration of 28800 seconds, results in a $N_{H>H_{max}}$ of 2.44. This means, there will be 2.44 waves that exceed the size of the maximum wave height. Out of the total amount of waves (in this case 2504 waves), 2.44 exceeded the 12.96m maximum wave height. This results in a probability of occurrence of $9.74*10^{-}4$ per 50 year storm. Finally, this means the probability of occurrence of a wave that is larger than the maximum wave of 12.96m is $3.23*10^{-}4$ in the 20 year life time of the project.
As in Chapter 3 was stated, the velocity of the tidal current and the wave oscillatory component are assumed to add up. It is possible that during the 50 year wave, the wave field and the tidal current do not align up as neatly as is assumed, which would mean the structure stays in place as the assumption is conservative.

Concluding evaluation terraced redesign

The redesigned structure is larger than the structure designed on the first design iteration, which adds to the weight of the structure. This is also observed in the safety factors against uplift, sliding and overturning. Analysing the structures placement with respect to the monopile, slightly increases the velocity of the current at the structure in some positions, but reduces the velocity in other locations. Taking the worst case situation, an increase in velocity, the maximum inclination for which the structure can be placed was found to be 9° for the friction coefficient 0.6. Recognising the sensitivity in the assumption of a friction coefficient, the an analysis was conducted for a lower friction coefficient of 0.5. The maximum inclination was then found to be at 5° for waves smaller than a 50 year wave. Analysing the performance of the structure, it was found that the structure is at risk when a 50 year wave strikes. During the project lifetime, the probability such a wave strikes the structure is 33.2% and when it does, it is advised to inspect the structure and the location of the structure.

Chapter 5

Discussion & Conclusions

As the amount of offshore wind farms grows in the future, the demand for nature-inclusive design methods for offshore wind rises. Ecological enhancement of offshore wind farms is a method to mitigate the impact on the previously present habitat, and contribute to a healthy and resilient marine ecosystem in the North Sea (Rijksoverheid, 2015a). The addition of hard substrate often seen in these OWFs, as scour protection, offers ample opportunity to exploit nature-inclusive designs such as oyster enhancing technologies. Oysters, being a keystone species, are disproportionally important in facilitating other species by providing shelter, foraging grounds and a habitat. The presence of hard substrate can enable the growth of oyster reefs that can increase the ecological value of the offshore wind farm. However, in order to enable nature enhancement by means of oysters, stock enhancement is required in order to provide the substrate with a source of oyster larvae. As the North Sea used inhabit the flat oyster, this species (*Ostrea edulis*) is the species that enjoys the focus of oyster enhancement. This goal of this research is to use ecological inputs to come to design criteria and viable concepts for an oyster broodstock structure, and to create an assessment tool to rapidly evaluate the stability and structural integrity of such a structure.

5.1 Discussion

Design criteria

The design of the oyster broodstock structure starts off by investigating the habitat requirements for a flat oyster, the subject of the application of the research. Using the characteristics of the flat oyster habitat as input, four categories for design criteria were drawn up. In these, design criteria for an oyster broodstock structure were conceived in a brainstorm session with project Ecoscour. The criteria are shown per category in Fig. 5.1. The design criteria were agreed upon with the partners in project Ecoscour, many of whom are experts on the flat oyster restoration and enhancement. The design criteria are interesting for future design attempts, in order to advance the field of oyster enhancement. Having drawn up the design criteria answers the first part of the first sub-question: *What are the design requirements for an oyster broodstock element?*.

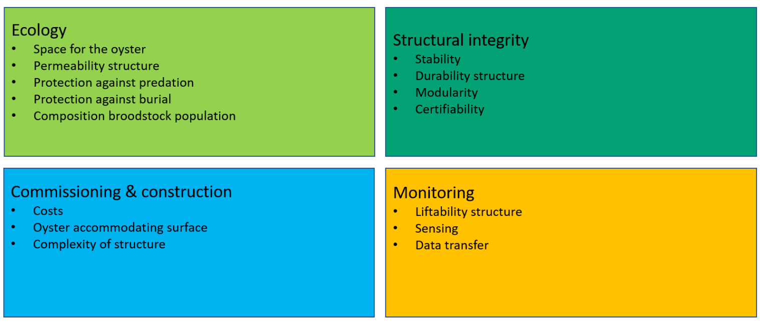

Figure 5.1: Design criteria

Oyster broodstock structure concepts

Together with the partners in project Ecoscour, eight structures were conceived. It is reasonable to assume there are more variations on a structure possible, having been conceived in a digital brainstorm session of two hours. A variation that has not seen the light in this research is one where protruding elements from a structure function as small piles or foundation in the bed upon which the structure is to be placed. This could potentially offer advantages for the structure, as the horizontal- and rotational loads would partially be carried by this penetrating element. The Tripod tree concept for example could be one of the concepts to benefit from this. The concepts that have been developed serve to answer the second and third part of the first sub-question: *What are concepts for such a structure, in order to inhabit flat oysters?* and *How to systematically compare concepts for oyster broodstock structures?*. The concepts were subjected to a SWOT analysis and compared relatively in Section 2.2.3 . The resulting concepts can be seen in Fig. 5.2 and 5.3.

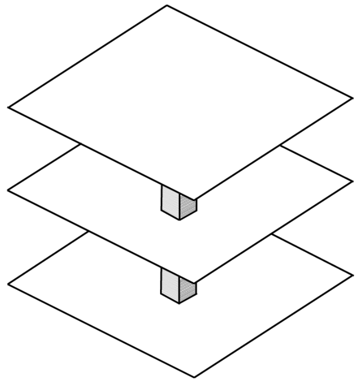

Figure 5.2: Terraced concept

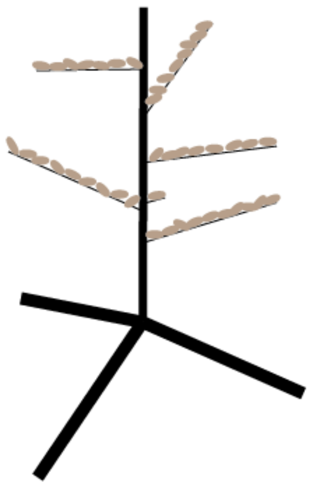

Figure 5.3: Tripod tree concept

Econstruct rapid assessment tool

In order to design a structure, forces and moments need to be calculated. With these loads known, the structural integrity can be evaluated. As no large projectteams of engineers or specialised construction software is used in the design of ecology enhancing structures, a cheap, rapid assessment tool is required for this purpose. In light of this research, this was developed and named Econstruct. The Econstruct design tool makes use of Object-Oriented Programming to create geometrical objects and join them together. In this way, one can create objects composed of cuboids and cylindrical shapes. This geometry is subsequently put under hydrodynamic loading, that consists of wave- and tidal induced currents. By conducting research on marine fouling, a fouling parameter was established to account for the effect of fouling on a structure. The species *Mytilus edulis*, or the mussel, was found to be the dominant species for the effect of marine fouling on the loads on the structure, growing at a rate of 1 cm per year, until a layer of 5 cm thickness is reached.

Application

The aforementioned steps form a design methodology that was applied in Project Ecoscour. First, the environmental characteristics of the Borssele V were researched, the bathymetry is studied for water depths, a map of morphological features examined, wave climate was determined and building drawings of the scour protections were analysed for rock gradings. Using this information, a geometry was designed to accommodate the 250 oysters that are required per structure to come to the sustainable broodstock population size of 1000. A minimum oyster carrying area of 5 m^2 was required. A structure was designed that was stable in currents caused by an extreme wave of 12.96 m. The structure is shown in Fig. 5.4, in Fig. 5.5 the stability is shown. After this design was

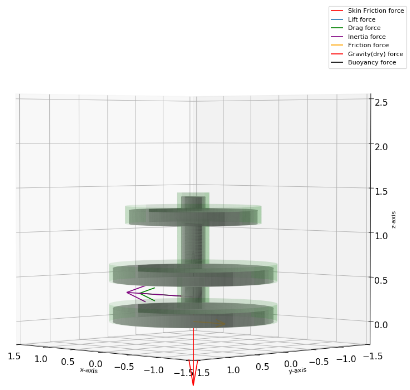

Figure 5.4: Stable design of the concept, 3D render obtained from the Econstruct tool

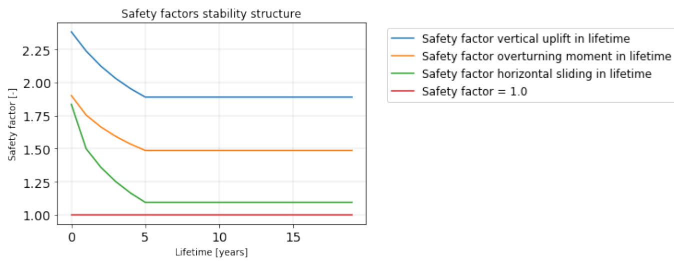

Figure 5.5: Safety factors for stability of the designed structure, using Econstruct

created, 13 potentially critical load cases on the structure were evaluated for structural integrity. Whilst the structural analysis was carried out by means of manual calculations, it offers a clear indication of the strength of the structure, without involving specialist construction software. In depth design could offer a more complete picture of stresses in the structure.

The design was reviewed with engineers from Van Oord and a manufacturer, D & M engineers. As the commissioning of the structures was set for a time window in October 2020, time constraints in the project led to a feedback loop with the manufacturer. The structure as shown in Fig. 5.4, required more complex reinforcing steel cages and complex formwork for the concrete to cure. In consultation with the manufacturer, the concept was altered and a revised design was created and built, as can be seen in Fig. 5.6. The structures were placed in October using a multicat vessel, shown in Fig. 5.7. The renewed design was simulated in the Econstruct tool and evaluated for stability. With success, as can be seen in Fig. 5.8 and Fig. 5.9. A safety analysis concluded that the maximum inclination for the structure was 9°. Using a reduction in friction and an inclination of 5° the 50 year wave was found to be critical for the structure. A probability of 33.2% during the lifetime of the structure is found for that wave to occur.

Figure 5.6: Realisation of the oyster broodstock structure

Figure 5.7: The structures being placed off the multicat vessel near the MP

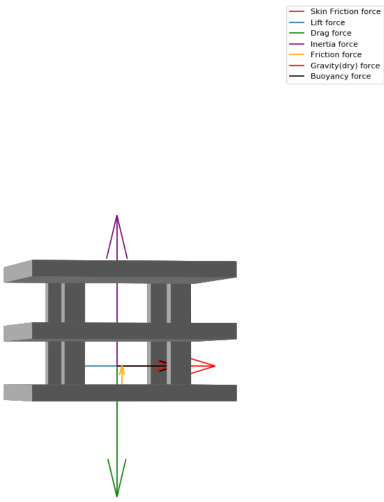

Figure 5.8: The renewed Terraced design, 3D rendered by the Econstruct tool

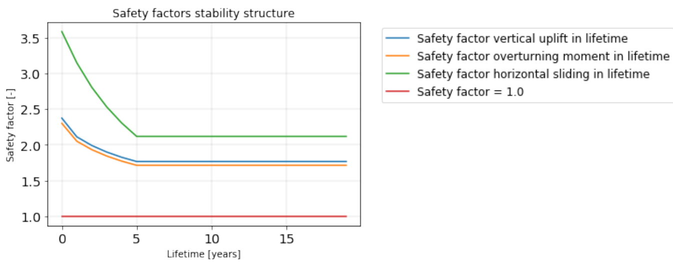

Figure 5.9: The renewed Terraced design is stable in time, as the safety factor lines stay well clear off the 1.0 line.

