Delft University of Technology

Nature enhancing opportunities for an artificial North Sea island

Opportunity study for the Dogger Bank

Master thesis
G. Frölke

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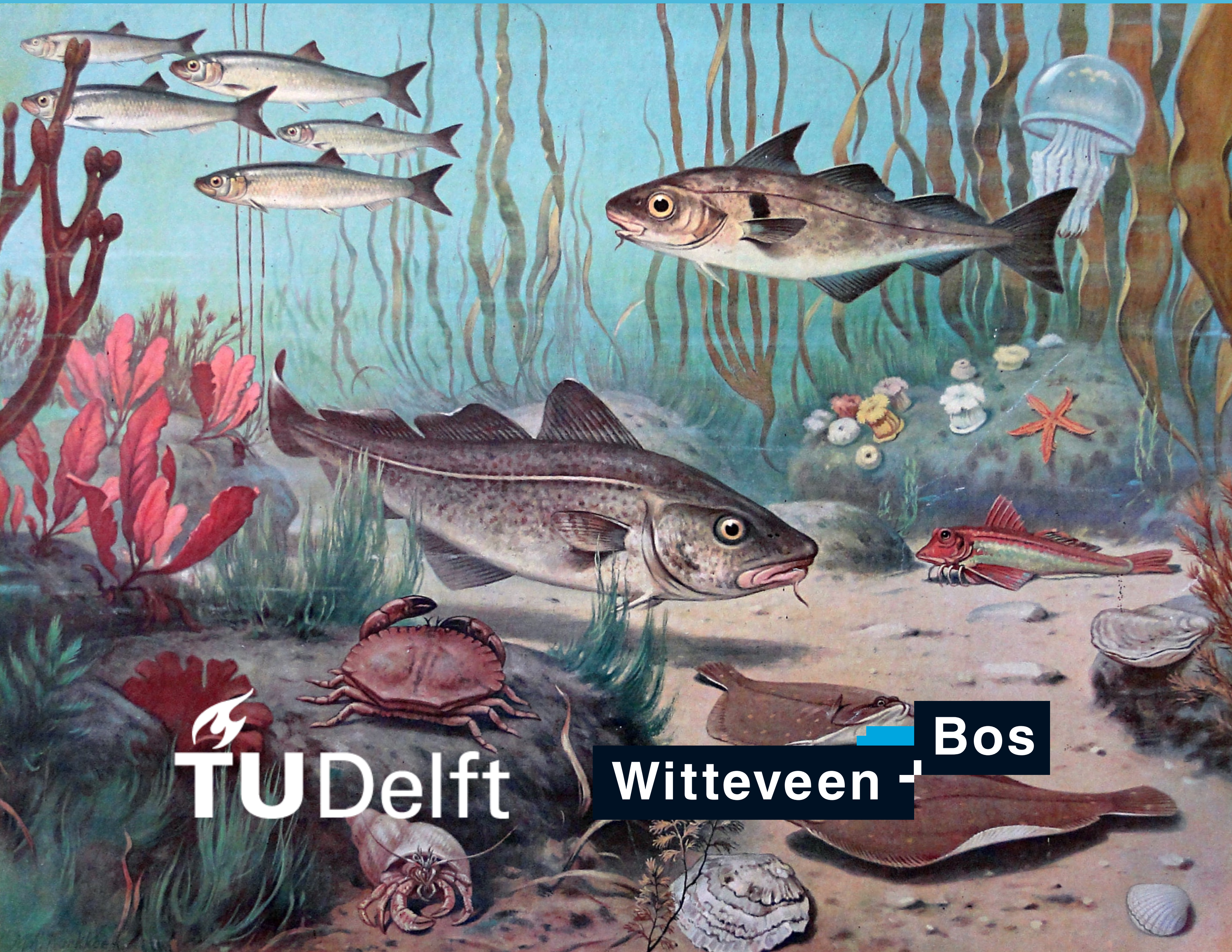

Nature enhancing opportunities for an artificial North Sea island

OPPORTUNITY STUDY FOR THE DOGGER BANK

By
Guus Frölke

Student number: 4189639

in partial fulfilment of the requirements for the degree of

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in Civil Engineering

Graduation committee:

Prof. Dr. Ir. S.G.J. Aarninkhof	TU Delft, Faculty of Civil Engineering and Geosciences *Section: Coastal Engineering*
Ir. E.J. van Druten	Witteveen+Bos *Group: Energy- and sustainable development, Deventer*
Dr. E.J. Houwing	TU Delft, Faculty of Civil Engineering and Geosciences *Section: Integral Design and Management*
Ing. C. Kuiper	TU Delft, Faculty of Civil Engineering and Geosciences *Section: Coastal Engineering*

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Cover image: “In de Noordzee” North Sea school plate from Marinus Adrianus Koekkoek
(Source: Pinterest)

Preface

This thesis reports on my graduation work for the master program Hydraulic Engineering at the Delft University of Technology. The work is part of the innovation hub, a group of students who are given the space to study the possibilities of an energy island in the Dogger Bank. The island can be an important link in the transition into sustainable energy and a small step in the reversal of ecological declination of the North Sea. The North Sea used to be a more biodiverse landscape, as shown on the cover page, but has turned into an underwater 'desert'. I sincerely hope my contributions will form a small step towards the recovery of the historic North Sea ecology around new future structures in the North Sea.

I would like to thank Witteveen+Bos, for allowing and facilitating me to conduct this research. It has provided a pleasant environment with expertise and helpful colleagues. Witteveen+Bos provided the opportunity for an innovation hub, of which I like to thank the members (Stefan Gerrits & Lucas de Vilder) for their discussion and help.

There are several persons I would like to express my gratitude towards for their contribution in this thesis. I would like to thank all members in the committee for their time and support in the search for the right direction in my research and for the feedback I received. To Emiel van Druten, who started the innovation hub, for his continuous enthusiasm and fascination for new developments in the field of sustainable energy. Thanks to Coen Kuiper who had time when I had specific question about coastal structures. Erik-Jan Houwing for his feedback and contacts and Stefan Aarninkhof for his feedback and his enthusiastic ideas about Building with Nature possibilities. Furthermore, I would like to thank the ecologists of Witteveen+Bos, Wouter Gotjé and Ivana Prusina, who helped me to elevate the ecological sections of my thesis to a higher level.

Also, I would like to thank my friends and the students at Witteveen+Bos for the necessary distraction, grammar checking and help during my thesis. The people around me who brought my student time to a higher level. And to conclude this preface, I would like to thank my parents, who were always supporting me and gave me the chance to have a very pleasant study time.

Guus Frölke
Rotterdam, January 2018

Samenvatting

Om de klimaat doelstellingen uit het Parijs-akkoord te bereiken is een energietransitie noodzakelijk. Hernieuwbare energie in de vorm van windenergie op de Noordzee is een van de oplossingen om hernieuwbare energie op te wekken. Een centraal gelegen zandbank in de Noordzee biedt ruimte voor grote windparken (mogelijk tot 100-200 GW). Deze zandbank genaamd de Doggersbank, heeft door de relatief ondiepe ligging en goede wind condities veel potentie. Om de energiewinning op zee te optimaliseren is de bouw van een eiland gewenst. Hiermee ontstaan mogelijkheden om de energie om te vormen naar gelijkstroom, en de bouw en het onderhoud van de windmolens goedkoper te maken.

De Doggersbank is echter een waardevol natuurgebied, en onderdeel van een Natura2000 gebied, waarvoor strenge wetgeving geldt. Om de realisatie van het eiland kansrijker te maken is het nodig de mogelijkheden voor natuurontwikkeling uit te werken.

In deze scriptie wordt verkend op welke wijze de aanleg van het eiland kan worden gecombineerd met het creëren van mogelijkheden voor de vestiging van natuurwaarden. Dit wordt uitgewerkt voor de kustdwarsprofielen. De exacte locatie en de vormgeving van het eiland zijn hierbij buiten beschouwing gelaten.

De gewenste natuurontwikkeling wordt in deze scriptie bepaald door een doelsoort: de platte oester (*Ostrea edulis*). Deze soort is gekozen omdat het een omgeving creëert waarvan een grote groep andere soorten kan profiteren. Het verdwijnen van de huidige ecologie door het bouwen van een eiland kan worden opgevangen door het herstellen van een oester habitat. Deze habitat is door menselijk toedoen over de afgelopen 130 jaar verdwenen.

De vestiging en handhaving van de platte oester is afhankelijk van een aantal abiotische en biotische factoren. De aanleg van het eiland heeft vooral effect op de abiotische factoren. De biotische factoren zijn buiten beschouwing gelaten binnen deze studie. Abiotische factoren op de Doggersbank zijn met name de golfhoogte en het getij, en daarmee de schuifspanning op de bodem. Om de gewenste randvoorwaarden voor succesvolle oesterriffen te bepalen, is onderzoek gedaan naar de relatie tussen de bodem schuifspanning en de historische aanwezigheid van oesterbanken. Dit is getransformeerd naar de gemiddelde en maximale bodem schuifspanning waaronder oester riffen succesvol kunnen zijn. De gemiddelde schuifspanning bleek daarbij een sterkere bepalende factor dan de extreme schuifspanning te zijn. Bovendien is hard substraat van belang voor de initiële vestiging van oesters, welke een harde ondergrond prefereert.

De randvoorwaarden voor succesvolle oesterbedden worden vergeleken met de aanwezige omstandigheden op verschillende locaties in het kustdwarsprofiel. Zo kunnen potentiele locaties voor oesterbedden worden gevonden of zo nodig worden gecreëerd in het kustprofiel. Voor het kustprofiel zijn de fysieke 1:10,000 jaar omstandigheden gekozen terwijl oesterriffen minimaal 1 op 10 jaar condities moeten weerstaan. Bij het ontwerpen van de kustverdediging van het eiland

zijn de volgende factoren bepalend gebleken voor succesvolle oesterriffen: de oriëntatie van de kustbescherming, de diepte, de profielen (zoals de aanleg van een rif of vooroever) en het gekozen materiaal.

De fysieke omstandigheden rondom het eiland vragen om verschillende soorten kustbescherming. Een hard kustprofiel lijkt door het aanwezige golfklimaat voor de hand te liggen. Voor de profielen is de kans voor oesterriffen rondom het eiland alleen aanwezig bij het diepste gedeelte van het profiel. Onder een diepte van 25.0 meter en met de aanwezigheid van hard substraat zijn alleen de teen en het onderste gedeelte van het talud beschikbaar voor oesterbanken. Het geschikte oppervlak kan worden vergroot door het aanbrengen van een vooroever van hard substraat. Een voorwaarde daarbij is wel dat de vooroever dieper dan 25.0 m onder gemiddeld zeeniveau ligt. Een andere optie die de vestigingslocatie voor oesters kan vergroten is een rif voor de kust, die een luwte creëert waar oesterriffen kunnen groeien. Dit rif kan oesterbedden mogelijk maken op dieptes waar dat voorheen niet kon. Dit kan aantrekkelijk zijn wanneer het eiland op een locatie ondieper dan 25.0 m onder gemiddeld zeeniveau wordt gebouwd of als het oester oppervlak groter dient te zijn. De hoogte van het rif wordt bepaald door de zijde van het eiland en de diepte tot waar oesters gewenst zijn. Voor de hoogte van het rif is het belangrijk dat een zekere mate van golf en getijde werking doordringt tot achter het rif om de toevoer van nutriënten voor oesters te garanderen. De luwte achter het rif zal moeten worden uitgerust met materiaal waarop oesters kunnen vestigen.

Gegeven de gevonden resultaten voor de twee-dimensionele doorsnede lijken maatregelen in het drie-dimensionele domein een effectief middel. Door het inzetten van riffen kunnen kalmere zones (luwten) gegenereerd worden die gunstig kunnen zijn voor oester riffen. Het ontwerp en de driedimensionale consequenties van de huidige tweedimensionale aanbevelingen worden aanbevolen om verder te onderzoeken, net als de mogelijke driedimensionale maatregelen. Daarnaast zullen de biotische factoren en het initiëren van oesterbanken verder moeten worden onderzocht om meer informatie te verkrijgen voor succesvolle oesterbedden rondom een eiland op de Doggersbank.

Abstract

Wind energy from the North Sea is one of the solutions to achieve the climate goals of the Paris agreement. A centrally located sandbank in the North Sea offers space for large wind farms (possibly up to 100-200 GW). This sandbank, called the Dogger Bank, has a lot of potential due to the relatively shallow location and good wind conditions. To optimise energy production at sea, the construction of an island is desirable. The island creates opportunities to convert the alternating energy into direct current, and to make the construction and maintenance of the windmills cost-effective.

The Dogger Bank, however, is part of Natura2000 area, for which strict legislation applies. To make the realisation of the island more promising it is necessary to work out the possibilities for nature development. This thesis explores how the construction of an island can be combined with the creation of natural values. This is worked out for the coastal cross-sections. The exact location and design of the islands contour have not been taken into account.

The desired nature development is represented in this thesis by a target species that represents the needs of a broader group of species. The flat oyster (*Ostrea edulis*) has been chosen as an umbrella species, a species that creates an environment in which a large group of other species can benefit. The disappearance of the present ecology by building an island can be counteracted by restoring an oyster habitat. This habitat has disappeared through human intervention over the past 130 years.

The settlement and conservation of the flat oyster depends on a number of abiotic and biotic factors. The construction of the island mainly affects the abiotic factors. The biotic factors have been left out of consideration. Abiotic factors on the Dogger Bank are in particular the wave height and the tide, and subsequently the shear stress on the bottom. To obtain the boundary conditions for a successful oyster bed, research was done into the relationship between the bed shear stress and the historic presence of oyster beds. This has been translated to the average and maximum bed shear stress that is sustainable for oyster beds. The average shear stress proved to be a more governing factor than the extreme and critical shear stress. Moreover, the substrate is important for the initial establishment of oysters, which prefers a hard surface.

The boundary conditions for successful oyster beds are compared with the conditions present at different locations in the coastal cross-section. Potential locations for oyster beds can be found and, if necessary, created in the coastal cross-section. The 1:10,000 year conditions have been chosen for the coastal profile design, while oyster beds must withstand at least 1 in 10 years wave conditions. In designing the coastal cross-sections of the island, the following factors have been found decisive for the success of oyster beds: the orientation of the coastal protection, the depth, the profiles (including the presence of a reef) and the chosen material.

The orientation of the physical conditions around the island require different types of coastal protection. A hard coastal design seems evident due to the existing wave climate. For cross-sections at the most exposed side of the island the chance for oyster beds is only present at the

deepest part of the profile. The toe and lower part of the cross-shore slope are available for oyster beds, as they are situated at a depth of 25.0 meters below MSL and provides the (required) hard substrate. The suitable surface can be increased by applying a foreshore of hard substrate. One of the requirements is that the foreshore is deeper than 25 m below MSL at the most exposed side. At the sheltered side of the island, a depth of -16 m MSL was found to be acceptable. Another option is to increase the surface for oysters with an offshore reef, creating a lee where oyster beds can grow. An offshore reef could make oyster beds viable at depths which were not found to be suitable previously. This can be attractive when an island is being built at shallower locations or when the desired oyster surface should be increased. The height of the reef is determined by the orientation of the cross-section and the depth at which oysters are desired. For the height of the reef it is important that a certain number of waves and tidal effects penetrates behind the reef for the supply and recirculation of nutrients for oysters. The leeside behind the reef will have to be equipped with some form of hard substrate on which oysters can settle.

Given the results found for the two-dimensional profiles, three-dimensional measures seem to be effective. Using reefs to attenuate waves which limit the success of oyster reef can be used to create a sheltered leeside. The design and three-dimensional consequences of the earlier stated two-dimensional measures are recommended to research into more detail. Just as the possible three-dimensional measures. In addition, the biotic factors and the method of initiation of oyster beds will have to be further investigated to obtain more information about successfully creating oyster beds around an island on the Dogger Bank.

Chapter Index

1.

Introduction

In this chapter, the subject of the thesis is introduced and the relevance of the study addressed. The chapter starts with a motivation for research, together with a brief introduction to the concept for a North Sea energy island. Next to that, a problem analysis is given in subsection 1.2. Subsequently, the objectives and research questions are discussed in 1.3, followed by the methodology, for answering these questions and the scope of this study in 1.4. Finally, the outline of this report is presented in 1.5.

1.1 Motivation for research

The world faces an increasing average global temperature, causing ocean warming, diminishing of ice caps and snow and sea level rise (IPCC, 2013). The largest contributor of temperature change is the increased CO_2 concentration. Climate change is perceived a serious threat, causing countries to cooperate more closely and sign treaties, such as most significantly the Paris Agreements (2015). This treaty aims to limit the global increase in temperature to 2°C (European

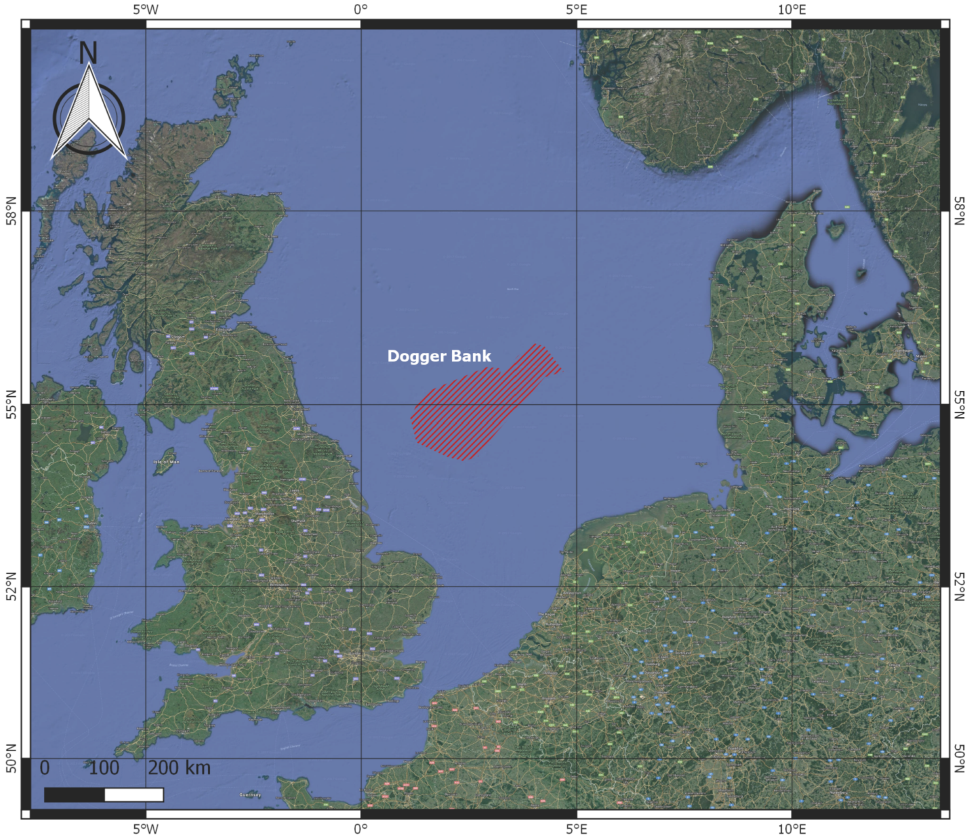


Figure 1: Location Dogger Bank, adjusted in Qgis.

Commission, 2017). Several strategies exist to reach this goal, one of which is sustainable energy provision with low carbon emissions. The European Union, whose members all agreed upon the Paris-agreement, has developed more specific goals to reduce the impact climate change. The EU aims for 20% fewer greenhouse gasses in 2020 and an 80-85% reduction in 2050 (European Commission, 2017). EU scenarios expect that, to reach these goals, offshore wind is an important sustainable energy source. More specifically, the North Sea is expected to have potential for 100-200 GW from wind energy (Tennet, 2017a).

To ensure long term growth of wind energy on seas as the North Sea, the Dogger Bank is regarded as an area with large potential for the development of wind mill farms, by energy companies (Forewind, 2010). The Dogger Bank is a sandbank in the English, Dutch, German and Danish Exclusive Economic Zone (EEZ), see Figure 1. This sandbank has positive annual mean wind resources (>10m/s), relatively shallow North Sea water depths (16-40m) and coarse sand ground conditions. It was Tennet, a Dutch Transmissions System Operator (TSO), that developed the idea to create an island on the Dogger Bank. This because an island offers the opportunity to install offshore windfarms under favourable nearshore conditions, which will reduce costs (Gerrits, 2017). The island could add substantial benefits in reducing energy losses, maintenance- and installing activities and improves the accessibility of the windfarms (Tennet, 2017b).

Furthermore, an island has space for multiple high-voltage direct-current (HVDC) converters. These plants are necessary to convert alternating current (AC) from the windmills to direct current (DC), reducing the loss of energy over long distances. By constructing an island, several offshore HDVC converters could be located central, providing enough conversion capacity for all future wind farms on the Dogger Bank. Maintenance of the wind farm and the related infrastructure could be centralised and for the continuous maintenance, permanent residences could be created. Moreover, an airport could reduce transport costs significantly. Besides, to reaches the windmills, a port at the island is constructed, which also could be the hub for construction ships required to build the turbines.

However, the construction of an artificial island will result in the disappearance of a section of nature the size of the island footprint. To clarify, the construction of an artificial island transforms a marine ecological system into a coastal ecological environment. It will impact the waves, currents and the sand ripples moving across the Dogger Bank, undoubtedly having consequences for the local ecosystem.

Currently, the Dogger Bank has some unique features due to its central and elevated location in the North Sea, which would be lost after the construction of an island. The Dogger Bank acts as a stepping stone for several species of similar habitats in other North Sea coastal areas (Van Moorsel, 2011). The Dogger Bank creates a border between the northern (with Arctic elements) and southern (influenced by the Channel region) North Sea conditions and species, where both species overlap on the sandbank (Jak, Bos, Witbaard, & Lindeboom, 2009). The unique features of the sandbank and the variety of species was reason for Germany to introduce the Dogger Bank as a Natura2000 site in 2004, for the Netherlands in 2008 and in the United Kingdom in 2010. Natura2000 regulations makes construction of a structure such as an island on the Dogger Bank without consideration for nature objectives impossible (Gerrits, 2017; Stolk, 2017). For projects that could cause significant environmental disturbance in a Natura2000 area an evaluation has to be made concerning the consequences the project has on the Natura2000 nature (Sundseth, 2008). When effects on the conservation goals are expected, the project could only continue when there are no other alternatives and it is considered vital for the public interest or when compensation in the form of new natural areas is available.

However, in the North Sea, historical natural values at the North Sea decreased during the last century (Coolen, 2017). Species as oysters, rays and long living molluscs disappeared or amounts decay and habitats at oyster beds and hard substrate disappeared largely. Due to human activity, like fishing, sand mining and eutrophication (in different degrees), the North Sea seabed and ecology has changed negatively (Kröncke, 2011). Building an artificial island has opportunities to enhance nature. To reduce the negative effects that the construction of an island will have on the environment, and to conform to the Natura2000 regulations, this thesis investigates opportunities to construct environments around the island that returns the aforementioned historical ecological value. This will be done within the coastal defences of such an island. In addition, approaches that reduce the consequences of building the island or even contributing to nature objectives should be identified. A nature inclusive design is essential to make realisation of the windfarm island feasible.

1.2 Problem analysis

First of all, a save coastal defence is necessary for a new artificial island. Within this objective, new or extra opportunities for nature enhancement are searched for. The Dogger Bank's habitat, which is conserved under the Natura2000 legislation is described as: 'Sandbanks which are slightly covered by sea water all the time' (Jak et al., 2009). 'Slightly covered by sea water all the time' means that above the sandbank the water depth is rarely more than 20 meters below Mean Sea Level (MSL). The surface of the envisioned island will beyond question change the protected habitat. However, the coastal profile around the island could create circumstances that conserve the Dogger Bank habitat.

Traditional approaches in civil engineering focus on minimising the negative impacts of infrastructure projects and compensating for any residual negative effects (De Vriend, H.J. and Van Koningsveld, 2012). With increasing pressure on ecosystems due to a growing world population, more 'pro-active' approaches are searched for. An example of such an approach is Building with Nature (BwN), which aims to be proactive, utilising natural processes and *providing opportunities for nature as part of the infrastructure development process*. The BwN approach tries to provide opportunities for nature. The main purpose is, however, to create a safe and stable island design. BwN is in this thesis not a goal in itself, though the guidelines are used to create value, to make the island more feasible.

At first, to provide opportunities for nature, it is necessary to understand what kind of Nature Based Design Elements (NBDE) could contribute to nature enhancing on the Dogger Bank. Furthermore, it is important to examine if the solutions are realistic on the island profile. Therefore, it is required to investigate the boundary conditions for the NBDE and the prevailing physical conditions around the Dogger Bank. After that, the NBDE boundary conditions are compared with the conditions found in the cross-sectional design, which result from the characteristics of the Dogger Bank physics. Finally, the measures which can change the conditions, in order to optimise the nature based design element, will be studied.

1.3 Objective and research question

To design a stable island coastal defence, which contributes to the North Sea ecology, it is researched how added value could be created to improve the North Sea ecology and to make the island licensable. Hence, the main objective of this thesis is to find opportunities in the design of an artificial island in the North Sea to create value for nature in the design. The main objective forms the basis for this research and is therefore translated into the main research question:

"Which nature enhancing opportunities can be identified in the design of an artificial island on the Dogger Bank?"

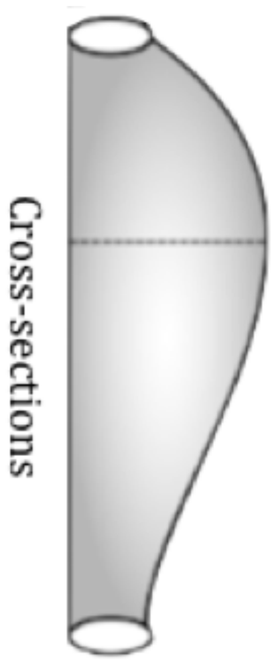
This main research question can be divided into the following sub-questions:

1. Are there Nature Based Design Elements for an energy island on the Dogger bank available?
2. What is a quantitative concept to find the applicability of the nature based design element?
3. Where can the nature based design element be applied and further optimised in the cross-sectional profile.

1.4 Research methodology & scope

This research is a conceptual design study for nature enhancing opportunities of a North Sea island. To answer the main question and its related sub questions, the following guidelines of the BwN methodology are used as guidance (Deltares, 2015). This thesis will focus on the first three steps of the BwN cycle (see Figure 2), so no elaborated optimisation will be done.

The first part of the BwN methodology prescribes to develop a deeper understanding of the system, tailored to the project objectives. To this end, this thesis will try to understand the main system by treating it in turn under three headings: (1) the physical system such as the hydraulic and geologic circumstances, (2) the stakeholders and (3) the ecological system. With these three headings the Nature Based Design Element could be determined, which can contribute to the nature enhancing of the island coastal defence.



1) Understand the system (including. ecosystem services, values and interests)
   - The system to be considered depends on the project objectives.
   - Information about the system at hand can/should be derived from various sources (historic, academic, local etc.)
   - Look for user functions and eco-system services beyond those relevant for the primary objective.
2) Identify realistic alternatives that use and/or provide ecosystem services.
   - Take an inverted perspective and turn traditional reactive perspectives into proactive ones utilising and/or providing ecosystem services
   - Involve academic experts, field practitioners, community members, business owners, decision makers and other stakeholders in the formulation of alternatives
3) Evaluate the qualities of each alternative and preselect an integral solution
   - More value does not necessarily imply higher construction cost
   - Dare to embrace innovative ideas, test them and show how they work out in practical examples
   - Perform a cost-benefit analysis including valuation of natural benefits
   - Involve stakeholders in the valuation and selection process
4) Fine-tune the selected solution (practical restrictions and governance context)
   - Consider the conditions/restrictions provided by the project (negotiable/non-negotiable)
   - Implementation of solutions requires involvement of a network of actors and stakeholders
5) Prepare the solution for implementation in the next project phase
   - Translate solution to a technical design
   - Prepare an appropriate request for proposals, terms of reference or contract (permitting)
   - Prepare risk analysis and contingency plans

Figure 2: BwN approach (source: Deltares, 2015)

The physical system will provide information regarding the external influences of the system on the design. The stakeholder analysis will describe all parties that have an interest in the Dogger Bank and the relevant legislation that applies here. The last part of the system description investigates the historical and present ecosystem of the Dogger Bank. This analysis showed that the construction of an island, as the foundation of windmills introduces a substrate which has been disappeared over the last 130 years. This hard substrate offers a habitat which could be beneficial for some North Sea species.

The habitats and typical species of the Dogger Bank are described of which subsequently an umbrella species is selected. An umbrella species represents the need for a group of other species (Lengkeek et al., 2017). The design should be optimised for the identified umbrella species, in order to provide nature enhancing on the Dogger Bank. The use of umbrella species makes the design of an optimised habitat for one or several species more understandable, instead of using a long list of species. Hence, use of the umbrella species concept could make a suitable design more conceivable for a non-specialist.

When the system is described and understood, the design approach will be defined. Here the system characteristics will be quantified into boundary conditions. The NBDE should be implemented in the design, therefore, a method where and how needs to be quantified. The physical system will provide quantified information regarding the Dogger Bank. The exact placement of the island on the Dogger Bank will not be specified in this assessment and thus the physical conditions will not be site specific. Instead, a wider range of conditions is searched for within the physics of the Dogger Bank.

Afterwards, the conditions umbrella species need for successful settlement will be identified. Subsequently, it will be discussed how the physics relate to and act on the design. For the design, only the cross-sectional plane is considered, three-dimensional effects will be neglected. This simplification is made to reduce the scope of this research and disregard broader effects of the physical elements on the island, such as wave refraction and sediment transport around the island.

When the design approach has been established, the possibilities of the NBDE in the design are discussed. The focus will be on providing opportunities for umbrella species. The oyster is a suitable umbrella species for this location, because it is a threatened species that creates a unique habitat and is of great value for nature enhancing. A traditional cross-section is reviewed and the potential areas for the umbrella species are pointed out. Next to that, measures are discussed to provide extra opportunities for successful settlement of oyster beds. First, for the side with the most extreme waves and later for the other directions. The 2-dimensional view is stretched to examine the possibilities in a 3-dimensional design of the island.

1.5 Report Outline

After the introduction, Chapter 2 will describe the system of the Dogger Bank. Information on physics, stakeholders and ecology will be collected to give a clear background for the other chapters. Taken this information into account, a solution will be chosen which will enhance nature around the island. Furthermore, this chapter will answer the first sub question whether the NBDE is available or not.

In Chapter 3 the design approach is outlined. Based on information and the selected NBDE of Chapter 2, it discusses how potential areas for umbrella species (flat oyster beds) can be found. This is done with the information concerning the system characteristics and the boundary conditions of the NBDE. The second sub-question will be answered at the end of this chapter, giving deeper insights on how to quantify the possibilities of the NBDE in the design.

