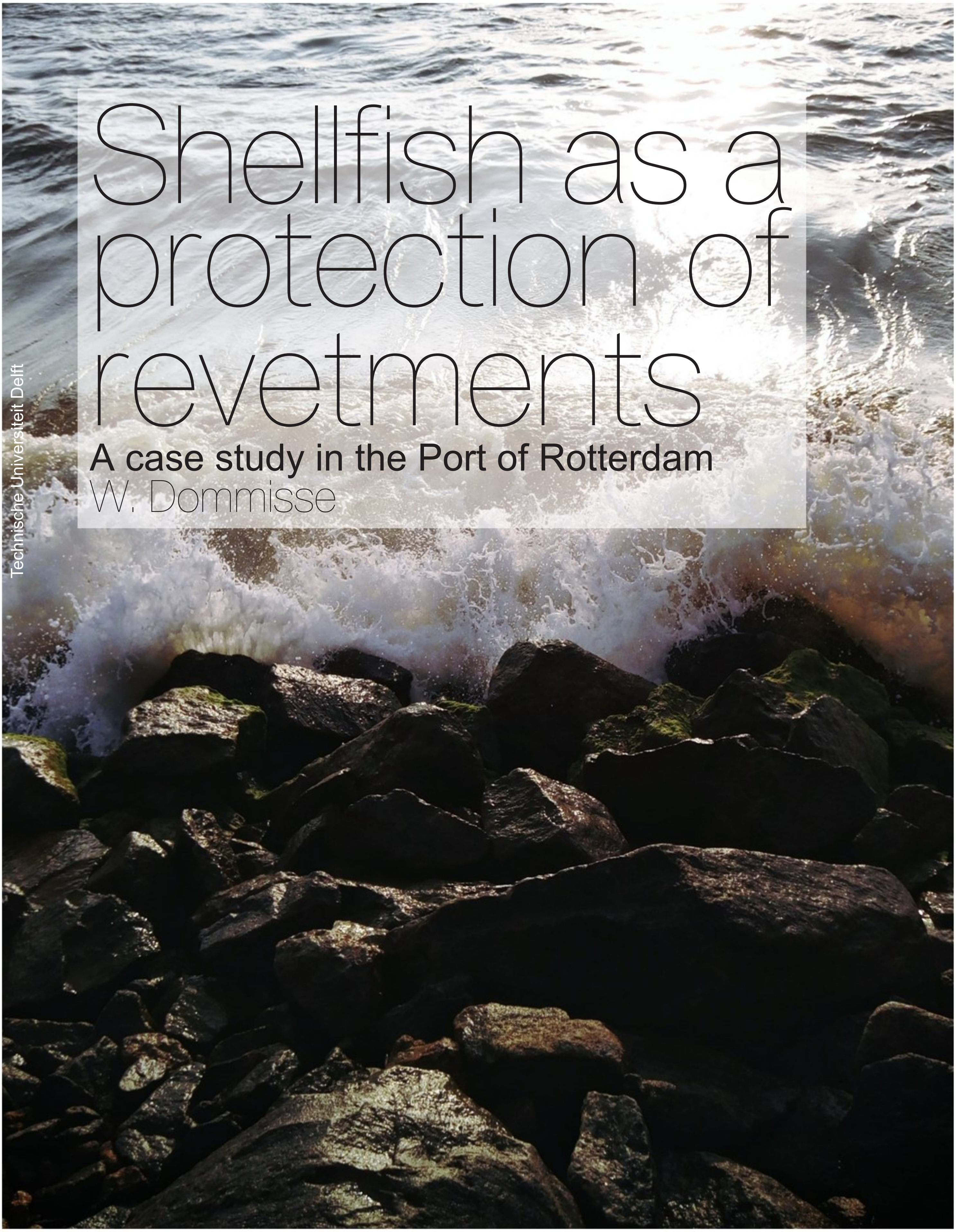

Shellfish as a protection of revetments

A case study in the Port of Rotterdam

W. Dommisse

Technische Universiteit Delft

TU Delft

Witteveen + Bos

Port of Rotterdam

Shellfish as a protection of revetments

A case study in the Port of Rotterdam

by

W. (Wilmine) Dommisse

to obtain the degree of Master of Science in Civil Engineering
at the Delft University of Technology,
to be defended publicly on Thursday, July 16, 2020, at 9:00 AM.

Student number:	4282493	
Project duration:	September 1, 2019 - July 16, 2020	
Thesis committee:	prof. dr. ir. M. van Koningsveld,	TU Delft, Chairman
	dr. ir. B. Hofland,	TU Delft
	prof. dr. P.M.J. Herman,	TU Delft
	ir. T. Wilms,	Witteveen+Bos, Daily supervisor
	R. Wolf, MSc	Port of Rotterdam

An electronic version of this thesis is available at http://repository.tudelft.nl/.

Cover image: stones under wave attack (Omkar Jadhav, n.d.). Retrieved from: unsplash.com/photos/Y4DcUToZa30

TU Delft

Adopt the pace of nature -
her secret is patience

- Ralph Waldo Emerson *1803-1882*

Preface

On a beautiful summer day in late August, I started the journey that finally led to this report. My interest in the subject originated from a passion for nature on one hand and hydraulic engineering structures on the other. I wanted to find out how nature, especially shellfish, could be incorporated in hydraulic engineering processes. I used to see oysters and mussels merely from an ecological point of view. I didn't know whether it was possible to use them in the design of revetments. This research shows possibilities but also raises many new questions that need to be answered in future research. I have learned a lot from working at the interface of ecology and civil engineering. I realized how difficult and important it is to look beyond a certain field and understand others to create amazing ideas. I hope that you will enjoy reading my report.

I would like to thank some people that helped me along the way. Among which are my supervisors from the TU Delft for their feedback and helpful advice: Mark van Koninsveld as my chair, Bas Hofland as my go-to for design questions, and Peter Herman as my help in the natural process, statistics and experiments. Furthermore Witteveen+Bos and the Port of Rotterdam for providing me all the necessities to complete my thesis successfully. Tom Wilms from Witteveen+Bos for your great guidance and weekly help. Robbert Wolf from the Port of Rotterdam for your insight into the port system and helping me connect with several interesting companies and people.

During my experiments, the advice and help of Peter Paalvast were indispensable, I enjoyed how you showed me your interest in nature. Ashley Cryan for helping me performing the detailed experiments and showing me what barnacles are. Tjeerd Bouma and Jan van Poppel for the help with testing the strength of oyster attachment. Lambèr Hulsen for providing me the SDS files to run the model. Jeroen Wijsman, Floor Heinis, employees of ARK, and J. Barbé for their insight and their knowledge.

I wish to thank all my friends who supported me throughout my study as well as during the final steps of this thesis. Especially Kate and Laurie with whom I enjoyed the hydraulic engineering courses. But also all my other friends for the sometimes much-needed distraction. You know who you are. To conclude this preface, I want to thank my family, my father who drove with me through the port area while doing research. My mother and Suzanne who always supported me along the way.

Wilmine Dommisse
Delft, July 2020

Summary

Many hard bank protections are located throughout the port area in Rotterdam. Including 202.0 kilometers of sloping bank protections. The port authority seeks to clarify whether they can incorporate nature in the design of these revetments and to what extent. Based on an ongoing interest in shellfish restoration in the North Sea area, the port authority wants to investigate the added structural value of shellfish for the bank protections. Therefore, the research question is as follows:

To what extent can shellfish presence affect the stability of loose rock revetments and how can shellfish potentially be used in the design?

Typical loose rock revetments in the Port of Rotterdam contain stones from stone class 10-60 kg, their slope is 1:3 or less, and their top layer goes down to NAP -5 m. The Pacific oyster (*Crassostrea gigas*) and blue mussel (*Mytilus edulis*) are common shellfish species in the port area and act as ecosystem engineers. They require a certain salinity level, water temperature, phytoplankton ratio, and sufficient submersion time for daily feeding and respiration. Various predators and diseases can threaten the development and survival of these species. In this study, the presence of *C. gigas* and *M. edulis* on loose rock revetments is quantified and their effect on the binding of stones in these revetments is studied.

The current presence of shellfish in the port area was predicted based on salinity levels generated by an operational flow model for the Port of Rotterdam (OSR). Outcomes were compared to qualitative observations performed in the port area. These qualitative observations indicate *C. gigas* and *M. edulis* presence at various accessible revetments. A comparison between these measurement results and the predictions showed that *C. gigas* presence was correctly predicted using the OSR model while *M. edulis* presence was overestimated. *C. gigas* is present on revetments where salinity levels exceed 16‰, which is the case at locations at Maasvlakte 2, Beerkanaal, and Calandkanaal. *M. edulis* were hardly observed in the port area on revetments. *M. edulis* can move relatively easily and detach from the surface after mortality occurs. They are, therefore, not considered a reliable structural addition, so only the effect from *C. gigas* was studied.

The increase in stability due to an increased nominal stone was described by a stability upgrading factor, Ψ_d. This factor is based on the definition of the nominal stone diameter, d_{n50}. The formula describes the relationship between the absolute number of exposed stones, S, and the effective number of exposed stones, E. The binding of stones, and therefore the decrease in the effective number of exposed stones, results in an increase in nominal mass per stone given that the total mass of the stones remains the same. This produces an increased d_{n50} value at a specified location. The stability upgrading factor can be multiplied with the d_{n50} of the original stone classes to come up with the increased value of the d_{n50}.

$$\Psi_d = \frac{d_{n50,\ oysters}}{d_{n50,\ original}} = \sqrt[3]{\frac{S}{E}}. \tag{1}$$

A relationship between the coverage ratio of oysters, r_{CR}, and the effective number of exposed stones was determined using a connectivity model. Combining this relationship with the formula for the stability upgrading factor, Ψ_d, led to a relationship between the coverage ratio of oysters and the stability upgrading factor, Ψ_d, depending on the stone grading. The connectivity model is based on the following assumptions: i) oysters settle only on hard material, ii) each settlement at a given distance from the edge will lead to binding of stones (with the distance depending on the packing density of the stones), iii) E=S if there is no oyster coverage (r_{CR}=0), iv) E=1 if there is full oyster coverage (r_{CR}=1), and v) binding is considered to have happened as soon as r_{CR} is greater than 0. For an initial version of the connectivity model, each oyster was expected to be strong enough to bind stones together. Measurements of the attachment strength of oysters showed that oyster cementation can handle an average

weight of 16.5 kg. Therefore, multiple oysters are necessary for effective binding. The number of necessary oysters is assumed to depend on the weight of the stones. Combining this information with the initial relationship resulted in an improved relationship between the coverage ratio of oysters and the stability upgrading factor. This improved relationship showed the effect of oyster presence on the stability of loose rock revetments.

$$\Psi_{d,\ model} = \sqrt[3]{\frac{S}{1 + (S-1) * (1 - r_{CR})^{\frac{A_{tot} * f_{im}}{(S-1) * A_o}}}}. \tag{2}$$

$\Psi_{d,\ model}$ = Modelled stability upgrading factor [-]
S = Absolute number of exposed stones [-]
r_{CR} = Coverage ratio of oysters [-]
A_{tot} = Total area [m^2]
f_{im} = Fraction of oysters settling at the edge of stones, leading to an effective binding [-]
A_o = Area covered by a single oyster [m^2]

Results of the obtained connectivity model were compared to values from quantitative measurements of shellfish coverage and the number of stones (representing the stability increase) within the Port of Rotterdam. Locations for quantitative measurements were based on the outcomes of the qualitative observations. For these quantitative measurements, 3 locations were observed with each location containing 3 areas and each area containing 5 plots of 1 m^2. Observations included: i) the coverage ratio of living *C. gigas*, ii) the coverage ratio of dead *C. gigas*, iii) the absolute number of exposed stones, S, and iv) the effective number of exposed stones, E. Quantitative measurements showed that the cumulative coverage ratio of dead and living *C. gigas* decreases as one moves up to the intertidal zone from the mean low water level (MLW). This is in line with the predictions regarding shellfish presence in vertical space. More stones are bound when the coverage ratio of *C. gigas* is larger. This implies that there is a relationship between the coverage ratio and the binding of stones. The extent of the effect of oysters on the stability of loose rock depends on the coverage ratio of oysters and the used relationship between the binding of stones and stability upgrading. A minimum cumulative coverage ratio of dead and living *C. gigas* of 0.12 is necessary for an initial stability increase. The stability upgrading factor corresponding to a coverage ratio of 0.6 is considered to be the upper limit for added stability from oysters based on an analogy with asphalt.

The binding of stones and therefore the increase in stability occurs when oysters are present on a revetment. The presence of oysters comes with structural, environmental, and ecological impacts. The conditions in the Port of Rotterdam as a system itself can pose various opportunities and threats for oyster coverage, such as global warming, pollution, and future port plans. Complementary measures can be implemented to mitigate the limitations and threats. Mitigation measures that are discussed are: i) allowing sufficient development time for oysters, ii) implementing a monitoring protocol, and iii) placement of extra material if additional stability requirements are not met.