5.1.1 Relevance of findings

The conducted research offers a contribution to the field for oyster enhancing projects. By taking the ecological aspects of such projects as starting point, a design cycle has been executed that can serve as a guideline for future oyster broodstock structure designs. The Econstruct design tool has been developed to use for a multitude of designs, as long as it can be broken up in cylindrical shapes or cuboids. This can serve many purposes as it can help users in swiftly evaluating any object that is to be placed offshore under some hydrodynamic condition and fouling. These findings will also contribute to the offshore wind energy sector, as more stringent requirements are put into place by the Dutch government to stimulate nature-inclusive designs of offshore wind farms. As more nature-inclusive design ideas will arise, so will the need to evaluate these concepts for stability and strength in a quick manner. This research could aid new ventures in this field by giving designers a guideline and a versatile design tool to work with.

5.1.2 Relation to state of the art

Preceding research has focused on the ecological part of oyster enhancing projects, studying survival rates of the oyster population, checking for predators and monitoring species that are drawn to the structures. However, none of these studies focused on what such a structure to initiate nature enhancement with oysters could look like and what criteria are important to consider in the design of such a structure. Not only does this study provide the reader with this information, this research has also brought forward a rapid assessment tool Econstruct to evaluate the stability and strength of structures that is open source to use, and will aid future designer of ecology enhancing structures.

5.1.3 Limitations

This study has the following limitations:

- **Fouling parameter**
  The fouling parameter was estimated for one species, *Mytilus edulis*, but in reality many different species will colonize the structure. This means, a variance in composition of the fouling colony will lead to variability of the growth rate and density of the fouling layer, which could alter the progression of loads. When the structure is placed in other areas, it is possible that a different fouling species is found to be dominant or that the growth rate will be altered.

- **Hydrodynamics**
  The model uses normally incident currents that are a result of wave action and tidal currents. However, the effect of large structures or inclines on the seabed is not completely incorporated. The wake effects of a large structure, such as a monopile, will have an influence on the hydrodynamics. It is also expected that the armour layer will have a significant effect on the disturbance of the flow around the structure. As the structure will be positioned close to the transition of the armour layer and the filter layer, this could cause significant flow enhancement.

- **Geotechnical characteristics**
  The structure is placed upon a scour protection, which gives a rigid foundation, but effects like settlement of the scour protection rocks is not regarded in this study. This could improve the sliding resistance when the structure is slightly embedded in the scour protection, however, it is also thinkable that the layer below the structure settles to form a slight slope. It is recommended to investigate this aspect, as this factor can contribute to stability or induce instabilities in the structure, which would call for more precise placement.

- **Costs**
  Costs of the material and production of the structure are not taken into account in the design.

- **Internal fluid dynamics**
  Between the plates of the structures, the fluid will have a complex flow pattern, which can alter the distribution of oxygen and nutrients to the oysters placed upon the plates. This movement of fluid between the plates is not studied.

- **Native species**
  The flat oyster has been present in the North Sea historically, however, its sharp decline has seen the species being pushed to a threatened status. Even though the hard substrate added by offshore wind farms offers an opportunity for flat oysters to inhabit, the sandy habitat that was present is destroyed by the construction of the wind farm. This study focused on oyster enhancement, but the enhancement of other species in the area is not regarded.

- **Validity of assumptions**
  The results of this research have been obtained by means of a literature study which aided in the input for the design study. However, dealing with a complex structure in a complex

environment calls for a variety of assumptions to be made, to enable a practical design process. Some of these assumptions influence the outcome of the design study, whilst the assumptions might not necessarily be correct. Below, the assumptions are presented and the sensitivity of each assumption on the outcome of the study is discussed.

- Assumption: Rigid bottom
  Sensitivity: The armour layer, upon which the structure is placed in this application, is designed to sustain a 50 year wave. The layer could show some damage, but should not be completely destroyed. The foundation is therefore generally quite stable, but could move due to extreme weather events. Also, settlement under the weight of the structure is not regarded, this could cause a tilt in the angle of the structure with respect to the flow. If the settlement is significant and hard to predict, the Econstruct tool can be used to test for larger inclinations and still stay stable.
- Assumption: Normally incident current
  Sensitivity: The current that acts upon the structure, is assumed to be normally incident on the structure, whilst in reality the vector of the current can take on about any direction. This could affect the uplifting force on the structure and threaten stability. The Econstruct tool could be adapted to incorporate a variation in the flow angle, but seen as the vertical stability is dominated by gravitational forces, this uplift would not threaten the stability of the structure.
- Assumption: Mussel as primary fouling species with linear growth
  Sensitivity: For the North Sea, this is the dominant species by size and weight. When designing for structures in different waters, it is important to check the fouling species present to find which one is dominant. The assumption for the North Sea is quite conservative, as the mean density and thickness will not be of the size of a homogeneous layer of mussels, but less.
- Assumption: No threat by sand waves
  Sensitivity: In consultation with ir. T. Raaijmakers, author of several reports on morphological features in the Borssele area, the morphological features in the Borssele V area were studied and deemed not threatening to the oysters on the structures. However, for a design in a morphologically dynamic area, caution should be taken. In these areas, the scour protections will also be designed to protect the monopiles from the seabed lowering that can occur due to these phenomena, so a detailed study of the features present should give insight as to the threat in such a case.
- Assumption: 50 year return period weather conditions are sufficient
  Sensitivity: As the armour layer of the scour protection on Borssele V is also designed for a 50 year wave, it would not be sensible to design for a 100 year wave or larger, as the foundation would fail before the structure would. This would still cause failure for the structure, but for external reasons.
- Assumption: Coefficients: cylinders and flat plate
  Sensitivity: The cylinder approach works for a structure on the seabed, as it is an assumption often made in practise by marine engineers for cables and pipes and was recommended. The flat plate approximation assumes a very thin boundary layer in comparison with the length of the body. This is probably an underestimation, as the surface is quite rough, the conditions highly turbulent and oysters are positioned on the plates. The assumption's invalidity would solely influence the lift force, which is negligible in this study, and as such the validity of this assumption has no significant ramifications.
- Assumption: Bottom friction coefficient
  Sensitivity: The bottom friction coefficient is determined for full contact with the bottom. Most likely, the contact between the structure and the bottom is determined by several point contact between the scour protection and the concrete bottom slab. This would somewhat reduce the friction, initially. Stagnation zones on the bottom of the structure and biofouling could fill up the gaps in between, whilst movement and settlement of the structure (as aforementioned) could beneficially influence the negative effects of this assumption. It is clear, however, that the interaction with the bed upon which the structure is placed, requires more research.

- Assumption: Distributions parameter input sensitivity analysis
  Sensitivity: The five parameters selected for the sensitivity analysis have all been sampled with a uniform distribution. Whilst this is okay for geometrical inputs as the radius and height, as they are manually selected, the currents have a different distribution. Being related to the tidal current and the 50 year wave, a dependency to a Rayleigh distribution for the extreme wave and Weibull distribution for the tidal component is to be expected. This could have led to an underestimation of the influence of the current velocity on the model, however, the SA shows that the current and current amplitude are both very influential on the stability, so it would not significantly alter the conclusion.
- Assumption: Maximum inclination on scour protection
  Sensitivity: The maximum inclination has been put at 5°, which is not a large inclination. As has been mentioned before, the interaction between the bed and the structure needs more research, and this will also play a role in refining this assumption. This assumption assumes a rigid bottom where, due to construction tolerances or an extreme weather event, an armour element has moved an protrudes above the layer. If it is shown that the structures placed have moved, it could mean that the angle of placement was too large or settlement has occurred which led to movement. Then, the inclination should be reviewed and the tolerance increased.
- Assumption: Beam simplification
  Sensitivity: Assuming half of the plate to be a beam of the width of the stem, with the weight of half the plate whilst being fouled, is conservative. A plate has 3D support along the inner radius of the circle, whilst the beam has only the connection between the stem. It is therefore suitable to use this simplification to make an estimation of the bending of the plates or the shearing.

5.2 Conclusions

The conclusions are presented by answering the sub-questions and consequently answering the main research question.

5.2.1 Sub-questions

Sub-question 1: *Which design criteria and concepts can be identified to determine a flat oyster broodstock structure?*
Firstly, the habitat of the flat oysters was studied in order to come to design criteria. The most notable environmental parameters for this study were the the current velocity, predation, the target substrate composition, oxygen content in the water and the critical mass of the oyster population on the structure. In Chapter 2, these characteristics are studied and were used to set up the brainstorm session with the partners in project Ecoscour. In collaboration with partners from NIOZ, WMR, Bureau Waardenburg, HZ and Van Oord, the design criteria have been drawn up in four categories: Ecology, Structural Integrity, Commissioning & Construction, Monitoring. The criteria are shown in Table 5.1.

Ecology	**Structural integrity**
Space for the oyster Permeability structure Protection against predation Protection against burial Composition broodstock population	Stability Durability structure Modularity Certifiability
Commissioning & construction	**Monitoring**
Costs Oyster accommodating surface Complexity of structure	Liftability structure Sensing Data transfer

Table 5.1: Design criteria for oyster enhancing structure

In a brainstorm session, a total of eight structural concepts were developed, of which two were found to be very promising for oyster enhancement. These are referred to as the Tripod tree concept and the Terraced concept. The Tripod tree concept has been eliminated in later stages due to difficulties in manufacturing, the Terraced concept was worked out in detail.
Sub-question 2: *Which environmental processes that occur in an offshore wind farm should be included in the design of an oyster broodstock structure?*
The parameters that were required for the application of the design method and Econstruct tool were the following:

- Hydrodynamics: peak wave period, significant wave height
- Positioning: Water depth, inclination
- Morphological features: Although assumed not relevant in consulation, they were studied.
- Fouling characteristics: The dominant fouling species was researched to find the fouling rate.
- Choice of construction material: Reinforced concrete was chosen, as it matched the desired substrate for the oyster
- Geometry of structure: Most important influence on the performance of the structure.

Sub-question 3: *What is a systematic method to assess the structural integrity andstability of an oyster broodstock structure?*
The relevant forces on the structure are:

- Gravitational force
- Buoyancy
- Drag forces
- Inertia force
- Skin friction force
- Lift force
- Bottom friction force

By creating a rapid assessment tool called Econstruct, an object composed of elementary shapes as a simple block or a cylinder, can be evaluated for stability and structural integrity. In this tool, the hydrodynamics, marine fouling, the positioning of the structure in the water column and the geometrical shapes are used as input. By using non-linear wave theory and involving marine fouling on offshore structures, the forces and moments are calculated, which are transformed to safety factors for horizontal, vertical and rotational equilibria to swiftly be able to assess the stability of the structure that is to be designed. This information can consequently be used for detailed structural analysis of the structure. A sensitivity analysis was conducted for the five most important parameters: the radius, the height, the total current, the amplitude of the oscillatory velocity component due to waves and the fouling rate. The radius was found to have the largest influence on the overturning moment. The current has the largest influence on the horizontal stability, and the radius also influences the vertical stability the most. The fouling parameter showed a large variance and thus uncertainty.