Subsequently, Chapter 4 starts exploring the chances for umbrella species in the cross-sectional design. At first this will be done for a traditional geometry, after this with cross-sections extended with possible nature enhancing alternatives and finally for a cross-section orientated in different directions, with or without the discussed alternatives. After chapter 4 the last sub-question can be answered about where the NBDE can be applied and further optimised in the cross-section.

In Chapter 5, the discussion, the scope of this thesis is expanded to a wider perspective, outside the main research question. Considering the results in Chapter 4 it is explored what the three-dimensional opportunities and limitations are. Also, it is discussed what the present knowledge is regarding the contribution of oyster reefs to the coastal defence. Finally, Chapter 6 describes the conclusions concerning the available nature enhancing opportunities in the cross-sectional design, followed by some recommendations for further research.

2.

Dogger Bank characteristics

In this chapter a system description will be given regarding the Dogger Bank. To find out how nature could be enhanced around a potential Dogger Bank island, the physical and ecological conditions should be known. The physical system will have major influences on both the coastal defence design as on the ecological system. Secondly, the social system will be analysed. The stakeholders are listed, and their opinions and contradictions between groups of stakeholders will be discussed. Finding a method which will increase both ecological value for the North Sea and a more sustainable energy market, could optimise the island feasibility. Subsequently, the ecological system will be described examine what kind of nature is desired. From this information a NBDE will be selected, which enhances the nature around the island and could be implemented in the design. The NBDE is represented by umbrella species, the flat oyster, which boundary conditions are used during the designing process in the following chapters.

2.1 Physical system

2.1.1 Bathymetry

The Dogger Bank, centrally located in the North Sea, stretches from the southwest to the northeast over a length of 300 km (Van Moorsel, 2011). It is a shallow area blocking the deeper northern part of the North Sea with the southern shallower part. The Dogger Bank is the largest sandbank in the North Sea, where the exact sizes are discussed between 17,600 (Diesing et al., 2009) and 30,000 km^2 (Roberts, 2007), depending on the slope or depth criteria for the contour of the Dogger Bank. The sandbank covers a part of the continental flat of the UK, the Netherlands, Denmark and Germany. In the western part (in UK waters), the bank is the shallowest and widest, with depths up to 15 m MSL. The bank becomes narrow and get deeper towards the Danish part in the northeast. The majority of the bank is flat and has a depth between 25-30 m (Bridge, 2011).

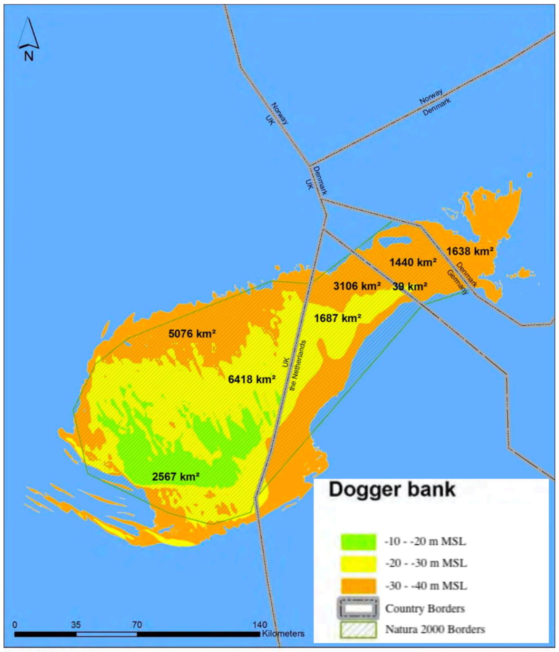


Figure 3: Bathymetry Dogger Bank (adjusted from Royal Hanskoning DHV, 2017)

2.1.2 Geomorphology

Geological history

During the Elsterian glaciations (750,000-675,000 BP) clay was deposited in the southern part of the North Sea. Erosion in later glaciations changed the profile of the Dogger Bank (Oele, 1969). The Dogger Bank was dry during the last glaciation (Weichsel glaciation, 30,000 BP) because the sea-level was much lower than in present times, approximately 100 meters below the actual level. The Dogger Bank formed the northwest coast (Russel & Stevens, 2014). At 18,000 BP a glacier from Scotland reached the east of the Dogger Bank, where it deposited stones and formed terminal moraines in the southeast part of the Dogger Bank. A landscape similar to the Utrechtse Heuvelrug (Netherlands). As the glaciers disappeared, sand was deposited and covered the Dogger Bank. During the same time, 9000 to 8000 BP, the sea level rose and the Dogger Bank became an island and got submersed later.

Present

Nowadays the islands top layer, above 30 m depth contours, has a sand fraction that does not reach below 94% (Sonnewald & Türkay, 2012). The sandy top of the Dogger Bank has a thickness of two meters at the upper side and a thickness of 0.5 meter at the edges (Oele, 1969). The centre of the Dogger Bank bottom has predominantly sediment with a particle size between 0.15 and 0.22mm, found by Gardline (2011) with particle analysis. Most of the seabed sand samples contain less than 5% gravel and less than 5% mud, and could be categorised as slightly gravelly sand. At the southeast edge of the bank more patches of gravel are found, median particle size could be 1.8 to 10.5 mm. However, on the northern edge of the Dogger Bank, not much gravel could be found. The bed is largely stable because the tidal current is relatively weak, below 0.4 m/s. There are however mega ripples observed that are aligned north-northwest to the south-southeast with amplitudes from 1.4 to 2.2 meters and wavelengths between 0.5 and 25 meters.

A special kind of bed material, which was present on the Dogger Bank, is moorlog. This is rotted wood, peat, or decomposed organic matter below the surface. The moorlog seemed to be a problem for fisherman. In 1909 was reported that for fisherman, moorlog is "a source of annoyance to them, because it chokes up the trawl, therefore it is broken into pieces and thrown overboard" (Russel & Stevens, 2014).

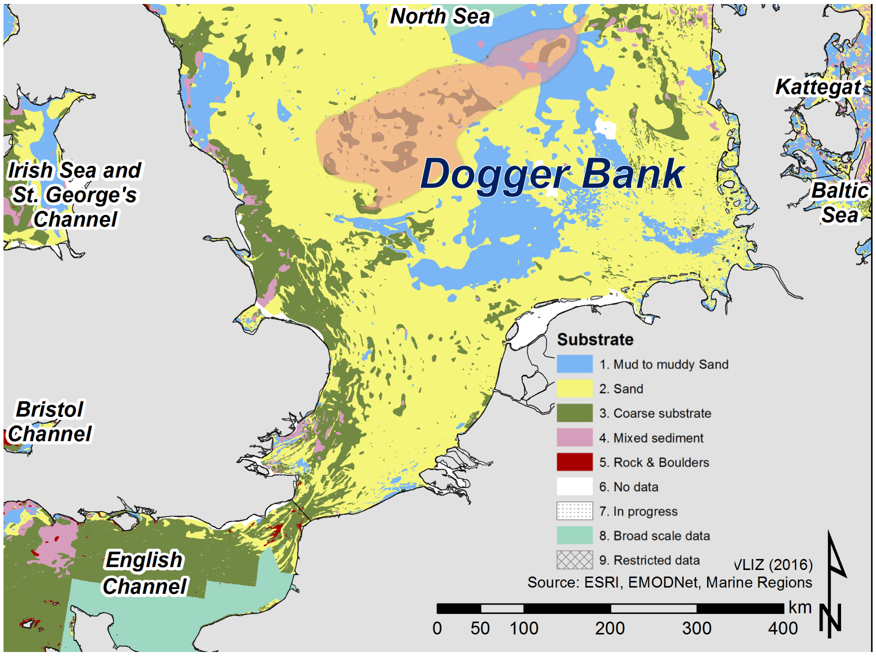


Figure 4: Sediment of seabed North sea (source: EMODnet Geology, 2017)

2.1.3 Waves

Waves generated by wind or swell on the Dogger Bank have an annual mean significant wave height of 1.8m and originate from all directions of the North Sea. The longest waves develop in the deeper part of the North Sea and break on the shallow parts of the Dogger Bank (van Moorsel, 2011). Gardline (2011) measured waves on two different location at the Dogger Bank, using several intervals, for a total period of one year. These measurements gave a mean significant wave height of 1.7 m and a maximal significant wave height of 6 meters. Other measurements have recorded a maximum one year significant wave height of 13.4m with a peak period of 11.7 seconds on the shallowest part of the Dogger Bank (Forewind, 2010). This data was not available for further analysis so the modelled data from Argoss (BMT ARGOSS, 2017) is used. The results of this model show an annual mean significant wave height of 1.8m in the centre of the Dogger Bank.

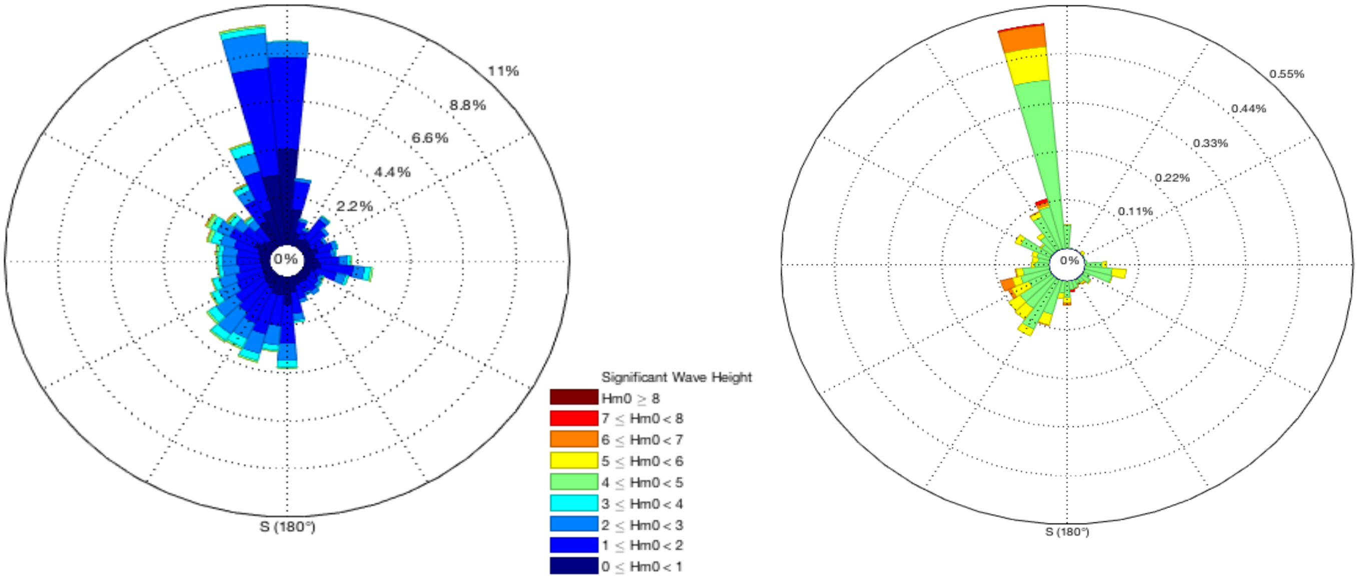


Figure 5: Wave Rose with significant wave height located between K13 and Aukfield, 01-01-2011 until 31-12-2016 with WAVEWATCHIII data, left all wave data, right significant wave height above 4.0 m

2.1.4 Currents

At the shallowest part of the Dogger Bank is a mean-spring depth averaged current of 0.44 m/s found and a velocity of 0.37 m/s at -1 m MSL. The predominant directions of the current are southeast and northwest. The extreme values for the currents are estimated by for 8 different locations (Mathiesen & Nygaard, 2011). The maximum values were 0.88, 0.98 and 1.11 m/s for return periods of 1, 10 and 100 years respectively.

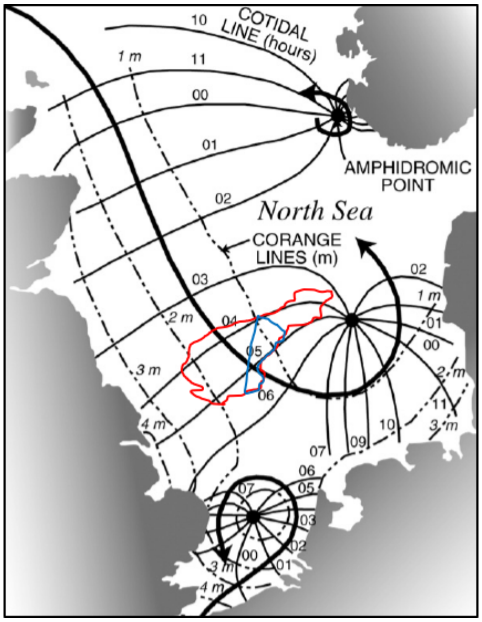


Figure 6: Tidal currents North Sea (source: de Vilder, 2017)

2.1.5 Water level

Tides

Tidal effects are measured at the UK coast and with a temporary deployed instrument by Forewind on the Dogger Bank. The data are not accessible. The mean high-water spring level at the River Tees at the UK coast has a height of 2.3 m MSL (Forewind, 2013). The Forewind report indicates that at two sites at the Dogger Bank the mean high-water spring level is 0.65 and 0.95 +m MSL, respectively 285 and 240km from the river Tees mouth. No analysis has been found for the low-water spring tide so this is assumed to be the same but below MSL.

Surge

Water levels on the east coast of the UK coast are strongly influenced by tidal surges, which are driven by low-pressure weather systems moving down the North Sea (Forewind, 2013). These have the effect of raising extreme water surfaces above levels that would be caused by only astronomical effects. From the analysis for the 100-year return period a level of 1.15 meter higher than the mean high-water spring level is found. The effect of surge could be assumed to be smaller for the island since less land the water can stow on is available. Nevertheless, a maximum value of 1.15m is assumed for the maximum high-water spring level.

Climate change

For sea-level rise due to thermal expansion of the ocean, melting of glaciers and change in the volume of the ice caps of Antarctica and Greenland an increase in water level is added. For an earlier constructed wind park is 0.2 m added for a lifetime until 2050. Since we design for a longer lifetime of the island there is looked to the UK climate predictions report (UKCIP, 2009) about the lower and upper boundary prediction for 2099, which are 0.30 and 0.46 respectively. In this case the middle of those boundaries is selected, which would be 0.38 meter.

2.2 Stakeholder analysis

On the Dogger Bank, several parties are involved with different opinions about activities on the Dogger Bank. First of all, electricity companies are involved. With the intention of increasing the generation of renewable energy, these companies are interested in building windmills in the North Sea. Secondly four counties (Denmark, the UK, the Netherlands, and Germany) and the European Union. With their own legislation, and most important the Natura2000 legislation. The next stakeholder is the fishery industry. The Dogger bank is very important for them for centuries (Christiansen, 2009). There are several NGO’s with different opinions about building an artificial island at the Dogger bank. Last but not least is the Paris agreement (2015). The Climate Goals are adapted and ratified in the countries involved.

2.2.1 Energy companies

Relatively new stakeholders are the electricity companies which are involved in building new energy sources. Energy firms (e.g. Eneco, Dong, RWE) are involved in the construction of wind farms on the North Sea (NOS, 2016). Tennet anticipates into the energy company goals for large scale offshore wind energy with an offshore island (Tennet, 2017a).

The energy companies are finding places for new offshore wind farms since nearshore locations are already build with windmills or are occupied for other activities, like sand extraction, military training area or shipping routes. Therefore, offshore locations become more attractive. Due to the depth and good wave climate, the Dogger Bank is seen as an optimal location. In the UK, part of the planning for construction of 4.8 GW windfarms is approved. This windfarm will cover 3,520 km^2 of the Dogger Bank.Owners of this farm are for instance SSE, a UK energy company, Innogy, an international Energy company and Statoil, an originally Norwegian energy company operating in 36 countries. So far (2017), no concrete plans on building more wind farms on the Dogger Bank are presented.

2.2.2 National and European legislation

The Dogger Bank is part of several Exclusive Economic Zones. Each zone is controlled differently. The attitude of the different countries to building an island at the Dogger Bank depends of the attitude to working at the climate goals. The climate goals on national level are powered by the Paris Agreement, which sets targets on a European and national level. Other European legislations are the Natura2000, OSPAR and the Common Fisheries Policy.

National legislations

As stated in chapter 2.1, the sandbank is shared by Germany, Denmark, the UK and the Netherlands. This means that the sandbank is part of 4 different Exclusive Economic Zones and therefore has several national legislations to deal with. An EEZ is described best as an area where the jurisdiction over the exploration and exploitation of marine resources is assumed by a coastal state (UN, 1982). The fact that multiple countries have legal authority over parts of the area might cause difficulties for future plans on the Dogger Bank.

Additionally, the different countries have a different approach on tackling the climate change. This leads to different methods of reducing CO_2 and inducing sustainable energy, and different views on the use of the Dogger Bank in generation sustainable energy.

Natura2000

Also, the EU influences the use of the Dogger bank through the Natura2000 legislation. Germany, the UK and the Netherlands have declared the area as a Natura2000 area, while Denmark does not have this ambition (NSRAC, 2012). Natura2000 is a network of protected nature areas in Europe with the goal to conserve the biodiversity (Sundseth, 2008).

The areas included in the Natura2000 legislation are selected by EU-members. After investigating, and deciding whether the area is important to the European biodiversity, the EU adds the area to the list of conserved areas in Europe. For each area, an assessment is made about the value of the natural habitat and the species of this habitat. This happens on a national scale. Each state creates their own management plan on how to protect and/or conserve the area. This causes different regulation and implementation between the different countries.

The boundaries are determined on the location of the living area of the species, the corresponding abiotic characteristics and the chosen natural habitats, which is in this case permanently flooded sandbank. All areas are coded, with H1110 for permanent banks, and H1110C specific for the Dogger Bank flooded bank. The EU definition of the habitat (H1110) is described by:

Sandbanks are elevated, elongated, rounded or irregular topographic features, permanently submerged and predominantly surrounded by deeper water. They consist mainly of sandy sediments, but larger grain sizes, including boulders and cobbles, or smaller grain sizes including mud may also be present on a sandbank. Banks where sandy sediments occur in a layer over hard substrata are classed as sandbanks if the associated biota is dependent on the sand rather than on the underlying hard substrata. "Slightly covered by sea water all the time" means that above a sandbank the water depth is seldom more than 20 m below chart datum. Sandbanks can, however, extend beneath 20 m below chart datum. It can, therefore, be appropriate to include in designations such areas where they are part of the feature and host its biological assemblages.

The species which are protected are the porpoise, grey seal and the common seal. The area should maintain, or sometimes restore, these species and habitats in favourable conditions. For the maintenance of the Natura2000, goals are introduced which give the goals per habitat type and specie. These goals are set with consideration of the opportunities in the area and the contribution to the national goals. For example, rankings about which species or habitats could disappear for other kinds are included. Habitat types that are not directly stated in the habitat type selection do have 'rights' as well. The Natura2000 legislation at the Dogger Bank focusses mostly on the species in the water column, and less on the species settled on the seabed and life just above the water column (Gotjé, personal communication).

The Dogger Bank is for the Netherlands 75% accountable for this habitat type (Jak et al., 2009). For the concerning species, the contribution of the Dogger Bank for porpoise is 2-6% and for both the grey and common seals less than 2%. The relatively low contribution is caused by the high mobility of the species. That is why the influence of the Dogger Bank should be seen in combination with the total southern North Sea region; with solely focussing on the Dogger Bank, a large part of the species dynamics is neglected.

For all species, the aimed goals are habitat quality, population and size conservation (Jak et al., 2009). The goals for habitat type are similar as they are focussed on the surface conservation as well. However, for the areas a certain quality and improvement is demanded. The report of Jak et al. (2009) stated that for conserving grey seals it is important that sandbanks are available, and not flooded during extreme storm conditions. Permanent dry sandbanks could contribute to this.

The borders of the Dogger Bank are determined on the slope angle for both the Netherlands and Germany, where an exceedance of 1:10 is the boundary (which is on the Dutch side around -40 m MSL). For the British part, the conservation objectives are not formulated yet. Neither is the management plan for the Netherlands, however the conservation goals for the Dutch part of the Dogger Bank are stated as follows:

- Abiotic preconditions: where a minimal physical bottom disturbance is seen as a very important aspect to achieve this;
- Other characteristics of good structure and function, requiring a balanced age distribution for each long-living species, and an increase of biomass ratio of benthic long-lived species over short-lived species;
- Typical species of H1110: all typical species in the list of Jak et al. (2009) must be present in the area (included in the list in appendix A).

The German objectives are stated in different words, but are essentially the same:

- Maintenance and recovery of specific ecological functions, biodiversity and natural hydro- and morphodynamics of the area;
- Maintenance and recovery of a favourable conservation status of H1110 with its characteristic and endangered communities and species;
- Maintenance and recovery of a favourable conservation status of the harbour porpoise and harbour seal and its habitats.

These goals could be kept in mind during the designing process in the next chapters in order to fulfil legislation.

OSPAR

Other legislation is formulated by the multi-national OSPAR Commission. This Commission consists of representatives of each of its 16 contracting parties, including Germany, Denmark, the UK and the Netherlands. The purpose of OSPAR (Convention for the Protection of the Marine Environment of the North-East Atlantic) is to protect the marine environment from the negative effects (including contaminants) of human activity.

The OSPAR list of threatened and/or declining species and habitats includes 29 species occurring in the North Sea (OSPAR Commission, 2008). Several live in the Dogger Bank area: ocean quahog, basking shark, cod, Short-snouted sea horse, thornback ray, spurdog and harbour porpoise. The flat oyster is believed to have been present in former times (Van Moorsel, 2011). The OSPAR list also mentions habitats of the wider Dogger Bank: ‘sea-pen and burrowing megafauna communities’ as well as nowadays disappeared beds of horse mussel and flat oyster (Trouwborst & Dotinga H., 2010).

Common Fisheries Policy

The Common Fisheries Policy (CFP) is legislation implemented by the EU. The primary objective of the CFP is to ensure exploitation of living aquatic resources that provides sustainable economic, environmental and social conditions. The revised CFP framework regulation makes the need for fisheries policy to take account of the impact of fishing activities on marine ecosystems more explicit, with the aim of the progressive implementation of an ecosystem-based approach to fisheries management. The revised CFP is intended to have an improved focus on the wider marine environment. This should include the development of a long-term strategy to promote the protection of vulnerable species, such as cetaceans, sharks, and marine birds (Unger, 2004).

2.2.3 Fishing sector

The edges of the Dogger Bank are one of the richest areas for fishing in the North Sea. There is commercial fishing on cod, haddock, plaice, sole, dab and sandeel. Fishery is considered to be the activity with the highest impact on the ecosystem of the Dogger Bank (Chuenpagdee, Morgan, Maxwell, Norse, & Pauly, 2003). Especially bottom and beam trawling are considered the most destructive ways of fishing.

Every concerning country has its own association representing the fishing sector within their country (EAPO, 2017). With these associations, each having their own agenda and goals, there might be different levels of interest of the construction of a windfarm at the Dogger bank. However, they will all share the opinion that the placement of an offshore windfarm will decrease the area available for fishing. Hereby, the Dogger bank is known as one of the richest fishing grounds which causes additional aversion to the plan.

2.2.4 NGO's

Between the non-governmental organisations are two different opinions on wind energy on the Dogger Bank. One side embraces the fact that the Dogger Bank is a potential area for sustainable energy. The other side knows about the sustainable transition but cannot allow to use the Dogger Bank for this. Due to the ecological value, this part cannot be disturbed by windmills, islands and cable infrastructure. They suggest to seek for other potential areas outside Natura2000 area.

Greenpeace seeks for opportunities for more renewable energy. They support the idea of windfarms at sea but ask for investigations about the effect on nature. The World Wildlife Fund however, is strictly opposed to the plan and is prepared to challenge it in light of European nature conservation law (Habitats Directive) (Lutter, 2017).

2.2.5 Paris Climate Agreement – United Nations

Each of the four countries involved have their own national law regarding environmental issues, which are mostly powered by the Paris Climate Agreement from 2015. These national strategies include to what extend a country wants to implement sustainable energy in their national energy policy. The level of interest in sustainable gives an indication to what extend countries are willing to contribute in a windfarm on the Dogger Bank. One of the targets from the Paris Agreement says that European countries should at least achieve a renewable energy consumption of 27% of the total energy in 2030 (EU, 2017), where individual countries may differ from this.

For the countries involved, the following goals are found:

- Germany wants a share of 30% renewable energy in the final energy use in 2035, which is planned to increase to 100% in 2050. For that same year, the production of renewable energy is planned to be 50-60% of the total produced energy (PBL, 2017).
- Denmark is ahead of the European schedule, as they plan on having 35% renewable energy in the final use in 2020. Also, the Danish government aims for sustainable energy production of 100% in 2030. This is the most ambitious goal compared to the other involved countries.
- The UK doesn't have formed specific goals on the consuming and production of sustainable energy in the far future. The only goal they set is to have a renewable energy production of 20% due to 2020. This may seem like low ambition; however, they have already built a wind park on the Dogger Bank which indicated the interest in offshore wind energy.
- The Netherlands plans to increase the use of renewable energy to almost 100% in 2050. For 2030, this percentage is set to 27%, according to the European directives.

2.2.6 Conclusion on stakeholders

The stakeholders involved have different views on building at the Dogger Bank. The Paris Climate Agreement forces countries to look for alternatives for fossil energy. Wind energy is a good alternative. The energy companies want to provide that kind of energy. But European and National laws (Natura2000) is very strictly conserving nature objectives. The fishing industry will lose important fishing grounds.

2.3 Ecological system

2.3.1 Communities and ecosystem

The Dogger Bank presents a fauna border between the northern and southern North Sea species, where species overlap on the sandbank (Jak et al., 2009). It consists mainly of fine sandy sediments but also larger grain sizes including boulders and cobbles, or smaller particles like mud (Van Moorsel, 2011). Due to the shallow depth, long waves from the deeper northern part of the North Sea are breaking on the Dogger Bank. These breaking waves are mixing the southern, warm and more nutrient-rich water column with the colder and less turbid northern water (Van Moorsel, 2011). Due to the mixing process, a flow of mixed water on the sandbank induces a current to the more homogeneous waters around the sandbank. This cause the flow of silt and nutrients towards the outer sides of the Dogger Bank where it sinks to the bottom, resulting in more biodiversity on the sides. The conditions on the Dogger Bank, such as waves, currents and storms, create significant difference between the fauna of north and south North Sea.

Due to the mixing process, organic and fine sediments are washed away from the top. Only coarse sediments and shell gravel remains. In some areas, the seabed consists only of a shell gravel layer. The consequences of this ‘hard’ seabed is a low amount of suspended sediment in the water column, that coupled with shallow water depths, results in more light at the sea bottom. The available light and shallow depths create optimum conditions for benthic diatoms (algae on the water-sediment interface), which is quite unique in the North Sea (Bos et al., 2017). Benthic diatoms contribute an estimated 45% of the total oceanic primary production of organic material. They are also an important component of marine food webs, both for pelagic and benthic secondary production (Wetz & Wheeler, 2007). Deposit feeders, who live from organic material on the seabed are not common. Contrary, filter feeders that feed by straining suspended matter and food particles from the water column (e.g. bivalves) are very common.

On the deeper southwest and northeast corner of the Dogger Bank, the bottom is composed of finer sediments. In total, the Dogger Bank has a higher production than other North Sea areas, especially the northern part of the bank. Species richness differs between surface and deeper layers of the Dogger Bank seabed: on the surface layer, due to the coarse soil and stronger waves, fewer species are available (17 species per $0.4m^2$), while in the deeper and silt layers more species are recorded (50 species per $0.4m^2$).

The Dogger Bank is roughly divided into five macro fauna communities (Figure 7). The edges of the bank contain more silt compared to the shallow top of the bank, that has more sand and shell gravel. On the shallow top part of the bank, only species which could withstand the wave stresses by being mobile, digging themselves in or creating strong seabed connections with gravel shell (Van Moorsel, 2011), could survive.

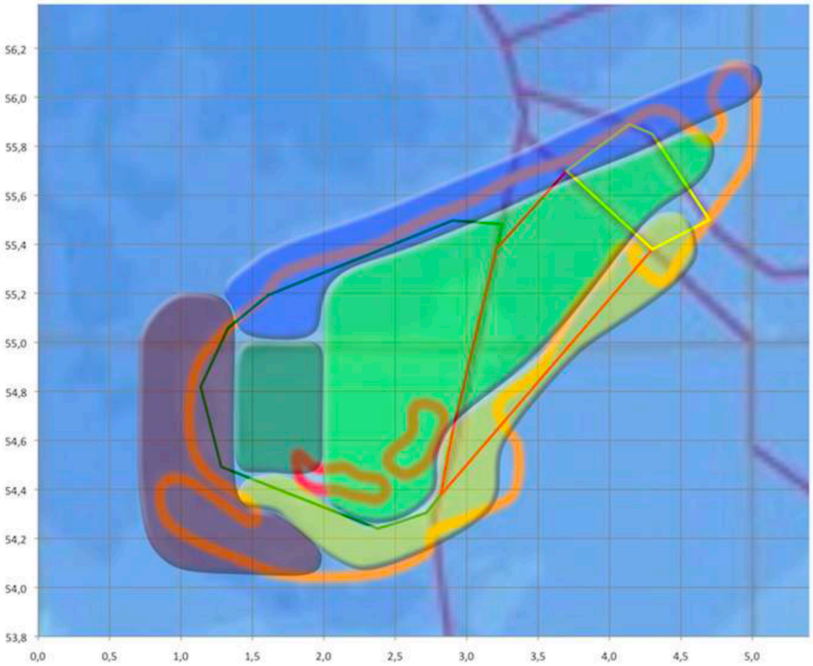


Figure 7: Macrofauna communities on the Dogger Bank:
- Light Green: top bank community.
- Dark green: western top bank community
- Yellow: southern community.
- Purple: western community.
- Blue: northeast community
(source: van Moorsel, 2011)

The west of the top community (dark green) is a sub-group of the overall top community with even less species due to higher shear forces. On the northern edge (blue community in Figure 7), there is more silt and species present there are also found in the north part of the North Sea. The northern area has a lower density of species but higher species diversity compared to the other communities. On the south, more silt sediments are found. Species found here resemble the ones at the south of the Dogger Bank, like the central oyster fields. The western part of the bank (purple in Figure 7) is a mix of the surrounding communities with more long living and larger species.

Historical developments

In the end of the nineteenth century, an artistic impression was made of the fish location for several fished species in the North Sea (Olsen, 1883). In the same period, the development of fishing with steam trawlers, probably already had a significant influence on the macro benthos. Large oyster banks that existed south of the Dogger Bank disappeared during this period, mainly because of specialised fishing for oysters. Due to the lack of information on historic densities of oysters, it is not possible to analyse these changes quantitatively (Van Moorsel, 2011). Between the World Wars much less research on macro benthos was carried out and the technical development of fishing was slower. After 1970, technical development of fishery increased again with clear consequences for the macro benthos. Stones and moorlog got removed by fisherman, changing the seabed of the Dogger Bank (van Duren et al., 2016).