The maintenance demand, and associated costs, decreases when oysters are present. Oysters are usually present naturally, their presence can be stimulated by enhancing *C. gigas* populations at locations with conditions that would allow potential oyster growth (Figure 1). Enhancement strategies depend on local conditions. A possible proposed stock enhancement method is the gluing of mature oysters to stones in the revetment. This will lead to the natural production of more larvae and thus to an increase in the oyster population. Possible habitat enhancement methods are improvement of the substrate or introduction of empty shells. A pilot study should indicate whether these methods are suitable for coverage ratio improvement on revetments. Application is most promising when bow thruster or ship wave impact is normative because oysters are mainly found up to NAP +0.5 m. Additional enhancement costs are approximately equal to the expected reduction in maintenance costs. Possible ways of application in the Port of Rotterdam are summarized in a flowchart (Figure 2).

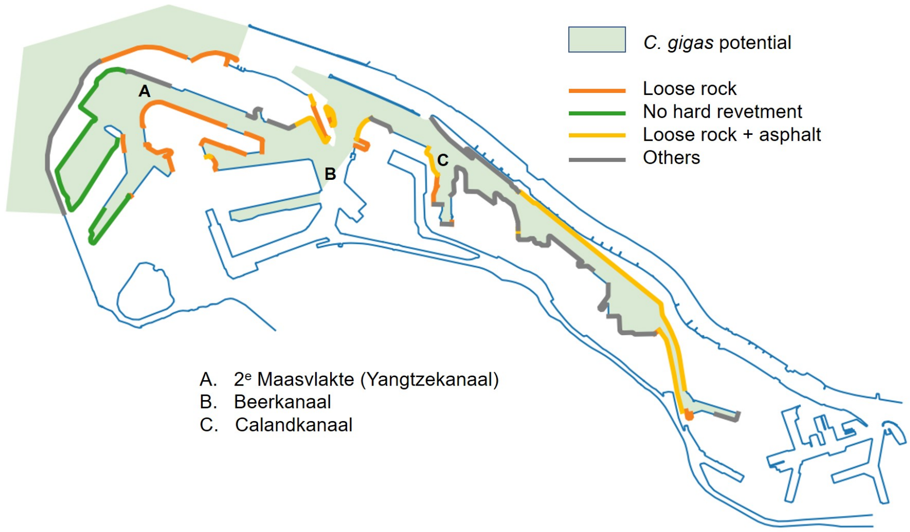

Figure 1: Potentially suitable locations for application of oysters in the Port of Rotterdam

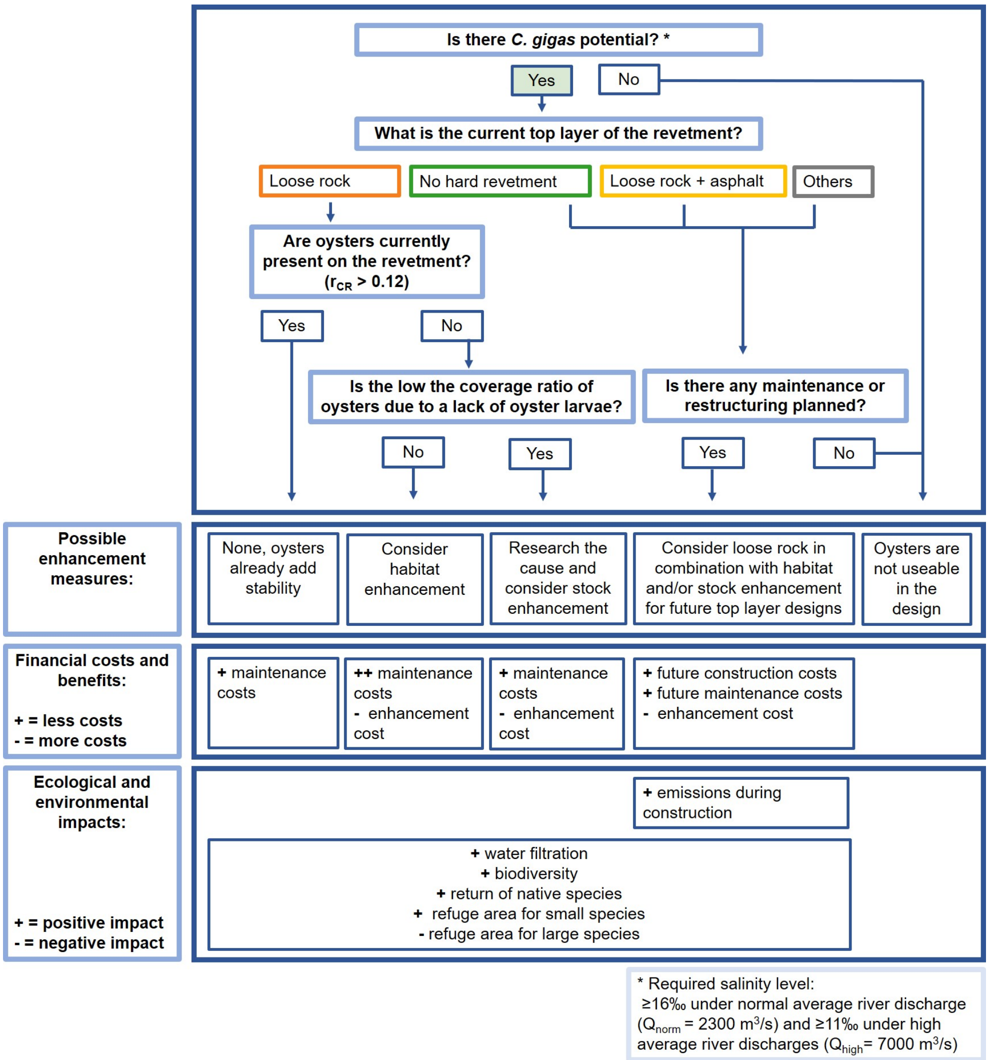

Figure 2: Flowchart for application of oysters in the Port of Rotterdam

Contents

List of Figures

List of Tables

Glossary of Terms

60%-line	Line that represents the location which is exposed to air for 60% of the time during an average tidal cycle
SDS	File extension; MIDI format that contains standardized System Exclusive (SysEx) messages
$CaCO_3$	Calcium carbonate
GHG	Greenhouse Gas
HWS	High water slack (tidal stream reverses from flood to ebb)
LS	Landside
LWS	Low water slack (tidal stream reverses from ebb to flood)
MHW	Mean high water level
MLW	Mean low water level
MWL	Mean water level
NAP	Normaal Amsterdams Peil (revetments in the port area are described with respect to this value)
OSR	Operationeel Stromingsmodel Rotterdam (operational flow model for the Port of Rotterdam)
RMSE	Root mean square error
SLS	Serviceability limit state
SR	Standard revetment
SWL	Still water level (water level at a given point in time in the absence of wind waves)
ULS	Ultimate limit state
WS	Waterside

List of Symbols

Symbol	Unit	Description
A_o	[m^2]	Area covered by a single oyster
$A_{o, tot}$	[m^2]	Total area covered by oysters
A_s	[m^2]	Area of a single stone
A_{tot}	[m^2]	Total area
a_f	[-]	Coefficient of the fatigue curve, depends on the type of asphalt
D	[m]	Vertical distance from impact point to still water level
d_{n50}	[m]	Median nominal stone diameter (=$(m_{50}/\rho_s)^{1/3}$)
E	[-]	Effective number of exposed stones
e	[m]	Settling distance of an oyster, measured from the edge of a stone, that enables effective binding
g	[m/s^2]	Standard gravity (=9.81)
F_{po}	[N]	Average force needed to pull an oyster from a surface
f	[-]	Fraction of oysters settling at the edge of stones, leading to a binding
f_{im}	[-]	Fraction of oysters settling at the edge of stones, leading to an effective binding
H_D	[m]	Design wave height
H_s	[m]	Wave height of an individual wave
H_{sc}	[m]	Significant wave height
k_f	[-]	Coefficient of the fatigue curve, depends on the type of asphalt
L	[m]	Characteristic length of the external load
M_{50}	[kg]	Median nominal mass
M_{em}	[kg]	Effective mean mass
M_{tot}	[kg]	Total mass of stones in the on the exposed portion of the top layer at a given area
N	[-]	Number of shellfish
N_f	[-]	Number of load repetitions leading to failure at size σ
$N_{f,i}$	[-]	Number of load repetitions leading to failure at stress level i
N_s	[-]	Stability number
n_i	[-]	Number of load repetitions at stress level i
p_{max}	[Pa]	Maximum pressure
r_{CR}	[-]	Coverage ratio of oysters
r_s	[m]	Radius of a stone
S	[-]	Absolute number of exposed stones
Γ_1	[-]	Clamping or friction factor
Δ	[-]	Relative density parameter (=$(\rho_s-\rho_w)/\rho_w$)
η	[-]	Packing density
Λ	[m]	Leakage length
ρ_s	[kg/m^3]	Sediment density
ρ_w	[kg/m^3]	Water density
σ	[N/m^2]	Tension stress, or bending stress, at the underside of the asphalt layer
Ψ_d	[-]	Stability upgrading factor
$\Psi_{d, model}$	[-]	Stability upgrading factor based on the created model
$\Psi_{d, data}$	[-]	Stability upgrading factor based on measurement data

1 Introduction

1.1. Background

Located in Rotterdam, bordering the North Sea, lies the Port of Rotterdam. The port functions as a gateway for the European hinterland and as a hub to other large ports. In 2018 alone, the Port of Rotterdam saw a total cargo throughput of 469 million tons, earning the title of the leading port in Europe. The port is a vitally important component of the Dutch and European economy (Port of Rotterdam, 2019). Shoreline infrastructure should be constructed safely and maintained regularly to ensure the safe transit and docking of vessels and to protect against flooding and erosion in the surrounding area. In this thesis, shoreline infrastructure is defined as hard bank protections inside the port area (i.e. revetments and quay walls). The port area consists of all the land and water area that is managed by the Port of Rotterdam (Figure 1.1).

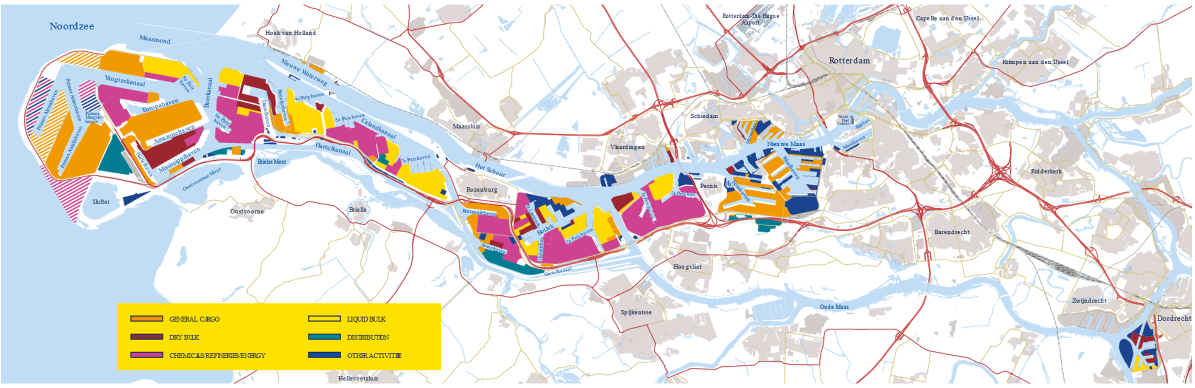

Figure 1.1: Overview of the port area of the Port of Rotterdam (Port of Rotterdam, 2019)

Bank protections in the port consist of 202.0 km of slopes and 77.3 km of quay-walls (Port of Rotterdam, 2019). An overview of different surface materials used in the construction of bank protections within the port is shown in Figure 1.2. Several properties determine the size of the stones used in loose rock revetments, among which is the stability of the stones under a specified load. Revetments should be designed against different loads such as ship waves, wind waves, and currents. The degree of stability required is determined using the weight of the stones, which is a function of the nominal stone diameter, d_{n50}, and the density of the material used, ρ_s.