5.2.2 Main research question

Main research question: *"How to design an oyster broodstock structure for offshore wind farms, that remains structurally robust and stable under prevailing environmental conditions?*

Having used the design methodology as described in Section 1.4, the following steps were taken in the design:

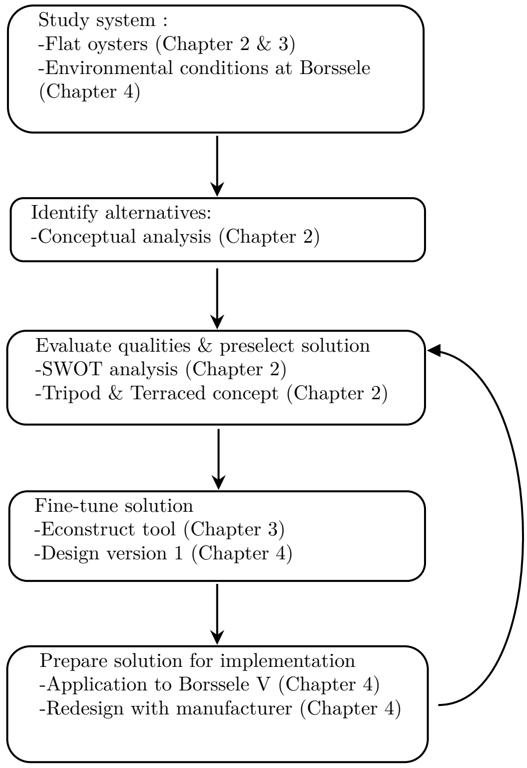

Figure 5.10: Design steps in order to design an oyster broodstock structure

As described in Fig. 5.10, five steps were followed, distributed over the chapters named in the same picture.
Studying the system, being step 1, entailed studying the desired characteristic for flat oysters, which resulted in knowledge that was moulded in design criteria, in collaboration with Project Ecoscour. The second step, identify alternatives, was taken in Chapter 2, in collaboration with Project Ecoscour. Eight concepts were drawn up that could be a suitable oyster broodstock structure.
These eight concepts were analysed by means of a SWOT analysis, which resulted in two structures, of which one was studied in depth. The Terraced concept was studied in depth, whilst the Tripod tree concept was disregarded in later stages due to manufacturing difficulties that arose. A replacement structure was conceived.
Fine-tuning the solution started off by developing a rapid assessment tool, named Econstruct. With this tool, one is able to create geometrical shapes and subject these to hydrodynamics in the form of wave action and tidal currents, while being under the influence of marine fouling. This tool has been put to use to form a first design for project Ecoscour. This is shown in Fig. 5.11, which was manually evaluated for structural integrity, by using 13 critical load cases. The structure was found to be stable and strong enough
The designed structure, is shown in Fig. 5.11, with a soft green layer of fouling and also showing the force vectors.

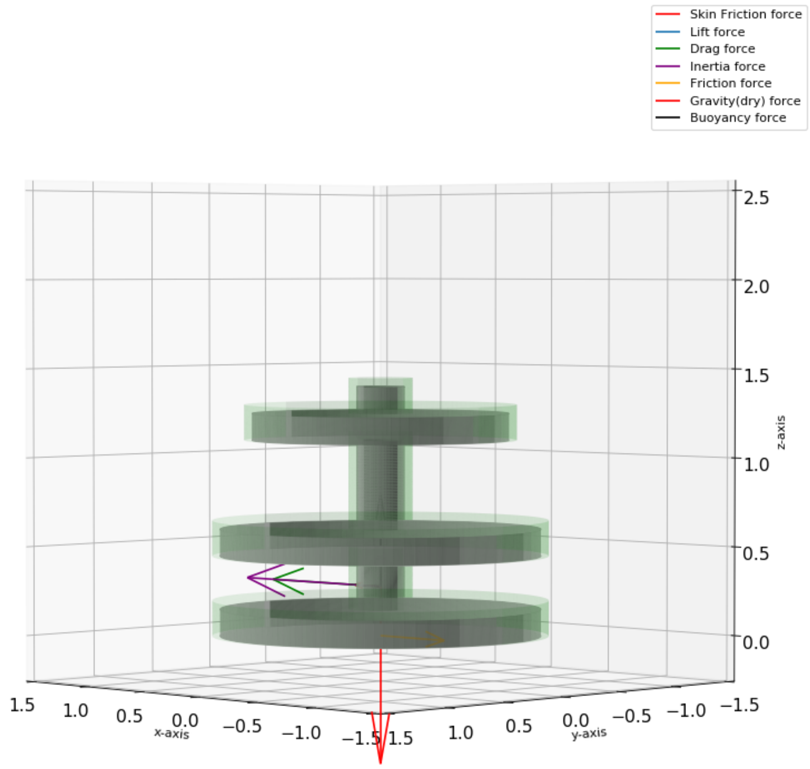

Figure 5.11: The Terraced concept design 3D render in the Econstruct design tool

In the final stages of this design, consultation with manufacturers resulted in practical changes in the final design, due to time constraints and construction constraints. This shows the importance of involving manufacturers in the design cycle, which in light of time came late in this project. Two alterations to the design were conceived, one with holes to improve permeability and reduce risk of sand accretion (Fig. 5.13), one with solid plates (5.12).

Figure 5.12: Manufactured oyster broodstock structure with flat, solid plates

Figure 5.13: Manufactured porous oyster broodstock structure with increased permeability

The final design is verified using the Econstruct design tool and was shown to also be stable. A safety analysis was made of the structure, which can be used to forecast when inspections are required after a certain weather event has passed, as shown in Fig. 5.15. In Fig. 5.12 and 5.14, the designed structure is shown as well as the 3D render of the structur. This proves the versatility and effectiveness of the Econstruct design tool.

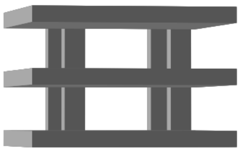

Figure 5.14: Oyster broodstock structure 3D render in Econstruct design tool

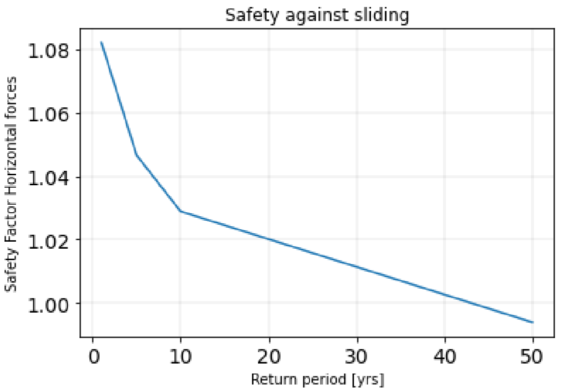

Figure 5.15: Safety analysis of the oyster broodstock structure, contains the sliding failure mechanism with respect to the return period of extreme waves

Four structures were outplaced in October 2020 at the Borssele V OWF innovation site, two of each concept. The structures will be visited for inspection after 1,3 and 8 years.

Figure 5.16: The structures have been placed offshore from a multicat vessels

Chapter 6

Recommendations

This chapter discusses potential improvements and elaborations on this research, as well as presenting an example of a monitoring campaign that could be used to evaluate the performance of the structure. Also, a physical scale test is proposed, to validate the stability and strength of the structure in a controlled environment.

6.1 Recommendations for future research

Multiple aspects to this research still remain ambiguous and could be clarified in future research in this field. In this respect, the following recommendations can be made:

- Fouling parameter
  More in depth knowledge about fouling patterns in the North sea in order to quantify fouling in the design could help predict loads. Site investigations of the Borssele V site could help shed light on the types of fouling species present on the structures.

- Investigate geotechnical aspects
  As described in Section 5.1.3, geotechnical effects due to the loading of the structure have to be investigated for a more complete picture of the stability of the structure. This could be done by scale testing.

- Study friction coefficient
  The friction force is important in stabilising the structure against failure due to sliding. As the structure is not in full contact with the scour protection, but has many point contacts with the rocky scour protection. This makes this assumption sensitive to changes, and research is recommended. This can be conducted by taking the full scale structure and subjecting it to tests on a rocky layer with a known amount of point contacts.

- Morphological threats
  Morphological features such as sand waves could threaten the survival of oysters on the structure. Research on a structure that could potentially move with these waves could increase the applicability of oyster enhancing structures.

- Monitoring
  A monitoring plan to investigate the performance of the structure is presented in Section 6.2, but was not used in project Ecoscour. It is valuable to test the performance of the structure for both stability, structural integrity as well as the functionality of the oysters.

- Positioning on scour protection
  From the work by Miles, positioning of the structures can be estimated. As experiments conducted in that work showed amplified flow at about 1.2 times the background velocity at 0.75 pile diameters from the center of the pile and peaking turbulence around 1.5 pile diameters behind the MP. It is therefore advised to attempt to place the structure outside of this region on the scour protection. The effect of horseshoe vortices that can be generated by the armour layer should also be taken into account. Investigations in this field can be done by scale testing.

- Hydrodynamics
  The hydrodynamics module in Econstruct uses second-order Stokes' approximation of waves in order to obtain a current velocity on the structure. As stated in Section 5.1.3, wake effects of the monopile nearby should also be studied, as well as spatial variations in the current velocity due to the inclination of the scour protection. In this study, the flow enhancement was taken into consideration, but not the turbulence. Also, the horseshoe vortices that can be formed by the armour layer should be taken into consideration. Due to the position of the structure with respect to the armour layer, this could have a profound effect, as flow enhancement due to this layer of the scour protection could see the velocity rise more significantly than due to the presence of the monopile.
- Design for commissioning
  In carrying out the fitting of the flat oysters on the structures, time was of the essence. When the oysters were glued upon the structures, they were out of the water. The maximum time for this is set at48 hours, which puts a time constraint on the preparation of the structures. It would be convenient to design the structure so that the oysters could be submerged while waiting for a suitable weather window to be installed.
- Different base material and coating
  The Tripod tree concept was promising, however, constructing it out of steel gave many problems regarding corrosion protection. Coatings and anodes are solutions for this, however, anodes create a toxic environment which could kill the oysters, and potential coatings should first be subjected to testing with oysters for toxicity. Research should focus on different coatings for steel structures that can sustain oysters on its surface.
- Modelling uncertainty
  Missing out on geotechnical aspects in the model and complex hydrodynamics, gives uncertainty in the predictive capacity of the model. These should be added, if a better evaluation is desired.
- Application for other types of enhancement campaigns
  The Econstruct design tool could be helpful for the design of structures for other ecological enhancement projects such as enhancement of coral reefs.

6.2 Monitoring

The designed oyster broodstock elements are irregularly shaped, and will be placed in an uncertain environment. An uncertainty analysis and sensitivity analysis of the important parameters has been carried out. However, in order to properly validate the design of the structures, a monitoring campaign is proposed in this section. Moreover, a physical scale test is proposed in order to come to terms with the complex hydrodynamics and geotechnical aspects.

6.2.1 Goal

Evaluating the performance of the structure is done by verifying whether the design requirements have been met. The aim of the monitoring campaign is divided in two parts:

1. Stability & structural integrity
2. Ecology

Stability & structural integrity

Stability for the structure is defined as follows:

- No lateral movement
- No vertical movement
- No rotations
- Durability

The structure is required to remain stable on the bed, in order to provide the adult oysters with a functioning support structure. Also, the structure must prove to remain durable during its lifetime.

Ability to function

As the oysters are fixed upon a stable unit, it is important to examine whether the oysters are able to function properly. Like stated in the design requirements in the category 'Ecology', the oysters require:

- Space for the oysters
- Permeability of the structure
- Protection against predation
- Burial protection
- Suitable conditions for flat oysters

6.2.2 Method

The monitoring campaign should consist out of the following elements:

- Monitoring on site: site visits
- Monitoring on site: remote monitoring
- Testing in a lab: monitoring in the lab

6.2.3 Monitoring strategy

The monitoring campaign will consist of two different types of investigations;

1. Site monitoring at Borssele V
2. Physical scale testing of the oyster broodstock structure

Site monitoring at Borssele V

Site monitoring will occur at set intervals, coupled to the dedicated campaigns to visit the site for monitoring. These inspections are scheduled to occur after one, three and eight years. An example of a sequencing of monitoring events is presented in Fig. 6.1.