Research of the Dogger Bank’s fauna, between 1950 and 1990, has shown that it has significantly changed (Kröncke, 2011). The number of species has increased. This growth is however only established due to short-living, opportunistic species. The abundance of the original, long living bivalves seems to decreased. Reports write about introduction of deposit-feeding polychaetes (e.g. *Spiophanes bombyx*) and the disappearance of bivalve species such as *Spisula* sp.(surf clam) and *Mactra* sp. (duck clam), whose patches were widely present on top of the Dogger Bank (Kröncke, 2011). Their disappearance was probably caused with the beam trawling, and thus having effects on the surrounding ecosystem. Surf clams were the main source of diet for the plaice, and the reason why the Dogger Bank was a rich fishing ground.

The decrease of long living bivalve species was also induced by eutrophication, which is the enrichment of water with nutrients. This occurred due to increased usage and little regulation for the use of fertilisers, mostly in agriculture, at that time. Via rivers, the redundant nutrients ended up in the North Sea. Eutrophication caused a biomass which was increased relatively more than the diversity itself.

The Dogger Bank once had a large ray population (De Vooys and Van der Meer, 1998). According to the landing statistics, about 400 tons of rays (Dutch: rog) came from the UK Dogger Bank area every year in the 1950s (Jak et al., 2009). From the mid-seventies, these figures showed a decline. Although there are no exact numbers, the ray population on the Dogger Bank used to be much larger than it is now (see also Olsen, 1883). If the limiting factor (i.e. fishing) for this population becomes smaller, their number will probably increase. The vulnerability of ray populations to fisheries is a consequence of the biology of these cartilaginous fish (Walker & Heessen, 1996), including the low fecundity (reproductive capacity) and relatively late maturation before reproduction takes place.

Another important species for the Dogger Bank is a sandeel (*Ammodytes* spp.). There is a commercial fishery for this species developed especially around the Dogger Bank. In the southwestern (English) part of the Dogger Bank, this fishery is so intensive that it has the potential to perturb food chain and impact higher trophic levels (Engelhard et al, 2008).

2.3.2 Selection of species

To find nature enhancing opportunities around a new build island, it was chosen to focus on a limited selection of ‘umbrella species’. These are the species that have either large habitat needs or other requirements whose conservation results in many other species being conserved at the ecosystem or landscape level (Millennium Ecosystem Assessments, 2005). Conserving umbrella species provides high quality habitat for many other species that are active on the Dogger Bank to be propagated or conserved - they provide a protective umbrella to numerous co-occurring species (Lengkeek et al., 2017). Focusing on the requirements of one of these umbrella species when designing an optimised habitat is more feasible, compared to a long list of potential species to be conserved. Selection of umbrella species could be based on the following criteria (Lengkeek et al., 2017):

1. Co-occurrence of species: umbrella species should be earmarked based on co-occurrence with other species; protecting species with large area requirements will conserve habitat for species that are more insular or sedentary.
2. Degree of ubiquity: an ideal umbrella species candidate should be neither ubiquitous nor extremely rare but instead should strike a balance between these two extremes.
3. Sensitivity to human disturbance: selecting umbrella species recognises that species respond differently to various disturbances.

An extra criterion could be added in the light of the BwN principle. An umbrella species could also be chosen to contribute to the island design and be utilised for the coastal defence while fulfilling the three criteria above.

4. Additional habitat requirement: representative of a habitat requirement that can contribute to the coastal defence.

In the following chapter, species which have the potential to fulfil the criteria mentioned above are summarised. Firstly, some typical species of the Dogger Bank are described and secondly, a list of North Sea reef builders with the potential to contribute to the coastal defence are presented.

Typical Dogger Bank species

A list of desired species in the Dogger Bank was compiled (see appendix A), following an inventory of species listed in the Red list of threatened species (IUCN, 2017), Natura2000 (Jak et al., 2009), Olsen Atlas (Olsen, 1883), Kröncke (2011)and indicator species for hard substrates (Lengkeek et al., 2017). Out of these listed species living on the Dogger Bank, three species were selected that could represent or stimulate the other species from the list for growing in their habitat. Those species are the thornback ray (*Raja clavata*) and the bivalve molluscs *Spisula* sp. and the *Mactra sp*. The thornback ray is selected because it is marked as “near threatened”, and it is known to utilise offshore windfarm foundation as a habitat. Moreover, it was present in the report of Olsen in 1883. The chosen bivalve species could facilitate for a larger group of benthic species. Historically these species have been present on the Dogger Bank but are driven away by more opportunistic and short living species. The bivalve species as filter-feeders could create a more beneficial habitat for other species.

Thornback ray (Raja clavata)

Thornback ray (*Raja clavata*) has been mentioned to become very rare at the Dogger Bank (ICES 2011). Historically, the Dogger Bank has been the centre of distribution of the thornback ray in the North Sea (Map 43 in Olsen, 1883). A light colour, however, suggests that the species was not caught in abundance on the shallower part of the Bank. Data from 1965 to 2005 showed a similar distribution in the large part of the southern and central North Sea (Daan et al. 2005; Ter Hofstede et al. 2005), but again, the thornback ray seems to be confined mainly to the borders of the Dogger Bank (Walker & Hislop 1998). Rays are known to be long lived and slow reproducing, so they are vulnerable to fisheries (Van Moorsel, 2011), and therefore worthwhile to protect (van der Weij, 2017).

Long lived bivalve species

Comparisons of data collected in the early 1950s and the late 1980s showed particularly marked changes for some deposit-feeding polychaetes worms (Berry, 1998). Extensive patches of the long lived bivalve molluscs *Spisula subtruncata* were found in the north-eastern border of the Bank, during early surveys. These were generally seen to be absent during the 1980s, when only relatively few specimens were found. Instead, high numbers of small, short lived bivalve molluscs such as *Kurtiella bidentata* (former name in Berry, 1998: *Montacuta bidentata)* and *Fabulina fabula* (former name *Tellina fabula)* were observed. In terms of the biomass of the benthos, investigations have revealed a decrease in the biomass in the north-eastern area of the bank, while other areas have exhibited from 2.5 to 8-fold increase. It has been hypothesised that such changes may have resulted from eutrophication, increased contaminant loading in sediments, temperature anomalies, or fisheries impacts.

Certain areas are fished many times while others may be completely missed. It is possible that the Dogger Bank might be exposed to negative impacts resulting from fishing activity (Berry, 1998). The change in the dominance of the long lived bivalve *Spisula subtruncata* in favour of smaller, short lived bivalve species could be a result from fishing related disturbance of the sea bottom.

Eco-engineers

Species identified as eco engineers have the ability to contribute to the coastal protection by modifying the local physical environment A description of such North Sea species could be found in the report from Deltares, specifically describing North Sea reef builders (van Duren et al., 2016). One species described in that report that can be frequently found on the Dogger Bank is the honeycomb worm (*Sabellaria alveolata*), which could settle on both hard substrate and hard consolidated sand. The other North Sea reef building species discussed are the northern horse mussel (*Modiolus modiolus*), the European flat oyster (*Ostrea edulis*) and the honeycomb worm relative, sand mason worm (*Lanice conchilega*). The horse mussel is a species more typical for intertidal areas and is not often found in deeper parts of the North Sea, therefore this species is not further discussed. The European flat oyster and honeycomb worm could be found in small groups or individually on the Dogger Bank.

Ross worm (Sabellaria alveolata and Sabellaria spinulosa)

The two polychaete *Sabellaria* species are reef-forming species that can create large reef structures on hard and hard consolidated sand. In the UK, Germany and France, these species are found as reefs. In the Netherlands, this is rare and only individual species are found. Reason for this scarcely occurrence is not clear but it is suspected that bottom disturbance is the main aspect. The structure of these reef is build up from sand and shell fragments, upon which individuals could grow to 30-40 cm or as group from 30 cm to 2 meters and stick to each other. The honeycomb worm *Sabellaria alveolata* can be found in areas with medium to strong wave forces, in both intertidal as shallow permanent flooded areas. The Ross worm *Sabellaria spinulosa* often is found on locations with relatively strong currents and suspending sand.

Sand mason worm (Lanice conchilega)

The sand mason worm *Lanice conchilega* is not a real reef builder, it does not raise the bed but creates concentrated aggregations on the bed that stabilise sandy sediments. Modelling showed that these areas can have significant effect on the sand transport. The reefs consist out of individual tubes which are not stacked together like the *Sabelleria*. The sand mason worm can be found on sandy and silt bottoms, where often seagrass and algae can be found. The worm can survive in both intertidal and deep water, with low and high salt concentrations. Although the sand mason worm stabilises the dynamics of the bed, it is also a determinant factor.

Flat oyster (Ostrea edulis)

A fifth of the North Sea bottom was covered with oyster reefs 130 years ago (see Figure 8). Due to overfishing, diseases and eutrophication, almost all reefs are gone (Olsen, 1883). Oysters, mussels, sand worms and other organisms can contribute to cleaner (less turbid) seawater and consequently increased biodiversity. But these species can as well attribute to the coastal defence by wave attenuation (Borsje et al. 2010) by increasing the friction coefficient or they can prevent erosion and stabilise shorelines by reducing water velocities (Piazza et al. 2005). Shellfish reefs can increase sediment cohesion by bounding particles (van Leeuwen 2010, Borsje et al. 2011). Attenuation of wave energy with shells would be an attractive and nature-friendly alternative for coastal defence but from practice it appears to be difficult to create reefs on wave exposed sites (de Vries 2007). The combinations of different species on a local scale and habitats on a larger scale can have a greater impact on hydrodynamics and sedimentation rates than one species in isolation (Bouma et al 2005, Bouma et al. 2010). There are no good methods yet which can guarantee good functional reefs on these locations. Oyster reefs restoration projects have not showed detectable effects on shoreline as well (Scypher et al. 2011), although the experiments in the Eastern Scheldt (Ecoshape project) have demonstrated that the use of oysters as ecosystem engineers for erosion prevention is feasible technically and biologically, and it is also socially acceptable. While there is evidence that biogenic coast habitats can contribute in protecting the shoreline, a knowledge gap is however the scale in which the protection services are applicable (van Wesenbeeck et al., 2013).

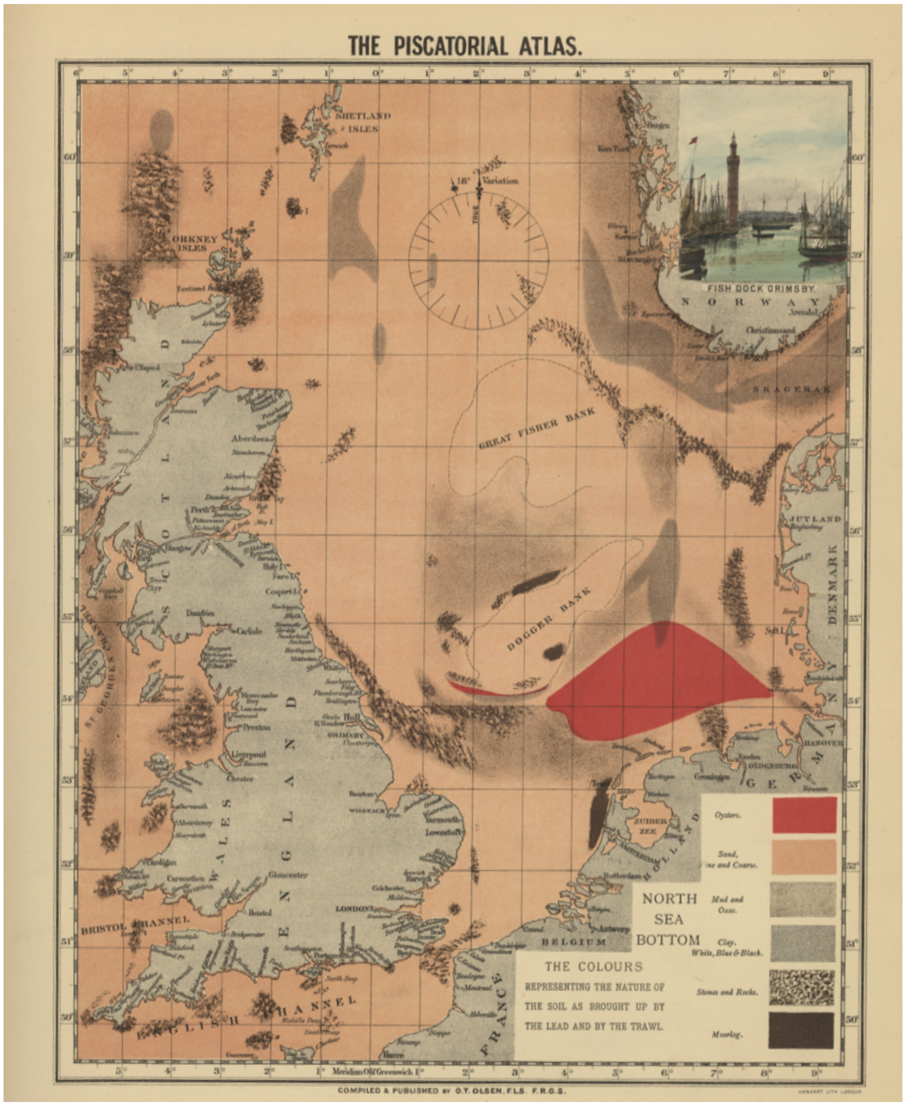


Figure 8: The piscatorial atlas of the North Sea with seabed characteristics (source: Olsen, 1883)

2.3.3 Umbrella species

The European flat oyster, which is not assumed to be present at the Dogger Bank in reefs but is seen as a keystone species. A keystone species plays a critical role in the way an ecosystem functions, by maintaining the structure of an ecological community and affecting many other organisms in an ecosystem. Oyster reefs create a biogenic, 3D structure and are renowned for their unique biodiversity. Oysters perform water filtration and may create a habitat available for some of the Dogger Bank species listen in Appendix A. Banks of flat oysters are currently regarded as one of the most threatened (marine) habitats in Europe (Airoldi & Beck, 2007; van Duren et al., 2016). Flat oyster utilises firm silty sand or silty gravel with shells and stones and they transform soft sediment into a hard structure. The oyster larvae settle on a hard surface, such as stones, shell fragments or oyster shells (Smaal et al., 2017). Once they settle on the substrate, the reef structure is renewed by attracting new oyster larvae. The island coastal defence can provide the initial substrate where the oysters can settle. The island can provide a function in returning a precious habitat which used to be a characteristic part of the ecosystems along the European and Mediterranean coasts (van Duren et al., 2016).

In the previous system analysis is found what stakeholders, physical conditions are present at the Dogger Bank and which historic developments have taken place. From this is determined what nature would be desired to enhanced. From the selection criteria and the discussed potential species, an umbrella species is chosen: the flat oyster.

2.4 Selection Nature Based Design Element

This umbrella species is the basis for the Nature Based Design Element (NBDE). Oyster reefs can be an *element* in the design which could create substantial value to the North Sea ecology. Considered that the island should resist extreme waves heights up to 13.4 meter and a relative high average wave climate, the island defence is very likely to be made from large stable units. The hard coastal defence which will be created, provides hard substrate.

Furthermore, the oysters beds are known to facilitate a larger number of associated benthic species. This can result in higher species richness compared to non-living hard substrate. The oyster reef introduces a habitat that disappeared in the last 130 years. Therefore, it can be an interesting species to restore around the Dogger Bank, especially when wind farms are being built around the island. The scour protection for wind mills will provide hard substrate where more settlement surface for oyster is available. The island can be the start for oyster distribution on the Dogger Bank. At last, the oysters can be used as eco-engineer and used to attenuate waves and retain sediments. This would be a cost-efficient for the coastal defence, and at the same time provide nature enhancing opportunities for the North Sea. Meanwhile present activities for wind farm constructions also include restauration of oyster beds.

3.

Design approach

This thesis aims to find opportunities to enhance nature around the island cross sections. From the system analysis, a NBDE is identified. Subsequently, this NBDE is implemented into the cross-sectional design of the island. The NBDE can enhance the nature around the island and is represented by oyster reefs. To find or oyster reefs are applicable and where they are applicable a method should be made to approach those opportunities in a quantitative manner.

Therefore, in this chapter the boundary conditions for the flat oyster beds are quantified in 3.1. Secondly, in 3.2 the basic formula which will be implemented into the method how oysters can be found in the cross-section are described. In the next part of this section some typical sections and materials for a coastal defence are described. The materials and cross-sectional parts are discussed for their contribution to the NBDE, such as their contribution to the settlement of oyster reefs. Subsequently, in 3.3 the return values are determined which should be specified for the design conditions of the coastal defence and the oyster bed. These return values will be implemented in an extreme value analysis in 3.4. Since the wave energy will be an important factor for the success of an oyster bed on the Dogger Bank, the boundary condition of wave energy for oyster is expressed in shear stress. With the boundary conditions for oysters and the physical conditions of the Dogger Bank, in 3.5 an approach is made with the bed shear stress to find the potential areas in the island coastal profiles.

3.1 Oyster boundary conditions

Flat oysters live on the seabed and can create biogenic reefs. They absorb oxygen through their gills and they feed themselves by filtering suspension from the water. The life of an oyster starts in the mantle cavity of the female oyster. After maturation, the oyster larvae are released in the water where they swim freely for about 7 to 14 days before settling on the seabed permanently (Smyth, Louise, Björn, Richard, & Dai, 2016). Flat oysters start living as males and become females after 3 to 4 years, as they grow older they can change sexes again. Change of sex, maturation and reproduction depend on the temperature and salinity of the water. They grow up to a size of 20 cm during their lifetime of a maximum 20 years.

Flat oyster occurrence depends on abiotic factors (e.g. sea bed dynamics, water depth, salinity, water temperature) and biotic factors (sufficient levels of phytoplankton, little predation, low mortality due to diseases, and sufficiently large populations for successful propagation). In this thesis, only the abiotic factors will be discussed since these can be influenced by the cross-sectional design. Organisms on the sea bottom are influenced by many aspects, such as the mean current, the maximum current, wave energy on the bottom, salinity and sedimentation. A current is imperative to feed the oysters with the passing water. However, too strong a current can break the reef from the bottom. Waves causes bottom forces and induce turbulence on the reefs as well, while it does not transport as much nutrients as currents do. To find the optimal conditions that oysters require for successful settlement in the North Sea, research was performed for scour protection of offshore wind farms (Lengkeek et al., 2017). A literature study has been done for this research including maps by Olsen (1883) used to compare historical oyster reef locations with present information on those locations. Below are the summarised results of the required conditions for oysters. Here only the conditions are discussed which can be influenced by a coastal defence.

3.1.1 Seabed shear stress

The seabed shear stress is a function of the roughness of the seabed surface and the velocity of the water. Tidal movements and waves causes the velocity of the water column and the seabed dynamics. Therefore, the bed shear stress is used here to describe the local seabed dynamics. Low seabed shear stress is prerequisite for oyster settlement although no direct measurement (laboratory) data for the shear stress boundary conditions are available. To obtain information about the possible tolerance conditions, Olsen's maps are compared with recent shear stress models of the North Sea (Smaal, Kamermans, Kleissen, van Duren, & van der Have, 2017). This model has been made for the EIA for sand extraction in the North Sea. Thereby a difference was made between the mean shear stress and the critical shear stress. Following the study, the old oyster grounds northwest of the Netherlands has a clear boundary line with the mean shear stress model. The mean shear stress that was surrounding the oyster field was 0.6 N/m^2. The critical shear stress is only discussed for the Dutch wind parks. In all the Dutch wind parks the maximum shear stress is between 5-8 N/m^2(except for Borssele 2 N/m^2). No clear relation has been found between the wind parks with or without oysters and the critical shear stress.

The type of substrate might change the boundary conditions of the oyster field. Harder substrate like gravel might create a stronger connection between the oyster and the seabed. This assumption is made based on the location of historical oyster fields in the English Channel with relative high mean and maximum shear stresses. The found boundary shear stresses for sand is tried to translate to shear stresses which would be present on oyster reefs in paragraph 3.5. There is however no research that can verify this assumption. Another point which is unclear is how individual oysters can grow on locations with higher shear stress conditions where oyster reefs cannot.

3.1.2 Seabed morphology

Since the seabed is continuously changing there is a boundary level for oyster reef resistance. Too low movement results in low nutrient transport to the oysters while a high the oyster's siphon for filtration or flow the oysters away. The motion of the seabed is also dependant on the amount of shear stress. In the laboratory experiments (Grant, Enright, & Griswold, 1990) it was found that concentrations of 0.1 cm/day can contribute to a positive effect on the growth of the flat oyster. When concentration reach 0.8 cm/day the growth of the oyster starts to decrease.

3.1.3 Suspended material

Oyster are filter feeders using the water current and the particles suspended in it. This can be phytoplankton, detritus and inorganic material. However, they can selectively choose and feed on phytoplankton, or algae, removing the algal biomass from the water, while other suspended inorganic solids are releases as pseudofeces. High concentrations of inorganic material can decrease the oyster growth. For the Japanese oyster (*Crassostrea gigas*) it was found experimentally that growth starts to decrease at 90 mg/L. For the flat oyster the peak values below 60 mg/L are optimal and 180 mg/L are sub-optimal.

3.1.4 Sediments

The sediments type of the seabed also determines the success of oyster settlement. The best substrate for oysters to settle is dead shells and oysters. When shells are not present, the sediment grain size is the most commonly used parameter for the success of oyster settlement. In a reconstruction of the oyster beds in front of the Belgian coast (Houziaux, Kerckhof, Degrendele, Roche, & A., 2008) the seabed was a heterogeneous gravel field partially covered by a thin layer (<15 cm) of sand where, in some places, stone protruded. From other reference locations (North Sea, California and Mediterranean) it has been found that coarse sand (grain size >210 μm) was classified as unsuitable, fine sand (>63 μm) as moderately suitable and firm silty sand or silty gravel with shells and stones (not defined in terms of grain size) as suitable for oyster growth.

3.1.5 Water depth

Water depth is an important factor for the survival rate since it provides oxygen and food to the bivalves. For oyster to filter they need to be covered with water, hence in the intertidal area oysters cannot feed, while at a depth of around 80 m MSL the amount of oxygen is lower and the light penetration is reduced, hence the food (algae) is not always available. In estuaries, the flat oyster can be found around the low water level.

3.1.6 Flow velocity

Current velocity accommodates the recruitment and supply of nutrients and oxygen for the oysters. The boundary velocity is, like the shear stress, dependent on the substrate. Oysters settled on hard substrate can resist much higher velocities compared to oysters on soft substrate. When the flat oyster was widely present in Dutch estuaries in the past, the maximum velocity the oyster could resist was 0.25 m/s with an optimum at 0.03 m/s (Drinkwaard, 1961). The reason for the low velocity boundary is due to the fact that oyster larvae prefer to settle on oyster shells, often close to their origin. Low velocities increase the chance of successful settlement on existing oyster reefs. From historical information, it is known that oysters were also present at edges and gullies where current could be much higher. From Olsen's maps and a model for the flow velocity an estimation is made for the optimal current velocity in the North Sea. The result showed that the optimal current velocity was between 0.25 and 0.6 m/s.

Parameter	Suitability		
	Unsuitable	Moderately suitable	Suitable
Mean shear stress (N/m^2) on sand	> 1	> 0.6	0.25 - 0.6
Bottom movement (cm/day)	unknown	? > x > 0.8	< 0.8
Suspended sediment (mg/l)	> 180	60 – 180	< 60
Water temperature (°C)	< 3 – >30	3 – 7	7 – 25
Sediment	Coarse sand (> 210 µm)	Fine sand (> 63 µm)	Strong silty sand, silty gravel with stones and shells
Water depth (m MSL)	< -80	-79* >	< -1*
Flow velocity (m/s)	> 0,8	< 0.25	0.25 - 0,8

Table 1: Summary of requirements for the flat oyster in the North Sea using comparison of reference locations and models, experimental and literature studies (Smaal et al., 2017).
*Exact border between moderate suitable and suitable is dependent on many other factors.

3.2 Coastal defence

3.2.1 General hydraulic formulas

Wave length

Wave length is the distance between two crests in a wave and is dependent on the kind of water the wave is in: shallow, transitional or deep (see Figure 8). In deep water waves can propagate undisturbed, but this change when waves start noticing the bottom. The classification of the water depth is dependent on the ratio between the wave length and water depth. The length is found iteratively, starting with the deep-water wave length (the formulas for the different water depths can be found in Table 2). The change in wave length will change other characteristics of the wave length as well, like the wave number and wave steepness, which will be discussed later.

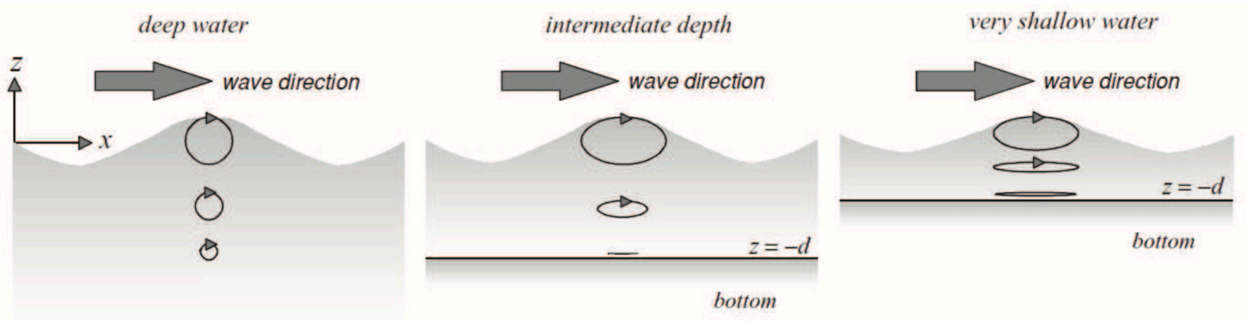


Figure 8: Wave propagation in different types of water depths.

	Shallow	**Transitional**	**Deep water**
characteristics	$\frac{h}{L} < \frac{1}{20}$	$\frac{1}{20} < \frac{h}{L} < \frac{1}{2}$	$\frac{h}{L} > \frac{1}{2}$
Wave length	$L = T\sqrt{gh}$	$L = \frac{gT^2}{2\pi} \tanh{(kh)}$	$L_0 = \frac{gT^2}{2\pi}$

Table 2: Wave length formula for different types of water depths

With		
	T	The wave period (s)
	L	Wave length (m)
	g	acceleration of gravity (m/s^2)
	h	Water depth (m)
	k	wave number (1/m)

Wave number

The wave number is the spatial frequency of the wave in radians per unit distance expressed in the following formula:

$$k = \frac{2\pi}{L}$$

Wave steepness

The wave steepness is the ratio between the wave height and the wave length. When waves become too steep, wave breaking occurs. This happens when the wave base can no longer support its top. In deep water the steepness is limited at 1:15 while average waves have a steepness of 1:30 (Holthuijsen, 2007).

Wave steepness can be expressed in the following manner:

$$s = \frac{2\pi H_s}{g\, T_0^2}$$

in which H_s is the significant wave height (average height of 33% highest waves) (m)

Wave stability

In the case of wave attack on a sloping structure the most important parameter that gives a relationship between the structure and the wave conditions is the stability number, Ns (-):

$$N_s = \frac{H}{\Delta D}$$

with D is the grain diameter (m)
Δ the relative density $((\rho_s - \rho_w)/\rho_w)$ (-)

Several formulas can describe the stability number. Small values indicate structures which are large and are not expected to move, whereas a large number indicates dynamic slopes with movement of the sediment. In the rock manual (CETMEF, 2012) a classification has been made for the kind of stability used for several structures with 1 for caissons or seawalls, so zero movement. Values from 1 to 4 for statically stable breakwaters, where limited movement is allowed under severe conditions. 3-6 for dynamically stable reshaping structures, of which is expected that in the first extreme conditions the shape will reshape and remain more stable after.

And values from 6 to 20 for dynamic slopes of rock and thereafter 20 to 500 for shingle and gravel beaches. The material cannot withstand the waves without no movement. Sand beaches are last with a N_s>500 where there is significant sediment movement.

Critical flow velocity

Waves and currents induce velocity of the water, resulting in shear stress along the bottom. For each material is searched for which velocity the sediments start moving. Therefore, the critical shear velocity is predicted with the Shields formula (1936), where the Shields parameter is depending on the Reynolds numbers and thus sediment size.

$$u_{*c} = \sqrt{\Delta g D \psi_c}$$

in which u_{*c} is the critical shear velocity
ψ_c is the Shields parameter, where for *sand* beds:
- $\psi = 0.03$: initial movement
- $\psi = 0.05$: limited movement
- $\psi = 0.10$: general movement/transport.

To obtain a critical velocity the critical shear velocity needs to be divided by the dimensionless friction coefficient c_f $(= \sqrt{g}/C)$. C can be found using the Nikuradse-Colebrook (CETMEF, 2012) equation:

$$C = 18\log\left(12R/k_r\right)$$

In which R is the depth which is assumed to be the mean depth over the bed slope. And k_r the roughness factor dependent on the seabed material and stability. For favourable conditions with little movement $k_r = 2D_{n50}$, for a flat bed in a flume, $6D_{n50}$ can be expected (Schiereck & Verhagen, 2012).

The critical velocity is then:

$$u_c = {}^{u_{*c}}/{}_{c_f}$$

This formula is valid for equilibrium flow where the Chézy equation is applicable, which is the case with uniform permanent flow, and thus not automatically applicable for non-uniform flows like waves. From the critical velocity can a sediment size be found, which stability is determined by the chosen Shields parameter (ψ):

$$D = \frac{u_c^2}{\psi \Delta C^2}$$

In case of a non-uniform flow the Izbash (1930) formula is more appropriate. Izbash considers the equilibrium of forces on an individual grain scale while Shields looks on the stress on the bed as a whole. For Izbash is the major drawback that the location of the velocity measurement in unknown and the diameter definition is unclear, which however is less relevant for shallow waters and big stones. The Izbash formula has been found experimentally and is defined as follows:

$$u_c = 1.2\sqrt{2\Delta g d}$$

Critical shear stress

Shear stress is used as a unit for the bed bottom dynamics in N/m^2, as earlier described in 3.1.1. It is dependent on the roughness of the bed and the flow velocity (Schiereck & Verhagen, 2012).

The material, the presence of structures and the stability of the bed influence the roughness. The flow is dependent on the currents and the waves. Wave flow is expressed as the orbit velocity: the velocity the water moves at the bed level. The orbit velocity is dependent on the wave height and water depth. High waves in deep water have less influence on the bottom than the same waves in shallow water. The shear stress can be calculated with two separate parts. One part is found by Shields (1936) for uniform permanent flow and the second, for oscillatory flow, partly by Shields and extended by Jonsson (1967).

Current induced shear stress

The first shear stress part calculated with Shields is for uniform flow and calculated with:

$$\tau = \psi \cdot (\rho_s - \rho_w) g D_n$$

with D the sieve size (m), ρ_s and ρ_w the mass density of the stones and water respectively. The shear stress calculation method is expressed with the dimensionless Shields parameter.