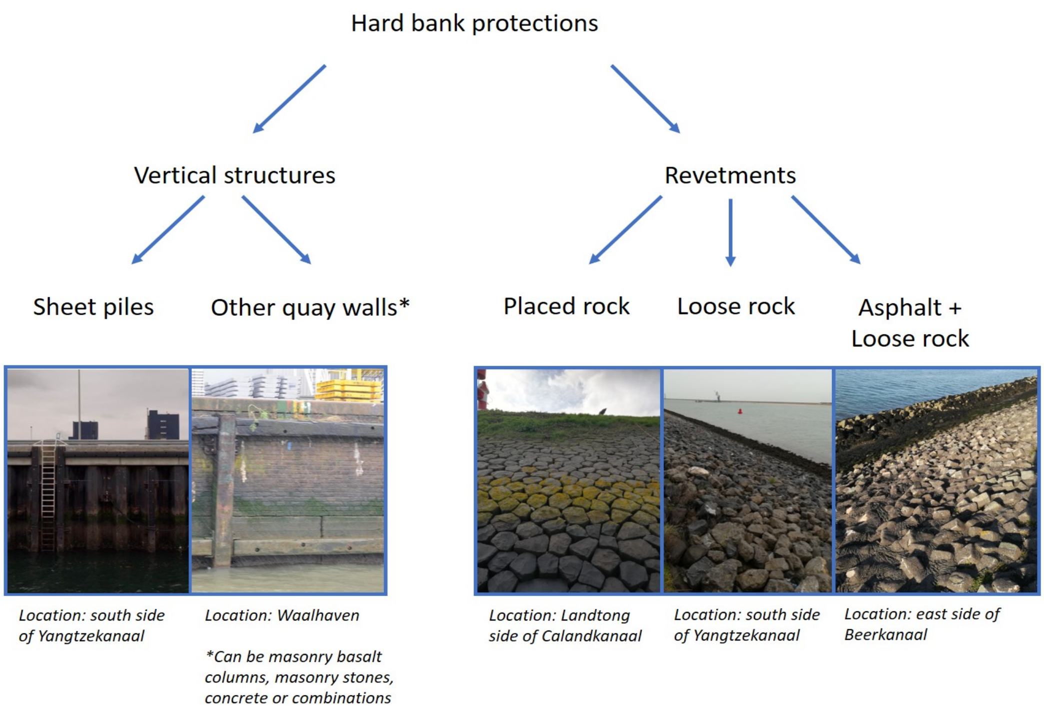

Figure 1.2: Schematic representation of the types of hard bank protections used in the port area, based on Paalvast (2017)

In addition to these artificial structures, nature plays a role in the port as well. The port area differs from the surrounding region in that its shoreline, mainly consists of artificial hard substrate. In contrast, the nearby coast of South-Holland and the delta of Zeeland mainly consist of sandy shores. Therefore, the port area provides a unique habitat for flora and fauna on the hard substrate. Many species are found inside the port area (Paalvast, 2017), including two that are of particular ecological relevance: the Pacific oyster (*Crassostrea gigas*) and the blue mussel (*Mytilus edulis*). These shellfish species act as ecosystem engineers, meaning that they create an environment that gives opportunities for other species to survive (Borsje et al., 2011).

1.2. Problem description

Revetments are used to protect the embankments within the port from flood risk and coastal erosion. These revetments consist of multiple layers of rock, the dimensions of which are specified according to engineering design formulas. In the case of loose rock, design formulas advise a nominal stone diameter, d_{n50}, which corresponds to a standard stone grading class (Appendix G). These stone grading classes are commonly used in Europe (European Standard NEN-EN 13383). Design calculations for revetments generally take into account extra safety factors to insure the completed structure against failure. In some cases, the calculation will specify a larger stone class when a smaller stone class does not meet the stated safety requirements. In this situation, the revetment is technically over-dimensioned, where customized grading could hypothetically produce a better option. In some cases, this problem is solved by applying grouting (CIRIA et al., 2007). The Port of Rotterdam regularly deals with revetment designs that are over-dimensioned or that require grouting using conventional approaches (Appendix A.1). There are alternatives to deal with this problem such as combining a smaller stone class with more frequent monitoring. Innovative Building with Nature solutions can also be used to incorporate the functions and qualities of natural ecosystems in the design and construction of a revetment.

Previous studies explored the presence and density of shellfish in sandy environments (Dankers & Fey-Hofstede, 2015; Sas et al., 2019; Smaal et al., 2018; van der Weide et al., 2018). The majority of this research was conducted to restore shellfish populations and improve the ecological value of an area. This research has generated knowledge about methods of reintroduction and habitat requirements of shellfish. In addition to their ecological value as a species, shellfish can probably also add technical value to engineering projects as a stabilizing element. Shellfish mainly attach to hard substrate where their presence can alter the physical properties of the substrate. When shellfish attach to a loose stone revetment, their natural cementation processes can bind stones together and therefore affect the stability of the revetment as a whole. This could have positive effects on the durability and longevity of the infrastructure. Knowledge about the effect of shellfish on hard substrate is currently quite limited. Increasing insight into the effect of shellfish presence and density on infrastructure stability might result in unique opportunities for Building with Nature principles to be applied in revetment design. Some of the aforementioned studies demonstrated the bolstering effect of shellfish populations on the stability of sandy environments. However, the added technical value of shellfish populations on hard substrate is not yet well understood.

At the same time, utilizing a Building with Nature approach comes with risks. Shellfish mortality, for example, could pose a threat to the integrity of the structure once shellfish are used in the design. Relying on their added stability in engineering specifications may not provide the level of protection necessary if populations experience natural fluctuations. Therefore, further knowledge about the habitat requirements of shellfish and their presence in the port should be developed to better predict the extent to which shellfish influence the stability of loose rock in revetments.

1.3. Research objective and questions

The main objective of this study is to increase the understanding of the effect of shellfish presence on the stability of loose rock revetments and to investigate the possibilities in the design.

The main research question associated with this objective is:

To what extent can shellfish presence affect the stability of loose rock revetments and how can shellfish potentially be used in the design

This question is divided in the following sub-questions:

1. How is the stability of typical loose rock revetments, used within the Port of Rotterdam, calculated and what are the characteristics of shellfish species commonly found living on these revetments?
2. What is the current presence of shellfish species in the port area and how can this presence be predicted?
3. To what extent can shellfish presence affect the stability of loose rock in revetments in the port area?
4. What are potential applications of shellfish in revetment designs?

1.4. Approach

A structured, stepwise approach is used to address the research questions as stated above.

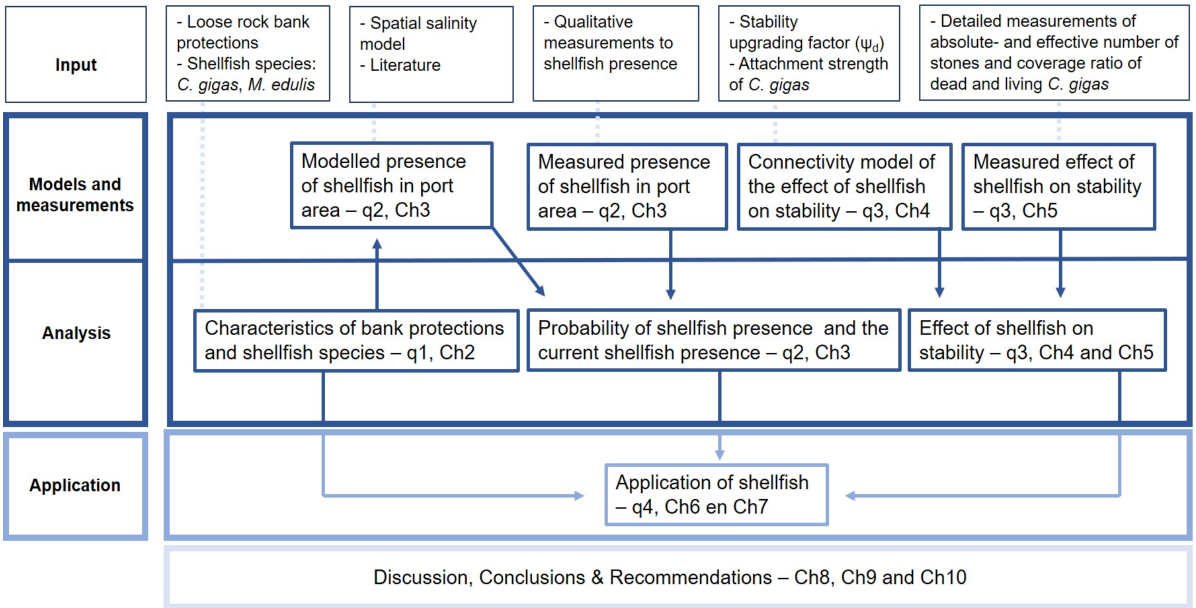

Figure 1.3: Framework of the planned approach

1.5. Research scope

Research is conducted within the following scope.

Port of Rotterdam vs. other locations

The port area in Rotterdam is the only location considered in this investigation (Figure 1.1). This location is chosen because it is associated with a large extent of loose rock revetments. Previous research on the restoration of shellfish banks in the North Sea area has shown that this area is suitable for shellfish populations.

Above MLW vs. at every vertical level of the revetment

Surveys of shellfish on revetments were conducted exclusively at locations above mean low water (MLW). It was impossible to obtain measurements below the waterline due to several limiting factors. Underwater photography is attempted using GoPro cameras, but the images obtained were not clear enough for analysis. Some videos made by divers were sourced, but too few were available to glean any meaningful results. Shellfish density is greatest below MLW and decreases with progressive distance from the water line in response to the harsh environmental conditions in mid- and high- intertidal zones (Vismann et al., 2016). For example, the variation in temperature conditions, which could negatively affect shellfish presence, is mainly limited to the upper 1 meter of the water column. For further applications below MLW, it is important to realize that any species data from above MLW would likely reflect a lower limit of species presence below MLW.

Bank protection vs. bed protection

In consideration of the aforementioned sampling limitations, only locations above MLW were surveyed in this study. Therefore, only results related to bank protections (i.e. revetments), and not bed protections, are discussed.

Revetments vs. all types of hard bank protections
Within the port area, only revetments are considered (Figure 1.2). Vertical structures like sheet piles and other quay walls are not observed. This is because the study was designed to specifically investigate the impact of shellfish attachment on revetments.

Loose rock revetments vs. all types of revetments
Due to time limitations and the nature of the hypotheses of this study, only the effect on loose rock revetments is studied. The effect on other types of revetments is not considered (Figure 1.2).

Instability vs. other failure mechanisms
Due to time limitations, the only failure mechanism considered in this study is the instability of the revetment (subsection 2.1.1).

***C. gigas* and *M. edulis* vs. other shellfish species**
C. gigas and *M. edulis* were selected for the purposes of this study as two of the most common shellfish species in the port area that attach to hard substrate.

1.6. Report outline

Chapter 2 uses knowledge from literature sources to discuss bank protections as well as two shellfish species that are common in the port area (*C. gigas* and *M. edulis*). Chapter 3 reports a prediction of shellfish presence in the port area based on literature discussed in chapter 2 and an accompanying spatial salinity model. The results from field surveys are compared against the predictions for shellfish presence. Chapter 4 discusses the effect of *C. gigas* on the stability of stones. A stability upgrading factor is proposed and a connectivity model describes the initial relationship between oyster coverage and stability upgrading. Measurements of the strength of the attachment of shellfish are used to determine the extent of the impact of shellfish on the stability of stones. These measurements provide an improvement of the initial connectivity model. Chapter 5 contains an analysis of field survey data, specifically focusing on shellfish presence and density at multiple study sites. Measurement results and connectivity model outcomes are compared. Chapter 6 presents potential and limitations for the enhancement of *C. gigas* populations. Chapter 7 discusses the specific application for shellfish presence and density in revetment design and construction, and chapter 8 is a wider discussion on the implications of this research. Finally, chapter 9 and chapter 10 describe the conclusions gained from this study and recommendations for future considerations and similar research.

2

Literature review

This chapter provides an overview of the literature in relevant fields and addresses the sub-question: *“How is the stability of typical loose rock revetment, used within the Port of Rotterdam, calculated and what are the characteristics of shellfish species commonly found living on these revetments?”* Loose rock and asphalt revetment designs are discussed. Loose rock revetment designs are within the scope of this study and asphalt-based designs will be discussed in comparison with shellfish later in this report. Two shellfish species that are currently present in the port area - the Pacific oyster (*Crassostrea gigas*) and the blue mussel (*Mytilus edulis*) - and their respective life cycles, habitat requirements, and methods of attachment to hard substrate are discussed.

2.1. Revetment design

The core of a revetment usually consists of clay or sand. Filter layers can be placed between the core and the top layer to prevent pressure build-up and erosion of the subsoil (e.g. geotextile or fine gravel) (Schiereck, 2016). Finally, the top layer is constructed. The top layer may consist of loose rock, placed rock, asphalt, or asphalt and loose rock mixtures (Figure 1.2). In this report, the focus will be on loose rock revetments. Figure 2.1 shows a typical loose rock revetment in the port area. Top layers are constructed to a depth of around 5 m below NAP. The most common stone grading class is 10-60 kg (M. Minnaard, personal communication, April 16, 2020). The thickness of the top layer of loose rock revetments equals 1.5-2.0 times the nominal stone diameter, d_{n50} (CIRIA et al., 2007).