Space for the oysters and the permeability of the structure are important characteristics for the survival of the oyster in order to supply sufficient oxygen and nutrients to the broodstock population. The space for the oyster could be reduced by significant sand accretion or the presence of many hard fouling species that hamper the growth of the oysters. This can be studied on site in two ways, either by lifting the structure to a vessel for inspection, or by observations with an ROV from a vessel. The distance between the plates and the thickness of the fouling layer should be inspected. For the porous structures, the thickness of the fouling in the holes should be assessed in order to study whether these places would become clogged by fouling organisms.

Protection against burial should be investigated using a ROV, as this gives an undisturbed image of the structure with the sediment on it. Inspecting both structures with a ROV before hoisting would give insight in whether the porous structure functions better in dodging sand accretion. After this visualisation, the structures can be hoisted to the vessel, in order to observe the state of the oysters. Dead oysters on the plates could indicate asphyxiation, but cause of death should be determined visually.

For predation, it is recommended to use a ROV to observe presence of predators on or around the structure. Closer inspection can be done after lifting the structure off the bed to inspect individual oysters, by inspecting the oysters and checking the deceased oysters for cause of death, predators can be deducted. In the same manner, burial can be inspected.

In order to evaluate the success of the oyster enhancement campaign, a ROV should be used to inspect the scour protection for settled spat. This would prove that the broodstock structures were successful in reproducing spat and that the scour protection is being colonised by oyster larvae from the structures.

For recruitment on the structures, inspection after lifting is a suitable method to assess the structures. Looking for new spat on the structures would mean that oysters have succesfully reproduced.

The durability of the structure is related to the cracking of the concrete of the structure, which can cause oxidation of the reinforcement steel. This can either happen due to corrosion or to excessive deflection of the elements. Whereas there is uncertainty in the amount of deflection of the structure, as a result of uncertainty in the loading, there is also uncertainty in the corrosion, as this is caused by corrosion due to the aqueous environment, but also corrosion due to the marine fouling by sulphate reducing microbes (Loxton et al., 2017) and crevice corrosion caused by barnacles (Beech and Sunner, 2010). Inspection of the structure would be possible during site visits, while the structure is on deck after being hoisted.

As the structure's location is known after placement (see Appendix C), movement of the structure can be measured using a multi-beam echosounder. The inclination of the structure on the seabed must be observed with the ROV.

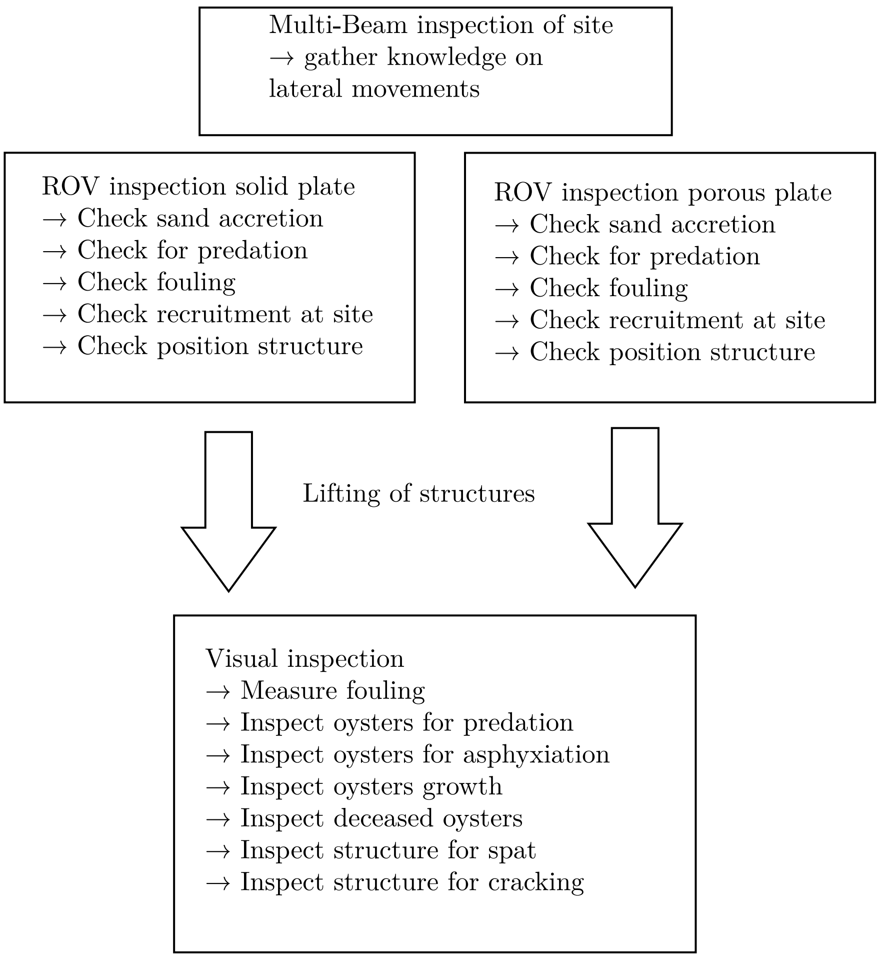

Figure 6.1: Sequence of events for a monitoring campaign on site

Physical scale testing of the oyster broodstock structure

As the structure's spatial positioning on the scour protection and the inclination can be changed after a weather event, it is desirable to anticipate the potential movements of the structure due to weather events ex ante. In order to do this, physical modelling could provide important information on the characteristics of the structure. As stated in Section 5.1.3, the coefficient related to the shape of the structure are assumed off simplifications. These could be verified in depth using physical scale modelling. Complex hydrodynamics and geotechnical instabilities could also be studied extensively using physical modelling.

Stability is measured by installing a motion sensor in the structure, to measure movements of the structure in a three-axis system. This could be done with a high-frequency accelerometer that can capture movements with a high δt, such as the ADIS16210 (Murphy, 2020), in order to measure the movements in a storm event. The selection of the accelerometer to be used depends on the mass of the structure that needs to be measured. As a large volume of data is expected, this study recommends an experiment in a controlled environment such as a wave flume, such as the Delta Flume at Deltares in Delft. The complete design of such an experiment is not in the scope of this research, however, it is advised to test the structure in an environment where a monopile and scour protection can also be modelled, to give a full insight of the situation. This experiment would give an insight in the lateral, vertical and rotational stability of the structure.

Concrete cracking can also be simulated in the wave flume, where cyclic loading induced by waves is taking place, cracking could occur. The structure can be fitted with deflection sensors to measure the deflection of the plates. Afterwards, the structure can be inspected for cracks.

Flow velocity sensors can be mounted inside the structure to measure the flow of water through the structure. These can also be mounted on the outside, to measure the variation in flow pattern due to wake effects of the MP or ramping effects of the scour protection.
The friction coefficient used can be tested in a full scale sense, by creating a rock layer of the grading of the scour protection upon which the structure is to be placed and attempting to slide the structure off the rocks. Monitoring which force is required for this whilst monitoring what contact points have been made with the structure could provide further insight into predicting the friction force on the structure.

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A Appendix A: Brainstorm with Project Ecoscour

This chapter discusses the brainstorm of April 9th which is used for the conceptual design phase. The brainstorm was held online on the 9th of April on 2020, with Microsoft Teams and Miro board, due to COVID restrictions in gathering in person. The brainstorm was organised to gather ecological experts in the field of oysters, notably the flat oyser, and gain insights and input on the design criteria and potential structural concepts.

A.1 Design criteria

Figure A.2: Brainstorm criteria

A.2 Concepts

Figure A.3: Brainstorm sheet from Miro boards on ecology

Figure A.4: Brainstorm sheet from Miro boards on structural integrity

Figure A.5: Brainstorm sheet from Miro boards on Monitoring

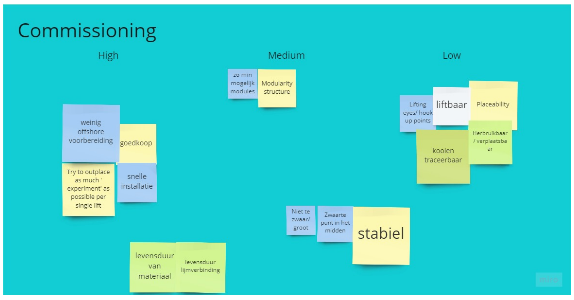


Figure A.6: Brainstorm sheet from Miro boards on ecology

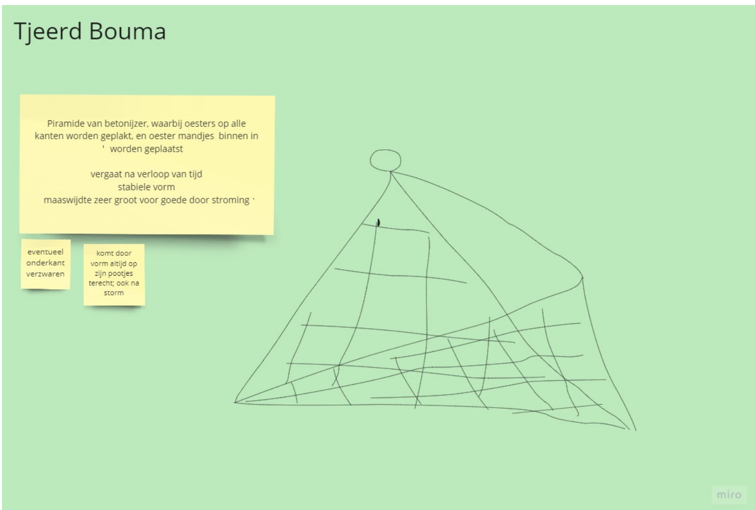


Figure A.7: Pyramid concept, conceived by T. Bouma (NIOZ)

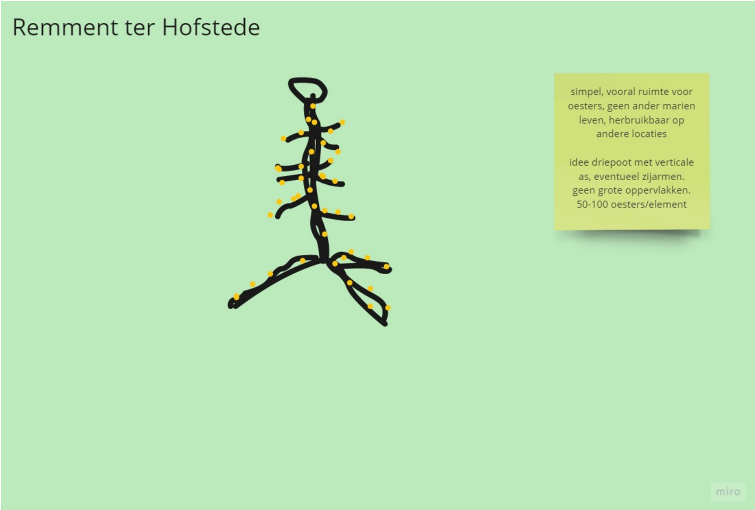


Figure A.8: Tripod tree concept, conceived by R. ter Hofstede (Van Oord)