When the Shields parameter is regarded with the initial motion condition (ψ = 0.03), it can also be written as:

$$\tau_{current} = \rho_w g \, {U^2}/{C^2}$$

Where U is the depth-averaged current velocity (m/s) and C the Chézy coefficient ($m^{1/2}$/s). Shields can be used for unidirectional steady flow and quasi-steady flow like tidal flow.

Waves induced shear stress

For shorter period of oscillations, like waves, this method is no longer valid. In that case the Shields curve for unidirectional flow must be introduced with a wave friction factor. The variation of the wave friction factor with relative orbital excursion at the bed under purely oscillatory flow is given by Jonsson (1967):

$$\tau_{waves} = {1}/{2}\, \rho_w c_f u_b^2$$

In which c_f is the friction factor, which empirically has been improved by Soulsby (1997):

$c_f = MIN\left(0.237\left(\frac{a_b}{k_r}\right)^{-0.52}, 0.3\right)$ in which:

$a_b = {0.5\, H_s}/{\sinh(kh)}$ Wave amplitude at seabed

$\hat{u}_\delta = \omega a_b$ Wave speed at bottom

$L_0 = \frac{gT^2}{2\pi}$ Wave length

$$k_r = \begin{bmatrix} 2 - 4 D_{n50} & \frac{fine}{coarse}\, without\ bedform\ roughness \\ 4 - 5\, D_{n50} & van\ Rijn \\ 6\, D_{n50} & Lammers, Boutoski \end{bmatrix} \text{Bottom roughness}$$

$\omega = \frac{2\pi}{T}$ Wave frequency

With the relations described above, the shear stresses can be found on different depths when wave height and current velocity are known. These can be compared with the boundary conditions estimated for the oyster reefs to find potential surfaces for oyster reefs. The boundary conditions for oyster reef are partly described in last paragraph 3.1, but will be further elaborated in the last paragraph of this chapter (3.5).

3.2.2 Cross-section characteristics

To find which location have potential for oysters to grow, are in this section some typical parts and additional features of a cross section described. Here is already a quick scan done to see which parts have potential for oysters to settle.

Crest

The wave overtopping parameter determine the crest height of a dike. Overtopping is the average discharge per meter which reaches the rear of the dike, for instance expressed in m^3/s. The amount of discharge is dependent on the profile and roughness of the used materials in the cross-section. The top will not be interesting for oyster to settle due to its dry conditions and will therefore not be considered further.

Upper slope

The upper slope is defined here as the part of the structure ranging from the crest to the water level, or in the case of a berm, until the top of the berm.

The slope determines the amount of absorbance of the wave energy. Steep slopes have shorter horizontal length over which the energy of waves and current can be absorbed compared to long, plane sandy slopes. Steep slopes coping with more energy on the surface resulting in a local climate which is harder for organisms to settle on. It also affects the amount of material required and the footprint it leaves on the bed. An island with gentle slopes will require a larger surface on the Dogger Bank which disturbs the ecology. Steeper slopes also create less space for the retention of water on the slope in which organisms can settle and all kind of live can occur.

Low slope environments solutions can be completely sediment based. With high energy tidal environments are wide and high sediment volumes necessary to produce equilibrium slopes and shorelines. In case of extreme conditions is also an extra bulk volume required. Systems exposed to a lot of energy are typically low in biomass. For BwN approaches in the North Sea area are soft solutions quite common, like the sand engine and the Hondsbossche and Pettemer sea defence. Sandy beaches results in long foreshore slope, reducing the wave attack on the levee or dunes. This results in additional volume that needs to be nourished. In addition, other BwN applications could be used to reduce the bed slope, for instance vegetation or artificial oyster reefs. Nonetheless might a hard and steep protection be more beneficial for the island, since this can be more stable, creating less dynamic environments and less buffer material is required.

The upper slope will normally not be covered with water and therefore, this location is not expected to have oysters on the revetment. This area however, also called supralittoral, is an ecological interesting zone for seaweeds and lichens due to splashing water (Baptist, van der Meer, & de Vries, 2007).

Berm

A berm is a horizontal part of a levee profile where wave reduction can be obtained. In the design of coastal defences this is used to reduce the size of materials and/or to lower the crest height. The slope of a berm varies between horizontal and 1:15. The width of a berm, is normally not greater than one-quarter of a wave length. The position of the berm is normally around the still water line. It is most effective when close to the still water line. Higher of lower location reduces the effect of wave breaking. At a depth of 2 times the wave height is assumed that berms have no influence on the wave height reduction. A simple determination of the expected wave height on a berm is: $H_{m0} \leqslant 0.5 \bullet$water depth. If the offshore H_{m0} is smaller than half the water depth, H_{m0} remains unchanged. In the other case H_{m0} is the same as half the water depth. The wave period and the angle of wave attack can be assumed to remain unchanged. Typically, one berm is sufficient for reducing the wave heights although, in some cases, two berms can be more efficient due to geo-stability (average slope) or for construction-matters.

Lower slope

This part is assumed to be the part from the waterline or lower side of the berm until the top of the toe. This area is similar to the upper slope although it is mostly located underwater. The slope and materials can, like the upper slope, be varied to obtain different kind of revetments design. The stability of the stones on this part is expressed by the wave stability formula which indicate when the material would move (see paragraph 3.2.1). The lower slope has potential for oysters but is also subjected to wave and current attack.

Toe

Where the slope of the levee changes into the foreshore is the toe located. It is where the transition of the soft foreshore to the hard structure is. Protection at the toe is essential to the stability of the levee since many failure mechanisms are the result of the 'foundation' of the slope (CETMEF, 2012). Two methods can ensure the toe protection: providing sufficient material at the right depth to withstand the scour, or by providing flexible revetment that will move with the scour. Choice of materials can be of a wider selection than that available for slopes, since the toe will in many cases be underwater and partly buried. The scour protection might at potential for oysters since it provides hard substrate at substantial depths. The surface will not be large, probably in the range of 1 time the wave height (DMC, 2014).

Foreshore

The foreshore in front of the coastal defence can be designed horizontal up to a maximal slope of 1:10. It can be defined as a foreshore when it has length of 1 time the wave length. It can be designed deep, shallow or very shallow. With shallow water depths, waves can break on this part and reduce part of their energy. Its provides the largest surface in the cross-section.

Low crested offshore structure

A structure can be made in front of the coastal defence to attenuate waves. Low-crested structures are defined as structures overtopped by waves with their crest level roughly around MSL. They can be emerged or submerged. The height of the breakwater is dependent on the desired wave transmission ($K_t = H_{s,incomming} / H_{s,transmitted}$). This ratio indicates the relation between the incoming wave and the wave behind the structure. The transmission coefficient is next to the height also dependent on the crest width. Long waves can have small influence of the breakwater when the permeability is high. There have been a lot of investigation into the effect of the breakwater height on the transmission coefficient. This resulted in the graph below.

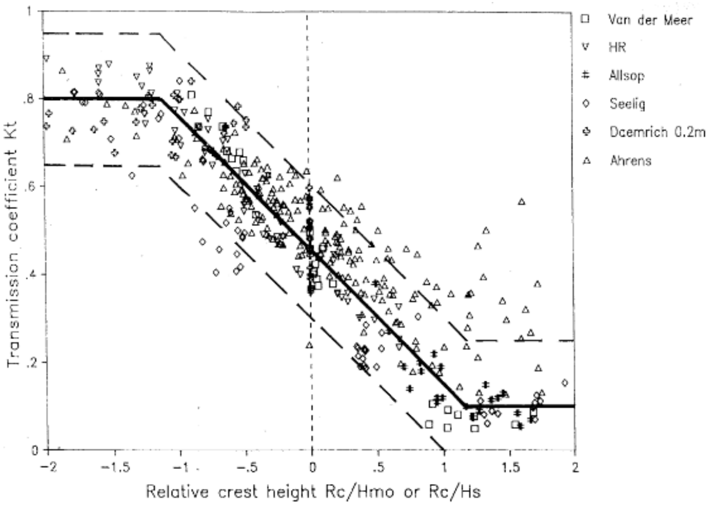


Figure 9: Transmission coefficient for dimensionless crest height (source: CETMEF, 2012)

Low crested structures can create potential natural area on the lower slope of the front and back side of the structure. More potential however, is the space between the structure and the slope of the primary coastal defence which is less exposed and has large surface. The primary defence strength can be decreased due to lower forcing.

The structures can be subdivided in statically stable structures and dynamical stable, of which the last can be called a reef breakwater. Reef kind of structures, consistent out of homogeneous masses of armour stones do not have a filter layer or core. Thereby is some reshaping due to wave action allowed, opposite to statically stable structures. Static low-crested structure materials are not intended to move and are therefore divided into several segments (front, crest and rear) to resist different kinds of forcing.

The discussed graph for wave transmission (Figure 9) can be expressed in the formulas below, different for permeable and impermeable breakwaters. All formulas have been limited by an K_t of $0.075<K_t<0.8$. The slope of the breakwater is assumed to be 1:2 to reduce materials, decreases the footprint and agrees with reference projects. The reef width (B) for smooth structures has a minimum length of H_s. This is for the reefs assumed, except for the wide reefs ($B>10H_s$).

Formula rubble mound and low crested reef:

(d'Angremond K., van der Meer, & R.J. de Jong, 1996):

Permeable narrow reefs: $K_t = -0.4 \frac{R_c}{H_s} + \left(\frac{B}{H_s}\right)^{-0.31} * \left(1 - e^{0.5\xi}\right) * 0.64$

Permeable wide reefs: $K_t = -0.35 \frac{R_c}{H_s} + \left(\frac{B}{H_s}\right)^{-0.65} * \left(1 - e^{0.41\xi}\right) * 0.51$

(CETMEF, 2012):

Impermeable reefs: $$K_t = -0.4\,\frac{R_c}{H_s} + \left(\frac{B}{H_s}\right)^{+0.31} * \left(1 - e^{0.5\xi}\right) * 0.80$$

Smooth low crested: $$K_t = -0.3\,\frac{R_c}{H_s} + \left(1 - e^{0.5\xi}\right) * 0.75$$

In which
R_c is the crest height
ξ is the breaker parameter showing the wave steepness relative to the structures slope $\xi = \frac{\tan\alpha}{\sqrt{H_s/L_0}}$
K_t is the transmission coefficient
B The width of the reef

Since the reef is made for nature enhancing of the island, a more natural reef is favourable. Several reef design opportunities are available effecting the natural value of the reef. A reef can be made permeable and can consist out of one (natural) material which can create shelter and spawning area for other kind of marine species (Baptist et al., 2007). Dynamically stable structures consist out of homogeneous piles of armour stones without a filter layer or core where reshaping by wave action is allowed. The equilibrium crest height and the corresponding wave transmission is the main design parameter. The transmission parameter should be chosen such that favourable conditions are created behind the reef. Therefore, the formula for a permeable narrow reef is used to find the required transmission. The conditions which are favourable are dependent on the depth behind the reef. Deeper water allows higher waves and thus a higher transmission coefficient. Lower depths behind the reef allows a lower transmission coefficient. The required conditions for the designing process will be elaborated in 3.5.

3.2.3 Materials

For the materials two characteristics are considered, first what wave height or current it can resist to contribute in a coastal defence and second how it can contribute to the settlement of oysters.

Poured sediments

Sand and silt (0.002-2mm)

The first discussed material which can be used for the island is sand. The material is widely available in the North Sea and is used for many applications of hydraulic engineering it is also extensively tested on its properties. For sand is no movement unlikely, with a stability number of 1 it would result in a maximum wave height of 1.48 mm with the largest sediments. More relevant is the wave height with a minimum $N_s = 500$ to maximum 2000 for sand what would result in a max wave height of 1.36 to 6.4m with significant to severe particle movement.

Coarse grading (2-180mm)

Natural cobble shores exhibit a remarkable degree of dynamic stability in the face of sustained wave attack. The typical S-shaped cross-shore profile absorbs the wave energy effectively because of the deformability, porosity and thickness of the cobble layer. Consequently, the design concept covering a sand core by a thick layer of gravel (natural pebbles or crushed cobbles) had already been considered in the past as a man-made dynamic shore protection.

Cobble shores are present at the UK coast and other small fields in the North Sea (May & Hansom, 2003). It is a natural and original protection for the North Sea coast and since it creates a habitat that is natural for the North Sea no materials from outside the region needs to import. Especially the gravel fields in front of the English coast are interesting, were layers of 0.5 to 1 meter thick are available. Extraction of these areas is however a threat for the fish population since it is an important spawning area, this area will be relocated (Ecomare, 2015). With gravel of a wide grain size range are holes created what is good for wildlife for shelter and nestling (Lindeboom, 2017). With $N_s = 1$ the maximum wave height for the bigest gravel size would be 29 cm. For a more realistic value of N_s this would be a dynamic gravel slope with $N_s = 6$, the maximum wave height is 1.7m whereby sediment can be transported longshore. For dyanmic beaches are also stability numbers of 500 used, which results for gravel with a size of 10mm in a wave height of 8 meter

Light grading (5-300kg)

Light grading is 5 to 300 kg which can be equal to a sediment size from 18cm to 44cm (Schiereck & Verhagen, 2012). This result in a critical shear velocity of 0.39 to 0.62 m/s ($u_{*c} = \sqrt{\Delta g D \psi_c}$, explained in paragraph 3.1.6. To obtain a critical velocity the shear velocity needs to be divided by the dimensionless friction coefficient c_f (= $\sqrt{g}/C$). C is found using the Nikuradse-Colebrook equation. In which is assumed that $k_r = 6d_{n50}$ and R is 20. This results in a critical velocity of 4.59 (C=36.8) and 5.91 m/s (C=29.8). This formula is valid for equilibrium flow where the Chézy equation is valid, which is the case with uniform permanent flow. In case a uniform flow is not the case the Izbash (1930) formula is more appropriate. The Izbash formula result in the case of light grading in a critical velocity of 2.85 to 4.46 m/s.

With $N_s = 1$ the maximum wave height for the bigest stone size would be 70 cm. For a more realistic value of N_s this would be a dynamically stable reshaping structure with $N_s = 4$, the maximum wave height is 2.8m with only stabilising sediment movement.

Heavy grading (300-15000kg)

Heavy grading is 300 to 1500 kg which can be equal to a sediment size from 65 cm to 174 cm (Schiereck & Verhagen, 2012). This result in a critical shear velocity of 0.75 to 1.23 m/s. In the same manner as the light grading this would result in 6.41 m/s (C=26.8) and 10.6 m/s (C=19.1). The Izbash formula (1930) results in a critical velocity of 5.42 to 8.87 m/s. This sediment type is not very often used in a natural form since the amount and size is not largely available.

With $N_s = 1$ the maximum wave height for the bigest stone size would be 2.8m. For a more realistic value of N_s this would be a statically stable breakwater with $N_s = 2$, the maximum wave height is 5.5m whereby stones almost don't move.

Ecology and Oyster preference

Sand

In the report about flat oysters in offshore wind farms (Smaal et al., 2017) it was suggested that for the North Sea optimal substrate is 'strong silt sand or silt gravel with stones and shells'. The stones and shells are important for favourable recruiting. When the latter is absent, the sediment is the determining factor. Least favourable is fine sand (> 63 μm) and unsuitable is coarse sand (>

210 μm). The top of the Dogger Bank exists mainly out of hard sand with size particles between 150 and 220 μm, mixed with shells. Sand on top of the Dogger Bank however, does not contain much silt that is transported to the Dogger Bank boundaries. Initiating oyster settlement on a sandy bed is however difficult due to the dynamic character. Once oysters have settled, their larvae can spread on the shells of others. Stones or shells are therefore useful to start reef building.

Coarse grading

Like sand, gravel is also present in the North Sea bed and thus presents natural habitat for the species living there. In the English channel, large gravel beds are located that probably can be utilised by oysters with higher strength compared to oysters on sandy beds. Gravel beds support larger biodiversity compared to sand and are an important spawning ground for several North Sea fish species (Bos, Dijkman, & Cremer, 2008).

Light grading

Light grading stones provide a more stable seabed compared to gravel or sand. These kinds of stones can be found in several sizes in irregular concentrations on several areas on the Dogger Bank (Coolen, 2017). They create small scale holes and crevices and attachment/settlement substrate increasing the small-scale habitat complexity. This is valuable following the design principles stated for eco-friendly scour protection in the North Sea (Lengkeek et al., 2017). Holes and crevices of a few centimetres to decimetres may improve the habitat of egg-, larvae- or juvenile stages of many species and for some small adult species.

Heavy grading

This size of rock is not or is not very rarely present in the North Sea and therefore cannot be a natural material. Large rocks can provide however large holes and crevices that are very valuable as shelter for large mobile species (Lengkeek et al., 2017). Holes with a size of 1 to 2 meter in diameter create higher habitat complexity for a large scale.

Concrete units

Random placed

Concrete units can be considered very broad, since concrete is able to be cast in many ways. An example could be Xblocs, cubes, Accropode or Dolosse, which traditionally are used as armour stone. Artificial armour units may be required for more severe design conditions or at sites where natural armour stone of sufficient size, quantity and quality is not available.

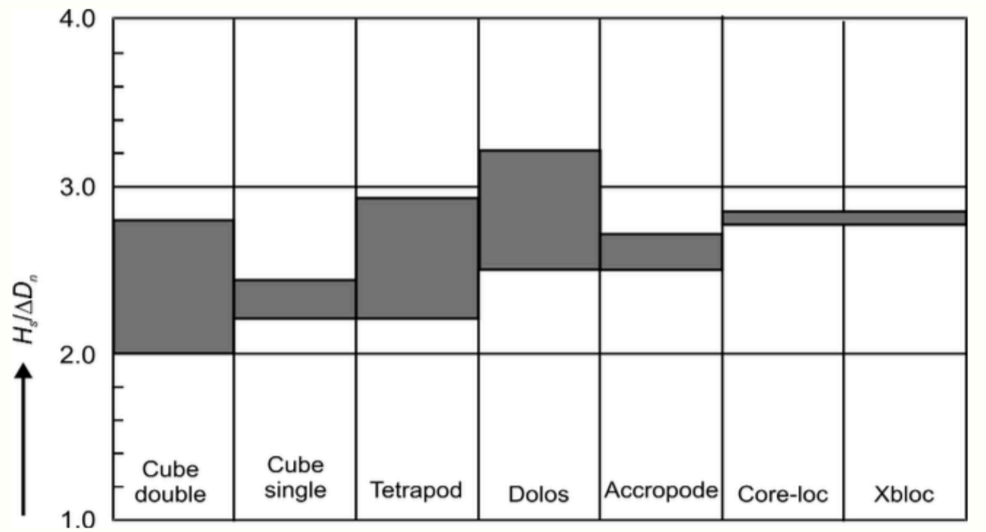


Figure 10: Stability different concrete units (source: Pilarezyk, 1995)

The concrete units can obtain stability through their weight, interlocking or friction, or combination of those. The units are often constructed in a single layer or double layer. For cubes D_n is the side of the cube, for tetrapods D_n= 0.65D (for Xblocs is the same value assumed), where D is the height of the unit, for accropode D_n= 0.7D and for Dolosse D_{n^n} = 0.54D (Jentsje W van der Meer, 1998). In the graph above is showed what the stability numbers of the different concrete units are (Figure 10).

The Xbloc manual (DMC, 2014) has drawn up a list of Xbloc types with the corresponding design wave height and weight. The lightest Xbloc is heavier than the heaviest rock grading and thus assumed to withstand at least the flow velocity of 8.87 m/s since the diameter is hard to determine. The highest design wave height an Xbloc can resist is following the table 10.0m, when it has a weight of 48t.

Placed revetment

The stability of uniformly placed hollow units is based on friction between neighbouring blocks and depends primarily on layer thickness and partly also on unit weight. The friction between uniformly placed units varies much less than interlocking between randomly placed units. The resistance of a friction type armour layer is therefore more homogeneous than for interlocking-type armour layers and is very stable. Examples of concrete armour units are Basalton, Hydroblock and Hillblock. These units have a height between 20 to 50 cm. The Hillblock have been tested at the flume of Deltares to have a stability parameter of at least 5.5 (van Steeg, 2012). With the largest size block this would result in a critical wave height of 3.5 meter.

Reef blocks or balls

Reef Balls are designed so that over half of the weight is in the bottom near the sea floor (Reef Ball Foundation, n.d.). Reef Balls have showed to withstand tropical storms in depths of 6 meter without anchors. Reef Balls are stable because the opening in the top of the unit breaks up the lifting force of the hydrofoil effect common to dome shapes. Side holes are wider near the centre of the walls and narrow near the units' surface. This feature creates miniature vortexes which further reduce lifting forces and bring rich nutrients to life on the reef. Reef Balls can be cast up to double the standard weight to accommodate high energy zones, or they can be cast at 75% of the standard weight to save concrete for bay, deep or protected water locations.

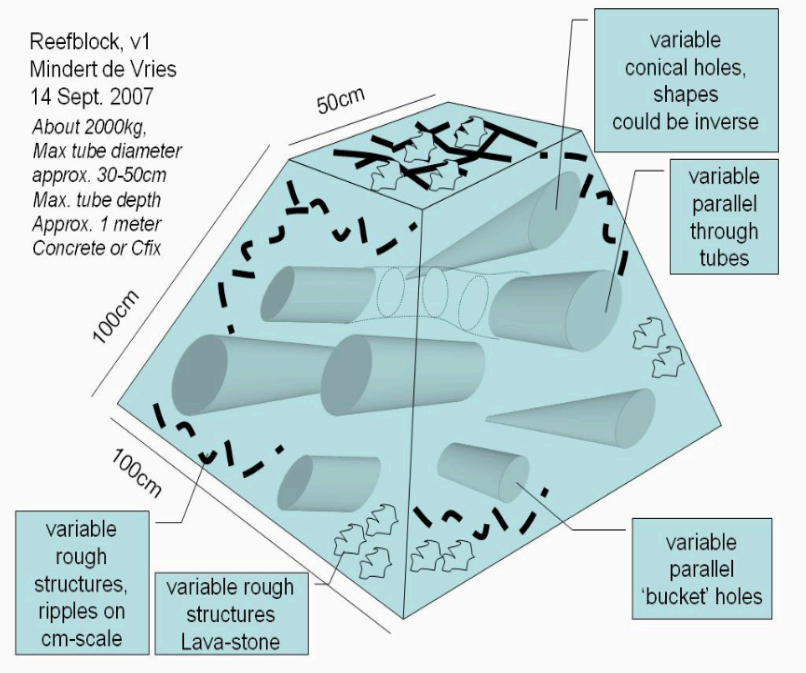


Figure 11: Reefblock (source: de Vries, 2007)

Ecology and Oyster preference

Concrete can be disadvantage for the settlement of species due to the chemical composition of the blocks. Oyster larvae have the sensory organ that allow them to "feel" the substrate, and if it is not similar to the natural oyster shells the larvae may not settle on the substrate. Moreover, the smoothness of the concrete structures can avoid some species to settle and attain enough grip. Both disadvantages can however also be conversed. Chalk rich materials are attractive for shell species to settle on (Lengkeek et al., 2017). Concrete can be enriched with chalk to increase the amount of settlement. The units can be mounted with rough outside walls or crevices to create grip for species. Concrete units can create, with the discussed additions, an improved habitat quality by creating large or small holes and surface for shells to settle on. Placed revetment however does not offer holes and shelter areas and is therefore less attractive for the marine ecology. With a rough surface, it can nevertheless provide a stable substrate for organisms to settle on.

Communities developing on concrete are typically less diverse communities attached to natural materials. Commonly the concrete in marine areas is dominated by nuisance and invasive species

(Glasby et al., 2007). This predominantly resulted from the unique physical characteristics of the concrete structures, mainly composition and design. The design often includes highly inclined, homogeneous surfaces with minimal surface complexity, compressing the intertidal zone to a narrow belt which supports only highly tolerant species (Chapman and Underwood, 2011). Moreover, over 50% of coastal structures are made of Portland cement, which is known as a poor substrate in terms of biological recruitment, presumably due to high surface alkalinity (pH ~13 compared to ~8 of seawater) and presence of compounds that are toxic to marine life (Lukens and Selberg., 2004, EBM, 2004). The ability of concrete structures to provide ecosystem services like those offered by natural habitats is severely compromised. Slight modifications to concrete based structures, like concrete composition, surface texture and macro-design, have the potential to elevate their ability to support engineering species forming biogenic build-up, as well as associated filter feeding assemblages (Perkol-Finkel & Sella, 2014)

Asphalt

(Pilarezyk, 1995) In the case of open stone asphalt placed on sand asphalt filter, the thickness of the system may be defined as the total thickness of both layers. For the edges of all bituminous systems the $\psi_c = 2$ should be applied. Because of possibility of liquefaction, the open stone asphalt on geotextile and sand is recommended only up to H_s= 2 m. For H_s> 2 m the sand-bitumen filter under the top layer of open stone-asphalt is recommended. Due to the limited resistance of open stone-asphalt against surface erosion (max. velocity, u = 7 m/s) this system can be applied up to H_s= 3 m, and, for a less frequent wave loading, up to $H_s = 4$ m. In general, the resistance of the sand-asphalt is limited to the velocity of 3 m/s and the wave height of 1.5 m (or H_s< 2 for less frequent loading). Currents are not usually a determining load in the design of asphalt concrete. For practical reasons, the minimum thickness of open stone asphalt is 0.08 m if prefabricated and 0.10 m if placed in situ. However, the more common thickness is respectively 0.10 and 0.15 m. Bituminous plate-systems (especially impermeable ones) should also be examined concerning the allowable stresses and strains (bending moments) and the uplift criterion. The calculation methods can be found in TAW (1985).

Ecology and Oyster preference

Asphalt is not thought to provide a suitable habitat for many algae species due to the suboptimal environmental conditions it provides, such as a high temperature and a slippery surface. There are several design options for mastic asphalt, most including some sort of overlay on rubble stones. Traditionally, rubble stones were entirely overlaid with mastic asphalt, leaving no clean spaces on the rubble stones. Rubble stones are thought to be more suitable for vegetation to grow on then the mastic asphalt itself. Therefore, to reduce the amount of mastic asphalt surface heads of the rubble stones were brushed clean after the overlay, resulting in so called "clean heads" of the rubble stones (Jentink, 2005). This application of mastic asphalt is thought to be better for ecology. Another way to provide more suitable surface for biota to attach, is by topping mastic asphalt overlays with lava-stones. The porous material can retain more water and reaches less high temperatures than the asphalt itself. Furthermore, the material is more irregular in surface and as a result, it is thought to offer better circumstances for biota to attach (Meijer & Didderen, 2012).

Gabions

Gabions are steel mesh cages that are filled with rocks, concrete and sometimes aggregates, and used to stabilise vulnerable areas, by absorbing wave energy. They can project out at right angles from the coastline like groins, or can be constructed as retained walls, battered or stepped back rather than being stacked vertically. The strength of the wire used to tie the cages together is the critical factor. Galvanised steel wire is commonly used, but stainless steel and PVC-coated wire can also be used.

The primarily requirement is that the gabion or mattress of thickness "d" will be stable as a unit (Pilarezyk, 1995). The thickness of the mattress can be related to the stone size D. In most cases it is sufficient to use two layers of stone in a mattress (d = 1.8D) and the upgrading factor can be recommended in the range $2 < \psi_c < 3$ (max). The secondary requirement is that the movement of stones in the basket should not be too high because of the possible deformation of baskets and the loading on the mesh-wires. To avoid the situation that the basket of a required thickness "d" will be filled by too fine material, the second criterion, related to D, have been formulated. The choice of ψ_c= 2 to 2.5 related to D means, that the level of loading of the individual stones in the basket will be limited roughly to twice the loading at the incipient motion conditions. Thus: D (dynamic stable) when ψ_c< 2.5, and d (stable) when d > 1.8 D. In more than 2-layer systems it is preferably to use a finer stone below the top layers (i.e. up to D/5) to create a better filter function and to diminish the hydraulic gradients at the surface of subsoil. The formulations for gabions and mattresses are only valid for waves with a height up to H_s=1.5 m, or for less frequent waves up to H_s = 2.0 m. In either case it is important that both the subsoil and the stone infill are adequately compacted. When the current exceeds 3 m/s or the wave height exceeds 1 m then a fine granular sublayer (about 0.2 m thick) should be incorporated. In other cases, it is satisfactory to place the mattress directly onto the geotextile and compacted subsoil.

Ecology and Oyster preference

In restoration projects, gabions are often used as settlement substrate to enhance the settlement of larvae. Gabions can be filled with (oyster) shells, which is the favourite settlement substrate for oysters. The fixed cages with shells create a stronger and more stable substrate compared to lose shells. In case gabions are filled with wide ranged stones, the circumstances can be created with relative stable holes and crevice. This can be valuable for small fishes to shelter or use as spawning grounds. The gabions were successfully used to “grow” a reef in the Ecoshape pilot project in Eastern Scheldt estuary (Ecoshape, 2018).

A different kind of gabion which can be used to enhance the settlement of oysters on the seabed are Biodegradable Elements for Starting Ecosystems (BESE). These ‘crates’ that temporarily can facilitate habitat modifiers, bridge critical thresholds and enabling ecosystem development in mostly wetlands. The biopolymers crates can create optimal circumstances for oysters. During the time, the crates provide settlement material and shelter, it slowly dissolves into the water. In the end only the oyster reefs are left behind, which further expand on the seabed and the other oyster shells (Didderen, Lengkeek, & Teunis, 2016).

3.3 Return periods

Return period is a chosen interval in which statistically an extreme value occurs. The return period shows the value which can be expected and the risk associated with this value. The return period determines the design of the cross-section to protect against extreme events. The return periods for coastal defences is dependent on the acceptable risk. In the Netherlands this is for large urban areas a protection of 10,000 years; less densely populated areas 4,000 years; and protection for high river discharge (without threat of storm surge) of 1,250 years (J.W. Van der Meer et al., 2016). For the design of crucial energy infrastructure, what will be located on the island, is chosen for a return period of 10,000 years. This is similar to reference projects like the Maasvlakte 2 and Flyland (see Appendix B). Since no data for the last 10,000 years is available the value corresponding to this return period will have to be found in an extreme value analysis.

In this thesis is search for the location where oysters can be found in the design. The oysters are not assumed as an essential part of the coastal defence. A return period of 10,000 year will result in high waves and currents. By increasing the acceptable risk of oysters flowing away can the return period be decreased. Since oysters need time to settle, to grow and to start reproduction, a minimum return period is necessary. Flat oysters need 3 years to become mature and start reproduction. Then the new generation needs again 3 years before reproduction of the new and old generation can proceed. Ecologists discussed that it takes 7 years before it is visible that an oyster reef is self-sustaining (Hanhock, 2017). It is unknown how often natural reef got damaged exactly. Senior ecologist Gotjé (2017) from Witteveen+Bos advised a return period between 5 to 10 years. Taking a conservative value, to give oysters enough time to settle and reproduction, a return period of 10 years is chosen. There is a chance that once in the 10 years the reef got damaged.