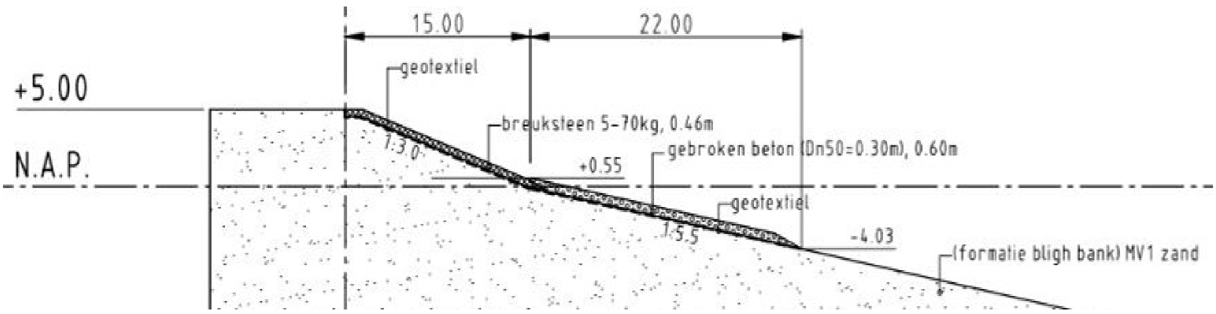

Figure 2.1: Schematic overview of the revetment at location 5 (see Figure 3.8 for the exact position of location 5)

2.1.1. Load and strength

Bank protections face contradicting demands. They should be strong, permeable, sand-tight, and flexible enough to prevent failure. Some of the most important failure mechanisms of a bank protection are instability of the top layer, wave overtopping, toe erosion, instability of the slope, collision, and subsidence (Schiereck, 2016). The most important failure mechanisms of revetments considered in the Port of Rotterdam are top layer instability, toe erosion, and subsidence (R. Duvaloois, personal communication, November 11, 2019). This report primarily analyzes instability. Stability of the protection depends mainly on the stability of the top layer. Failure occurs if the load on the structure exceeds the strength capacity. Therefore, the strength of the structure should be greater than the loads applied to the structure.

Structural strength is mainly determined by the weight of the stones and therefore by the applied stone class and sediment density. Typical loads that affect stability are currents due to tidal conditions, wind waves, continuous ship waves, and propeller wash. Currents are not considered in this report, the reason behind this is explained later (subsection 6.3.3). Wind waves are irregular and can lead to high-impact loads especially during storm conditions. Previous research showed that the maximum impact of wind waves occurs at -0.500 < D / H_s < -0.250. With D being the vertical distance from the point of impact to the still water level (SWL) (Grüne, 1988). This means that the maximum impact for a wave with wave height, H_s, of 1.5 m occurs at a vertical distance of 0.38 to 0.75 m from SWL. Setup can lead to relatively high still water levels during storm conditions. These high still water levels produce wave impacts at higher locations on the revetment. Ship waves pose a lesser but constant load on revetments. Ship waves can be divided into primary and secondary waves which impact the revetment around SWL. Small vessels sailing full power near the bank can do the most harm. Propeller wash can have an impact on a revetment around the depth of the propeller or bow thruster. This impact is especially large if a ship is stationary or maneuvering near the revetment.

2.1.2. Design of a loose rock revetment

Stability of stones in sloping conditions can be estimated with the stability number (equation 2.1).

$$N_s = \frac{H_{sc}}{\Delta d_{n50}} \tag{2.1}$$

N_s = Stability number [-]
H_{sc} = Significant wave height [m]
Δ = Relative density parameter (=(ρ_s-ρ_w)/ρ_w) [-]
d_{n50} = Median nominal diameter (=($m_{50}/\rho_s)^{1/3}$) [m].

H_{sc} is the load parameter and Δd_{n50} is the strength parameter. N_s is a measure of stability. For rock slopes, the stability number lies between 6-20 (Schiereck, 2016). The Hudson and Van der Meer formula can be used for stability calculations and are based on the formula for the stability number (Schiereck, 2016). These formulas imply the same calculation for the right-hand side as the stability number, but add a more complicated calculation with more parameters on the left-hand side. At this point, the change in stability is the point of interest. Therefore, only the simple derivation of the stability number has been taken into account here.

2.1.3. Design of a loose rock revetment penetrated with asphalt grout

A combination of loose rock and asphalt grouting is often used to bind stones and increase the stability of a revetment. Asphalt is stiff and strong under short loading periods. Under long-term loading conditions, such as settlements, asphalt is rather weak and flexible. Asphalt consists of a mixture of bitumen and mineral aggregate. The composition of this mixture determines the type of asphalt. One type which is further discussed here is asphalt grout, which is often used to penetrate between loose rocks. There should always be a non-penetrated layer of stones underneath the asphalt-bound stones for safety reasons, i.e. if stones are washed out of the revetment (TAW, 1984). Asphalt grout can either be applied as full penetration or as pattern penetration. Full penetration asphalt grout fills all the voids in the stone layer while pattern penetration only partly fills voids in a pattern of stripes or dots. Filling all the voids creates impermeability. The top layer of the revetment is considered impermeable if the porosity is <10% (De Looff et al., 2002).

The stability number (Equation 2.1), used for loose rock revetments, is still applicable to an extent in the case of pattern penetration where larger elements are created. These larger elements increase the nominal stone diameter and therefore the stability of the structure. The increase in stability due to asphalt penetration depends on the percentage of voids that have been filled and can be expressed as a stability upgrading factor. The stability upgrading factor for 60% filled voids is equal to 1.5-2.0 depending on the quality of the penetration and the stone grading (D'Angremond et al., 1970; CIRIA et al., 2007; De Looff et al., 2002). A larger percentage of filled voids will not lead to significantly higher added stability. Thus, 60% is generally seen as the upper limit. The stability upgrading factor is empirically determined for pattern penetration. TAW (1984) advises that this factor should be defined based on empirical research for other compositions of the top layer.

When permeability is limited, the top layer is not acting as different individual elements but merely as one plate. In that case, "the revetment can be schematized as an elastic beam supported by small springs (Winkler foundation)" (De Looff et al., 2006. See Figure 2.2). Asphalt usually fails due to material fatigue (Cirkel et al., 2015). The number of loads determines the degree of fatigue (De Looff et al., 2006).

$$N_{f,i} = k_f \sigma^{-a_f} \tag{2.2}$$

N_f = Number of load repetitions leading to failure at a size σ [N/m^2]
σ = Tension stress, or bending stress, at the underside of the asphalt layer [N/m^2]
k_f and a_f = Intercept and coefficient of the fatigue curve, depended on the type of asphalt [-]

Failure will occur if the number of loads applied exceeds the number of loads that causes material fatigue. This is expressed in the Miners rule,

$$\sum \frac{n_i}{N_{f,i}} \leq 1. \tag{2.3}$$

n_i = Number of load repetitions at stress level i [-]
$N_{f,i}$ = Number of load repetitions leading to failure at stress level i [-]

The bending stress, σ, depends on the behavior of the asphalt layer and the wave load. Maximum pressure, p_{max}, width of the load, layer thickness, modulus of subgrade reaction, stiffness modulus of asphalt, and the Poissons' ratio of asphalt determine the bending stress. Calculation of the moment of failure is difficult since not every wave impacts the revetment in the same way; maximum pressure and width of the load differ for each wave.

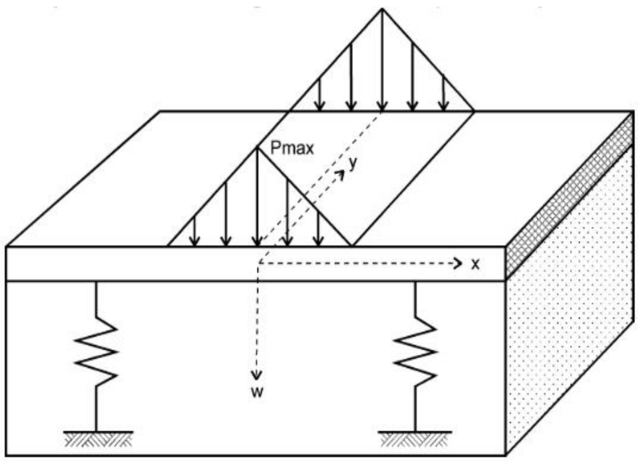

Figure 2.2: Schematization of the load impact on an impermeable revetment (De Looff et al., 2006)

The degree of stability upgrading for full penetration is generally equated to the maximum stability upgrading when 60% of the voids are filled. This implies that stability increase for a higher percentage of filled voids is at least equal to the stability upgrading provided by 60% filled voids. More filling and therefore impermeability may result in high internal hydraulic pressures which can lead to uplift and thus failure of the revetment.

2.2. Pacific oyster (*Crassostrea gigas*)

Pacific oysters (*Crassostrea gigas* Thunberg, 1793) are keystone species meaning that they play a critical role in the ecosystem (Frölke, 2018; Rodriguez-Perez et al., 2019). Organisms with a high impact on their surrounding are also called ecosystem engineers. According to Borsje et al. (2011), “they modify their local hydrodynamic and sedimentary surroundings” which creates an environment that allows opportunities for other species to survive. The reef-building capacity of oysters can fundamentally help to restore the ecological value of a location.

Figure 2.3: Pacific oysters (*Crassostrea gigas*) (Nunuk, 2013)

2.2.1. Life cycle

Larvae of *C. gigas* tend to settle permanently on hard substrate. Water temperature primarily influences settlement timing. When water temperature is 20 °C, settlement takes place 21 to 24 days after fertilization. At colder temperatures, larvae may take up to 30 days or more before settling (Menzel, 2017). Larvae develop in the open water prior to settlement. They are more likely to settle if their spat or a relevant biofilm is present on a given substrate (Rodriguez-Perez et al., 2019). Settled oyster larvae are called ‘spat’ until six months after settling (Walne, 1979). *C. gigas* is a protandrous species, which means that it can change sex from male to female during its life cycle. The change to female depends on secondary genes and environmental conditions like temperature and food availability. If food becomes scarce, females can return to being male (Guo et al., 1998; Menzel, 2017; Ó Foighil & Taylor, 2000). Eggs and sperm are released in the water column where fertilization takes place externally. Fertilization must occur within 10-15 hours after spawning. The mass spawning occurs from June to August in response to optimal temperature and salinity conditions (Sas et al., 2018). Spawning usually takes place at around 20 °C and within a salinity range of 23-36 PSU (Kang et al., 2004). *C. gigas* can live for over 20 years if they survive and grow sufficiently. The lifetime of a complete reef can differ due to local circumstances. In general, the survival of an oyster reef is dependent on sufficient levels of reproduction and consistent recruitment of young oysters into the population (Sas et al., 2019). According to Ysebaert (de Vriend & van Koningsveld, 2012), “Some of the natural oyster reefs in the Eastern Scheldt are at least 30 years old”. If an oyster reef is not damaged, for example by overfishing or destructive harvest methods, it can survive for over 100 years (J.W.M. Wijsman, personal communication, November 22, 2019).

2.2.2. Habitat requirements

The most important habitat requirements of *C. gigas* are explained in this paragraph. The values mentioned in Table 2.1 are explained and elaborated on in appendix B.1.

Table 2.1: Habitat requirements of *C. gigas*

Habitat requirements	Preferred condition	Transition zone	Unworkable condition
Salinity [‰]	16 - 35	16 - 11	< 11
Water temperature [°C]	6 - 20	3 - 6	< 3 and > 30
Water depth [m]	60%-line - 40 m below MWL	< 40 m below MWL	> 60%-line

C. gigas requires a sufficient supply of phytoplankton for growth. Excessive amounts of inorganic suspended material in the water column can hamper the growth of this species (Utting, 1988). Some predators like the common starfish (*Asterias rubens*), the common whelk (*Buccinum undatum*), the dog whelk (*Nucella lapillus*) and the green shore crab (*Carcinus maenas*) have an impact on oyster reef development, though predation is rarely lethal to the entire reef (Dare et al., 1983; Spencer, 1990, Lützen et al., 2012, Weerman et al., 2014). Herpes-like infections can affect oyster populations and lead to mass mortality (Elston, 1993; Renault et al., 1995; Renault et al., 2014; Segarra et al., 2010). Oysters are not able to migrate once settled, and sedimentation can be harmful if sand smothers oysters. Therefore, adequate rates of erosion are generally beneficial for oyster survival (Alferink, 2016).

2.2.3. Physical attachment

Oysters attach themselves to the substrate by cementation. Oysters cement themselves as they grow. Secretions of an organic film from the mantle edge allow crystals to precipitate from seawater, creating a cement layer (MacDonald et al., 2010). This cement layer produces a very tight adhesion of the left shell valve with the substrate. The cement mainly consists of inorganic calcium carbonate ($CaCO_3$), which makes it durable (Harper, 1992; Yamaguchi, 1994). This left valve is also called the bottom valve or convex valve. The upper valve or concave valve is usually seen as the right valve (Nehring, 2011). The two valves are held together by the oyster's muscular system, in particular by the sphincter. Detaching the valve will generally result in the breaking of the shell or the substrate (Yamaguchi, 1994). The microstructural arrangement and overall morphology of an attached valve are not different from that of an unattached shell (MacDonald et al., 2010). When oysters die, the soft biological tissue disappears but the shell structure remains attached to the substrate (Yamaguchi, 1994; E. Schrijver, personal communication, December 9, 2019). It is unknown how long this shell structure stays attached; no literature was found. Given the composition of the cement layer, which is very similar to the composition of the shell itself, it is believed that the cementation lasts for a considerable time (hypothesis: up to 6 months). A pilot study can be used to determine the exact value.