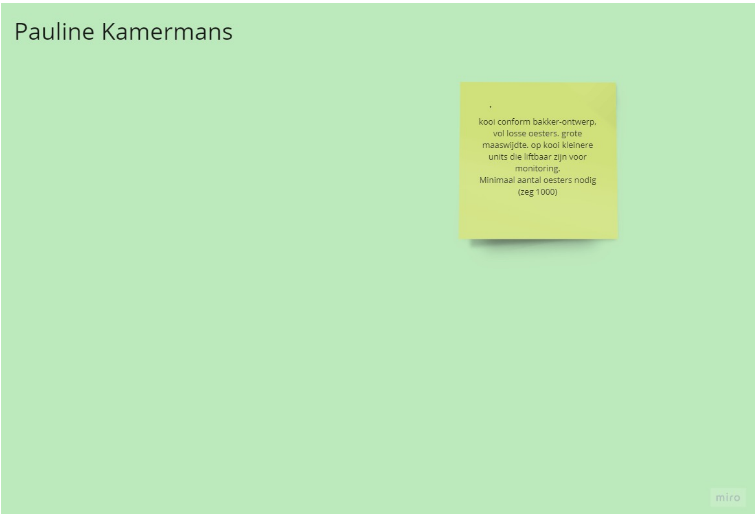


Figure A.9: No sketch by P. Kamermans (WMR) present

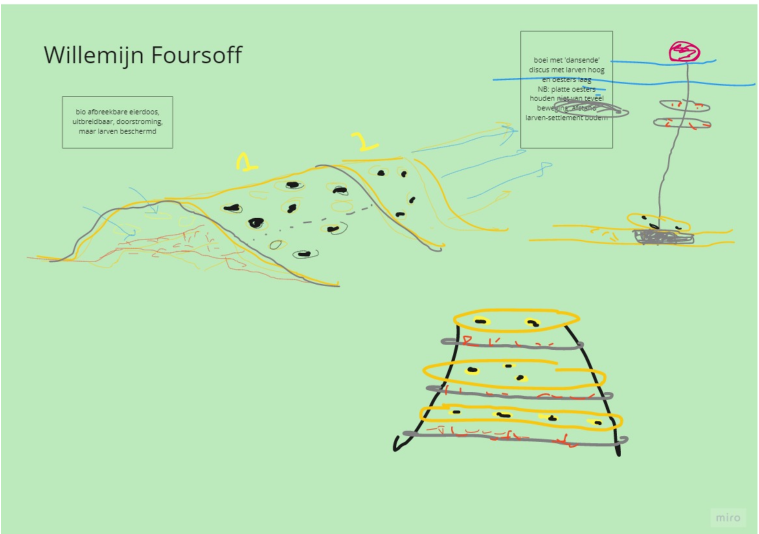


Figure A.10: Egg container concept by W. Foursoff (Van Oord)

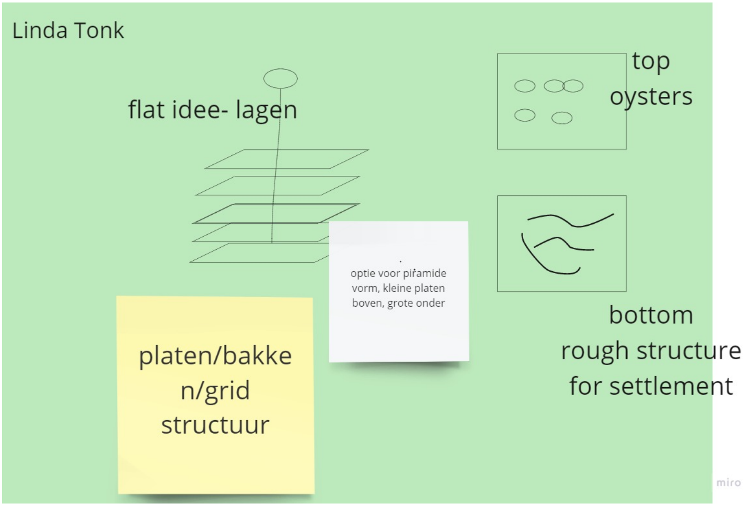


Figure A.11: Terraced concept by L. Tonk (WMR).

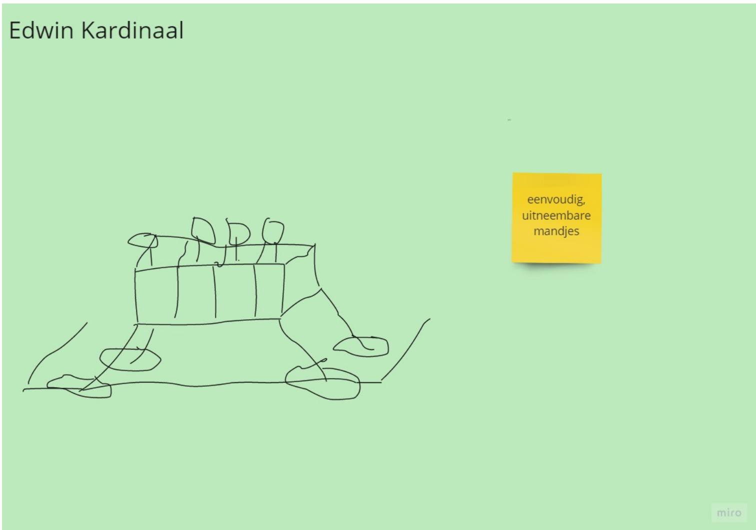


Figure A.12: Bakker cage hybrid by E. Kardinaal (Bureau Waardenburg)

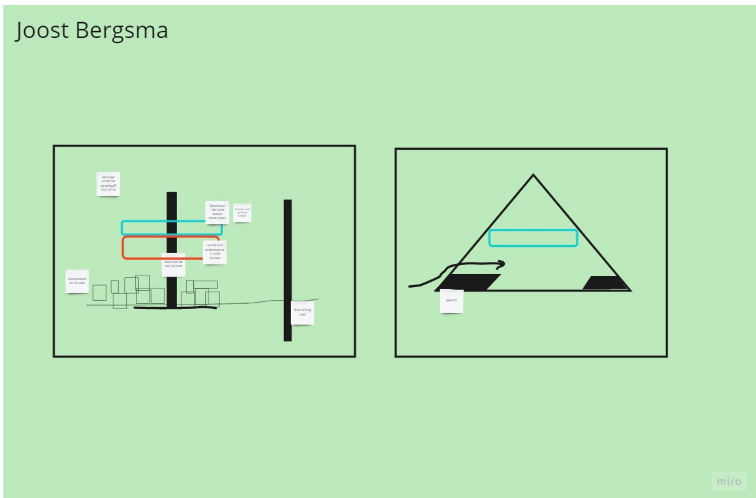


Figure A.13: Piled concept integrated in the scour protection by J. Bergsma (Bureau Waardenburg)

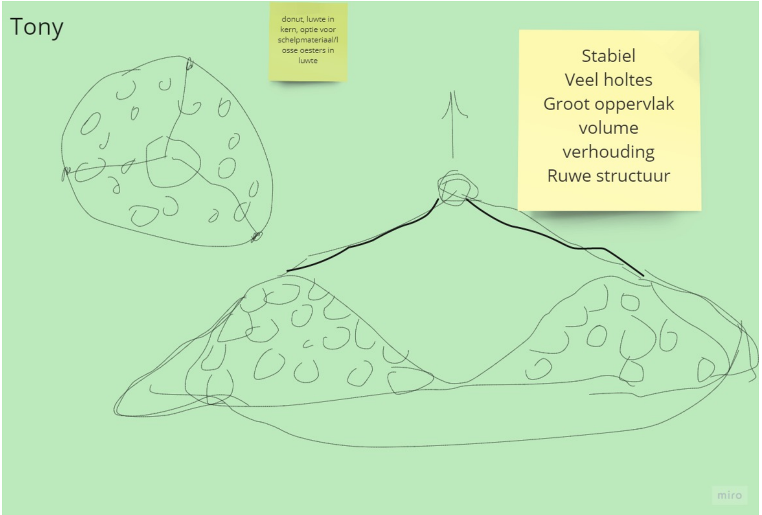


Figure A.14: Donut concept by T. van der Hiele (HZ)

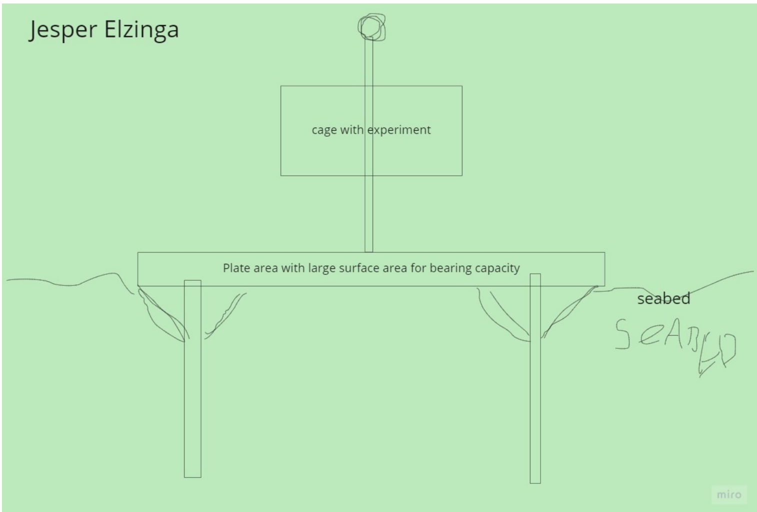


Figure A.15: Piled Bakker cage by J. Elzinga (Van Oord)

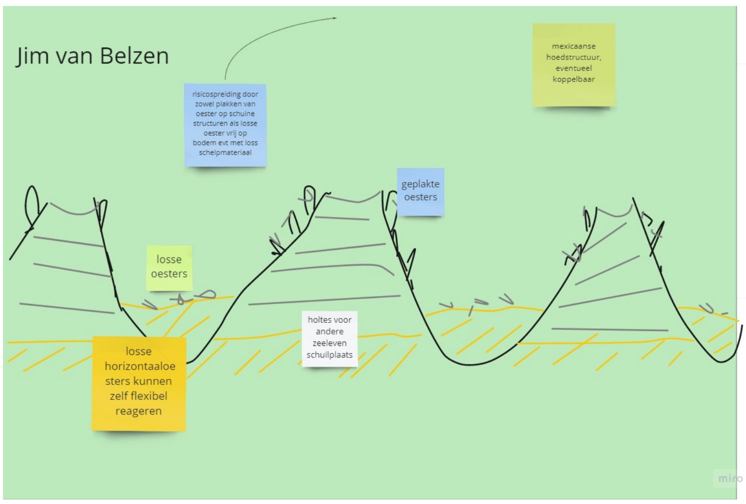


Figure A.16: Hat concept by J. van Belzen (NIOZ)

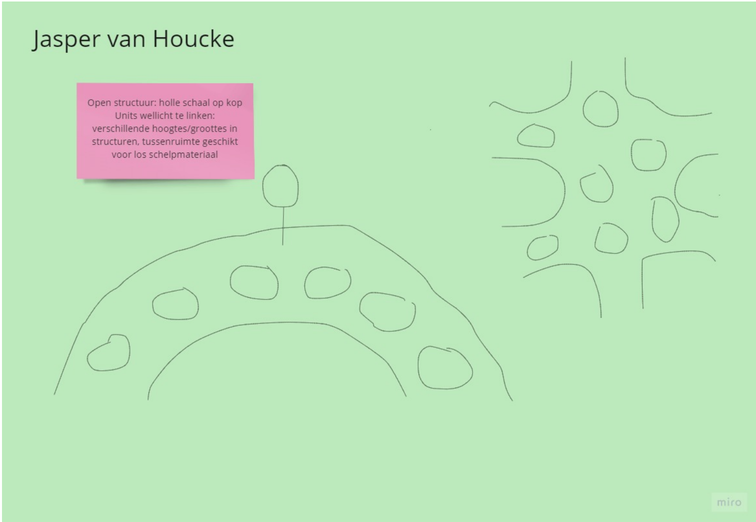


Figure A.17: Bowl concept by J. van Houcke (NIOZ)

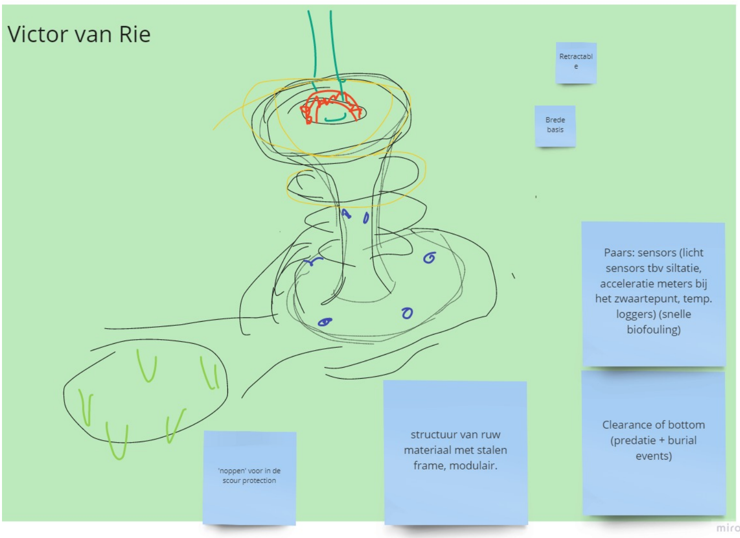


Figure A.18: Terraced concept with studs by V. van Rie (TU Delft & Van Oord)

B Appendix B: Technical drawings of broodstock design

This appendix presents the technical drawings of the designed broodstock element.