3.4 Extreme Value Analysis

It has been established in the previous paragraph that that for coastal engineering a design period of 1:10.000 year is common. However, for oysters are smaller return period is realistic since damage may occur. Therefore, a return value of 1:10 has been assumed in the previous paragraph. For the waves and currents the return values are analysed. Since data has been measured by Argoss for a period of 22.4 year an extreme value analysis (EVA) is performed for the wave heights. For the currents was a study performed by Forewind (2012) for the depth-averaged extreme tidal current velocities on different location of the Dogger Bank.

The EVA can be done with several methods but the most common method is the Peak Over Threshold (POT). For this method, a threshold is chosen above which measurements of the Argoss data set are selected and used. The threshold is chosen to find the distribution of the extreme event, or storms only. These storms are assumed to last 6 hours and occur 3 to 6 times a year. For these extreme measures is the best distribution the Weibull distribution to extrapolate the measurements into a 1:10 and 1:10,000 years return period. A more precise explanation of the extreme value analyse can be found in Appendix D. The values have been searched in bins of 30 degrees to see in which direction the waves can be expected. In Table 3 are the results showed for the return period waves and currents. The study for the expected currents in the different directions by Forewind (2012) is done until a maximum return period of

1:100 year. Since no other current data is available these are the used data.

	Extreme Value Analyse				Argoss Waves (22.4 y measurements)	
Direction	1:10y		1:100y	1:10,000y	H_s (mean)	H_s (max value)
Degrees	Currents (m/s)	Waves (m)	Currents (m/s)	Waves (m)	m	m
0-30 NE	0.64	5.1	0.69	7.6	1.1	5.2
30-60 NE	0.70	5.3	0.78	8.2	1.2	5.64
60-90 NE	0.62	4.3	0.70	5.4	1.3	4.58
90-120 SE	0.60	4.7	0.68	6.2	1.4	4.9
120-150 SE	0.75	4.0	0.85	4.8	1.2	4.34
150-180 SE	0.84	4.8	0.94	7.5	1.3	5.2
180-210 SW	0.80	5.3	0.89	6.9	1.5	5.55
210-240 SW	0.63	5.6	0.69	7.2	1.6	5.77
240-270 SW	0.50	6.2	0.55	9.3	1.6	6.57
270-300 NW	0.46	6.0	0.51	7.9	1.7	6.52
300-330 NW	0.46	7.0	0.50	10.9	1.6	7.14
330-360 NW	0.57	7.5	0.61	11.9	1.9	7.61

Table 3: Significant wave height and depth-averaged current velocity from different directions for different return values.

3.5 Shear stress concept

In the last paragraphs the boundary conditions for oysters are discussed and the physical conditions quantified. Subsequently, the characteristics of the different parts in the cross-section were discussed and how the different parts can contribute to both oyster settlement and coastal defence. Since no clear boundaries exist for describing the maximum wave height and currents for oyster reefs, an estimation has been made. The estimation for the boundary conditions is expressed in shear stress to make it independent of the depth. Once the shear stress has been established on the different parts of the cross-section it can be compared with the estimated boundary conditions of the oyster reefs. When the mean and critical shear stresses match the part in the cross section might have potential for oyster reefs in terms of abiotic factors.

3.5.1 Roughness oyster beds

The boundary conditions discussed in paragraph 3.1.1 gave the shear stress of the historical oyster reef location based on shear stress models for the EIA sand extraction. The shear stress is dependent on the roughness of the bed, which is different for oysters and sand (Alferink, 2016). The roughness affects the friction factor and thus the shear stress. The roughness can be expressed with two different parameters:

- The bottom roughness k_r which is dependent on the D_{n50} times a factor influenced by the bed stability.
- The bed roughness length z_0, the reference level near the bed (m), defined as the level at which the velocity is zero.

The relation between the two values can be described with $z_0 = k_r/30$.

The roughness length of oyster has been described in a report of Alferink (2016). De Vries et al. (2012) investigated the influence of traits of mussels and oysters on the hydrodynamics and bed forms. In a flume, the flow velocity was measured for several discharges on different depths. The average flow velocity above the flat bottom and above the mussel or oyster bed is different. This is the result of the changed velocity profile due to the higher roughness of the bed. From the velocity profile over the depth can the roughness length can be determined (results are given in Figure 12).

		Van Duren						De Vries		
		Flat bottom			Mussel bed			Oyster bed		
		L	M	H	L	M	H	L	M	H
z_0	$[mm]$	0.02	0.011	0.06	0.67	1.30	3.20	13.14	14.45	15.17
u_*	$[mm\ s^{-1}]$	2.2	5.7	14.9	3.9	9.1	36.3	26.9	60.3	88.5
$\overline{u}$	$[m\ s^{-1}]$	0.047	0.104	0.291	0.051	0.106	0.34	0.107	0.226	0.321
Q	$[m^3\ s^{-1}]$	0.011	0.024	0.064	0.011	0.025	0.066	0.009	0.018	0.026

Figure 12: An overview of the determined roughness length (z_0), shear velocity (u_*), average flow velocity and discharge (Q)

In the thesis, the results were compared with simulated results of flows over oyster and mussel bed. The vertical velocity profile of the simulated results of Alferink (2016) showed good agreement with the measurements of de Vries et al. (2012).

The other method for assuming the roughness is with the bottom roughness. This factor k_r can be determined with a factor times D_{50}. This factor is dependent on the bed stability, which is 2 for a stable bed profile and can become 6 for unstable beds. When an oyster bed is assumed to be stable and with a height between 80 and 200 mm the bottom roughness will be in a range of 160 and 400 mm, assumed that D_{50} is similar to the oyster height. Expressed in roughness length (z_0) it is between 5.3 and 13.3 mm. The roughness length calculated with the largest size oyster is similar to the measurements of de Vries et al. (2012). Since there will be large and small oysters growing in the bed, orientated in different directions, the roughness can vary. For further calculations, the chosen roughness length (z_0) was 13.3 mm for the lower region of the measurements of de Vries et al. (2012) and in the higher region with the calculating method with the factor k_r with the largest size shells.

3.5.2 Shear stress boundary conditions

With the roughness length known, the old maps with historical locations of oysters and the bottom shear stress model are now compared. On the edges of the historical oyster ground an increasing shear stress is present. This analysis shows that the optimal mean shear stress is between 0.25 and 0.6 N/m^2. On the borders of the historic located reefs are values between 0.6 and 1.0 N/m^2 found and are considered sub-optimal. Since the roughness of sand is different to oyster reefs, an assumption was that they are forced with different shear stresses. To obtain the oyster reef boundary shear stresses, the wave data of a location on the edge of the oyster grounds was collected from Argoss. The location is chosen at the site where the new wind farms of Gemini will be build. In the report of Smaal et al. (2017) it was described that the maximum shear stress was 7.0 N/m^2 for this location.

With the available wave data and depth, the mean and critical shear stress which match with the found values of Smaal et al. (2017) was searched for. The roughness value of sand varied in order to obtain the right shear stress. With a roughness length of 0.0612 mm the mean and maximum shear stress showed good agreements. With the same data and a roughness length of 13.3 mm the mean and maximum shear stresses can be found for a location existing out of oyster beds. The mean shear stress for oysters should stay between 2.5 and 10.3 N/m^2 for successful oyster reefs. The maximum shear stress for oysters which has been found to be 7 N/m^2 for this sandy location would be 119.8 N/m^2 for oyster reefs. This value was not normative for oyster reefs since these shear stresses can also be found on locations without oysters.

When the roughness of oyster beds is used for the shear stress of oscillatory flow with varying wave height and periods, a graph can be made for the shear stress for different depths. The wave periods are determining the wave length and correspondingly the wave number. The wave periods are estimated from the steepness of the Dogger Bank waves, found in Appendix C. The wave length is calculated iteratively.

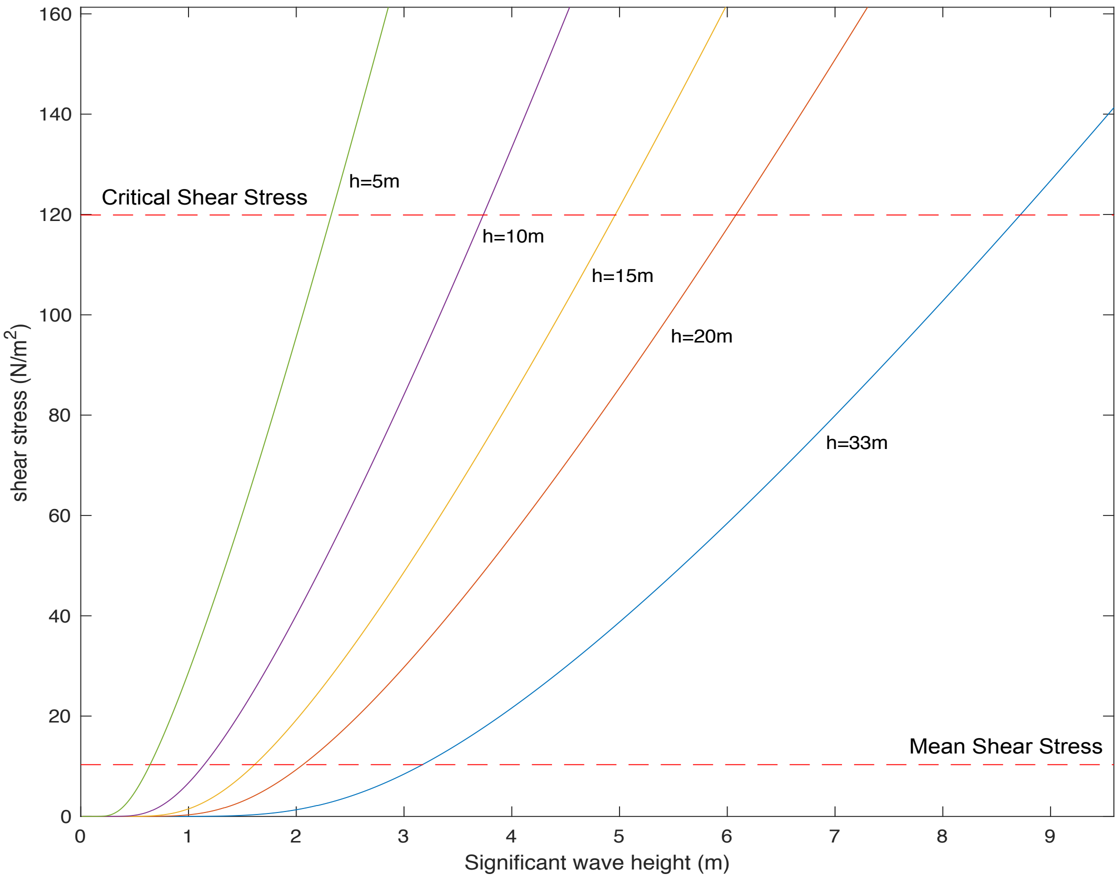


Figure 13: shear stress estimation for different wave heights and water depths for oysters with the boundary mean shear stress for the average waves and maximum shear stress for the 1:10y return significant wave.

The graph above (Figure 13) shows the hypothetical shear stresses different wave heights will cause on different depths. This graph shows two different things. First, which significant wave will be critical in the cross section to obtain potential surface where oysters can settle. To calculate the critical shear stress the values found in the extreme value analysis will be used with the period abstracted from the expected wave steepness. Secondly the mean shear stress can be found for the specific location. The striped horizontal lines represent the extreme and mean shear stresses which are acceptable for oysters to settle. The mean shear stress is based on the average wave conditions of the total wave data that is selected for that specific location. The critical shear stress is the stress which will break down the oyster reef. This is maximum shear stress is compared with shear stress the 1:10y significant wave can cause on this depth. When the induced shear stress is below this value the location is seen as suitable for oyster reefs. The mean shear stress appeared to have a significant effect on the occurrence of oyster reefs in the shear stress model which was compared with the historic maps with oyster reefs (paragraph 3.1.1). This is probably caused due an optimal flow with nutrients, oyster larvae and sediments. The mean shear stress is not calculated with the mean significant wave height and wave peak period but with the mean of the shear stresses calculated with all available data. Since the shear stress is dependent on both the wave period and significant wave height, this gives a more realistic result.

Knowing the boundary conditions for the shear stresses for the mean and critical conditions can the present shear stress be calculated with the known wave and current climate. For the total shear stress is the wave shear stress and tidal shear stress summed for both the mean as maximum value. Thereby is the formula for combined mean effective shear stress of Bijker (1967) neglected since the wave shear stresses are continuously higher than the current shear stress (CETMEF, 2012). Hereby is assumed that the currents around the island equal to the currents when no island was present.

With the boundary shear stresses and the shear stresses which can be calculated from the return periods and the Argos database, a quantitative model is made that can analyse which locations around the island are suitable for the NBDE oyster reefs.

4.

Cross-sectional Design and Evaluation

In order to find opportunities for the NBDE, taking the potential for occurrence of oyster beds in the cross-section as the baseline, this chapter compares the shear stresses on the cross section with the boundary conditions for successful oyster beds. After finding the NBDE, oyster reefs, in chapter 2, a method which quantifies the success off oyster reefs on the coastal profiles is made in chapter 3. In this chapter, the potential locations for the NBDE are searched and when possible optimised. The first cross-section evaluated is a typical design which would be plausible when no nature enhancing is considered. For the cross-sectional design the 1 in 10,000 year exceedance will be used, established in chapter 3. For the potential areas of oyster beds the 1 in 10 year return values are used. Subsequently, measures are discussed which can enlarge the potential surface for oyster beds. The effects of these measures are discussed and their contribution to the oyster bed's suitable surface. Lastly, the opportunities for the typical design and the nature enhancing measures are discussed when the wave conditions around the island are considered.

4.1 Typical cross-section potential

First is started with a typical cross section which would traditionally be used for coastal defences. Armor layers in severe design conditions, where natural armour stones of the right size are not available, are normally equipped with artificial units (CETMEF, 2012). Example of these are concrete element like xblocs, tetrapods and cubes. These are traditionally used in order to protect new coasts like artificial islands and land extensions. As mentioned, there are several concrete structures available, but assumed is that the revetment is prepared with a Xbloc layer. Xblocs are chosen since there is a useful design guideline available for this kind of artificial units. Other unit could be used as well but the choice has no significant importance on the cross-sectional design. For nature enhancing of the coastal defence is therefore no distinction made. The protection is classified as statically stable structure where the mass of each individual elements must be large enough to withstand waves of the designed conditions. The design parameter is expressed in damage instead of stability, since no movement is allowed. The size of the units is determined with the Hudson formula which has a parameter K which includes all different variables like permeability, wave period, number of waves and the damage level. The allowed damage is 5% but the practical meaning of this is unclear.

Crest levels have been selected to ensure the acceptable overtopping during the design storm. The height above mean water level to satisfy this condition depends on the wave run up which is a function of the wave height, type of slope protection and gradient of the slope. The design is calculated for the 1 in 10,000 year conditions, similar to the Maasvlakte 2 and Flyland (Appendix B.2 and B.3). The acceptable overtopping is 10 l/s like the Maasvlakte 2. An Xbloc revetment has typically an armour slope of 1:1.33 or 1:1.5, in this situation is 1:1.5 assumed to keep the islands footprint as small as possible. The design is executed with formulas formulated in the Xbloc manual (DMC, 2014) and EurOtop manual (J.W. Van der Meer et al., 2016).

For the design of the cross section are the following parameters assumed. The depth of the Dogger Bank is mostly between 25-30 meter (paragraph 2.1.1) with outliers to 14-16 meters. Since no exact location is selected, a depth of 25 m is assumed. This value is chosen because a shallow water depth will be economical since less volume is required but still a large area on the Dogger Bank is available. The tidal range is between -0.9 and +0.9. The storm surge 1.15 m and the sea level rise due to climate change is an increased level of 0.38 used.

For detailed design of the island traditional coastal defence is referred to Appendix C.1. For the design of a coastal defence for the most extreme waves was found that the required concrete unit volumes are bigger than normally available. To reduce the element sizes is a berm recommended. The design of Flyland is used as a reference for the design of the Dogger Bank island. Flyland is a conceptual island in the North Sea which would be equipped with the Netherlands national airport (Waterloopkundig laboratorium, 1997). The cross section, for the most exposed side, has in this design two berms, each 67-meter-long, on a depth of 0 m MSL and -10 m MSL. Two berms are made in this design to create extra hard substrate surface which can be beneficial for the North Sea ecology and the stability of the total structure. This design can also have an advantage during the construction of the island, where each berm is built during different time intervals. With this measure, the Xbloc volumes can be reduced to the largest available size. Initially all slopes will have an angle of 1:1.5. See Figure 14 for the design.

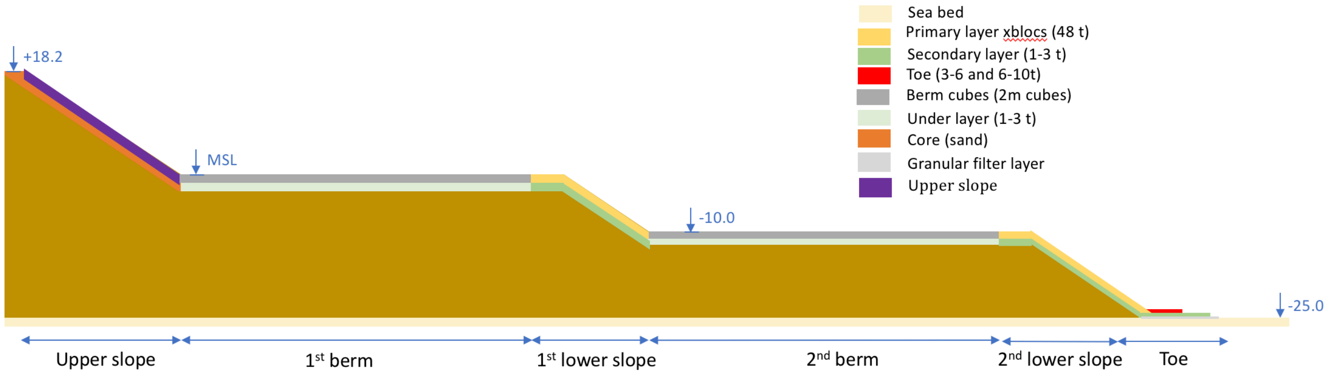


Figure 14: Cross-section with an artificial foreshore for the Northwest flank of the island

In this design is searched for the potential for oyster reefs with return periods of 1:10,000 and 1:10 years on the different parts of the revetment. When 1:10,000 year significant wave conditions are exceeding the shear stress boundary conditions the 1:10y conditions are still satisfactory. Therefore, the shear stress approach is used as explained in paragraph 3.5.

4.1.1 Upper slope

The upper slope of the cross-section has not to deal with much forcing due to waves. Because much of the waves strength got lost when propagating over the berms, no large concrete units are necessary on this part of the cross-section. The lowest section of the upper slope is only flooded during high water and storm surge and with waves hitting the structure. This area is therefore not interesting for settlement of oysters, since a minimum depth of 1 m is required. The upper slope can be interesting zone, called the supralittoral, for other kinds of nature due to spraying saltwater (Baptist et al., 2007).

4.1.2 Berm

In the traditional design are two berms located which contribute to the coastal defence by attenuating the waves so smaller volumes of concrete units are sufficient. The berms, each 67 m long, provide a wide area of hard surface where oyster settlement might be potential. The berm on 0 m MSL is not fulfilling the requirement of 1 m below MSL but the berm on -10 m MSL does. To find the forcing on this part of berm is the shear stress calculated. Assuming a depth limiting wave height of 0.5 times the water depth the expected maximum wave height is 6.25 m. The wave period is assumed to remain constant. An oyster reef on this depth would result in a shear stress of 242.2 N/m^2. This is double the amount of maximum shear stress which is assumed the maximum shear stress on the historical oyster grounds. While the 1:10,000 year condition is not the limiting condition for the settlement of oysters a return period of 1:10 y was suggested. The maximum height of 1:10y wave at the most exposed side is 7.5 m so a depth limited wave of 6.25 m is still propagating over the berm. The wave length and period are shorter for this kind of waves since the offshore wave is lower. The expected shear stress is 252.6 N/m^{2}which is higher than the 1:10,000 year conditions since the wave height is the same while the wave period and length is shorter. The berm can thus not be expected to be a surface where oyster can settle. Calculating the shear stress with the Argoss data, for the assumed depths a mean shear stress of 33.9 N/m^{2}is found, which again indicates that this location is unsuitable.

4.1.3 Lower slope

In the design are two slopes located below water, of which one is located between 0 and -10 m MSL and one between -10 and -25 m MSL. The berm at -10 m MSL has shown not suitable for oyster reefs and therefore the slope between is 0 and -10 m MSL is considered the same. The slope between -10 and -25 has a maximum shear stress of 118.5 N/m^2 at -25 meters and a shear stress of 331.9 N/m^2 at -10 m MSL for 1:10y significant wave conditions. The transition is located at -25 m MSL for the maximum shear stress and for the mean shear stress at -22 m MSL. Therefore, possibilities are only available on the deepest part of the lower slope. This part is armed with hard substrate to withstand the wave climate, so assumed extra suitable for initial oyster settlement. The maximum depth averaged current in 10 y around the island is 0.84 m/s. This result in in a shear stress of 2.74 N/m^2 which has no significant influence for the stability of the oyster beds. Therefore, concluded is that the current will not have enough influence to stop oysters from growing on the revetment on this location.

4.1.4 Toe

In the evaluation for the lower slope of the coastal defence has been found that below a depth of -25 m MSL the chances for oyster reefs are available. The toe in the typical design has therefore potential to create oyster reefs, assuming an initial depth of 25.0 m and the most extreme wave orientation. Since the toe exists out of hard substrate, the oysters can have advantage of the stable bed to settle on.

4.1.5 Foreshore

In the typical design, made in this paragraph is no adjustment made in the foreshore. The foreshore in this case is the natural bed of the Dogger Bank. When the island is located at a depth of 25 meter, the surrounded area can have potential for oyster reefs. The success of the reefs will be dependent on the biotic factors and the chance of successful settlement. Sandy substrate is not an ideal substrate for successful settlement. However, near the island there cannot be fishing activities and therefore the bed will be undisturbed. Once oysters can settle on this sandy bed the chance of expansion increases.

4.2 Optimisation for Nature Based Design Element

From last paragraph, it was found that in a design for the coastal defence of an artificial island in the North Sea, a chance for oyster reefs is located at a depth of -25.0 m MSL. This is valid for the side with the highest extreme significant waves. The settlement of oysters might have potential on the toe and foreshore due to the presence of hard substrate. The foreshore has positive hydrodynamics on the bed but due to the ‘soft’ substrate the settlement of oysters can be uncertain. When only the toe can be potentially successful for oysters, the surface which can add value to the nature enhancing is in de order of several meters per m coastal defence.

Subsequently, island design at shallower depths will be more economical since less filling material is needed. Since more shallow water depths are available on the Dogger Bank, this aspect of the design can be promising. For an island in more shallow water (shallower than -25.0 mMSL) disappears however the potential for oyster reefs due to exceeding shear stresses. The nature based design element in the typical design is found to be scarce, or when the island is built at more shallow water depths there are even none. This paragraph searches for measures that can change the physical circumstances into favourable conditions such that oysters can settle and grow. Measures which are discussed are an adapted berm height, extended toe/foreshore and offshore reef. These measures are chosen since these adjust the hydrodynamics or add hard substrate to the profile. These measures are again discussed for the side of the island where the highest waves are affecting the coast.

4.2.1 Berm height

First measure which is discussed is changing the level of the berm. Since a berm has significant length in the cross-section, a level where oyster suitable conditions are available is favourable. Changing the height of the berm will affects the wave attenuation negatively. Berm levels around mean sea level is optimal for wave breaking so deviating from this level will demand heavier coastal defence. The favourable conditions are created at -25 m MSL. A berm on this level will not have effects on the waves. For the wave conditions on the north-west side can therefore be concluded that berms cannot contribute to nature enhancing opportunities.

4.2.2 Toe and foreshore slope

From the typical design was found that the lower slope, toe and foreshore has potential for oyster settlement, when located below -25 m MSL. The lower slope is made with Xblocs, the toe from heavy grading (3-6t and 6-10t) and some granular filter layer and the foreshore is assumed to be the original bed which existed out of sand. With the creation of a slope in front of the toe, the Xbloc revetment can be made smaller and a larger surface where oysters can settle is created. The maximum gradient for depth variation for Xblocs is 1:10. A slope steeper than 1:10 is also the boundary condition for the Dogger Bank. A slope flatter than 1:10 fits in the geometry of the Dogger Bank.

Adjusting the foreshore at -25 m MSL creates a surface which might be potential for oyster reefs. The foreshore further stabilises the coastal defence and any scour in front of the embankment. More gentle slopes will provide more surface for the NBDE but volumes and the footprint will increase as well. The material used for this part must be stable enough to withstand the waves and provide optimal conditions where oysters can settle. Since the toe is seen as the foundation of the slope it should be strong enough to remain on its place or provide a buffer which allow some damage or movement. The protection located at the toe can remain the same size (3-6 and 6-10t) but the area in front and below the toe can be made of smaller gradients. Smaller gradients will be cheaper and more natural for the North Sea.

With the Shields (1936) formula can be assumed which size rock could be used in order to create a dynamically stable revetment ($D_{n50} = \frac{\bar{u}_c^2}{\theta \Delta C^2}$ in which $\bar{u}$ is the velocity caused by orbital motion of waves) (CETMEF, 2012). For a dynamically stable bed ($\theta = 2.5$) on a depth of 25 m, significant wave height of 11.9m, peak period of 15.1 s and $k_r = 6D_{50}$ is a sediment diameter found of $D_{n50} = 0.35\ m$.

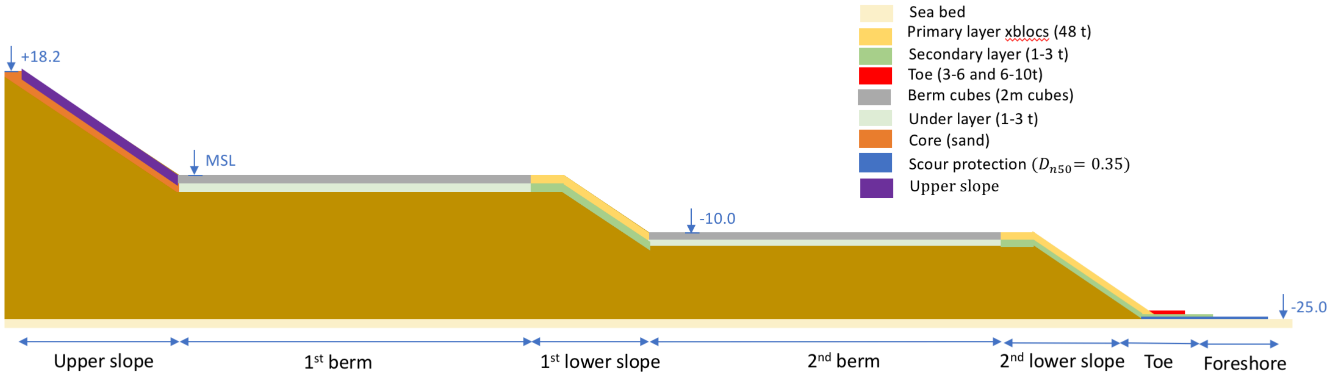


Figure 15: Nature enhancing cross-section with an artificial foreshore for the Northwest flank of the island

4.2.3 Offshore breakwater

Wave forcing reduces the chance of oyster reefs on most parts of the coastal defence. To reduce the forcing by waves a reef can be made to attenuate the waves. Wave attenuation can be reached with a statically stable breakwater or dynamic reef. As described in the reef design approach in chapter 3.2.2, the offshore breakwater dimension is chosen such that optimal conditions are established at the lee side of the reef. The kind of reef chosen is a permeable and homogeneous structure of which is expected to contribute the best to nature enhancing compared to other reefs. This was a permeable narrow reef with a width of 1 times the wave height. The structure is assumed to be dynamic during the 1 in 10,000 year conditions but the transmission coefficient should be designed for the 1 in 10 year conditions.

Favourable conditions for the area behind the structure could be distracted from in chapter 3.5 where the wave boundary conditions can be found for different depths. The results are summarised in Table 4.

Depth	Mean significant wave height	Extreme significant wave height
(m MSL)	(m)	(m)
-5	0.64	2.32
-10	1.14	3.72
-15	1.61	4.95
-20	2.05	6.06

Table 4: Significant wave height boundary conditions for successful flat oyster beds on different depths

The mean wave height for the Dogger Bank from the north to west is 1.66 m, showing that the mean shear stress can be reached at a level above -15 m MSL. This result is striking with the level found with the Argoss calculation for the mean shear stress. This difference is created due to different wave periods, which are assumed with a constant steepness for the expected shear stresses in Figure 13 while the Argoss data uses real wave periods.

To find an appropriate reef height is the height first determined for the extreme wave conditions. After finding the reef height for extreme wave attenuation, the expected wave can be calculated for the mean wave height and the corresponding shear stress. The transmission coefficient for the extreme 1:10y wave is assumed first to find the crest height to attenuate to a suitable level. The 1:10y wave is 7.5 m, so the transmission coefficient and reef height for different depths can be calculated, see Table 5.

Depth	Incoming 1:10y significant wave	Preferred transmitted significant wave	Transmission coefficient	Reef height (permeable)
m MSL	m	m	(-)	m MSL
-20	7.5	6.1	0.81	-6.17
-15	7.5	5.0	0.66	-3.17
-10	7.5	3.7	0.49	+0.08
-5	7.5	2.3	0.31	+3.58

Table 5: Northwest boundary wave for oyster reefs with corresponding transmission coefficient and required reef height for oyster settlement.

The water depth behind the reef limits the distance upon which oyster reefs have potential to grow. With a reef height at +0.08 m MSL have oyster reef potential to a depth of 10 m MSL. The mean shear stress is however a more important parameter than the critical shear stress. A reef deeper than 2 times the wave height will have none effect on the wave. Therefore, assumed is that the reef is located at +0.08 m MSL to attenuate the average wave height of 1.66 m. The transmitted wave is 0.5 m when sea level is at 0 m MSL. Running the script for calculating the shear stress from the Argoss data with a transmission factor, the mean shear stress can be found. For a depth of 15 m MSL the mean shear stress is 4.4 N/m^2 and the maximum shear stress over 22.4 y is 98.32 N/m^2. For a depth of -10m a mean shear stress of 7.8 N/m^2 is found. This level is presumed as acceptable for creating oyster reefs in the area behind the reef. A depth of 5 m MSL results in mean shear stresses of 16.13 N/m^2. A reef with a crest height at MSL is thus not sufficient to obtain oysters at 5 meters below mean sea level. A crest height of +3.58 m MSL would be sufficient to obtain favourable extreme wave conditions at a depth 5 m MSL, mean shear stress would be 1.33 N/m^2. Often the waves do not overtop the structure. The shear stress is smaller than the favourable shear stress for oyster reefs.