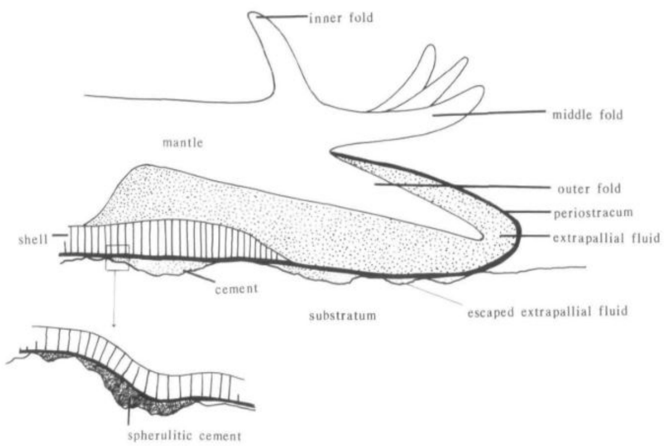

Figure 2.4: Cementation process of Pacific oyster (*Crassostrea Gigas*) (Harper, 1992)

2.3. Blue mussel (*Mytilus edulis*)

The blue mussel (*Mytilus edulis* Linnaeus, 1758) is the only other shellfish species in the port area that tends to attach to hard substrate. Other shellfish species are present but grow mainly in sandy environments (F. Heinis, personal communication, September 10, 2019). *M. edulis* flourishes in a salty environment such as the port. Like oysters, mussels are ecosystem engineers.

Figure 2.5: Blue mussel (*Mytilus edulis*) (Zenz, 2006)

2.3.1. Life cycle

Larvae of *M. edulis* need to stay in the water column for a minimum of 22 days to grow their foot, which is necessary for settling. The larvae of *M. edulis* will settle after metamorphosing to the post-larval stage. Succesful settlement relies on the availability of a suitable settling place and adequate water temperature conditions. If the conditions for settlement are not ideal, the larvae can stay in the water column up to 55 days after fertilization (Bayne, 1965). Because of their long stay in the water column, they are capable of moving great distances before they settle. Mussels prefer to attach to filamentous algae for primary settlement. Settling directly on adult mussel beds can result in high mortality as the recruits are in immediate competition with the adult mussels for food. *M. edulis* can make small movements when settled using their byssal threads. This in contrast to *C. gigas*, which do not move after settling. After a while, young mussels migrate and secondary settlement occurs at a location where they will spend their adult life. This is often on an adult mussel bed (Bayne, 1964). *M. edulis* is mostly dioecious, meaning that they have distinct male or female reproductive organs. *M. edulis* is reproductive after one year. In regions with a distinct winter and summer like the North Sea area, adult females release their eggs once a year, between May and September. Around the same time, adult males release their sperm, and fertilization takes place in the water column. *M. edulis* can live for over 8 years. However, the lifetime of a mussel bank can differ because of local circumstances (Koehn et al., 1976; Sukhotin et al., 2006). In the Eastern Scheldt area, mussel bed lifetimes of about 3-5 years are observed (J.W.M. Wijsman, personal communication, November 22, 2019).

2.3.2. Habitat requirements

The most important habitat requirements of *M. edulis* are explained in this paragraph. The values mentioned in Table 2.2 are explained and elaborated on in appendix B.2.

Table 2.2: Habitat requirements of *M. edulis*

Habitat requirements	Preferred condition	Transition zone	Unworkable condition
Salinity [‰]	> 16	6 - 16	< 4 or > 40
Water temperature [°C]	3 - 20	20 - 29	< 3 or > 29
Water depth [m]	60%-line - 25 meters below MWL		

Similar to *C. gigas*, *M. edulis* requires a sufficient supply of phytoplankton for growth. Too much inorganic suspended material in the water column can be detrimental (Brinkman, 2013). Diverse species of birds, shrimp, and starfish prey upon mussels. When accretion of young mussel larvae is sufficiently high, predation will not lead to mass mortality of a mussel bed (Dankers & Fey-Hofstede, 2015; Nehls & Thiel, 1993). Additionally, diseases are not likely to destroy an entire mussel bank and are likely to only have a local impact (Bower & Figueras, 1989; Bower et al., 1994).

2.3.3. Physical attachment

M. edulis attaches to hard substrate with byssal threads. Temperature and salinity play a role in byssal thread production (Young, 1985). Byssal threads are composed of a root, stem, thread, and plaque (Figure 2.6). Attachment to the substrate takes place with the plaque. Primary settlement takes place with a single byssal thread, which can be broken and reformed multiple times. Once final settlement has occurred, more threads are created. Threads are usually formed in the direction of forces on the mussel (Gosling, 2004). More dynamic situations and thus higher force will cause the mussel to produce more and stronger byssal threads. When mussels die, the byssal threads disappear and so the mussel shell is detached from the substrate.

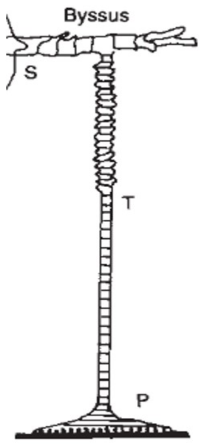

Figure 2.6: Byssus of the blue mussel (*Mytilus edulis*) with stem (S), thread (T), and plaque (P). Root not shown (Gosling, 2004; Waite, 1992)

2.4. Conclusions

The stability of typical loose rock revetments in the Port of Rotterdam can be calculated with the formula for the stability number and depends on the ratio between the load applied to the structure and the strength of the structure itself. Structural strength is a function of stone weight while the applied load comes from ship waves, wind waves, or currents. The stability of loose rock increases when penetrated with asphalt grout. The stability of combined asphalt and rock can be calculated with the formula for the stability number until impermeability, which occurs when approximately 60% of the voids are filled. The asphalt layer acts as a uniform plate when more asphalt is added. This plate behavior makes determination of the stability more difficult. Previous projects used the same stability factor for the plate situation as for when 60% of the voids were filled with asphalt. Therefore, it seems plausible that the plate situation is at least as stable as when there are 60% filled voids. However, hydraulic uplift can become a problem if the revetment becomes impermeable.

C. gigas and *M. edulis* are ecosystem engineers. They start their life as larvae and settle preferentially on an adult bed for final settlement. Oysters remain in the same position after settlement while mussels can move. Salinity, water temperature, and organic suspended material are important for the survival of both shellfish species. At the same time, various predators and diseases can reduce their survival rate. *M. edulis* attach to hard substrate with byssal threads while *C. gigas* cement their valve to the substrate. The attachment of *M. edulis* is not permanent and will break down once the mussels die. Attachment of *C. gigas*, on the other hand, is permanent and is preserved even after the oyster dies.

3

Prediction and verification of shellfish presence in the Port of Rotterdam

It is important to know where shellfish occur in both horizontal space (i.e. throughout the port area) and vertical space (i.e. on a revetment) to understand the potential effect of shellfish presence and density on the stability of revetments. First, the probability of the presence of shellfish species in the port area is determined. This allows for more focused research through observations. The presence of shellfish in the port area is predicted. This prediction is jointly based on existing literature as described in chapter 2 and a spatial model named OSR (Operationeel Stromingsmodel Rotterdam). A probability figure is generated for shellfish presence in both horizontal and vertical space.

The predictive values are compared to observations from field surveys at study sites within the Port of Rotterdam and previous in-situ observations by Paalvast (1998) (Appendix C). Observations of *C. gigas* and *M. edulis* presence were conducted because previous observations were relatively outdated since they were taken before the construction of Maasvlakte 2. Revetments were observed from a distance to qualify each area according to shellfish presence. Methodologies used to collect, and process data are described and results are visualized. More extensive elaboration on safety protocols used during data collection can be found in Appendix D. The obtained observations of shellfish presence in the port are used to answer sub-question 2: *"What is the current presence of shellfish species in the port area and how can this presence be predicted?"*.

3.1. Boundary conditions

3.1.1. Horizontal space

The port of Rotterdam is located within the Rhine-Meuse estuary. Here, saline water from the sea meets fresh water from the river Rhine (Figure 3.1). Daily variations in isohalines in the port area are caused by tidal fluctuation. Specific salinity conditions within a tolerable range are essential for shellfish survival. Therefore, it is crucial to understand the values and variations in salinity conditions over time.

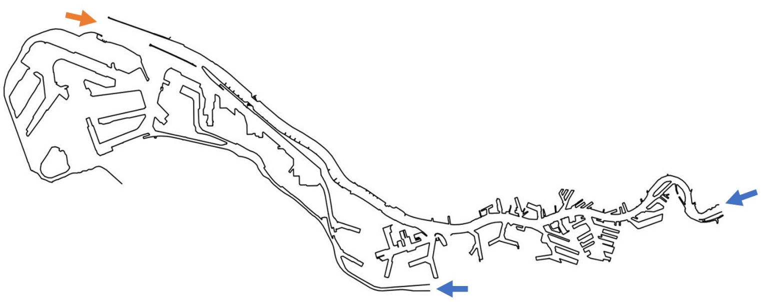

Figure 3.1: Overview of the Port of Rotterdam. Orange arrow = saline water inflow, blue arrow = freshwater inflow

Shellfish survival also requires access to a sufficient food supply. Phytoplankton is the main food source for many marine organisms, including *C. gigas* and *M. edulis*. The ratio of phytoplankton to suspended material in the water column is important to shellfish fitness (Brinkman, 2013; Gosling, 2004; Utting, 1988). Because of its proximity to a major urban center (Rotterdam), the system is not expected to be nutrient-limited. There is plenty of runoff coming from the river that supports phytoplankton growth. Shellfish species are therefore likely to have enough food available for survival and growth; this ratio is not discussed any further in the analysis. No sources could be found relating to the phytoplankton ratio in the port area. If local observations were to show vast differences from expected levels, the phytoplankton ratio could be of importance and should be taken into account.

Water temperature also impacts shellfish growth and reproduction. The maximum mean water temperature in the port area is 18.8 °C in August and the minimum mean water temperature is 5.6 °C in February (Climate-data.org, 2020). This range is physiologically acceptable for both *C. gigas* and *M. edulis*. Based on these data, water temperature is not expected to limit shellfish presence within the port area.

Based on these previous studies and metrics, food supply and water temperature most likely have a minor influence on shellfish populations within the port area. Therefore, only salinity is further discussed as an indicator of shellfish performance in horizontal space. Freshwater outlets where observed (Figure 3.2). They are not any further taken into account in this study although when applying shellfish the area should be studied on freshwater outlets.

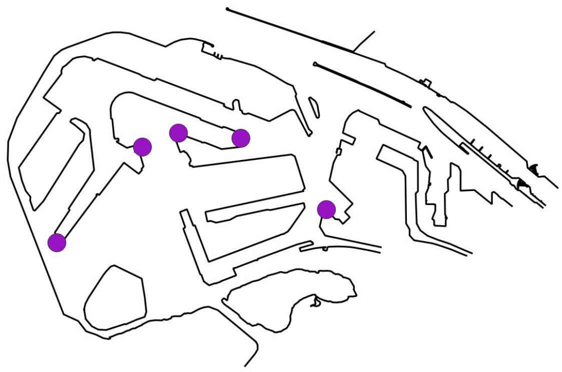

Figure 3.2: Locations of freshwater outlets

Spatial model

OSR (Operationeel Stromingsmodel Rotterdam) is used to model salinity levels in the port area at varying water depths and tide heights, and under different river discharge scenarios. Input is based on actual data. This model generated an SDS data file, and Delft3D software is used to visualize the data. The output of the model predicted the salinity level for each location in the port area. Four (extreme) scenarios are taken into account and are ranked from high salt penetration to low salt penetration. For each location surface water (k=1) is used to represent mean water level (MWL). High water slack (HWS) and low water slack (LWS) are modeled for situations under normal river discharge (Q_{norm} = 2300 m/s^2) and high river discharge (Q_{high} = 5700 m/s^2). HWS and LWS represent the highest salt penetration and the lowest salt penetration during one tidal cycle, respectively.