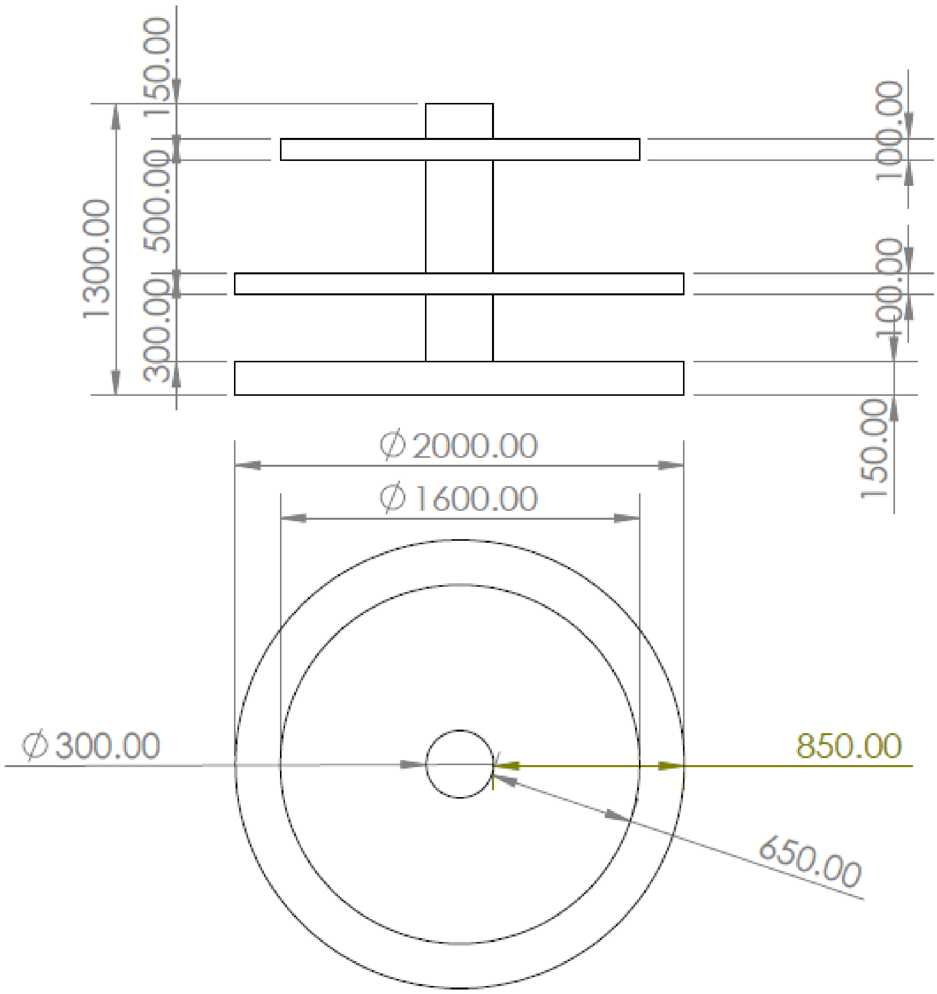


Figure B.19: Technical drawing of the terraced concept made with Solidworks

B.1 Output design terraced concept

```
Oyster_area 5.152211951887261
Facilitated upward facing oyster area Area:5.15 m^2
Total mass structure (in air) Mass:3278.06 kg
             Forces  At time = 1 yrs            Forces  At time = 5 yrs
0       Gravity(dry)         34824.92      Gravity(dry)        46552.14
1       Gravity(wet)         19576.95      Gravity(wet)        22232.17
2               Drag          3268.61              Drag         4788.56
3           Buoyancy         15247.97          Buoyancy        24319.97
4      Skin friction           741.94     Skin friction         1337.87
5               Lift           305.86              Lift          305.86
6           Friction         11562.66          Friction        13155.79
7            Inertia          3697.90           Inertia         5898.02
8    Vertical forces        -19271.09   Vertical forces       -21926.31
9  Horizontal forces         -3854.21 Horizontal forces        -1131.34
         Moments  At time = 1 yrs         Moments  At time = years yrs
0   Gravity(dry)        -19576.95   Gravity(dry)             -22232.17
1   Gravity(wet)           161.08   Gravity(wet)                201.35
2        Inertia        -34824.92        Inertia             -46552.14
3           Drag          1941.13           Drag               3111.59
4       Buoyancy          1953.72       Buoyancy               2835.38
5           Lift         15247.97           Lift              24319.97
6  Skin friction           305.86  Skin friction                305.86
7       Friction           404.56       Friction                743.38
Required minimum area of reinforcing steel (FE500b) Area:0.00021386 m^2
1
Structural integrity = True 48634.73119104253
Structural integrity factor 33.9127225080338
```

```
Oyster_area 5.152211951887261
Facilitated upward facing oyster area Area:5.15 m^2
Total mass structure (in air) Mass:3070.71 kg
             Forces  At time = 1 yrs             Forces  At time = 5 yrs
0      Gravity(dry)         32767.87       Gravity(dry)         44400.68
1      Gravity(wet)         18371.65       Gravity(wet)         21005.50
2              Drag          3122.50               Drag          4636.25
3          Buoyancy         14396.22           Buoyancy         23395.18
4     Skin friction           735.77      Skin friction          1327.74
5              Lift           305.86               Lift           305.86
6          Friction         10839.48           Friction         12419.78
7           Inertia          3491.34            Inertia          5673.75
8   Vertical forces        -18065.80    Vertical forces        -20699.64
9 Horizontal forces         -3489.87  Horizontal forces          -782.04
         Moments  At time = 1 yrs        Moments  At time = years yrs
0   Gravity(dry)        -18371.65   Gravity(dry)           -21005.50
1   Gravity(wet)           159.22   Gravity(wet)              199.03
2        Inertia        -32767.87        Inertia           -44400.68
3           Drag          1786.64           Drag             2916.76
4       Buoyancy          1855.20       Buoyancy             2725.22
5           Lift         14396.22           Lift            23395.18
6  Skin friction           305.86  Skin friction              305.86
7       Friction           397.55       Friction              731.05
Required minimum area of reinforcing steel (FE500b) Area:0.00021241 m^2
1
Structural integrity = True 48308.04953736634
Structural integrity factor 34.14205621899261
```

C Appendix C: Scour protection location

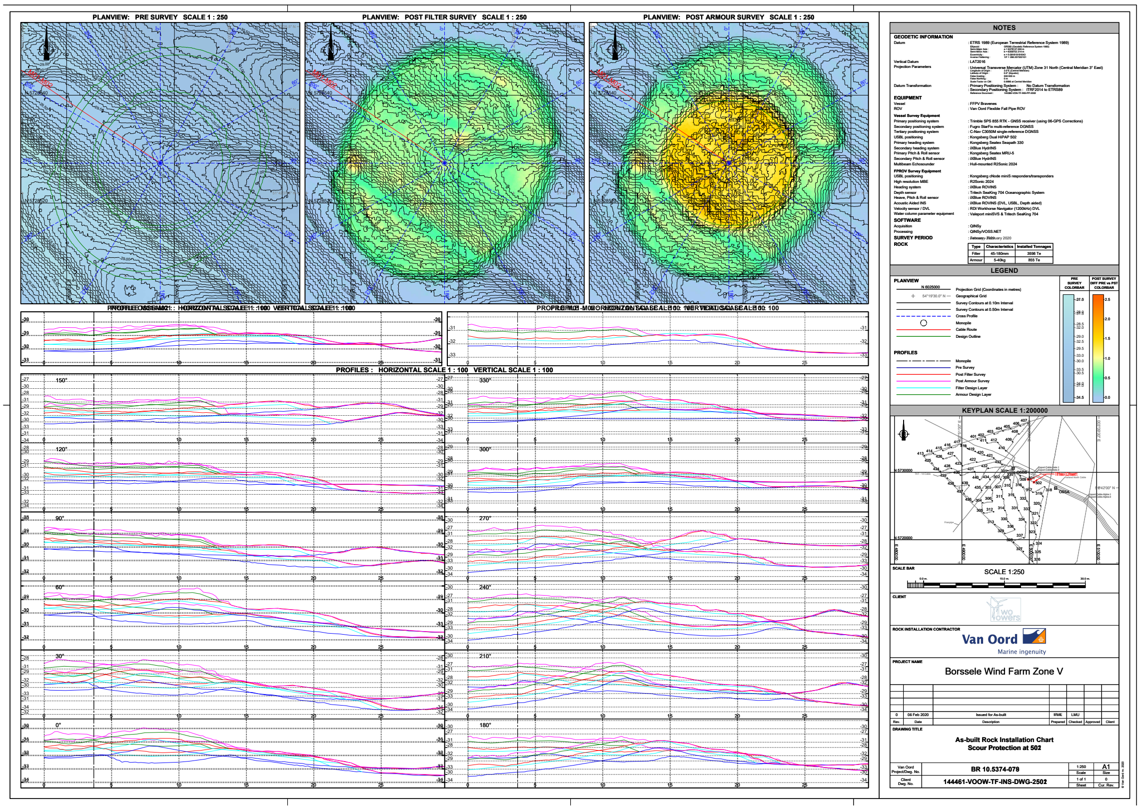


Figure C.20: As-built chart of the scour protection for WTG 501 after construction(Van Oord, 2020b)

Figure C.21: As-built chart of the scour protection for WTG 502 after construction (Van Oord, 2020c)