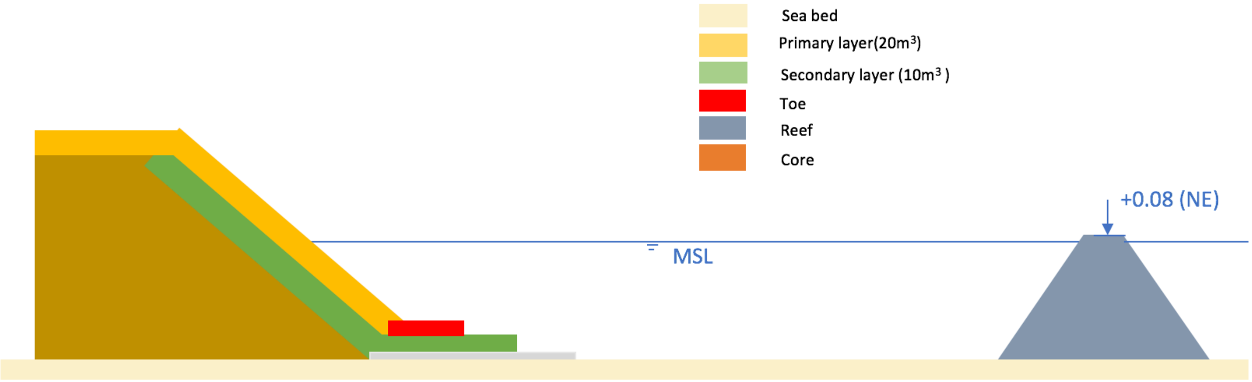


Figure 16: Nature enhancing cross-section with a reef for the Northwest flank of the island

4.3 Cross-sectional opportunities in a 360 orientation

The search for areas in the coastal design which are suitable for oyster reefs is up to now executed for the most exposed side of the island. For this direction is found that

- On most parts of the typical design no oysters can be found. From depths below 25 m MSL, the mean and 1:10y significant waves become suitable for oyster reefs to settle.
- The toe and deepest part of the lower slope can contribute to this as it provides hard substrate which is required for initial settlement of oysters. The foreshore has suitable hydrodynamics but consists normally out of sand, which is difficult for oysters to settle on.
- Berms are not effective for providing conditions where oysters can settle.
- Reef appeared to be successful in attenuating waves such that conditions behind the reef are optimal for oysters.

The wave climate is changing over the different directions, see the system analysis for wave (paragraph 2.1.3). Wave from the northeast are the strongest of the spectrum. Wave from the southwest are less strong but occur more often. From the north-east and south-east are the lowest waves of the spectrum. The wave climate from the different direction influence the typical design and the mean and maximum shear stresses on the design. From Appendix C.1 was found that waves only directed from the north-east and south-east can be designed with a constant slope of xblocs, without berms was sufficient for save design.

If ranges of 30 degrees waves are directed perpendicular to the coast can be found which directions can be opportune for oyster reefs for different depths. This is displayed in a ‘oyster suitability’ rose which shows the direction in which the oyster boundary conditions match with the hydrodynamics for both the 1:10y significant waves and mean values. Therefore, the 1:10y wave and the Argoss dataset for each 30 degrees is used to calculate the shear stress. This is done for both -20 m MSL and -25 m MSL, since 25 m earlier showed few opportunities for oysters and while 20 m depths are also widely present at the Dogger Bank.

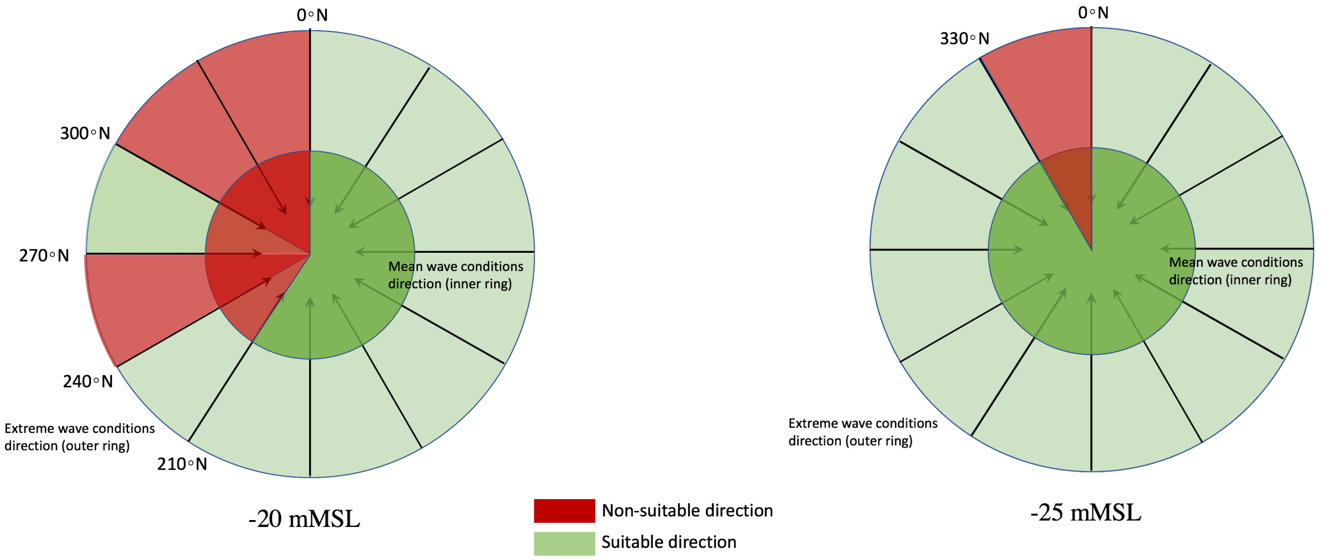


Figure 17: Suitable and unsuitable direction for successful oyster settlement due to mean wave conditions (inner ring) and extreme 1:10y significant wave conditions (outer ring) for both 20 (left) and 25 meter (right).

The oyster suitability roses show that at depths of 25 meter opportunities are only not available at the most extreme side of the island. At depths of 20 meter, the chance has decreased for many other orientations. Since waves do not propagate to only one part of the island like is shown in Figure 17, but parallel to each other, a wider part of the island is affected. Waves from 330ºN are reaching the whole northern flank of the island, although refraction take place (Holthuijsen, 2007). Refraction is the turning of the wave direction when the wave front starts to be affected by the depth contours at shallow water. The refraction is triggered by the fact that waves propagate more slowly in shallow water than in deep water. A consequence is that the wave fronts tend to become aligned with the depth contours.

4.3.1 Typical design southwest side

In a design for the least exposed side, the southeast, a constant slope is sufficient. For this design are also other shear stresses found on the cross section. As found in Figure 17 the conditions for oysters are such that settlement on depths of 20 m is possible. This increases the possible range for oyster settlement on the slope. The 1:10 year wave from the most exposed does not influence this side of the island so opportunities are increasing on this side. The wave height with a 1:10

year return period is for this side 4.87 m. The critical shear stress boundary is reached at a depth of -14 m MSL, the mean shear stress at -18 m MSL.

Boundary conditions indicate that with a traditional design, the oyster reef opportunities can be found at -18 m MSL. The toe and deepest part of the lower section can contribute to nature enhancing. To increase this area for nature enhancing, a berm will not be beneficial since this does not provide optimal conditions for oyster reefs.

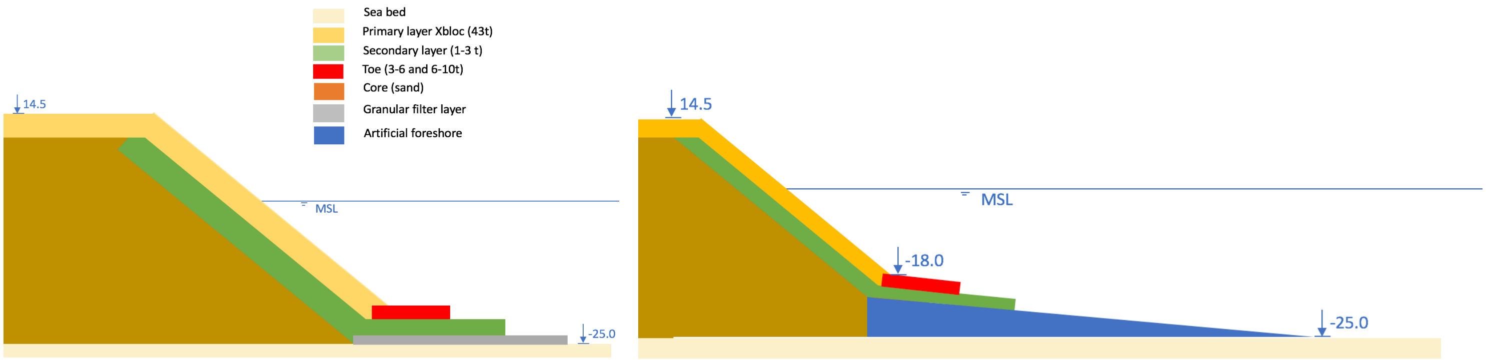


Figure 18: A cross-section for the southeast flank of the island for a typical design (left) and for an adjusted cross section with nature enhancing opportunities at the toe (right). (See material calculations in appendix C)

4.3.2 Toe and foreshore slope

The foreshore on the other sides of the island can be made such that it connects the foreshore with the slope on the boundary level where oysters can grow. The boundary level will be varying around the island since the wave conditions vary. For the least exposed side for instance, the level is at -18 m MSL. When a 1:10 slope is constructed from this level to the seabed at -25 m MSL a surface of 70m/m is created. This will reduce the amount of xblocs necessary and increases the surface which are potential for oyster reefs. Like the shear stress boundary level will the available surface which can be created vary around the island. The materials to create the foreshore can be smaller since the forcing is less severe compared to the northwest.

4.3.3 Berm

Also for the least exposed side, a berm is not potential for the settlement and growth of oyster reefs. Since this side experience lower extreme significant waves and mean waves the shear stress will be less. However, from paragraph 4.3.2 already became clear that only at 18 meters depth the conditions are fulfilled. Since a berm at this depth will not contribute to the coastal defence this is not recommended as an effective measure for the desired NBDE.

4.3.4 Reef

The reef opportunity is possible for other side of the island since it appeared already effective for the exposed side at the northwest. This side could be equipped with a lower reef since lower waves are directed to this direction. Table 6 shows the required reef heights for the southwest orientated flank of the island. Alongside, the corresponding 1:10y significant waves from this direction and the corresponding transmission coefficient are given.

Depth	Incoming 1:10y significant wave	Preferred transmitted significant wave	Transmission coefficient	Reef height (permeable)
m MSL	m	m	(-)	m MSL
-20	4.9	6.1	1	none
-15	4.9	5.0	1	none
-10	4.9	3.7	0.76	-2.31
-5	4.9	2.3	0.46	+1.19

Table 6: Southeast boundary wave for oyster reefs with corresponding transmission coefficient and required reef height for oyster settlement.

Since reefs of which the crest reaches above mean sea level so most of the waves break, a climate is created where only during extreme conditions waves break over the structure. Since oysters need water flow due to waves or currents, this blockade is not favourable. Therefore, a reef around MSL would be preferable to block the most extreme waves and transmit partially the average waves.

5.

Discussion

In chapter 4 the following items were discussed: what parts of the cross section can be suitable for oyster beds, how suitable parts can be enlarged and how new surfaces could be created. This chapter interprets the results and the research needed. Although this thesis treats the two-dimensional design, three-dimensional effects can be expected. This outline will be discussed shortly. Subsequently, the possible contributions of the eco-engineering flat oyster to the coastal defence are discussed. Then is discussed, how oyster reefs are expected to settle on the Dogger Bank island, far from existing oyster reef. As last, other relevant marine species are described who could also have advantage of the island's hard substrate.

5.1 Three-dimensional effects

Previous chapters have discussed where chances for the NBDE can be found and how the opportunities could be increased. The chances are sought in the cross sections of the coastal defence, perpendicular to the coast. To find a design which can contribute to oyster settlement, the wave conditions were divided into the sections of 30ºN degrees. The waves were assumed to arrive at the coast in perpendicular direction, which is not realistic since the waves propagate parallel to each other to the coast. This will cause some three-dimensional effects which are not in the scope of this research but expectable. The three-dimensional effect can consist out of waves propagating to the coast orientated from originally other directions, tidal and wave induced currents imposing sediment transport and flow induced by waves overtopping the reef.

5.1.1 Longshore waves

Waves from directions other than the perpendicular waves will change the kind of protection and opportunities for nature enhancing on most part of the island. The waves from the most extreme direction, north-northeast (330-360ºN) will affect the northern side (±240-90ºN) of the island. For this kind of wave attack were 2 kinds of solutions possible: a berm protection with a foreshore that is extended with hard substrate, or a reef in front of the coast which attenuate waves. Waves from the east-southeast (240-270ºN), affecting the north-south (±150-360ºN) part of the island, has the same two solutions since waves demand heavy protection for wave attack (Appendix C.1). From this analysis appears that only the west part (90-150ºN) of the island is suitable for oyster settlement without berm or reef. The study from last chapter raised the possibility that oyster can grow on the western side of the island from depths of 18 m MSL. However, when a 3D perspective is taken, waves from the north and west which pass along the island. In Figure 19 all waves which can reach specific locations from the island are used to find the shear stresses on that location. There will several 3D effects be involved when waves cross the island, like diffraction and refraction. From a wave developments study around an island appears that commonly refraction has an significant higher influence compared to diffraction (Robert, 1951). Figure 19 does neither contain refraction nor diffraction, but assumed is that suitable depths will decrease to deeper elevations further from the island.

The island will block the most severe waves from the northwest but cannot create shelter for oysters to settle on shallower depths at further distances from the island. The consequence is that the opportune area for oysters further decreases. These findings suggest that the only opportunity for oyster reefs around the islands cross section to grow below 20 meter MSL is at the southeast, except when reefs which reflect the waves are used.

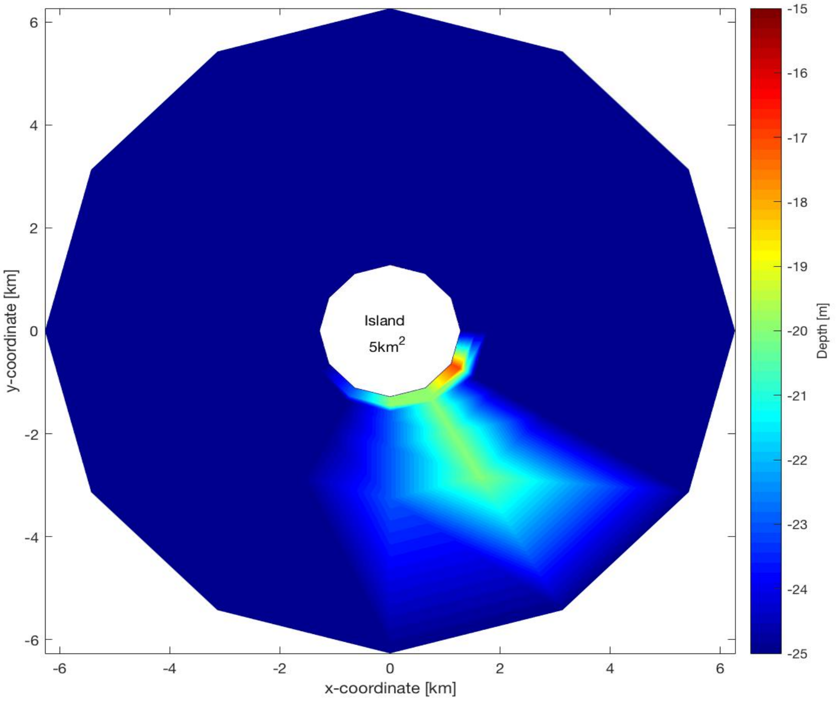


Figure 19: Indication of suitable depths for oyster beds based on the boundary shear stress conditions.

5.1.2 Sediment transport

Another expected effect when an island is built on the Dogger Bank is the sediment transport which will be imposed due to currents and waves. As long a stable structure is used over the whole levee, the only expected effects are found on the seabed. When the taken measures to increase the area where oysters might settle are implemented more dynamic sediment will be available. The sediments used for enlarging the foreshore or the surface between the reef and the island might be sensitive to currents induced by tides and waves. A short study is performed in Appendix C.3 about the direction of the sediment transport. The study can give an indication of the expected sediment transport direction. It appeared that the net transport over a year is directed southwest. A real impression of the amount and direction can only be found by modelling the flow around the island. However, this is beyond the scope of this research.

5.1.3 Reef induced currents

Due to the transmission of waves and the availability of hard substrate reefs are seen as a possible alternative to increase the nature enhancing potential of the island. However, if not properly designed, submerged shore-parallel breakwaters may cause shoreline erosion as a result of structure-induced circulation currents (Villani, Bosboom, Zijlema, & Stive, 2012). A review of the shoreline response to submerged structures pointed out that 7 out of 10 considered cases have resulted in unexpected shoreline erosion (Ranasinghe & Turner, 2006). The onshore forces due to wave breaking over the structure are balanced by a combination of onshore flow and set-up over the breakwater depending on the reef dimensions. Mass conservation requires that the water flowing onshore over the structure returns off-shore again through openings in the reef. To create nature enhancing opportunities the reefs are necessary around most parts of the island. This will demand a reef with different alignments and waves orientated from all direction. The oblique waves can create even stronger current due to the overtopping and induced currents. Therefore, the choice of offshore reefs should be studied in detail to find the possible effects and prevent negative consequences.

5.1.4 Ideas in 3D design

From the previous chapter some successful measures have been discussed which can contribute to enlarging or creating new opportunities for oyster beds. Together with the three-dimensional findings described in first part of 5.1, thoughts are discussed which might contribute to a more feasible, stable and cheaper design for the NBDE. The wave climate from the southeast to the north (210-360ºN) create a climate which prevent oyster reefs upon depths shallower than 20 meters, see Figure 17. Reefs are a measure which can create a larger and more suitable area for oysters. However, reefs can have negative effects when designed incorrectly. Joining the suitable wave orientation, the expected sediment transport from northwest to southeast and the chances of reefs is an opportunity suggested to use the reef perpendicular to the unsuitable wave directions. By reflecting unsuitable waves with reefs (and the island) an area can be created with more favourable conditions from the east to southeast (see Figure 20). In this area, which can be seen as a bay, the prevailing wave conditions allows oyster beds at shallower water depths (-18 m MSL) over a larger area. The levee, protecting the island can with the eastern wave conditions be designed with a constant slope to -18 meters. From there, a gentle slope with favourable substrate for oysters can be used until the seabed. Further elaboration of 3D effects will add extra information about the suggested ideas.

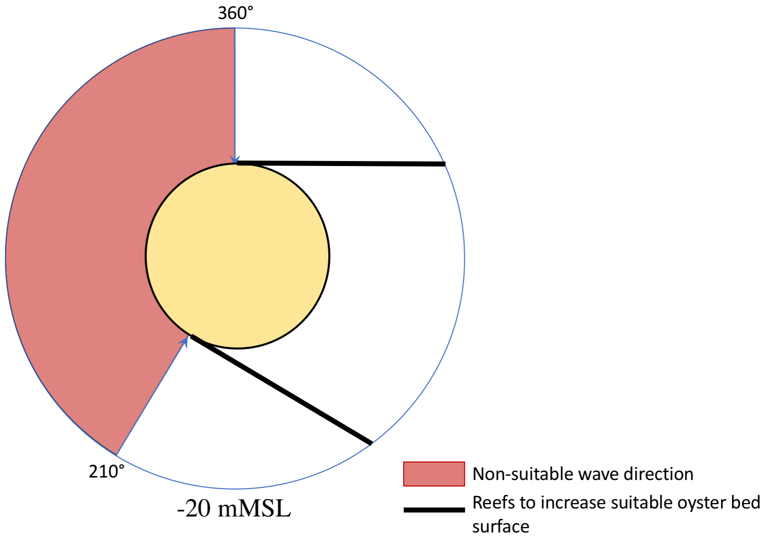


Figure 20: A 3D-alternative reflecting the northern to southwestern waves

The combination of findings provides some support for the conceptual premise that a reef oblique to the coastline, reflecting the waves from the undesired wave directions (210-360ºN), could create a bay with favourable oyster conditions. Combining the reefs with other island infrastructure could make the oyster bay more feasible. For instance, port breakwaters could reflect the waves from the north while another perpendicular reef reflects the waves from other directions.

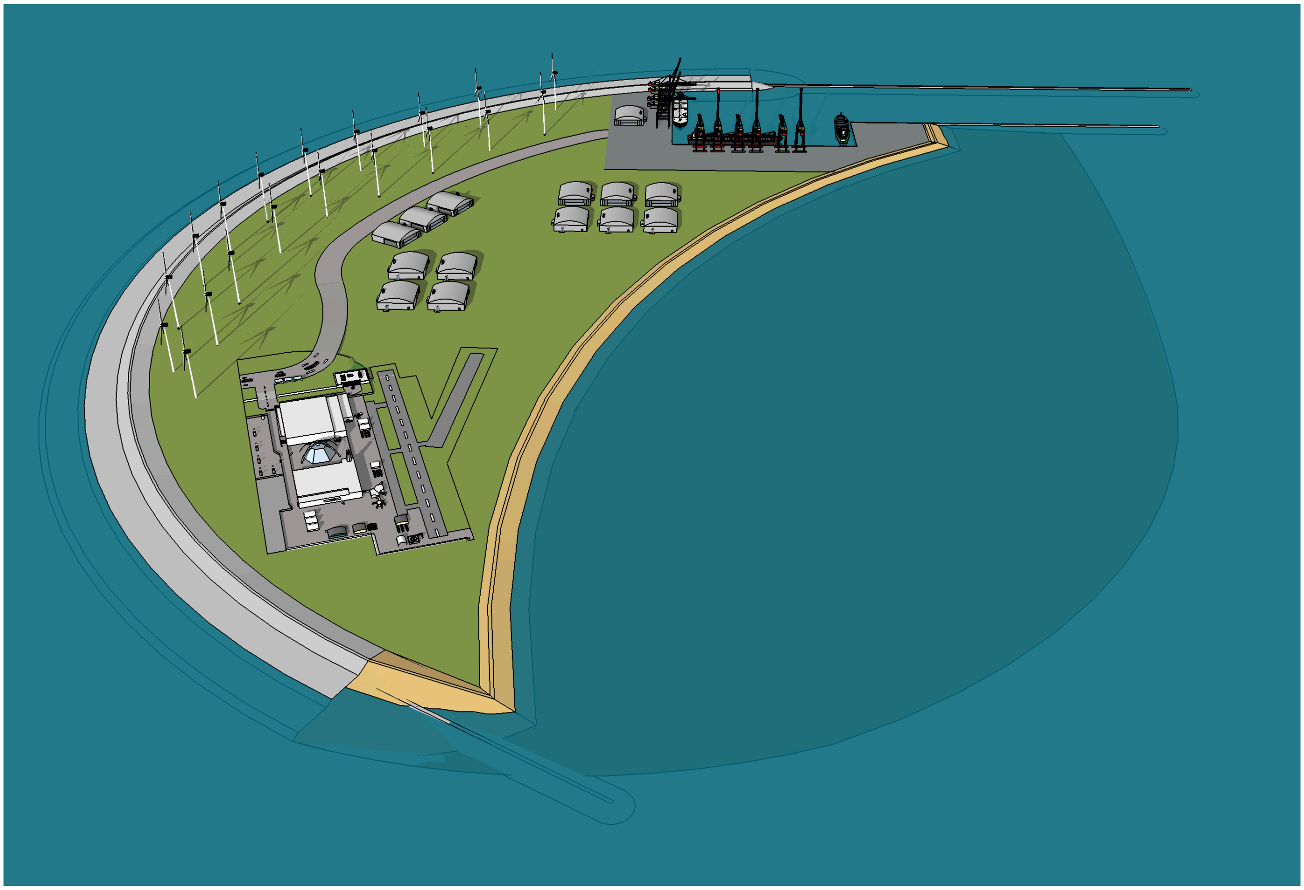


Figure 21: Artist impression of island design, optimising surface for the oyster beds.

5.2 Attribution of oyster reefs to the coastal defence

This thesis attempts to find locations for oyster settlement, and so restore and enhance a natural element that was abundantly present in the North Sea 130 years ago. Additional value would be added when oyster reefs could contribute to the coastal defence. Oysters are known as eco-engineers; consequently, they have an influence on the hydrodynamics and sediment transport (van Wesenbeeck et al., 2013). Reefs can stabilise eroding coastal areas. They protect sediment on the flats from direct erosion by currents and waves. This together with enhancing of the bed roughness, affecting near-bed water flow and wave action, the sediment transport, sedimentation, consolidation and stabilisation processes can be influenced. At this moment, it is unknown to what extent these bivalves influence the hydro- and sediment-dynamics on a patch scale (Alferink, 2016). Also, the environment in which they can contribute to coastal defence is unclear. Most researches and pilot studies discuss the use and effects of oyster reefs in inter-tidal zones with moderate wave heights, different than the Dogger Bank (like the Oosterschelde (Walles, 2015), (Walles, 2015) Alabama coast (Scyphers, Powers, Heck, & Byron, 2011), Wadden Sea (van Leeuwen, Augustijn, van Wesenbeeck, Hulscher, & de Vries, 2010).

In a flume the invasive pacific oyster *Crassostrea gigas* has shown that in a water depths of 25 cm it can reduce wave heights by up to 40% (Borsje et al., 2011). The wave attenuation depends on water depth, reef height and width and wave height. A bivalve bed of 7.90 m from the wave generator, length of 3.1 m, water depth constant at 25 cm and waves with a significant wave height of 3.34 cm was exposed for finding the wave attenuation (see results in the Figure 22).

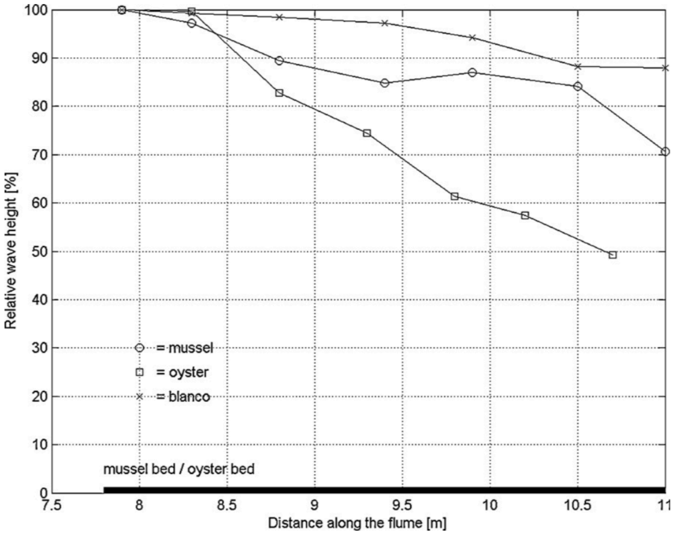


Figure 22: Wave attenuation of oyster and mussel beds, with a significant wave height of 3.34 cm (source: Borsje et al., 2011)

The high roughness and high bed heights can result in the accumulation of sediment between and behind the mussel bed due to turbulence and a calmer zone behind reef (Alferink, 2016). Oysters protect the sediment below them by covering the sediments with their shells. Oysters form reefs by cementing themselves permanently on oyster shells or hard substrate (Arakawa, 1990). When sediment and bio-deposits start to settle between the shells, oysters can become buried. This creates a strong shell-mud matrix where later generations can settle on (Walles et al., 2016). The cemented oysters stay in the reef structure, whether dead or alive. The heavier weight of the oysters cemented together, prevents them from being flushed away by waves and currents. Oyster reefs are, however, vulnerable to high sedimentation rates due to their permanent location.

5.3 The introduction of oyster reefs

Important habitat factors described in this thesis for the development of flat oyster beds in the wind farms of the Dutch part of the North Sea are large-scale, small-scale soil dynamics and sediment composition (Smaal et al., 2017). Other important habitat factors like the suspended concentration in the water column and the possibility for successful recruitment are not discussed, since these factors can hardly be influenced by the coastal design. Other factors such as the presence of phytoplankton, salt and oxygen content are also important but they are not restrictive. Predation and competition are also important, but to what extent is hard to predict.

The suspended concentration is important habitat factor for oysters to ensure growth. Oysters filter suspended material from the water, which consists of phytoplankton, detritus and inorganic material. They use phytoplankton for growth, but the inorganic material cannot be used for metabolism. If the content of inorganic material increases, the possibility for growth decreases. The conditions of the suspended material for oyster reefs are unknown at the Dogger Bank. Investigation would be needed to confirm the possibility of successful oyster beds on this location.

The recruitment for successful settlement of oyster reefs in the initial and later phase is important to guarantee a self-sustaining reef. Firstly, the substrate where oyster should settle is of large importance. As earlier described, stable and hard substrate is important for initial settlement. Calcareous substrate is favourite for oyster settlement, with large preference for oyster shells. In areas where recruitment is predictable, shells or other kinds of cultch material can be distributed for attachment of oyster larvae. Once oysters are settled the oyster larvae can settle on each other, creating an increasing three-dimensional reef. Once oysters are settled they can continue to grow on sandy beds.

Providing that in the initial phase enough suitable substrate is available, oyster larvae should also be provided. Since the island is located in the middle of the North Sea, no oyster larvae are expected to reach the island naturally (Smaal et al., 2017). Therefore it may be necessary to rely on an oyster hatchery to produce the required amount of larvae (NOAA Habitat Conservation, 2017). In this case material is placed inside mesh bags and immersed in tanks of mature oyster larvae that are ready to settle. After larvae have attached themselves, the bags are suspended from docks or rafts for a few weeks to allow the larvae to grow. Than they are placed on the restored reef.

Another alternative is to obtain seed oysters from areas known to produce large amounts of oyster seed. The seeds are transported to areas where they can grow to establish new reefs. Depending on the hardness of the bottom, shell or other material may be needed on-site before the seed oysters are placed.

5.4 Enhancement for species other than oysters

The present study was designed to determine the effect of opportunities to enhance nature around the island. The findings suggest that in general oysters can boost and create major opportunities for ecological enhancement. The measures found before are intended to stimulate the settlement of oyster reefs. There are, however, other species which could profit from hard substrate and a coastal environment. Adding large structures like concrete units create holes and crevices providing shelter and holes for large mobile species (Lengkeek et al., 2017). A higher habitat complexity can improve the environment for many species, like the codfish. Adding small scale substrate can create more small-scale holes and crevices but also attachment substrate and settlement substrate. This may improve the habitat of egg, larvae or juvenile stages of many species, such as the queen scallop or squid. Small substrate can also improve habitat quality for small species (incl. adult stage), such as the rock gunnel and the shore clingfish. From a list of species utilising hard substrate (Lengkeek et al. 2017), it was found that most species may benefit from the extra addition of small-scale structures such as gravel beds. Some species utilise gravel beds throughout their life, often as attachment substrate (e.g. the coral dead man's fingers, ross worm and dahlia anemone). Some species are not dependent on the substrates as such, but inhabit species that are dependent on the substrates (like cowrie species living on dead man's fingers, a cold-water coral).