1. Normal river discharge (Q_{norm}) and high water slack (HW)
2. Normal river discharge (Q_{norm}) and low water slack (LWS)
3. High river discharge (Q_{high}) and high water slack (HWS)
4. High river discharge (Q_{high}) and low water slack (LWS)

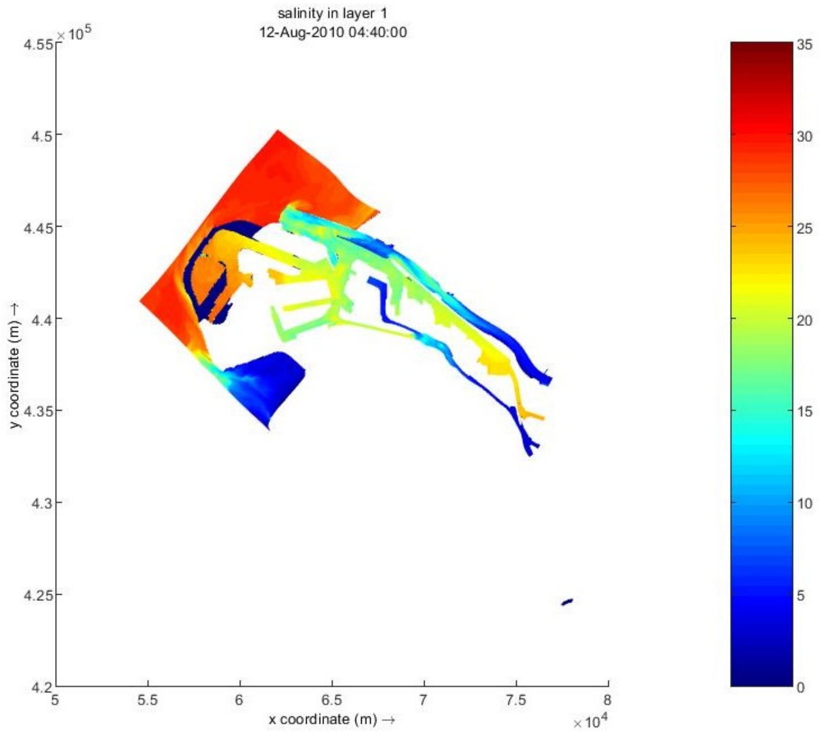

Figure 3.3 (a) Scenario 1: HWS, during an average normal water discharge at Lobith of 2300 m^3/s

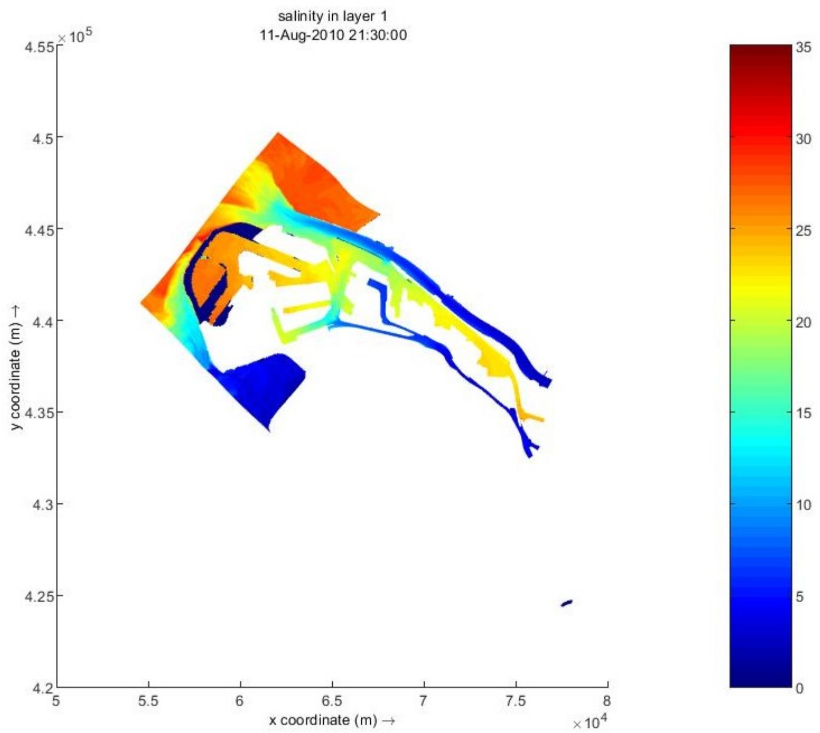

Figure 3.3 (b) Scenario 2: LWS, during an average normal water discharge at Lobith of 2300 m^3/s

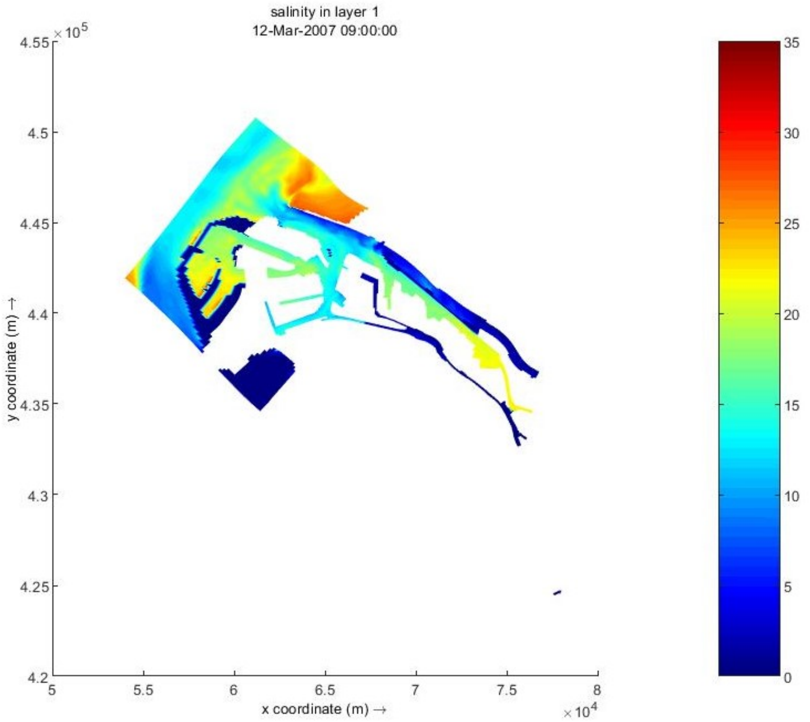

Figure 3.3 (c) Scenario 3: HWS, during a high water discharge at Lobith of 5700 m^3/s

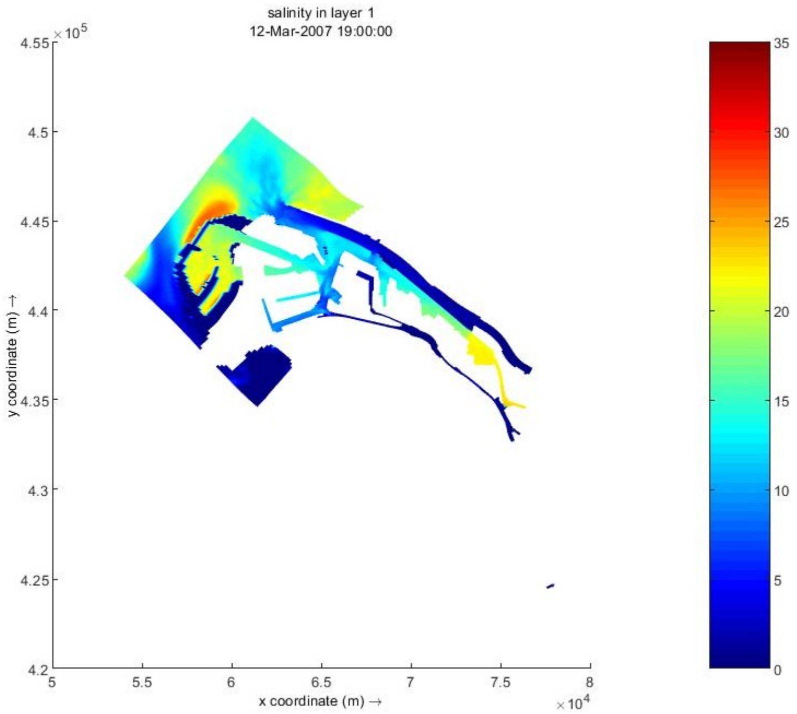

Figure 3.3 (d) Scenario 4: LWS, during a high water discharge at Lobith of 5700 m^3/s

Figure 3.3: Modelled salinity levels for different situations in ‰ at the water surface

3.1.2. Vertical space

Data from previous studies are used to predict shellfish presence in vertical space at an individual revetment level. Figure 3.4 shows a simplified cross-section of a revetment.

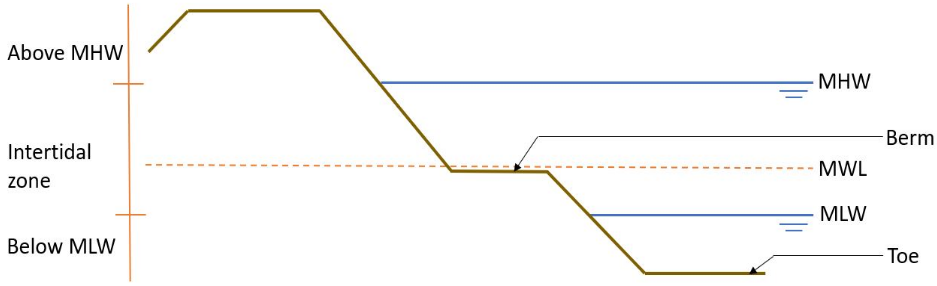

Figure 3.4: Schematic drawing of a revetment in vertical space

Shellfish are non-mobile filter feeders and thus rely on sufficient submersion time for daily feeding and respiration. Low intertidal areas are submerged for the greatest portion of each day, while mid- and high-intertidal areas are subject to increasing aerial exposure. Exposure to aerial conditions is highly stressful to intertidal organisms, which have adapted accordingly to be able to survive until they are again inundated with the tide. Intertidal zonation patterns are well documented in the literature down to the species level. For the purpose of this study, revetments are divided into different zones representing low-, mid-, and high- intertidal heights (Figure 3.4). Average river discharge at a random location in Maasvlakte 2 is assumed for analysis.

It is assumed that above mean high water (MHW) the revetment remains dry or perhaps sporadically inundated under normal river discharge conditions in the absence of set-up due to storms. Conversely, in the intertidal zone (MHW to MLW) inundation levels fluctuate over the tidal cycle. Below MLW it is assumed that the revetment is always submerged under normal river discharge conditions in the absence of set up due to storms. Although, locations below MLW are not discussed herein due to data limitations, and instead this study focuses on intertidal areas.

MWL is considered equal to NAP in this report.

3.2. Prediction of shellfish presence in horizontal space

3.2.1. *C. gigas*

C. gigas thrive best under salinity levels between 25-35‰. They can survive conditions of 16-25‰ and even at 11‰ for a limited amount of time (subsection 2.2.2). A ranking system is used to distinguish between salinity levels that are suitable for *C. gigas* (in green), salinity levels that can be suitable for *C. gigas* (in orange), and salinity levels that are not suitable for *C. gigas* (in red). Based on Figure 3.3 a probability figure is presented which is used to visualize predicted *C. gigas* presence (Figure 3.5).

Green: salinity >16‰ in scenario 2 & salinity >11‰ in scenario 4
(Salinity is always larger than 16‰ under normal average discharges,
salinity is larger than 11‰ under high average discharges)

Orange: salinity >16‰ in scenario 1 & salinity >11‰ in scenario 4
(Salinity is larger than 16‰ under normal average discharges and HWS conditions,
salinity is larger than 11‰ under high average discharges)

Red: salinity <16‰ in scenario 1 or salinity >16‰ in scenario 1 & salinity <11‰ in scenario 4
(Salinity is always less than 16‰ under normal average discharges or
salinity is less than 11‰ under high average discharges.)

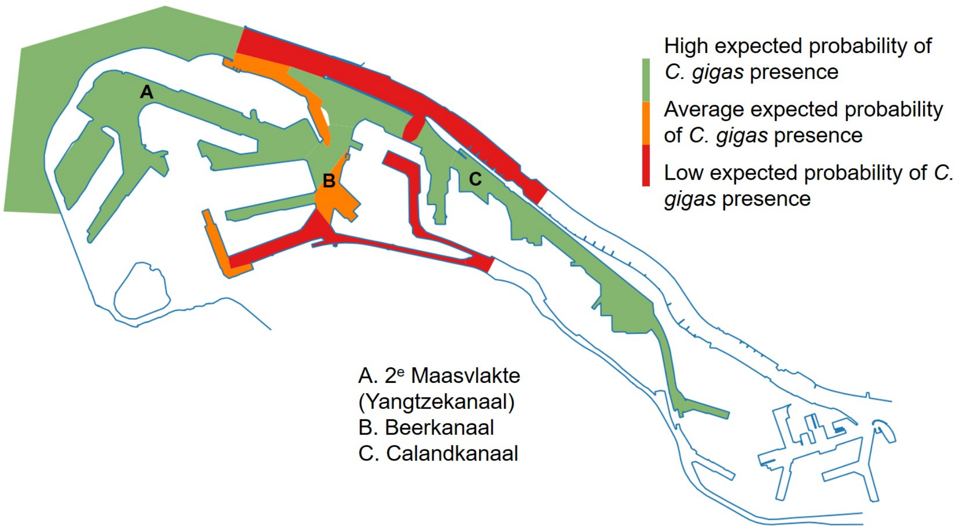

Figure 3.5: Probability figure of the expected probability of *C. gigas* presence in horizontal space at MWL

In previous surveys, *C. gigas* were found at the Zuiderdam. In the Beer- and Calandkanaal 13 out of 35 locations supported populations of *C. gigas*, while at the outer edge *C. gigas* were present at 2 out of 7 locations (exact locations are unknown) (Paalvast, 1998, see Figure C.1). These results show that previously *C. gigas* were present throughout the saline part of the port area. The lack of information about the exact locations makes it impossible to determine the reason of the absence of *C. gigas* at locations were, based on the spatial model, ubiquitous presence is expected.