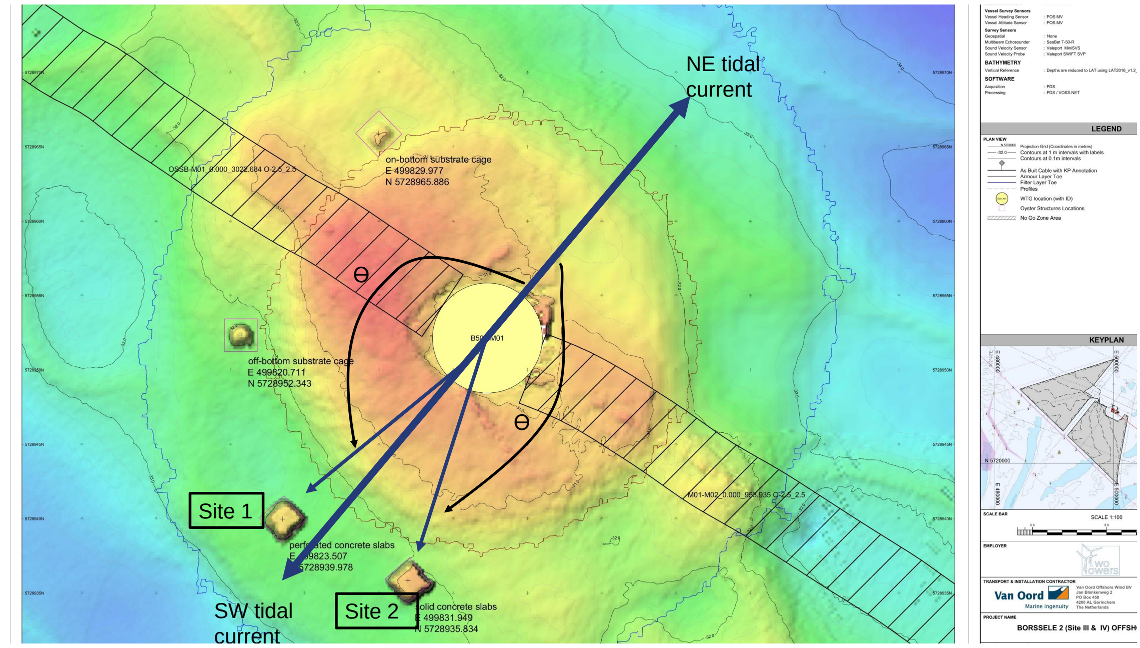


Figure C.22: As built multi beam imagery of the placed structures on Borssele site V. Obtained from Van Oord, 2020a

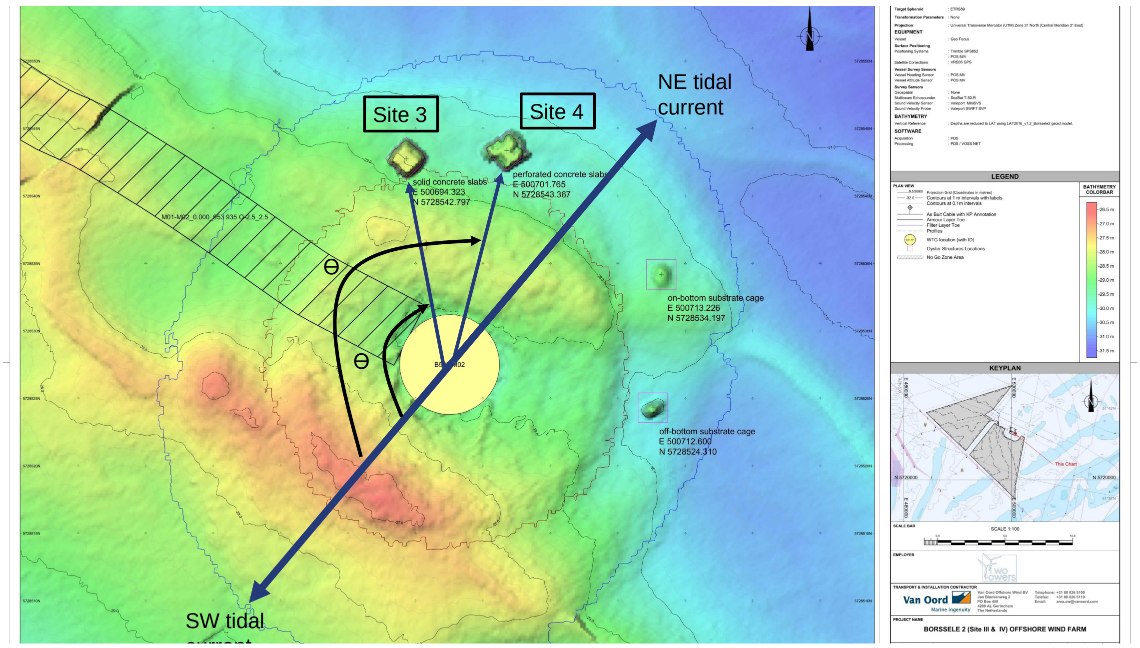
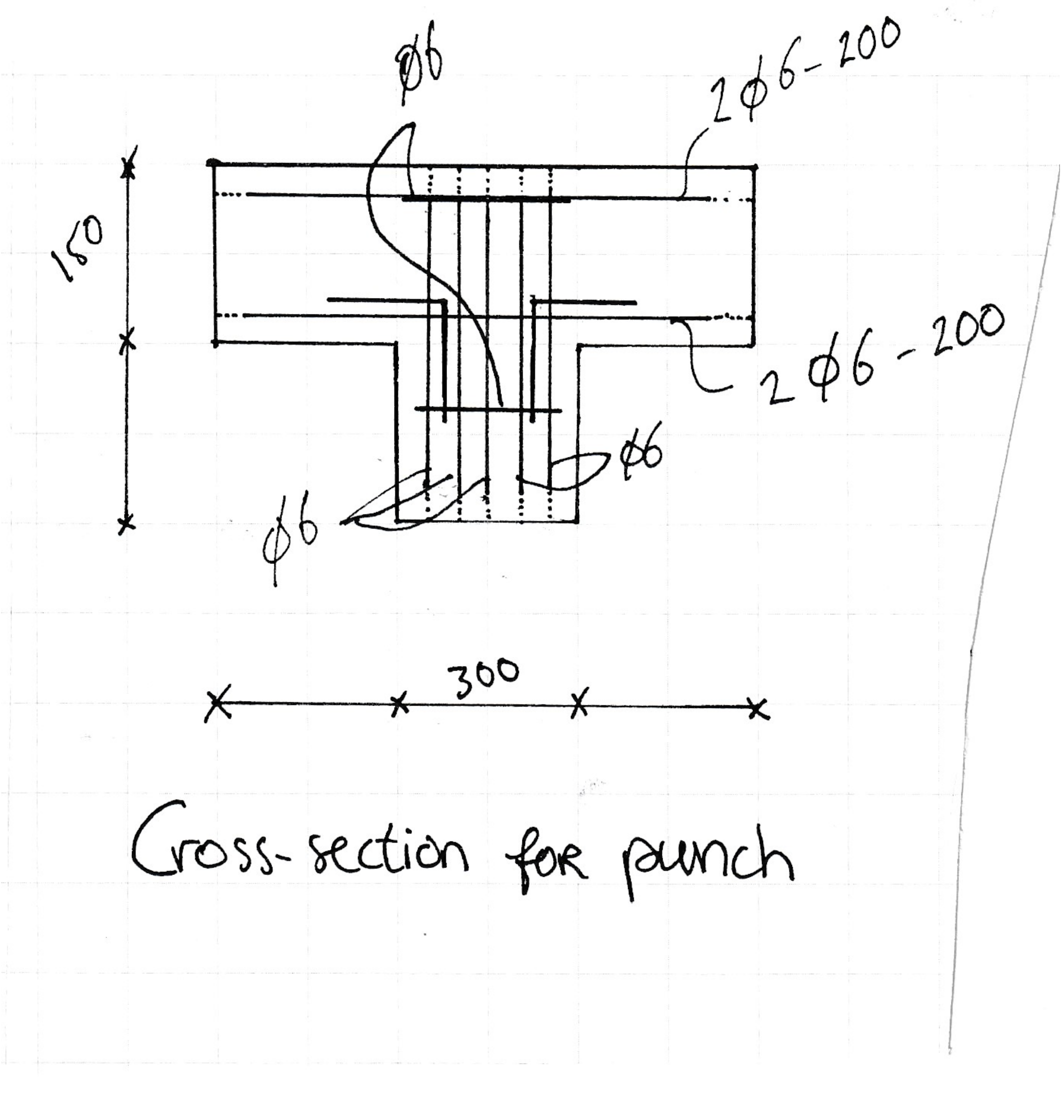


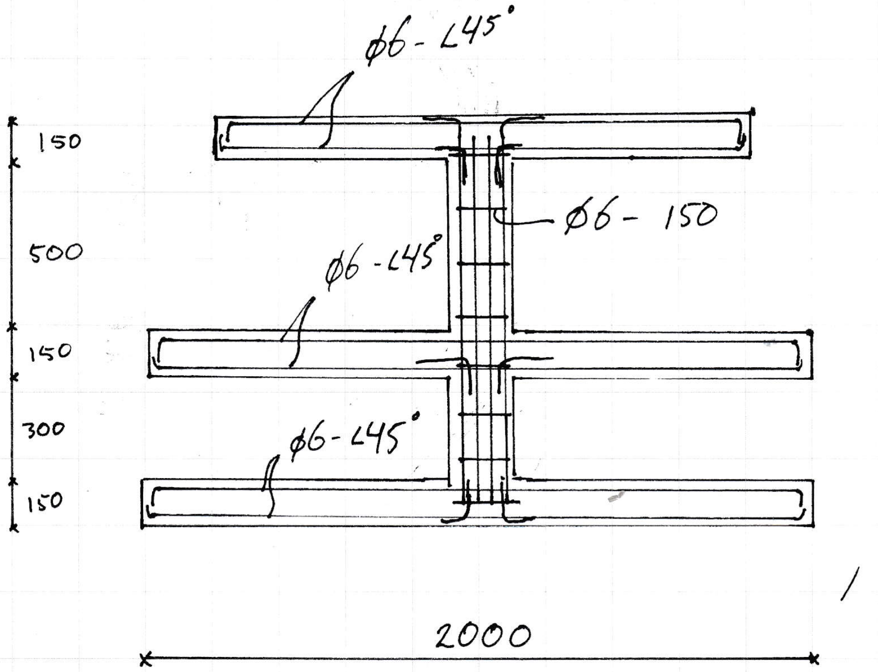
Figure C.23: As built multi beam imagery of the placed structures on Borssele site V. Obtained from Van Oord, 2020c

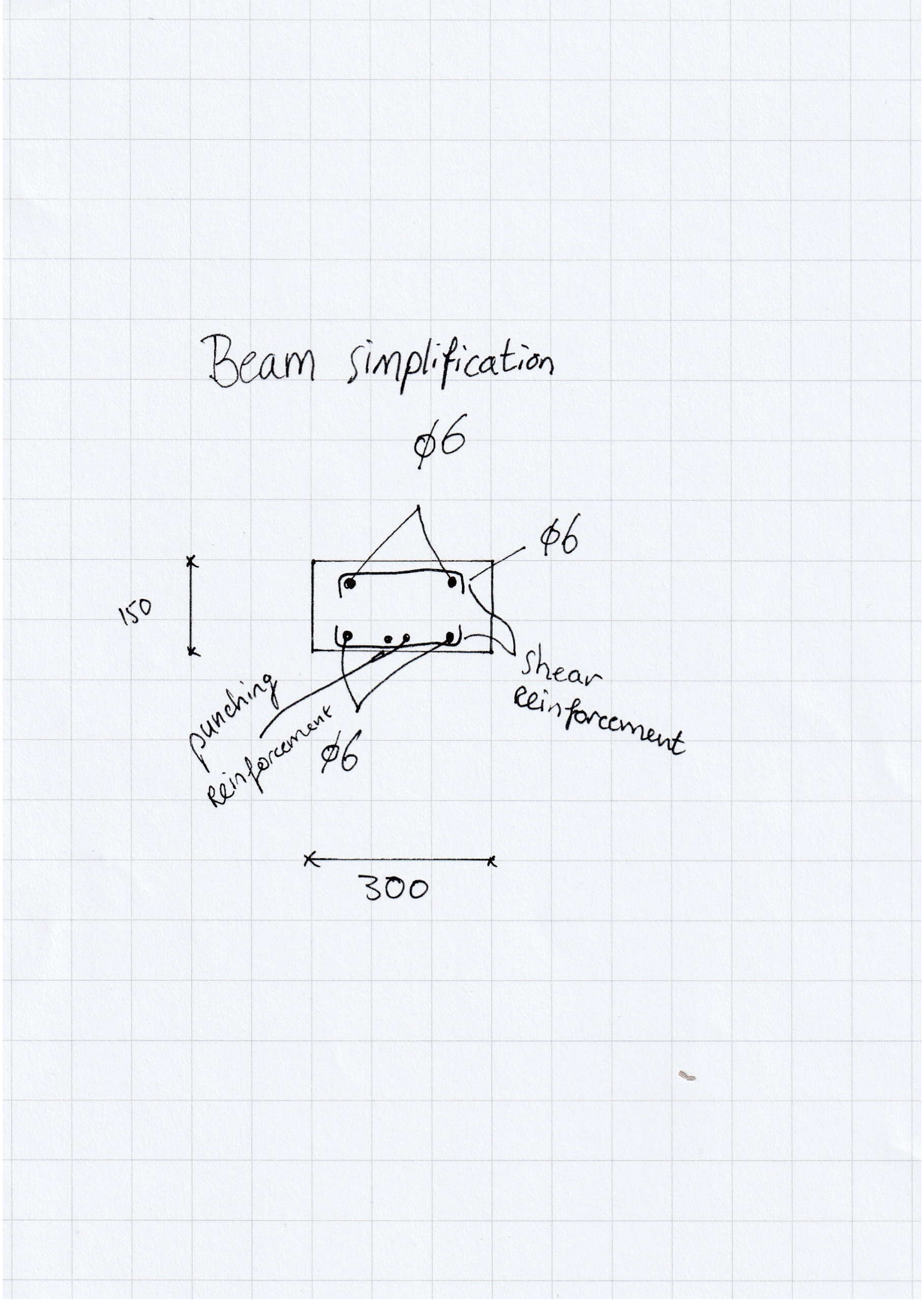
D Appendix D: Structural design calculations & drawings