6.

Conclusions and Recommendations

6.1 Conclusions

The Dogger bank is a sandbank in the North Sea that has some unique characteristics, which are favourable for both the North Sea ecology as for large scale wind energy. The water depth and wind conditions are optimal for large scale wind parks, necessary to reach climate goals. An island hub on the Dogger Bank could support the energy transition into a more sustainable energy market.

Due to water flow, water column mixing and wave action affecting the bottom, a unique North Sea habitat exists. Because of this unique habitat, the Natura2000 regulation does not allow possible environmentally disturbing activities, such as the construction of an island. Without the indication that there will be no or minimal effect on the environment or implementation nature compensation within the project, the construction of an island will be difficult. By designing an island in which nature enhancing opportunities are included, the realisation of such island in the North Sea becomes more likely. To improve the North Sea biodiversity, legal likelihood, public support and to mitigate the negative ecological consequences of an island, *nature enhancing opportunities in the design of an artificial island* are called for. This is the main question of this thesis which is found by answering the following three sub-questions.

Sub-question 1: Are there Nature Based Design Elements for an energy island on the Dogger bank available?

Firstly, the nature favourable to enhancement was studied in this thesis. For the nature enhancing design of the island, an umbrella species represented the desired habitat. This well-selected species is expected to contribute to enhancement for many other species around the island. For a Dogger Bank island the *Ostrea edulis*, or flat oyster, could contribute to its natural value. With creation of oyster reefs, a habitat could be created, facilitating a habitat for a larger number of associated benthic species. The oyster reef introduces a habitat which has disappeared over the last 130 years. As eco-engineering species, oysters remove large quantities of suspended material from the water column by filter feeding and producing bio-deposits that accumulates in the reef and its surroundings. It can be considered as an umbrella species which creates a unique bed with a three-dimensional structure, consists of living oysters, oyster shells and associated species.

Sub-question 2: What is a quantitative concept to find the applicability of the nature based design element?

To find how nature enhancing opportunities, especially for the oyster reefs, could be stimulated, research was done on the boundary conditions of oysters and the characteristics of the Dogger Bank. For oyster reefs the shear stress is an important abiotic factor. To locate the parts where nature enhancing with oyster reef are opportune, a shear stress method was introduced that compares the shear stress forcing with the shear stress resilience of oyster reefs. The shear stress strength of oyster reefs is found with historical Olsen's maps compared with a shear stress model for the extreme and mean shear stresses of those locations in the North Sea. The shear stress boundary condition for the highest significant waves was 119.8 N/m^2 while the shear stress due to the average significant wave climate must stay between 2.5 and 10.3 N/m^2. From the analysis, it appeared that the *mean* shear stress has a clearer correlation with oyster reefs existence than the shear stresses caused by the highest waves.

From the shear stress method, it seems that waves have a significant higher influence compared to the shear stress induced by the tides on the Dogger Bank. With the shear stress model and the analysed waves of the Dogger Bank, an estimation was made for the boundary wave heights for successful oyster reefs on different depths (see Table 7). The shear stress model shows where the shear stresses on the coastal defence matches with the oyster boundary conditions.

Depth	Mean wave height	Maximal significant wave height
(m MSL)	(m)	(m)
-5	0.64	2.32
-10	1.14	3.72
-15	1.61	4.95
-20	2.05	6.06

Table 7: Wave boundary conditions on different depths for successful oyster reefs for both the mean wave climate as the highest critical significant wave height.

Sub-question 3: Where can the nature based design element be applied and further optimised in the cross-sectional profile?

For the design of the coastal defence, 1 in 10,000 year conditions are used to fulfil the safety requirements. To find the potential oyster reefs in the design, 1 in 10 year wave conditions are used. This number is chosen as damage of the reefs is acceptable. The investigation of a typical, or traditional, coastal defence has shown that chances for nature enhancing are relatively small. Due to the wave conditions, a hard protection with large concrete units as xblocs, cubes or accropode, on some sides with berms, it is necessary to obtain safe conditions. The toe and deepest part of the revetment have potential for oyster reefs due to favourable shear stress conditions and presence of hard substrate. The surface is relatively small since shear stresses are only favourable when the toe and slope are located below 25 m MSL, on the most exposed side (north-northeast), or 18 m MSL, on the least exposed side (south-southwest). A 3D view shows that extreme waves, passing the island long shore, will dissipate the favourable conditions on shallower water depths on the lee side. When an island is constructed on shallower depths, which economically or logistically could be more favourable, the potential for nature enhancing would disappear.

To increase the opportunities for the nature enhancing, the cross-section measures were discussed, which could increase the oyster growing surface. This thesis has identified the following measures to successfully increase the potential surface where oyster reefs could grow:

- *Foreshore:* When located in deep water (below the specific level when the hydrodynamics are most suitable for oysters) the toe and foreshore could be adjusted to a gentle slope. Instead of a direct slope to the sea bed, a slope from the minimum water depth where oysters might be found until the sea bed, is made. When the slope is made gentle (<1:10) and provides hard substrate (>35cm) the surface oysters could settle increases and the length of conservative revetment is reduced. The foreshore which is suitable for oyster beds but not adjusted with hard substrate, has potential for oyster beds in the long term since no fishery takes place close to the island. The sea bed will remain undisturbed.
- *Reef:* A structure, like a reef or breakwater, around the island could provide preferable conditions on the lee side of the structure. A reef structure has been selected since this is considered to contribute more to nature enhancing for species other than oysters. The height of the reef determines the depth to the point that oysters have favourable conditions. A reef around mean sea level is sufficient to create desirable conditions to a depth of 10 m MSL at the most exposed side or to 2.3 m MSL at the southeast side. An emerged reef could cause a shortage of hydrodynamics, which are necessary for nutrition of oysters. The distance between the reef and the coast and the used substrate defines the potential surface in the sheltered area. For initiating oyster beds between the reef and island, gabions or degradable crates could be used to provide substrate to settle on.

Main conclusions

Answering the main question regarding the opportunities that are available for nature enhancing design of the artificial North Sea island, it can be concluded that such chances exist in the coastal defence design. Hard solutions are needed to protect the island during extreme conditions. However, the nature enhancing chances of the oyster beds in typical cross-section are rather small. For the most exposed side (330-360ºN), it is opportune for oyster beds to grow around the toe and foreshore when located in water deeper than -25.0 m MSL. At the least exposed side (120-150 ºN) this is -18.0 m MSL. Reefs and prolonged foreshores are expected to be effective in creating larger nature enhancing surfaces, given the fact that they are well designed. Reefs change hydrodynamics and offer shelter behind the structure where, with suitable substrate, oysters could grow. The foreshore could enlarge the potential surface with hard substrate in the present hydrodynamics.

Three-dimensional effects and opportunities

The initial objective of this thesis was to identify nature enhancing opportunities in the cross-sectional design. In a three-dimensional view the chances in the cross-section are, due to the wave climate, only available in the deepest regions below 20 m. Reefs appeared to be effective in creating conditions which are favourable for oyster settlement. However, reefs could create undesired and damaging currents which harm the structure. Further research is needed for obtaining an effective reef design. This combination of findings provides some support for the conceptual premise that a reef oblique to the coastline, reflecting the waves from the undesired wave directions (210-360ºN), could create a bay with favourable oyster conditions. Combining the reefs with other island infrastructure could make the oyster bay more feasible. For instance, port breakwaters could reflect the waves from the north while another perpendicular reef reflects the waves from other directions.

6.2 Recommendations

Taking into account the conclusions drawn from the research findings, there are several recommendations for further research, which can be summarised as follows:

- *Optimisation in general:* In this thesis, a conceptual design study is presented. It is recommended to optimise the supposed design further, with respect to the morphological development of the system, costs, constructability and technical feasibility.
- *Optimisation reef constructions:* There are several design alternatives for reefs. The parameters of the design are reef width and length, gap length and distance to coast. The effects of reefs could be negative if not designed well. Extended research about the consequences of a reef is recommended.
- *Optimisation foreshore constructions:* The measure with an extended foreshore will require more investigation. The design and transition of the toe of the slope with the concrete unit revetment and the foreshore is important and requires more research. A greater focus on the costs of the different measures could produce new insight in the most advanced design.
- *Oyster characteristics:* The preferred hydrodynamics for oyster reefs are now derived from historical maps and modelled data. To increase the accuracy of the data, more laboratory measurement would be helpful. It is unclear what amount of shear stresses, both mean and extreme, oyster can resist exactly on different kind of sediments like sand or hard substrate.
- *Effects of oyster banks on stabilisation:* It would be interesting to assess the effects that oyster reefs have on deeper water depths. Now, studies are focussed on the effects oyster reefs have on tidal flats. Oyster reefs in tidal flats have been found to stabilise eroding areas and attenuate waves. The strength and effects of oysters at larger water depths would be interesting.
- *Location and island shape:* Given the time frame and clear focus of this study, some determining factors are not discussed within this research. For instance, the exact location of the island, which will have varying effects in a further design due to e.g. different depth, geology or currents is important. Furthermore, the shape of the island is not determined as well as its dimensions. This will influence the size of the area with oyster potential as well as the morphological processes, stimulated by the island shape.
- *3D-effects:* The three-dimensional effects are only limited discussed in this thesis while effects are expected because of refraction, oblique waves imposing sediment transport and currents imposed by for example a reef. Since three-dimensional measures are seen as potential in this thesis, further research on the sediment transport, current and wave development is recommended. The sediment transport that has been calculated now is obtained from simplified transport principles but will have significant effect on the islands stability. BwN solutions, as the sand engine have not been investigated, though

might be an alternative. This would require better understanding of the morphological processes.

7.

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List of Symbols

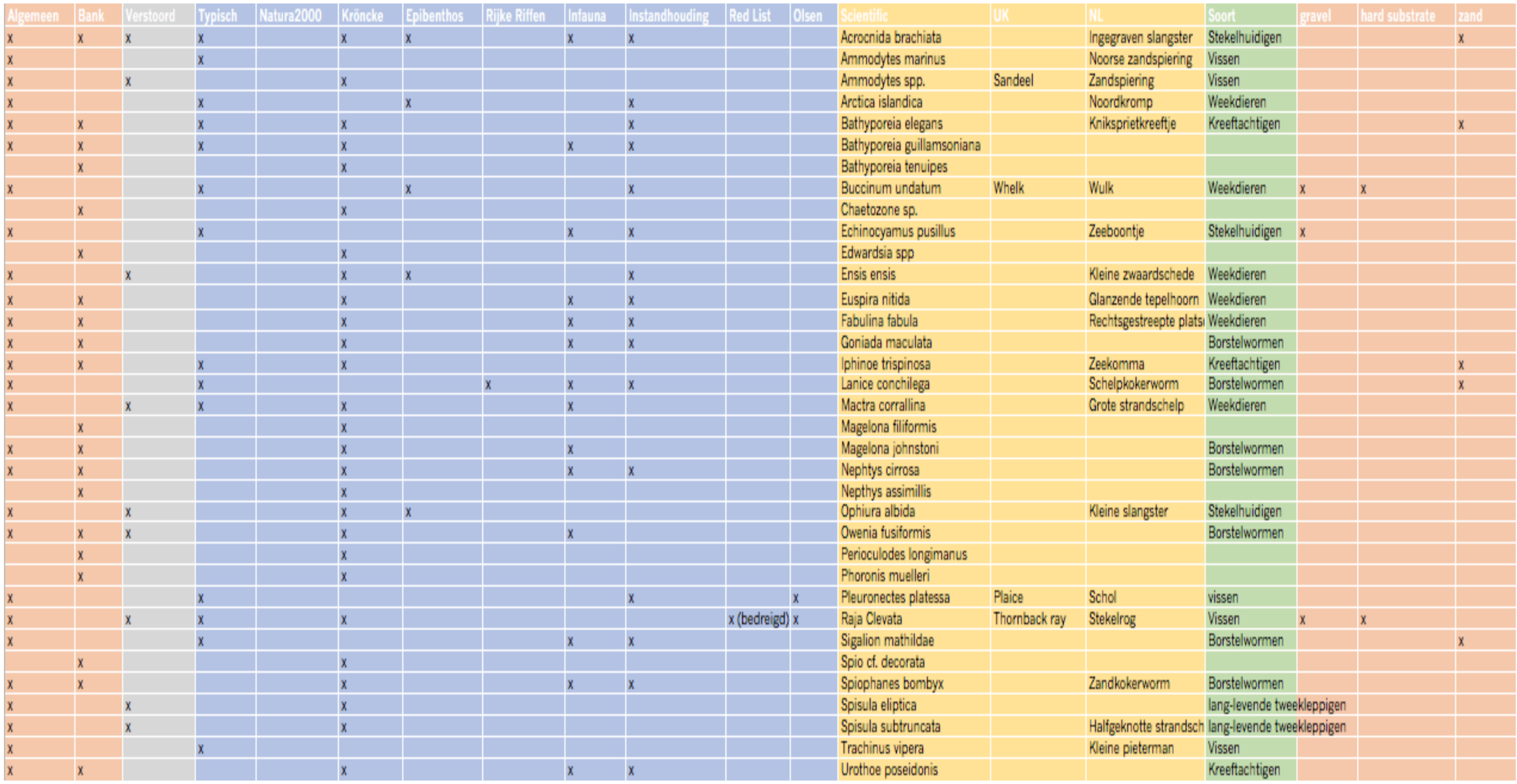
a_b	Wave amplitude at bottom	(m)
B	Width reef or berm	(m)
C	Chezy coefficient	(m$^{1/2}$/s)
c_f	Dimensionless friction coefficient	(-)
d_h	Berm level with respect to MSL	(m)
D_n	Nominal block diameter	(m)
D_{n50}	Median nominal diameter	(m)
g	Accelaration due to gravity	(m^2/s)
h	Water depth	(m)
H_s	Significant wave height	(m)
$H_{s,incomming}$	Incomming wave before reef	(m)
$H_{s,transmitted}$	Transmitted wave behind reef	(m)
k	Wave number	(-)
k_r	Bed roughness	(m)
K_t	Transmission coefficient	(-)
L	Wave length, in the direction of propagation	(m)
L_{berm}	Horizontal length of the berm structure from height -1.0H_s to +1.0H_s	(m)
N_s	Stability number	(-)
r_b	Influence factor for berm width	(-)
R_c	Crest freeboard, in relation to MSL	(m)
r_{dh}	Influence factor for berm level	(-)
T	Wave period	(s)
$T_{m-1,0}$	Spectral wave period	(s)
u_{cr}	Critical flow velocity	(m/s)
$\hat{u}_\delta$	Peak bottom velocity	(m/s)
x	Factor dependent on berm level below or above still water line	(-)
γ_b	Reduction factor for berm influence	(-)
γ_f	Reduction factor for roughness influence	(-)
ξ	Iribarren number	(-)
ρ_s	Mass density sediment	(kg/m^3)
ρ_{w}	Mass density water	(kg/m^3)
τ	Shear stress	(N/m^2)
τ_{current}	Shear stress, induced by currents	(N/m^2)
τ_{waves}	Shear stress, induced by waves	(N/m^2)
Ψ_c	Shields parameter	(-)
ω	Wave frequency	(-)
°	Degrees	(-)

Abbreviations

BwN	Building with Nature
CFP	Common Fisheries Policy
EEZ	Exclusive Economic Zone
EIA	Environmental Impact Assessment
MSL	Mean Sea Level
NBDE	Nature Based Design Element
NE	Northeast
NW	Northwest
SE	Southeast
SW	Southwest

Appendix

A. SPECIES



Algemeen	Bank	Verstoord	Typisch	Natura2000	Kröncke	Epibenthos	Rijke Riffen	Infauna	Instandhouding	Red List	Olsen	Scientific	UK	NL	Soort	gravel	hard substrate	zand
x	x	x	x		x	x		x	x			Acrocnida brachiata		Ingegraven slangster	Stekelhuidigen			x
x			x									Ammodytes marinus		Noorse zandspiering	Vissen			
x		x			x							Ammodytes spp.	Sandeel	Zandspiering	Vissen			
x			x			x			x			Arctica islandica		Noordkromp	Weekdieren			
x	x		x		x				x			Bathyporeia elegans		Kniksprietkreeftje	Kreeftachtigen			x
x	x		x		x			x	x			Bathyporeia guillamsoniana						
	x				x							Bathyporeia tenuipes						
x			x			x			x			Buccinum undatum	Whelk	Wulk	Weekdieren	x	x	
	x				x							Chaetozone sp.						
x			x					x	x			Echinocyamus pusillus		Zeeboontje	Stekelhuidigen	x		
	x				x							Edwardsia spp						
x		x			x	x			x			Ensis ensis		Kleine zwaardschede	Weekdieren			
x	x				x			x	x			Euspira nitida		Glanzende tepelhoorn	Weekdieren			
x	x				x			x	x			Fabulina fabula		Rechtsgestreepte plats	Weekdieren			
x	x				x			x	x			Goniada maculata			Borstelwormen			
x	x		x		x							Iphinoe trispinosa		Zeekomma	Kreeftachtigen			x
x			x				x	x	x			Lanice conchilega		Schelpkokerworm	Borstelwormen			x
x		x	x		x			x				Mactra corrallina		Grote strandschelp	Weekdieren			
	x				x							Magelona filiformis						
x	x				x			x				Magelona johnstoni			Borstelwormen			
x	x				x			x	x			Nephtys cirrosa			Borstelwormen			
	x				x							Nepthys assimillis						
x		x			x	x						Ophiura albida		Kleine slangster	Stekelhuidigen			
x	x	x			x			x				Owenia fusiformis			Borstelwormen			
	x				x							Perioculodes longimanus						
	x				x							Phoronis muelleri						
x			x						x		x	Pleuronectes platessa	Plaice	Schol	vissen			
x		x	x		x					x (bedreigd)	x	Raja Clevata	Thornback ray	Stekelrog	Vissen	x	x	
x			x					x	x			Sigalion mathildae			Borstelwormen			x
	x				x							Spio cf. decorata						
x	x				x			x	x			Spiophanes bombyx		Zandkokerworm	Borstelwormen			
x		x			x							Spisula eliptica			lang-levende tweekleppigen			
x		x			x							Spisula subtruncata		Halfgeknotte strandsch	lang-levende tweekleppigen			
x			x									Trachinus vipera		Kleine pieterman	Vissen			
x	x				x			x	x			Urothoe poseidonis			Kreeftachtigen			

Figure 23: Species found on Dogger Bank in literature, names in different languages, kind of specie and favourite habitat (when available)

B. REFERENCE PROJECTS

B.1 RICH DIKE DESIGN

In the report ‘Diverse dike design’ on behalf of the Port Centre Rotterdam-Delft is globally elaborated how new build dikes along the Dutch coast would look like when civil engineers and biologists would cooperate. In the report is stated that the Netherlands have created a ‘rocky shore’ in which more opportunities are available. It focusses on the subtidal area and tries to mention all characteristics that can contribute to a more sustainable design. Therefore, are costs and maintenance omitted and three characteristic combinations composed of which the ‘exposed dike on deep water’ is the most corresponding design. Neither are the difference between brackish and salt water distinguished.

For the design is looked to the following design aspects:

- The cross section, by creating a gentle slope in the intertidal area can the surface for intertidal habitats be increased. Likewise, can an interruption in the profile help in creating tidal pools.
- Materials. Porous, rough material with large water containing ability can offer great advantageous for settling of species.
- Placement of revetment. Irregular placement of stones can contribute in creating pools and holes.
- Grading, rubble with a large range of grading can contribute to the creation of holes and pools as well
- 3D-design. Creating design in three dimensions can natural rocky coast be imitated so habitats can be increased.

For the exposed dikes in deep water are locations like the outside of harbours, seaside of large coastal defences or primary sea defences intended. Here are dikes exposed to large wave attacks and strong currents, the water is deep and water can be clear very. In the present designs are the energy absorption area short and shore steep. Aims in creating a more ecological interesting habitat are inspirited on natural rocky coasts. In these habitats are rocky benches creating large plateaus for the eulittoral, also rocky outcrops (protrusions into the sea) are typical. Those create microhabitats on the lee and exposed sides of the structure. As last are reefs typical, steep structures where species can hide and spawn. Guidelines for this design propose to utilise the eulittoral and sublittoral by stretching this areas over a longer area. The first can absorb more energy, the second has much potential for biodiversity and productivity. In Figure 24 is the ideal design for a deep exposed dike sketched.

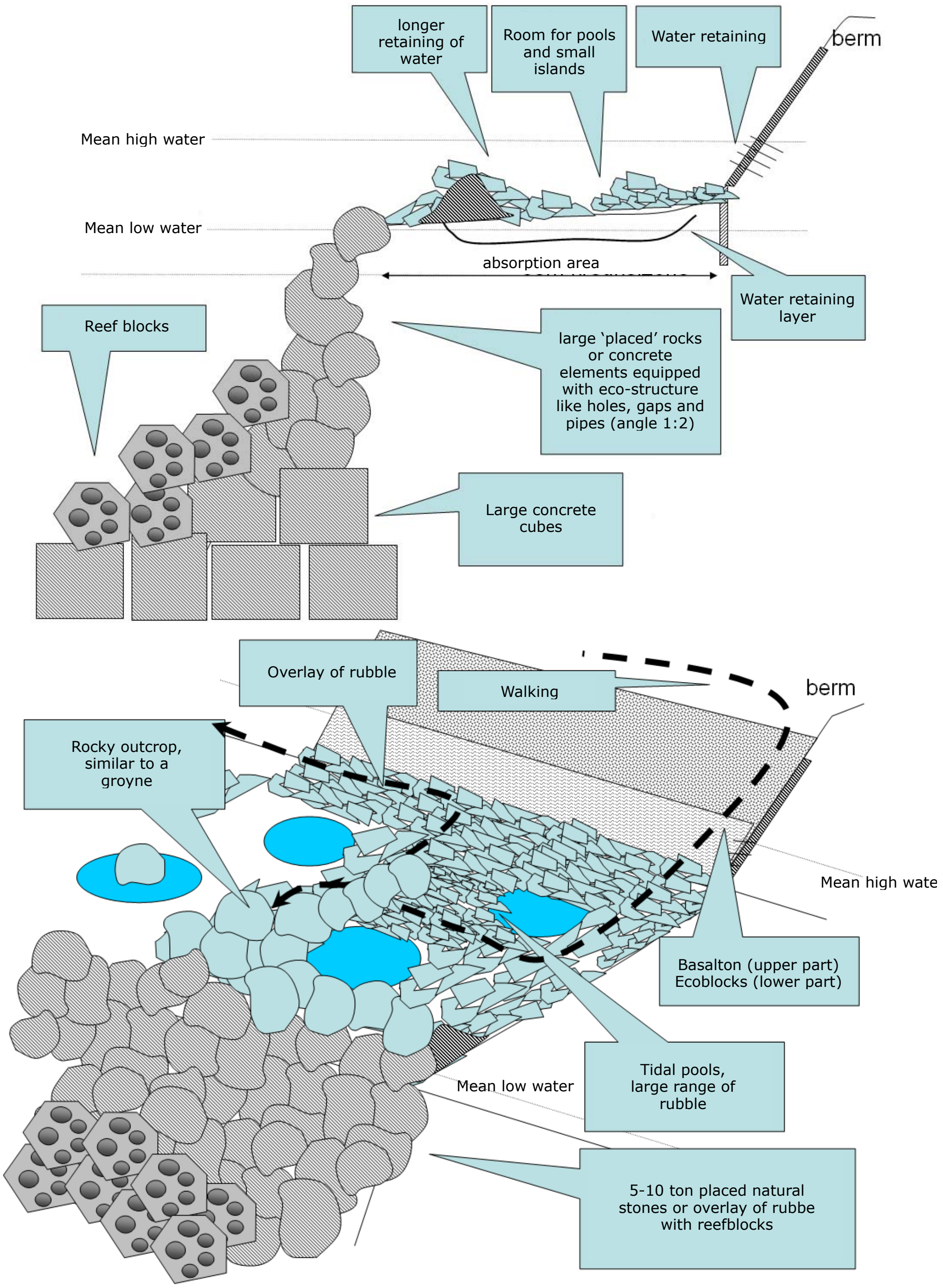


Figure 24: Rich dike design for exposed and deep dikes (source: Baptist et al., 2007)

B.2 FLYLAND

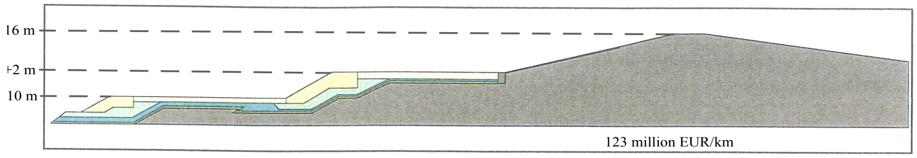
For an island on sea, about 10 to 17 km from the Dutch coast, with as purpose to create an airport have been assigned the following parameter for a flooding once in the 10.000 year:

- Overtopping of q=2L/s/m
- High-water is equal to 5 +mMSL
- A by depth limited significant wave height of 10 meter
- A wave period of 12 to 15 seconds and a wavelength of 225m
- A current of 1.5 m/s
- Depth of -20 mMSL

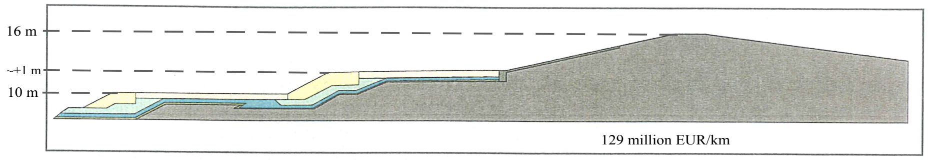
In the design is stated that the design of a single slope dike would be extreme high and heavy; the required blocks would be 100 ton each and the crest height would be 25 +mMSL. That is why there is chosen for a construction with several steps that each break the waves partially. The design has a submerged berm with a crest at -10 mMSL, subsequently a berm at 0 +mMSL and at last, the dike. The blocks used in this case are 20 ton (2x2x2) for the lowest dam and 40 ton (2.6x2.6x2.6) or similar tetra-blocks for the dam at MSL. The berms between the breakwaters are constructed with cubes of 20 t. and have lengths of 25% of the wave length what would result in 60 m. These cubes will be made on several filter layers and finally on sand.

For ecological purposes are extra adjustments made to give space for maritime live. For the northwest and southwest sides of the island are berms designed with a gentle slope from -1 mMSL to +1mMSL to enlarge the intertidal area. It will also be a good place for birds. The gentle slope which is located a bit lower will affect the price too; it increases with 5.1% compared to the hard-straightforward design. In the report of rich dikes defences (Baptist et al., 2007) are the berms of the structures covered with rocks of 3-7 ton for the deepest berm and 5-10 ton for the more shallow berm. It is mentioned that the stones should not be placed in an ordered manner but semi-random. In this way are holes created which can be valuable for animals and plants.

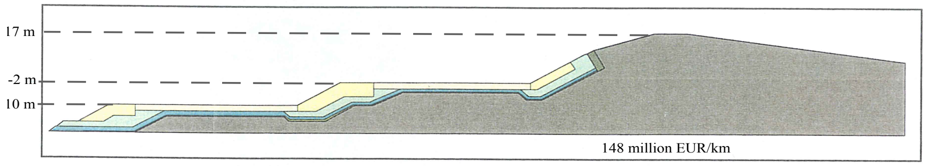
At the north and south point is a berm that is located -2m+MSL go give marine life maximum change without attracting birds. Consequence is that a larger crest is necessary and thus the price increases with 21.1% compared to the conservative hard design. For the east side of the island are several breakwaters not necessary since the wave attack is not severe on this side, so a straight slope is sufficient. This will reduce the price per kilometre significant. For this side were also different opportunities studied to increase ecology. An option was to construct an 'eco-berm' of 200m between -1m and 1m +MSL covered with rocks what would be 114% as expansive (97.1 EUR/km) while it doesn't add that much value to nature. Another opportunity is a soft slope protection, which would demand enough sand to create a stable dike design, what would result in a slope of 1:100. This would require so much sand that the price would increase from 45.3 to 278.4 million EUR/km following the research (see Figure 25).



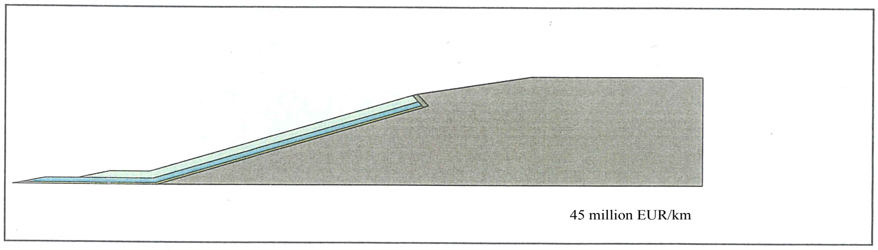
Western point of the Island



North and South side of the Island



North and South point of the Island



Eastern side of the Island

Figure 25: Coastal defense Flyland. Prices converted from NGL to EUR with IISG converter. (source: Waterloopkundig laboratorium, 1997)

B.3 MAASVLAKTE 2

For the design of the Maasvlakte 2 were the following requirements drawn up:

1. The hard sea defence must be stable against storm conditions having a return period ("RP") of 10,000 years with significant wave height increased by a factor of 1.1, and corresponding wave peak period and water level.
2. The hard sea defence must not need repair up to once-in-100-years storm conditions.
3. The hard sea defence must protect the harbour area of MV2 against wave overtopping:
    a. q < 1 litre per second per meter during once-in-10-years storm conditions; and
    b. q < 10 litres per second per meter during once-in-10,000-years storm conditions.
4. The wave reflection coefficient of the hard sea defence must not exceed 0.3 for prescribed unidirectional, perpendicular waves representing operational conditions.
5. The hard sea defence must have a lifetime of at least 100 years.
6. Uncertainties related to verification of the hydraulic stability of the hard sea defence by the prescribed physical scale modelling must be taken into account. (Loman, van der Biezen, B, & Poot, 2013)

With storm conditions of 1:10.000 year is for the Maasvlakte 2 a water depth presumed of 5.0 mMSL and a wave height of 8 meter (Port of Rotterdam, 2010). For sea level rising is an additional 0.3 meter added to the water depth and is space created to increase the dike height with 0.5 meter. For the design process were 2 options developed for further investigation, showed below of which the first one was the first traditional design and the second one is chosen for construction. This one is made with gravel and the old concrete cubes from the first Maasvlakte seawall.