3.2.2. *M. edulis*

M. edulis prefers a salinity level of over 16‰ and can survive conditions down to 6‰ for considerable periods of time (subsection 2.3.2). Locations within the port area are divided according to these thresholds into those with salinity levels that are suitable for *M. edulis* (in green), salinity levels that can be suitable for *M. edulis* (in orange), and salinity levels that are not suitable for *M. edulis* (in red). Based on the output of the spatial model (Figure 3.3), a probability figure is presented to visualize the predicted presence of *M. edulis* (Figure 3.6).

Green: salinity >16‰ in scenario 2 & salinity >6‰ in scenario 4
(Salinity is always larger than 16‰ under normal average discharges,
salinity is larger than 6‰ under high average discharges)
Orange: salinity >16‰ in scenario 1 & salinity >6‰ in scenario 4
(Salinity is larger than 16‰ under normal average discharges and HWS conditions,
salinity is larger than 6‰ under high average discharges)
Red: salinity <16‰ in scenario 1 or salinity >16‰ in scenario 1 & salinity <6‰ in scenario 4
(Salinity is always lower than 16‰ under normal average discharges or
salinity is less than 6‰ under high average discharge.)

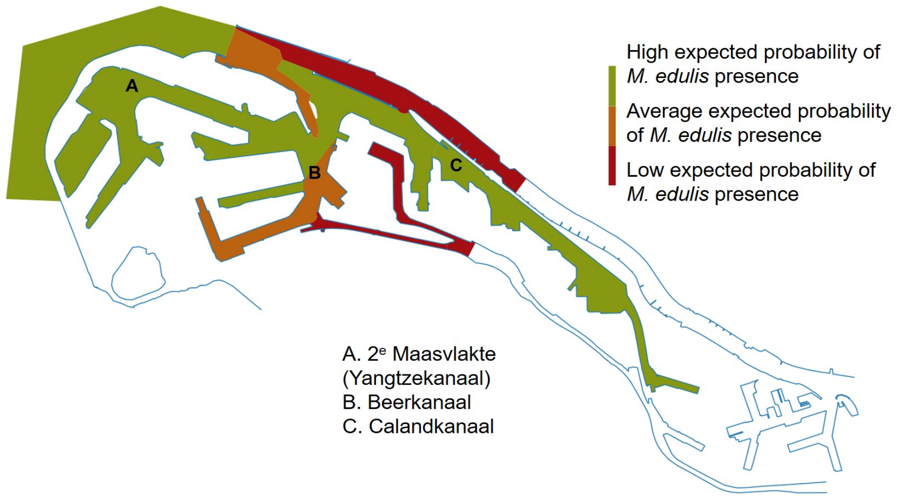

Figure 3.6: Probability figure of the expected probability of *M. edulis* presence in horizontal space at MWL

In previous surveys, *M. edulis* were found in high densities on hard substrate locations within the estuary. Locations in Beer- and Calandkanaal were more developed and corresponded with high mussel population density. In the Beer- and Calandkanaal *M. edulis* were found at 34 out of 35 locations, and on the outer edge at 6 out of 7 locations. These data are in line with Figure 3.6. Again, exact survey locations are unknown (Paalvast, 1998).

3.2.3. Predators

Previous observations by Paalvast (1998) gave an overview of the presence of species that are known predators for *C. gigas* and *M. edulis*. In the Beer- and Calandkanaal 10 out of 34 hard substrate locations contained the seastar *Asterias rubens*, and 34 out of 35 locations contained the crab *Carcinus maenas*. On the outer edge, 1 out of 7 hard substrate locations contained *A. rubens* and 5 out of 7 locations contained *C. maenas*. Therefore, predators relevant to shellfish populations are expected to be widely spread throughout the port area. During qualitative observations, later discussed in this chapter, and during quantitative measurements discussed in chapter 5, no predating species were observed. Mainly because observing these species was not the main research purpose and therefore no attention was paid to it. Based on these previous observations, predating species can be expected in the port area.

3.3. Prediction of shellfish presence in vertical space

Above MHW

C. gigas and *M. edulis* are not expected to live above MHW because they depend on the long duration and a high volume of water flow found exclusively at lower intertidal heights, for feeding and respiration (Schellekens et al., 2012).

Intertidal zone, MHW - MLW

C. gigas can survive up to 60% aerial exposure during a given day. On average, an exposure period of ~30% vs. submersion is physiologically preferable (Schellekens et al., 2012; J.W.M. Wijsman, personal communication, November 22, 2019). Therefore, the upper boundary of the intertidal zone where *C. gigas* occur is the zone that is submerged at least 40% of the time. This line will be referred to as the 60%-line (Figure 3.7).

M. edulis is able to acclimate to increasing aerial exposure (1993, Demers & Guderley; 2008, Letendre et al.). As a result, mussels can be present at intertidal locations that are exposed to aerial conditions more than 60% of the time (2008, Letendre et al.). Therefore, for *M. edulis* the 60%-line is also used as an indication for species presence (Figure 3.7).

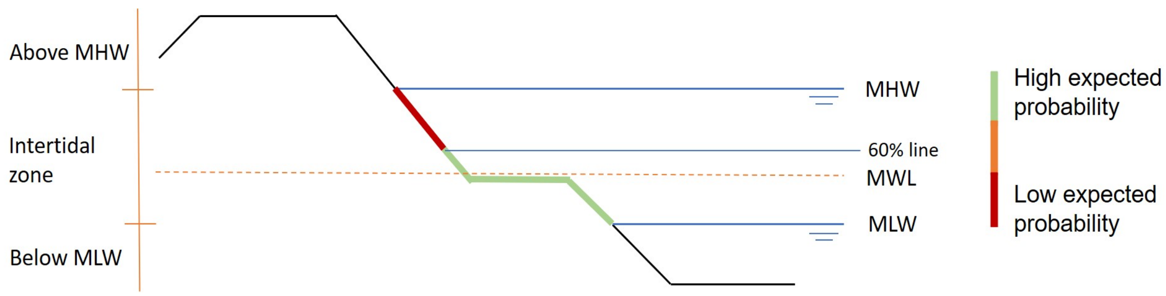

Figure 3.7: Probability figure of the expected probability of *C. gigas* and *M. edulis* presence in vertical space in a saline environment

In 1998 (Paalvast), *M. edulis* were observed around MWL and below MLW on concrete blocks, berms, and asphalt revetments in the port area. *C. gigas* were observed on concrete blocks around MLW in the port area.

3.4. Qualitative observations of shellfish presence

3.4.1. Approach

Qualitative research was performed to determine the dispersion of shellfish presence in the port area and to verify predictions that were made in section 3.2 and section 3.3. The study area consisted of Maasvlakte 1, Maasvlakte 2, and Europoort. First, the physical accessibility of the revetments was determined. An overview of accessible revetments is shown in Figure 3.8. Accessible revetments are those where the top of the revetment could be easily accessed. Locations were not considered accessible when there were obstacles that could not be safely passed, when entering the area was forbidden or when there were any other reasons why the safety of the observer could not be guaranteed. Some observed locations are located on revetments that were initially designated as inaccessible, but site visits showed that these locations were accessible.

Section 3.2 showed the expectation of *C. gigas* and *M. edulis* presence in horizontal space. *C. gigas* and *M. edulis* are expected at locations colored green and orange. They are not expected at locations colored red (Figure 3.5, Figure 3.6). In consideration of the aforementioned predictions, the expected presence of shellfish is visualized for every observed location (Figure 3.8). Expectations for *C. gigas* and *M. edulis* are visualized together in one map because the hypothesis at the observed locations is the same for both species.

The different revetments were observed from the nearest point that was safely possible. Every site was photographed using an LG HUAWEI P10 LITE 12 MP rear camera with a 1.25-micron pixel size on a 1/1.28 inch sensor.

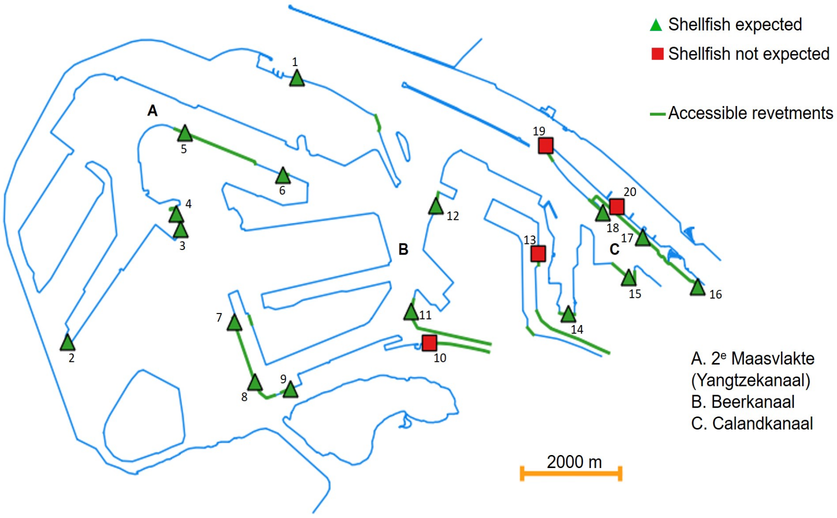

Figure 3.8: Overview of observed locations for qualitative research and the predicted outcome for each location

3.4.2. Data processing

Visual observations were used to classify each location.

C. gigas

+ overgrown with *C. gigas*
+ - some *C. gigas*
- few/no *C. gigas*

"Overgrown with *C. gigas*" indicates that all stones were covered with an average of 3 to 5 oysters per stone. "Some *C. gigas*" represents an average coverage of 1 oyster per 1 in 3 stones, with a maximum of 3 oysters per stone. "A few *C. gigas*" represents a maximum coverage of 1 oyster per 5 stones.

Figure 3.9 (a) Overgrown with *C. gigas* Figure 3.9 (b) Some *C. gigas* Figure 3.9 (c) Few/no *C. gigas*

Figure 3.9: Classification of *C. gigas*

M. edulis

It was impossible to make the same distinction in coverage ratio for *M. edulis* as for *C. gigas*. *M. edulis* is not widespread at all locations and only appeared in some dense spots. Therefore, three different distinctions were made.

+	many *M. edulis*
+ -	sporadically occurring *M. edulis*
-	few/no *M. edulis*

"Many *M. edulis*" means near-complete coverage of the stones with mussels. An upper limit of 15 mussels per stone and a lower limit of 10 mussels per stone was observed. "Sporadically occurring *M. edulis*" was designated when mussels were observed in random groups of 4-7 individuals. "A few *M. edulis*" represents locations with less than 4 mussels per group of mussels.

Figure 3.10 (a) Many *M. edulis*

Figure 3.10 (b) Sporadically occurring *M. edulis*

Figure 3.10 (c) Few/no *M. edulis*

Figure 3.10: Classification of *M. edulis*

3.4.3. Results and comparison with predictions

An overview of pictures of each location is presented in Appendix E.1.