D.1 Reinforcing steel drawings

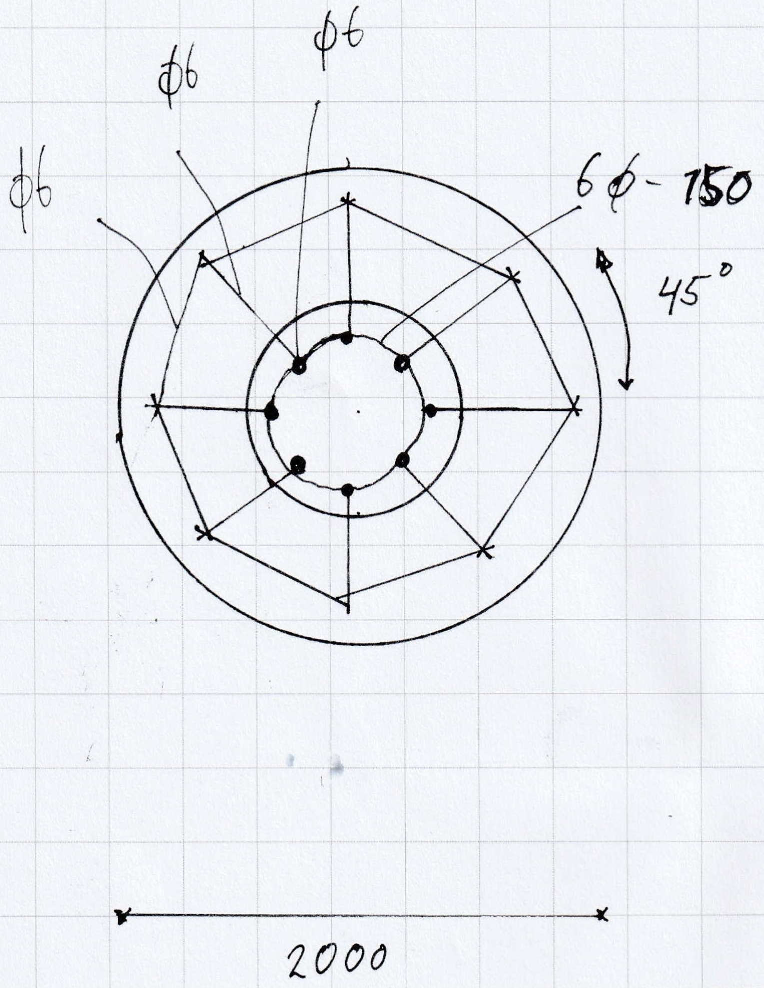


Cross-section of structure




Beam simplification
ϕ6
ϕ6
150
punching
Reinforcement
ϕ6
Shear
Reinforcement
300

Cross-section of a plate



E Appendix E: Validation Econstruct tool

Parameter	Value	Parameter	Value
Radius	1m	Height	1m
Fouling rate	0.0025 m/yr	μ	0.5
H_{max}	6m	C_d	0.7
C_l	0.01	C_a	1.57
C_f	0.00658	ρ_f	1325kg/m^3
ρ_s	2500 kg/m^3	ρ_w	1025 kg/m^3
α	0	ϕ	0

Table 1: Inputs used in validation of disk module

Forces	At time =1 yr
Gravity(dry)	77457 N
Gravity(wet)	45550.8 N
Drag	1720.75 N
Buoyancy	31906.4N
Skin friction	101.41 N
Lift	38.3 N
Friction	6803.05 N
Inertia	12920 N
Moments	**At time =1 yr**
Gravity(dry)	-77650 Nm
Gravity(wet)	-45664.7 Nm
Drag	860.4 Nm
Buoyancy	31986.1Nm
Skin friction	50.7 Nm
Lift	-38.3 Nm
Friction	0 Nm
Inertia	6460 Nm

Figure E.24: Results manual calculations unit disk validation

Forces	At time =1 yr
Gravity(dry)	77457.19 N
Gravity(wet)	45550.81 N
Drag	1720.75 N
Buoyancy	31906.38 N
Skin friction	101.41 N
Lift	38.33 N
Friction	6803.05 N
Inertia	12920 N
Moments	**At time =1 yr**
Gravity(dry)	-77650.93 Nm
Gravity(wet)	-45664.68 Nm
Drag	860.38Nm
Buoyancy	31986.1 Nm
Skin friction	50.7 Nm
Lift	-38.4 Nm
Friction	0 N
Inertia	6460 N

Figure E.25: Results Econstruct calculations unit disk validation

Parameter	Value	Parameter	Value
Width	1m	Height	1m
Length	1m	U_{amp}	1.5 mm/s
Fouling rate	0.0025 m/yr	μ	0.5
U_{top}	2.5 m/s	C_d	1.0
C_l	0.01	C_a	1.005
C_f	0.00775	ρ_f	1325kg/m^3
ρ_s	2500 kg/m^3	ρ_w	1025 kg/m^3
α	0	ϕ	0

Table 2: Input used for the validation of the unit block

Forces	At time =1 yr
Gravity(dry)	24720.95 N
Gravity(wet)	14514.1 N
Drag	3235.26 N
Buoyancy	10206.83N
Skin friction	75.1 N
Lift	32.3 N
Friction	7241.2 N
Inertia	3129.16 N
Moments	At time =1 yr
Gravity(dry)	-12360.5 Nm
Gravity(wet)	-7257 Nm
Drag	1617.6 Nm
Buoyancy	5103.02Nm
Skin friction	50.06 Nm
Lift	16.02 Nm
Friction	0 Nm
Inertia	1564.6 Nm

Figure E.26: Results manual calculations unit block validation

Forces	At time =1 yr
Gravity(dry)	24720.95 N
Gravity(wet)	14514.12 N
Drag	3235.24 N
Buoyancy	10206.83 N
Skin friction	100.12 N
Lift	32.03 N
Friction	7257.06 N
Inertia	3129.16 N
Moments	At time =1 yr
Gravity(dry)	-12360.48Nm
Gravity(wet)	-7257.06 Nm
Drag	1617.62 Nm
Buoyancy	5103.42 Nm
Skin friction	50.06 Nm
Lift	16.02 Nm
Friction	0 Nm
Inertia	1564.58 Nm

Figure E.27: Results Econstruct calculations unit block validation

Parameter	Value	Parameter	Value
Radius	1m	Height	1m
Fouling rate	0.0025 m/yr	μ	0.5
H_{max}	6m	C_d	0.7
C_l	0.01	C_a	1.57
C_f	0.00658	ρ_f	$1325 kg/m^3$
ρ_s	2500 kg/m^3	ρ_w	1025 kg/m^3
α	0	ϕ	0

Table 3: Input used in disk assembly validation

Forces	At time =1 yr
Gravity(dry)	154709 N
Gravity(wet)	910558 N
Drag	7343.71 N
Buoyancy	63654.03N
Skin friction	325.40 N
Lift	81.99 N
Friction	45486.58 N
Inertia	17912.31 N
Moments	At time =1 yr
Gravity(dry)	-155096 Nm
Gravity(wet)	-91282.8 Nm
Drag	7334.6 Nm
Buoyancy	63813.2 Nm
Skin friction	271.2 Nm
Lift	82.2 Nm
Friction	0 N
Inertia	17890 N

Figure E.28: Results manual calculations disk assembly validation

Forces	At time =1 yr
Gravity(dry)	154709 N
Gravity(wet)	910558 N
Drag	7343.71 N
Buoyancy	63654.03N
Skin friction	325.40 N
Lift	81.99 N
Friction	45486.58 N
Inertia	17912.31 N
Moments	At time =1 yr
Gravity(dry)	-155095.95 Nm
Gravity(wet)	-91282.79 Nm
Drag	7334.56 Nm
Buoyancy	63813.16 Nm
Skin friction	271.17 Nm
Lift	82.19 Nm
Friction	0 N
Inertia	17889.98 N

Figure E.29: Results Econstruct calculations disk assembly validation

Parameter	Value	Parameter	Value
Width	1m	Height	1m
Length	1m	U_{amp}	1.5 mm/s
Fouling rate	0.0025 m/yr	μ	0.5
U_{top}	2.5 m/s	C_d	1.0
C_l	0.01	C_a	1.005
C_f	0.00775	ρ_f	$1325 kg/m^3$
ρ_s	2500 kg/m^3	ρ_w	1025 kg/m^3
α	0	ϕ	0

Table 4: Input used for the validation of the block assembly

Forces	At time =1 yr
Gravity(dry)	49376.26 N
Gravity(wet)	29013.37 N
Drag	6452.4 N
Buoyancy	20362.08N
Skin friction	150.3 N
Lift	32.03 N
Friction	14490.49 N
Inertia	6242.8 N
Moments	**At time =1 yr**
Gravity(dry)	-49376.26 Nm
Gravity(wet)	-29013.37 Nm
Drag	6446.33 Nm
Buoyancy	20362.89 Nm
Skin friction	124.96 Nm
Lift	32.03 Nm
Friction	0 N
Inertia	6234.97 N

Figure E.30: Results manual calculations block assembly validation

Forces	At time =1 yr
Gravity(dry)	49376.26 N
Gravity(wet)	29013.37 N
Drag	6454.38 N
Buoyancy	20362.89 N
Skin friction	150.05 N
Lift	32.03 N
Friction	14490.67 N
Inertia	6242.75 N
Moments	**At time =1 yr**
Gravity(dry)	-49376.26 Nm
Gravity(wet)	-29013.37 Nm
Drag	6446.33 Nm
Buoyancy	20362.89 Nm
Skin friction	124.96 Nm
Lift	32.03 Nm
Friction	0 N
Inertia	6234.97 N

Figure E.31: Results Econstruct calculations block assembly validation

F Appendix F: QR code Github

Econstruct tool

If the tool has not yet been made public in Github, you can access the tool by signing up to Github and requesting access to the tool. https://github.com/TUDelft-CITG/Stability_Oyster_Structure