The initial height of the only cobbled beach design was 33 meters (crest height of 15 meter) with a foot width of 250 meters and a required volume of 900 m^3, in order to withstand a 1 in 10.000 year storm. The thickness of this gravel layer was 9 meters with a widely graded gravel.
On the Maasvlakte 1 was already a cobble beach which is known as ‘Zuidwal’, which was the start of the cobbled beach concept. This 2.3 km long beach had a D_{50} of 18 mm, layer thickness between 2.5 to 3.5 meter and a slope of 1:8.

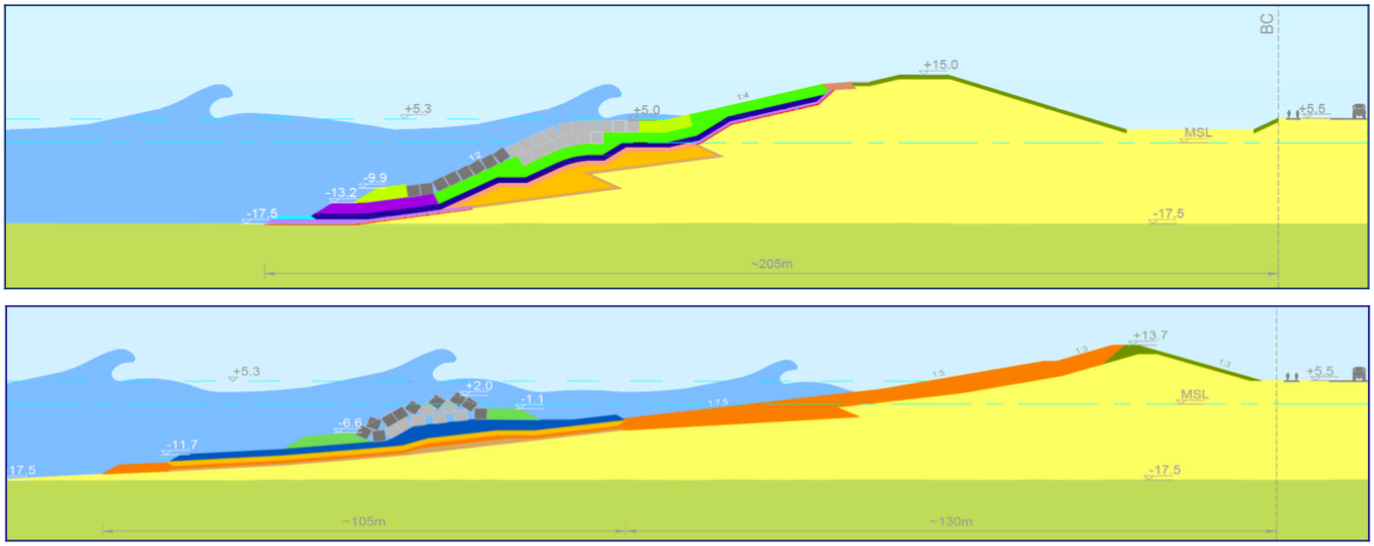


Figure 26: Initial (conservative) and final (gravel with reef) design coastal protection Maasvlakte 2 (source: (G J A Loman, van der Biezen, B, & Poot, 2013)

Another reference project similar to the Maasvlakte 2 cobble beach concept was the beach in Oregon where a 3 meter thick cobble (D_{50}=60mm) layer with a slope of 1:5 is protecting the Cape Lookout State Park eight years for El Nino storms (Gerard J A Loman, 2009).

C. COASTAL DEFENCE DESIGN

C.1 TRADITIONAL SLOPE

Crest height

The height of the structure will be dependent on the wave overtopping. The wave overtopping discharge can be described by two formulae, one for breaking (plunging) waves on the slope, and one for non-breaking (surging) waves. The overtopping can be calculated with the following formulae of which the minimum value determines the height:

$$\frac{q}{\sqrt{gH_m^3}} = \frac{0.026}{\sqrt{\tan\alpha}}\gamma_b\xi_m\, exp\left(-2.5\frac{R_c}{H_m\xi_m}\frac{1}{\gamma_f\gamma_\beta}\right)^{1.3}$$

$$\frac{q}{\sqrt{gH_m^3}} = 0.1035 exp\left(-1.35\frac{R_c}{H_m}\frac{1}{\gamma_f\gamma_\beta}\right)^{1.3}$$

where ξ_m is the breaker parameter showing the wave steepness relative to the structures slope $\xi_m = \frac{\tan\alpha}{\sqrt{H_s/L_0}}$. Since the wave steepness in the EVA is determined for a determined steepness is the breaker parameter for a 1:1.5 slope 4.4

q is the amount of overtopping discharge, for high safety this is 0.01 m^3/s/m (10 L/s)

R_c is the crest elevation

γ_f friction coefficient what is dependent on each revetment, for Xbloc this is 0.44 (Bruce, Van Der Meer, Franco, & Pearson, 2008)

γ_β is the wave angle coefficient, but assumed that the waves shoal straight into the dike this value is 1.

γ_b influence factor for the berm. First assumed without berm so $\gamma_b = 1$

The wave characteristics are found in the extreme value analysis in paragraph 3.4 and Appendix D.

Orientation	Wave height (m)	Wave period (s)	Crest height (m)
Northwest (0-90ºN)	8.2	15.1	11.45
Southwest (90-180ºN)	7.5	14.5	10.31
Southeast (180-270º N)	9.3	16.1	13.27
Northeast (270-360º N)	11.9	18.2	17.70

Table 8: Overtopping characteristics for a 1:1.5 slope and 10 L/s overtopping assumption for 4 different orientation

Revetment size

For the size of a Xbloc is assumed that the element does not moves during a design wave. The size is dependent on the wave and the correction factor which takes all kind of matters into account. The formula and ruling factors are showed below:

$$V = \gamma\left[\frac{H_s}{2.77\Delta}\right]^3$$

here is V is the Xbloc volume [m^3] and γ the correction factor with the factors in the table below.

Criteria:	When:	Factor:	Present:
Head or curved section	yes	1.25	x
Frequent occurrence of wave height during lifetime	yes	1.25	
Foreshore steepness	1:30-1:20	1.10	
	1:20-1:15	1.25	
	1:15-1:10	1.50	
	>1:10	2.00	
low crested structure	$R_c/H_s<0.5$	2.00	
	$R_c/H_s<1$	1.50	
Water depth in front of structure	$>2.5\ H_s$	1.50	
	$>3.5\ H_s$	2.00	
Core permeability	low	1.50	
	Impermeable	2.00	x
Mild armour slope	>1:1.5	1.25	x
	>1:2.0	1.50	

Table 9: Application of correction factor for Xblocs.

If more than one of the above-mentioned phenomena is applicable to a design, it is advised to apply the largest correction factor as a starting point for the physical model tests. Since the levee is not permeable this factor would be 2. The results of the Xbloc volume is showed in Table 10.

The structure has a maximum allowable number of Xblocs rows on the slope. To limit settlements is a maximum of 20 units possible. This means that the vertical distance of the Xbloc revetment is limited, dependent on the required crest height and the depth of 25 meter. With the given height of the Xblocs is calculated or this requirement is fulfilled with the following formula: $19D_y + 0.5D$

Coast orientation	Design wave (1:10000)	Crest height (m)	Unit volume (m^3) (incl γ)	Unit height (D)	Unit weight (t)	Thickness armour layer (m)	Rock grading under layer (t)	Thickness under layer (m)	Vertical placement distance (D_y)	Height Xbloc revetment (m)
Northeast (0-90ºN)	8.2	15.1	22.2	3.91*	48.0*	3.8*	3.0-6.0*	2.4*	2.47*	48.9* (OK)
Southeast (90-180ºN)	7.5	14.5	16.9	3.78	43.2	3.7	3.0-6.0	2.4	2.38	47.1 (OK)
Southwest (180-270ºN)	9.3	16.1	32.28	-	-	-	-	-	-	-
Northwest (270-360ºN)	11.9	18.2	67.6	-	-	-	-	-	-	-

Table 10: Xbloc characteristics for four corners of the island. (*values for biggest Xblocs of 20 m^3)

Calculating the volume which is required to fulfil the stability requirements is for three sides of the island above the largest standard Xbloc size (DMC, 2014). Only the southeast can be equipped with normal Xblocs and a constant slope. For the other directions are volumes above normal, although the required volume for the northeast flank is close to the largest size Xbloc. For this difference, a small increase in the Xbloc size should be possible to a volume of 22.2 m^3. The other flanks are significant larger than the biggest Xbloc so solutions should be searched to reduce the forcing or to increase the strength.

In the design of Flyland is chosen for berms that attenuates the wave heights. On the most extreme flanks is chosen for a berm at -10 mMSL and at +0 mMSL with a length of 25% of the wave length. The northwest berms would each, in the case of the Dogger Bank, need a length of 67 meter. In the design of Flyland is an extreme significant wave height of 10m expected, effecting the whole west flank. Similar conditions are orientated from the southwest of the Dogger Bank island. From the northwest are stronger waves coming which also effect the southwest flank. For the different sides of the island are in the Flyland design increased berm height used to increase the wave attenuation.

Assuming a similar design like Flyland for the whole western flank with a berm at -10m MSL would result in a maximum significant wave of 6.25m. Hereby is assumed that the surge, tide and sea level rise is on a maximum level of 2.48 m. The maximum wave height is assumed to be half of the water depth (J.W. van der Meer, 2002). At the berm of +0m MSL is the wave height maximal 1.24 m. In the design for Flyland is a higher surge expected (5 m) but are crest heights still at 16 to 18 meters. Therefore, the overtopping height are maintained. For the slopes are the largest Xblocs used to withstand the waves on the northwest/southwest flanks. In the Flyland design the slopes are made with a double layer of cubes or tetrapods of 20t (2.0m wide) and above it 40t cubes which are 2.6m wide.

Under layer

The rock layer between the core and armour layer must be made such that no erosion of the core can occur. In the xbloc manual (DMC, 2014) is given that the under layer underneath the largest xblocs has the weight between 3.0 and 6.0t and has a layer thickness of 2.4 meter.

Toe

The toe of the structure is formed with a special shaped xbloc, called xbase and a rock layer in front of the xbase. With a sandy bottom which is supposed on this location the bottom of the toe is mounted with a geo textile with a protective rock layer on top. This layer has a foundation rock layer with a size of $W_{50}/30$ of the Xbloc. On this foundation layer is the xbase placed and encapsulated with a rock layer with a minimum height of $2D_{n50}$ and minumum length of $3D_{n50}$. The D_{n50} is determined by van der Meer 1995:

$$D_{n50} = \frac{H_s}{\left(2 + 6.2\left(\frac{h_t}{h}\right)^{2.7}\right) N_{od}^{0.15} \Delta}$$

With h_t the depth above the toe

h water depth in front of the toe

N damage value, which is recommended to be 0.5.

Presumed that the under layer has a thickness of 2.4 meter and the granular filter layer a thickness of 0.5 meter can the D_{n50} be assumed. D_{n50} for the toe is found to be 1.82m. This is larger than the largest class in heavy grading (1.67-1.74 m) in standard grading classes of EN13383 (Schiereck & Verhagen, 2012). Since the difference is small, this class of heavy grading (6-10t) is still chosen. To compensate, a larger volume can be used than assumed in the Xbloc manual.

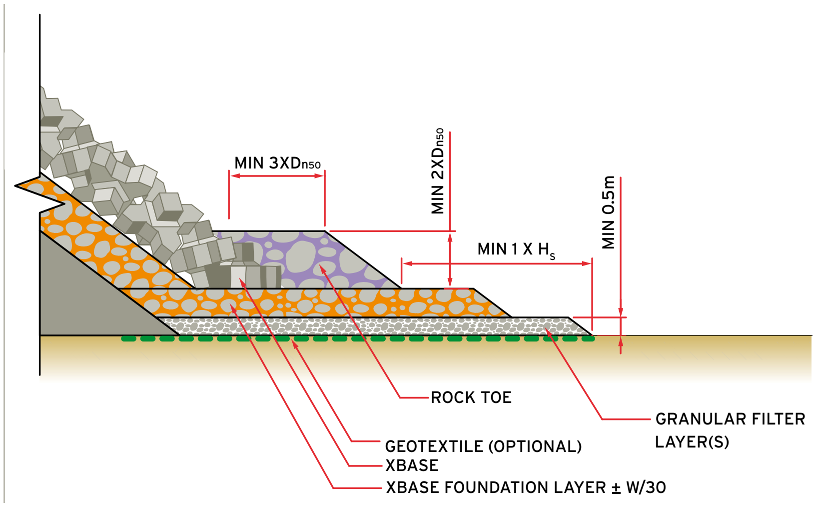


Figure 27: Toe design (source: DMC, 2014)

C.2 REEF

A reef can be made to attenuate the wave heights to establish favourable conditions behind the reef. The crest height of the reef will determine the transmission coefficient. Depending on the transmission coefficient can the crest be emerged or submerged. A rule of thumb is existing for the D_{n50} of reefs located below and above mean sea level (CETMEF, 2012) under the condition that it is in depth-limited wave conditions, in this context: $^{H_s}/_{h} = 0.6$.

$$\text{Submerged breakwater: } D_{n50} > 0.3d$$

$$\text{Emerged breakwater: } D_{n50} > 0.3h$$

In which d is the height of the structure and h the water depth at the toe of the structure. Since the crest of this structure is around MSL the values for D_{n50} are harder to calculate, therefore the formula made by (Ahrens, 1987) is used, he found that more displacement of material for conditions with a longer wave period is expected than for conditions with a shorter period.

$$N_s\left(H_s/L_p\right)^{-1/3} = \frac{H_s}{\Delta D_{n50}}$$

This result, for the most extreme waves and an N_s of 2.0, into a D_{n50} of 1.82 m which would be larger than the largest size of heavy grading rock (6-10 t).

C.3 BERM

In the design of Flyland are berms included in the design. In the report, the berms are 60m long (in the report also 25% of the wavelength). The berms are equipped with a single layer of 20 t cubes on some filter layers and finally sand. With van der Meer (1998) for plunging waves is an estimation made for the berms on the Dogger Bank. Since the berm is flat, a plunging wave climate is expected.

$$\frac{H_{sc}}{\Delta d_{n50}} = 6.2\, P^{0.18} \left(\frac{S}{\sqrt{N}}\right)^{0.2} \xi^{-0.5}$$

With P is the permeability parameter, which is equal to 0.1 for impermeable cores.
N is the number of waves, where an equilibrium in damage is expected at 7500 waves.
S is the damage level wherefore a value of 2.5 is assumed.

d_{n50} is with the values above and the most extreme waves 1.39 m. Since a more extreme wave climate is expected at the Dogger Bank compared to the Dutch coast (for Flyland), is the value of 2.0 m blocks adopted.

C.4 LONGSHORE TRANSPORT

It is likely that due to currents the sediment will be transported alongshore. Water on the Dogger Bank does not contain much sediment and not much sediment is transported along the bottom during average conditions. Currents and flows induces by waves will transport sand into the currents direction. Due to this flow of sediments and the fact that it is an island the volume of sediment in the system will decrease. Extra sediments will be necessary to fill-up the lost material. This can be done for a lifetime of 100 years in once or with several nourishments during its lifetime.

On the Dogger bank is a similar grain size 150 to 220 μm normal. With larger sediments, the slope can become steeper. In the report for Flyland (Programmabureau Flyland, 2003), an airport on sea is a sandy slope discussed, located at the lee side of the island. Which underwater slope would have an average of 1:100. The costs are estimated around 278 million EUR, much more than the earlier calculated 120 million EUR/km, probably due to the erosion which requires a lot more sand.

A sandy slope will be affected by sediment transport imposed by waves and tide. The tide at this location will be around 0.4 m/s, a lot smaller than near the Dutch coast which flows 0.7 m/s during neap tide and 1.5 m/s during spring tide. During the design of Flyland, an island for an airport is looked to the effect of an island on the tides and flow speed. They concluded that the flow speed close to the island would increase with 30%. Causing a greater amount of current induced sediment flow.

To indicate the amount of longshore transport are several formulas developed which determine the amount of erosion by a certain angle. Those formulations are discussed below:

Codes

A new development in the longshore transport calculation is a coastal development tool which can simulate sediment transport along the coastline for several coastal and waves angles (from ECMWF database). This model does not implement tidal currents. Since waves have several orientations and the island has a curved beaches the earlier discussed methods are hard to apply with simply implement the parameters. Codes use the Kamphuis (1991) formulation for sediment transport and includes all the different directions, occurrence and bottom profiles. It assumes a bed profile with a slope of 1:50 from MSL to the bottom.

Kamphuis (1991)

The amount of erosion which is generated by waves and induces a longshore sediment transport is in the past described by different formulas. A method of expressing the longshore erosion is with Kamphuis (1991), who included the beach slope as the wave steepness into the formula. This formula gives the bulk longshore sediment transport, which is the sediment what is transported due to waves in the breaker zone. The formula is calibrated with large numbers of prototypes and laboratory measurements. The formula is expressed as:

$$S = \frac{2.27 H_s^2}{\rho(s-1)(1-p)} T_p^{1.5} \tan(\alpha_b)^{0.75} D^{-0.25} \sin(2\varphi_b)^{0.6}$$

with:
- $T_p^{1.5}$ is the wave period at the breaker depth
- α_b is the bed slope at the breaker depth
- D is the grain size.
- S is the volume of the transported sediment.
- s is the relative density of the sediment, here 1.75 (ρ_s=1800, ρ_w=1025)
- φ_b is the wave angle of incidence

A graph of the formula with a varying angle of incidence on the x-axis will show a maximum sediment transport at 45 degrees. In practice, the transported sediment will be lower since the angle is reduced due to refraction to a maximum angle of -20 to 20 degrees.

This indicates the amount of sediment transport per transect, of which the inner arrow is the amount of sediment going anti clockwise, the middle arrow the clockwise direction and the outer arrow the net sediment transport. Concluding that all sediment will flow from the northwest to the southwest. The maximum value of the net transport is 422.719 m^3 on the northern side which subsequently decays to the southeast direction. The sediments will disappear further southwards or cumulate on this location. Sediment on the other parts will not return to the original location thus needs to be nourished in advance as a buffer or in regularly time intervals.

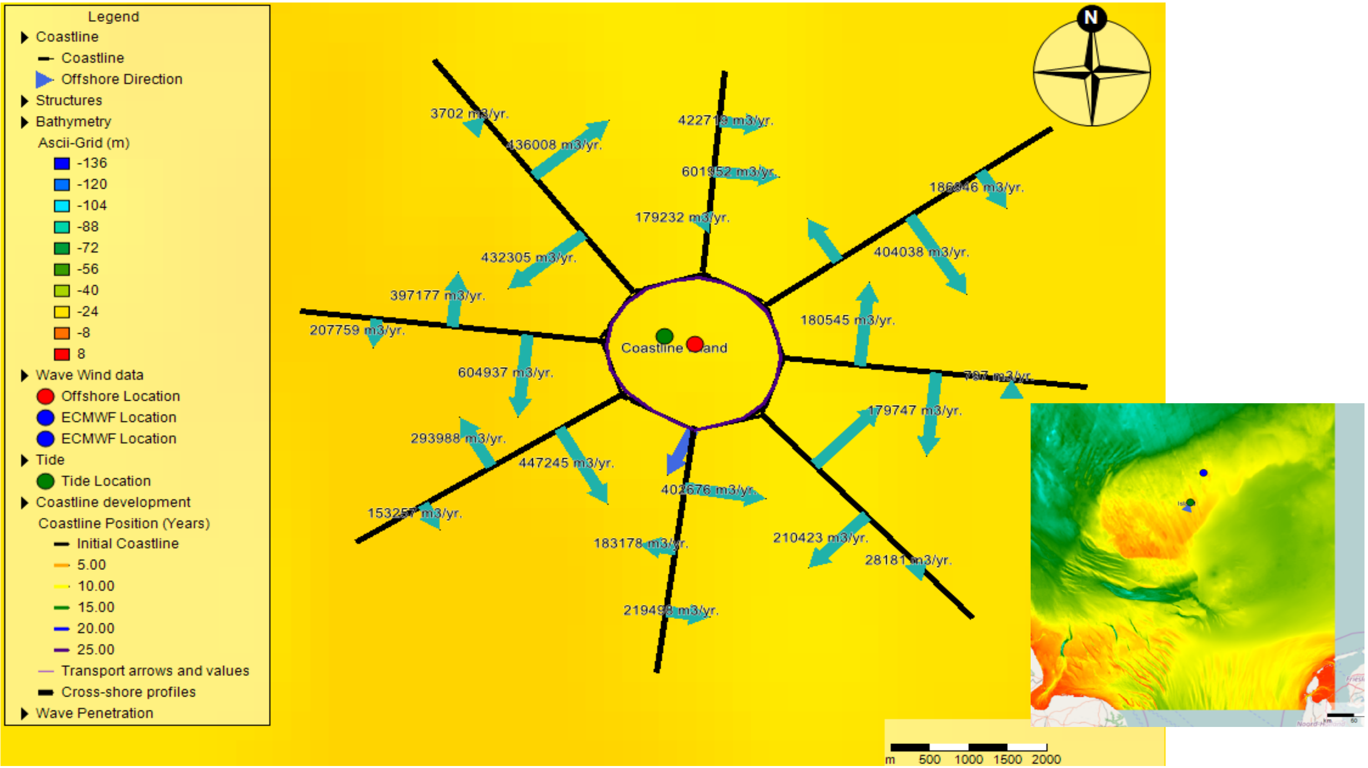


Figure 28: Codes longshore transportation model

D. EXTREME WAVE HEIGHT

The significant wave height in the design storm Hs is determined with the Peaks-Over-Threshold (henceforth POT) method. Observations with the greatest significant wave height and a minimum duration are defined as storms. The Threshold is determined such that the level is high enough for the tail to have approximately the standardised form, but not so high that too few observations remain above it. The standardised form exists due to the fact that observation in the extreme tail of a distribution often has a rather simple form, regardless of the shape of the more central parts of the distribution.

Of particular interest in wave analysis is how to find extreme quantiles and extreme significant values for a wave series. Often this implies going outside the range of observed data, i.e. to predict, from a limited number of observations, how large the extreme values might be. Such analysis is commonly known as Weibull analysis or Gumbel analysis, from the names of two familiar extreme value distributions. Both these distributions are part of a general family of extreme value distributions, known as the Generalized Extreme Value Distribution, (GEV). The Generalized Pareto Distribution (GPD) is another distribution family, particularly adapted for Peaks Over Threshold (POT), analysis.

Assumed is that storms take up to six hours and happen 3 to 5 times a year (personal communication with Witteveen and Bos engineers). The POT method relies on two properties of peaks over the selected threshold: they should occur randomly in time according to an approximate Poisson process, and the exceedances should have an approximate GPD distribution and be approximately independent. Storm and their extreme values occur often in clusters which cause a wrong impression of the extreme wave height. Therefore, the data is declustered to identify the largest value in each of the clusters. Subsequently is a Poisson distribution used for the distribution of the clusters. The selected peaks should be sufficiently far apart for the exceedances to be independent. Using the POT method results in this case in 100 storms with a threshold of 4.84 m, during minimal 2 hours with a frequency of 4.46 storms a year (satisfies the 3-5 storms a year). The data processed is from BMT ARGOSS which can online be accessed via waveclimate.com. The information is based on a validated wave model computations and satellite measurements (BMT ARGOSS, 2017). ARGOS distinguishes over the total data, sea waves and swell, of which the sea waves are used for the analysis. Sea waves are causing the higher waves in the spectrum and therefore filtered from the total data (Holthuijsen, 2007).

After finding the threshold and the decluttered storms can with estimation in MATLAB the optimal parameters be found for the Weibull, Gumbel and GDP distributions. Because these distributions are often used distributions for extreme values, are other distributions neglected. The distribution with the best fit, tested with a maximum likelihood test, is subsequently used to extrapolate the significant wave height in time.

D.1 GOODNESS OF FIT

The likelihood of a set of data is the probability of obtaining that particular set of data, given the chosen probability distribution model. The log-likelihood is the expression which must be maximised to determine the optimal value of the estimated coefficients. Log-likelihood values cannot be used alone as an index of fit because they are a function of sample size but can be used to compare the fit of different coefficients. Because the log-likelihood has to be maximised, the higher value is better (Minitab, 2017). Another value is the R-squared, this statistic measures how successful the fit is in explaining the variation of the data (MathWorks, 2017). It is the square of the correlation between the response values and the predicted response values, or the square of the multiple correlation coefficient and the coefficient of multiple determination. R-square is defined as the ratio of the sum of squares of the and the total sum of squares. R-square can take on any value between 0 and 1, with a value closer to 1 indicating that a greater proportion of variance is accounted for by the model. Continuously is the Root mean squared error an estimate of the standard deviation of the random component in the data. It displays the difference between the model and data with the unit meter.

$$RMSE = \sqrt{mean(model - measurements)^2}$$

Distribution	Loglikemax:	RMSE:	R-squared:
General Pareto Distribution	0.9603	-49.9567	0.1576
Weibul	0.9569	-49.9566	0.1489
Gumbel	0.9616	-68.6694	0.3940
Generalised Extreme Value	0.9388	-98.0094	0.4023

Table 11: Goodness of fit values for applied distributions, in yellow the most favourable value.

D.2 EXTREME VALUE ANALYSIS

Giving the values of Table 11 can be concluded that the Weibull distribution is the optimal distribution in estimating the right parameters in order to simulate the wave heights. Given that the Weibull distribution is the most accurate with this dataset are the years extrapolated to different return periods.

Return period	Wave height (m)	Mean wave period (s)	Adjusted mean wave period (s)	Peak wave period (s)
1:5	6.71	13.60	11,35	10,16
1:10	7.13	14.02	11,70	10,46
1:25	7.67	14.55	15,05	10,86
1:50	8.08	14.93	16,29	11,14
1:100	8.50	15.32	17,54	15,82
1:1000	9.88	16.51	21,65	17,06
1:10000	11.25	17.62	25,73	18,20

Table 12: The return periods and their corresponding values

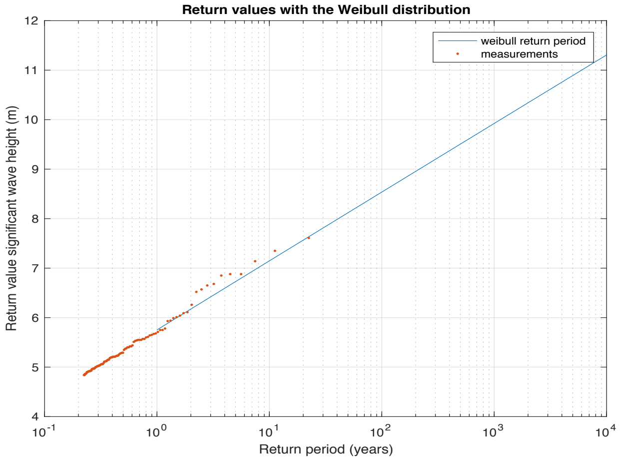


Figure 29: return period significant wave height Dogger Bank

With this test appeared that the 1 in 10.000 wave will be 11.25 meter. The highest storms which are measured or modelled in the data file are put into a list together with the corresponding wave period. This wave period and wave height of the largest 3 storms is averaged and transformed to a steepness, which can be indicated as the maximum steepness the waves can reach. The average wave height and mean wave period over the data over the 3 largest waves is 7.46 and 14.35 respectively.

$$s_0 = \frac{2\pi H_s}{g\,T_0^2}$$

The steepness for the extreme waves is discovered to be 0.023 (1/44) with this method. This would result with a 1 in 10.000-year wave of 11.25 in a mean wave period of 17.62. However, plotting the steepness profile into the wave data results in a deviant profile compared to the extreme values (Figure 30). Observing the wave data seems the maximum steepness for waves until 7 meters to have a value of 0,033 (1/30). Therefore, for the highest group of measurements a trend line is plotted to find the local tendency. Using the steepness of 0.033 for the first part of the waves and the trend line formula for the part after results in the fourth column of Table 12. The wave period of this analysis is still remarkable since the period becomes very long. Reason for the difference might be the water depth of the Dogger Bank. When waves reach certain heights, it might be that its effect reaches the bottom and waves cannot become steeper.

Peak period

For the peak period is the same analysis, with the mean of the highest three waves similar to the mean wave period, executed. With this analysis is again a difference between the steepness and the data found. The results of the analysis are in Table 12 as well, here is a different steepness for the first 8,50 meter used than for the higher extreme values.

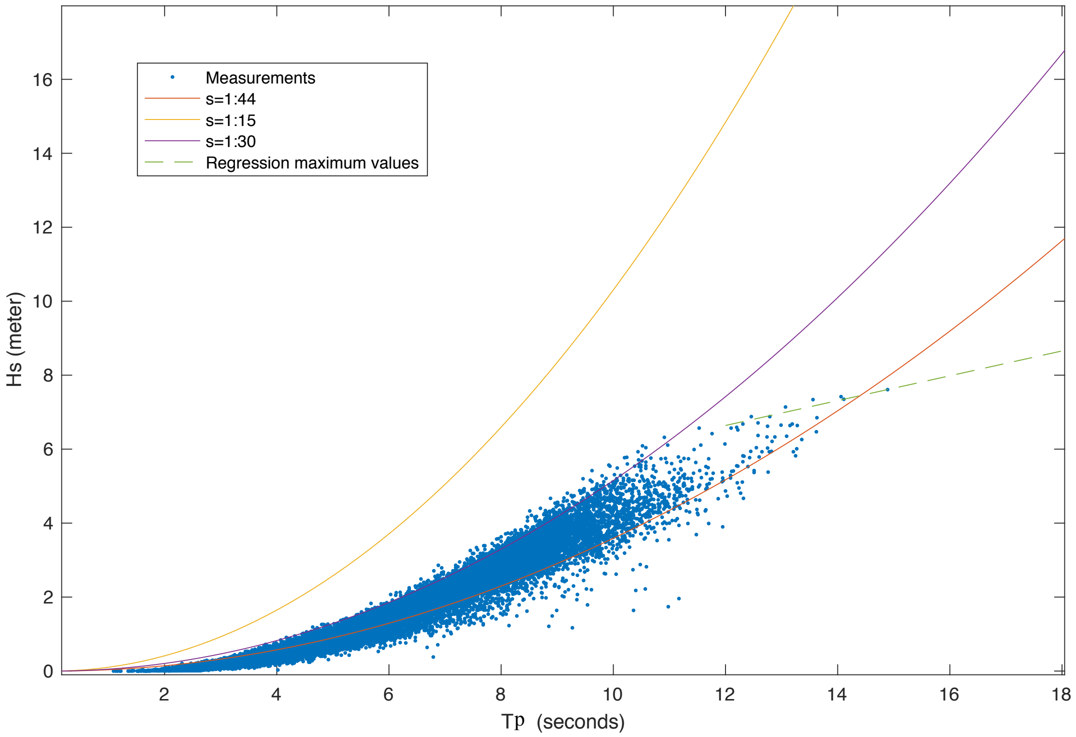


Figure 30: Wave data ARGOSS, significant wave height plotted against the peak period. Including wave steepness for extreme and lower value.

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