C. gigas

C. gigas presence differed within the port area (Figure 3.11). The observed density of oysters was evenly distributed over a revetment. To compare the prediction with results of the observations, Figure 3.11 and Figure 3.5 are superimposed resulting in Figure 3.12. Notably, 19 out of 20 observations showed results that supported the hypothesis. Only results from observation location 2 did not support the hypothesis. No oysters were observed at this location likely due to the sandy shore that is present at location 2. Of the 6 locations where conditions were predicted to be suitable for oyster presence, 4 did not show oyster presence. At locations 1, 7, 8, and 9, *C. gigas* presence is potentially possible, however, no oysters were observed. Salinity can be variable at those locations. A lower salinity under higher freshwater discharge could be the reason for the absence of oysters. This would imply that those locations are not suitable for shellfish enhancement and that the boundary conditions regarding salinity need to be clarified. Oyster application in the orange area should be reconsidered. Regions where *C. gigas* were observed included Maasvlakte 2, Beerkanaal and Calandkanaal

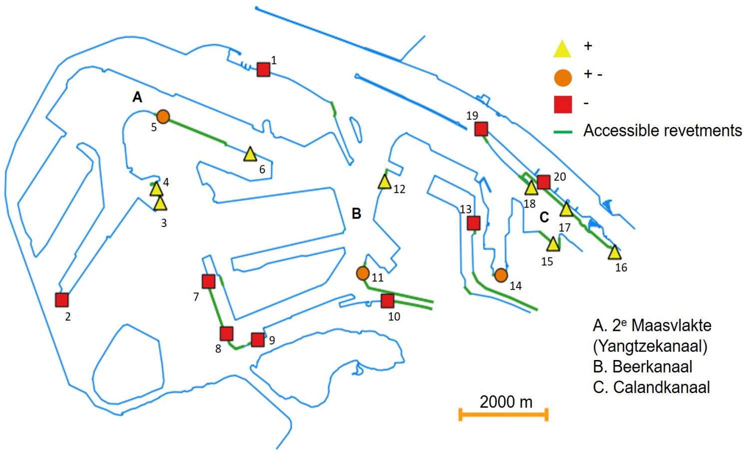

Figure 3.11: Qualitative observations of *C. gigas*

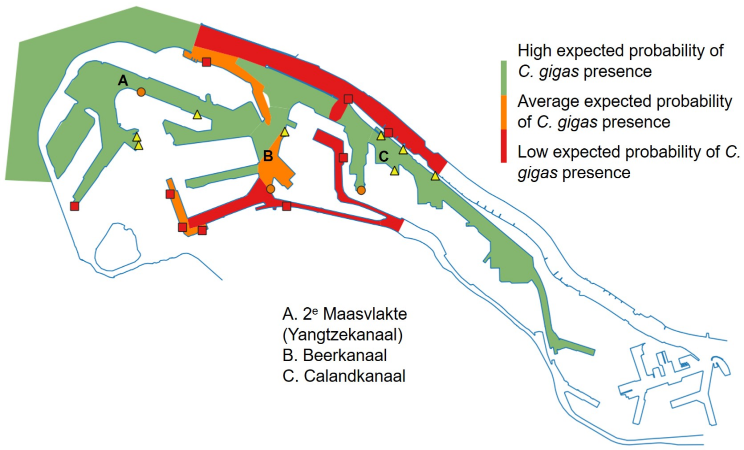

Figure 3.12: Comparison between qualitative observations and the predictions of *C. gigas* presence

M. edulis

Results from surveys of *M. edulis* are shown in Figure 3.13. *M. edulis* were observed in small dense populations that were patchily distributed over a revetment. Superimposing Figure 3.13 and Figure 3.6 resulted in Figure 3.14. This figure shows a comparison of prediction values with field observations. 7 out of 20 observations throughout the port area did not support the hypothesis regarding *M. edulis* presence. Mussels were expected at these 7 locations, however, they were not observed. 4 out of 6 locations with possible suitability for mussel presence did not have any mussels present. *M. edulis* were expected to be common throughout the port area but observations did not show general presence of *M. edulis*. The largest mussel population was found at location 12 in the Beerkanaal. Other spots could be found in Maasvlakte 2 and the Calandkanaal. Observation errors may play a role in the fact that mussels are observed less frequently than expected. Mussels are smaller than oysters and sometimes observations are done from a distance that may prohibit clear identification.

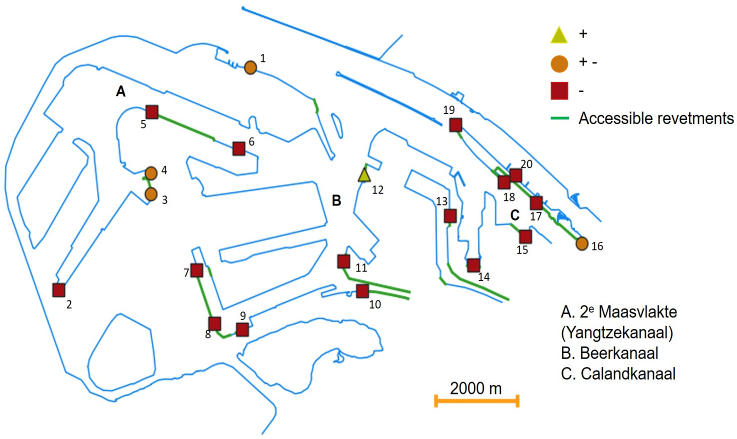

Figure 3.13: Qualitative observations of *M. edulis*

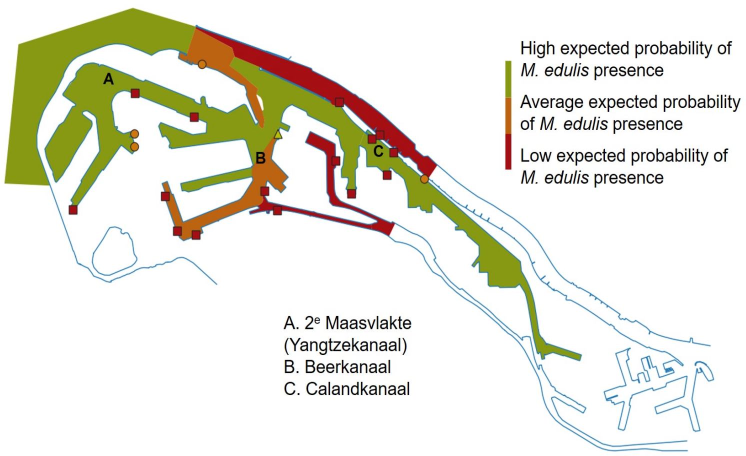

Figure 3.14: Comparison between qualitative observations and predictions of *M. edulis* presence

3.5. Conclusions

Presence of *C. gigas* and *M. edulis* in the horizontal and vertical space is predicted using data from existing literature sources and a spatial model (Figure 3.5, Figure 3.6, and Figure 3.7). In horizontal space, salinity is considered as the limiting factor for shellfish survival and growth. Based on this assumption, both species have a higher likelihood of presence at the Maasvlakte 2, Beerkanaal and the Calandkanaal sites. In the Hartelkanaal, conditions are slightly better for *M. edulis* survival vs. *C. gigas* (Figure 3.5 and Figure 3.6). Species that are known predators for *C. gigas* and *M. edulis* are present in the port area, observations have not gone into this in detail. In the vertical space, submersion time is considered as the limiting factor for shellfish survival and growth. *C. gigas* and *M. edulis* presence is expected in the intertidal zone up to the 60%-line (Figure 3.7).

The presence of oysters in horizontal space on revetments was correctly predicted by the spatial model at 19 out of 20 observed locations. Only one location, located at the area that had a high expectation regarding oyster presence did not show oyster presence. Hard substrate was not available at this location. According to the results of the field surveys, locations with an average expected oyster presence did only show a minimal oyster presence. These locations should be reconsidered when determining a location for application (Figure 3.5). One conclusion of the surveys was that a lack of oyster presence could be linked to sandy substrate, as oysters need hard substrate to settle. The survey data for *M. edulis* presence from almost half of the site locations (7 out of 20) differed from the horizontal prediction. Far fewer mussels were observed in the port than expected. They were also not evenly distributed over the revetment. Measurements of shellfish presence in vertical space on the revetments are further elaborated in chapter 5.

4

Connectivity model for the effect of *C. gigas* on the stability of stones

The effect of *C. gigas* on the stability of stones is modeled in this chapter. The extent to which shellfish connect stones and therefore increase the stability of the revetment is considered. *M. edulis* is not taken into account since this species can move relatively easily and therefore do not reliably add strength to the structure. *M. edulis* shells detach from the surface after mortality occurs; unlike *C. gigas* whose shells remain strongly connected to the surface after the animal dies, as concluded in section 2.4. Therefore, only the effect of *C. gigas* is considered. *C. gigas* connects to hard substrate by creating a cement layer between their shell valve and the substrate (subsection 2.2.3). Generally, this hard substrate is composed of stone material. Oysters can bind stones together if the cement layer is applied to more than one stone, overlapping the interstitial space between the stones (Figure 4.2). Connected stones are assumed to have an effectively increased stone size, which increases the stability of the hard substrate.

A stability upgrading factor is proposed to evaluate added stability that results from the connection, or binding, of the stones by oysters (section 4.1). This stability upgrading factor describes the effective increase in the nominal stone diameter, d_{n50}, and the corresponding increase in design wave height, H_D. Using a connectivity model and an analogy between asphalt and oysters, a relationship between the coverage ratio and the stability upgrading factor is generated. In the first part of this chapter, every binding of stones by oysters is expected to be strong enough to withstand the forces applied on the stone. Measurements show the actual strength associated with oyster cementation. The connectivity model has therefore been improved with the application of additional information about the attachment strength of *C. gigas*.

4.1. Defining the stability upgrading factor

4.1.1. Derivation

The stability upgrading factor, Ψ_d, describes the increase in nominal stone diameter, d_{n50}, resulting from the binding of stones by *C. gigas*. The factor is based on the definition of the d_{n50} (CIRIA et al., 2007)

$$d_{n50} = \sqrt[3]{\frac{M_{50}}{\rho_s}}. \tag{4.1}$$

Binding of stones by oysters changes the sediment density, ρ_s, and the median nominal mass of a stone, M_{50}. No published studies were found regarding the volumetric mass density of the oyster biomass. The change in sediment density is expected to be small compared to the change in median stone mass. Therefore, only the change in median nominal mass of a stone is considered.

This change in mass is described based on the change in the number of exposed stones after binding. For this study, the absolute number of exposed stones, S, describes the number of exposed stones before binding. The effective number of exposed stones, E, is a measure of the number of exposed stones after binding. As an example; two bound stones are considered as two absolute stones and as one effective stone. The total mass of stones on the exposed portion of the top layer at a given area, M_{tot}, does not change in response to the extent of binding. The ratio between the median nominal mass, M_{50}, and the effective mean mass, M_{em}, is assumed to stay the same for the situation before and after binding. With subscript “bb” stands for “before binding by oysters”. Subscript “ab” stands for “after binding by oysters”.

$$M_{tot} = S * M_{em,\ bb} = E * M_{em,\ ab} \tag{4.2}$$

Because $M_{50,\ bb}$:$M_{em,\ bb}$ = $M_{50,\ ab}$:$M_{em,\ ab}$ is assumed, Equation 4.2 can be rewritten to

$$\frac{M_{50,\ ab}}{M_{50,\ bb}} = \frac{S}{E}. \tag{4.3}$$

The change in mass of stones in the exposed portion of the top layer can be written as S/E. The corresponding stability upgrading factor, Ψ_d, describes the change in nominal stone diameter

$$\Psi_d = \frac{d_{n50,\ bb}}{d_{n50,\ ab}} = \frac{H_{D,\ ab}}{H_{D,\ bb}} = \sqrt[3]{\frac{S/E}{1}} = \sqrt[3]{\frac{\mathrm{S}}{\mathrm{E}}}. \tag{4.4}$$

Ψ_d = Stability upgrading factor [-]
d_{n50} = Required nominal stone diameter [m]
H_D = Design wave height [m]
S = Absolute number of exposed stones [-]
E = Effective number of exposed stones [-]

The nominal stone diameter, d_{n50}, can be multiplied by the stability upgrading factor, Ψ_d, to obtain the updated nominal stone diameter caused by the binding of stones by oysters. The relationship between the stability upgrading factor and the coverage ratio, r_{CR}, is described in section 4.2. The modeled stability upgrading factor will be called $\Psi_{d,\ model}$, and the measured stability upgrading factor will be called $\Psi_{d,\ data}$.

4.1.2. Limitations

The number of absolute and effective exposed stones can only be quantified on the exposed portion of the top layer (section 5.1), as stone layers are 1.5-2.0 d_{n50} thick (section 2.1). This multiple layer aspect is not taken into account. Therefore, the change in d_{n50} only applies to the exposed portion of the top layer. Binding of stones by oysters changes the physical shape of the stones. Since the binding is expected to occur horizontally (i.e. stones are only bound together in a horizontal space) and uniformly over the area, stones are assumed to gradually increase in size as a result of oyster settlement and growth. This change in shape is not considered herein. Further research should investigate whether effective stone size will increase gradually and the extent to which the change in physical shape affects the stability of the revetment as a whole.

4.2. Initial connectivity model, single oyster connection

The relationship between the stability upgrading factor, Ψ_d, and the coverage ratio, r_{CR}, is determined in this section using a connectivity model. The coverage ratio is a more effective way to determine the stability upgrading factor because it is easier to measure than the number of effective stones and it can give an indication for the stability upgrading at a given location.

4.2.1. Model set up

For the exposed portion of the top layer, the optimal packing of circular stones in a hexagonal lattice is considered. This results in the highest-density 2D packing for circles in a lattice arrangement (A. Thue, 1890).

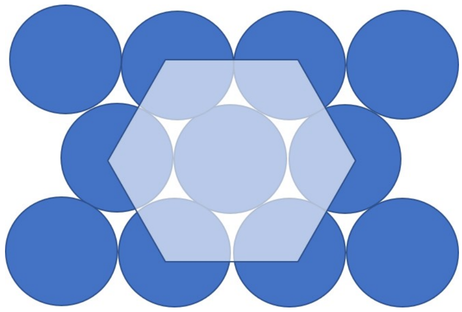

Figure 4.1: Hexagonal circle packing in 2D (based on A. Thue, 1890)

Stones can have a square shape, which would potentially enable even higher-density packing. In reality, packing is random instead of optimal, and lower-than-optimal packing density can be expected. For now, the packing density that applies to hexagonal circle packing is used.

$$\eta = \frac{\pi\sqrt{3}}{6} = 0.9 \tag{4.5}$$

η = Packing density [-]

The absolute number of exposed stones, S, that fit in a specified 2D area depends on the considered area, A_{tot}, the packing density, η, and the area of a single stone, A_s.

$$S = \frac{A_{tot} * \eta}{A_s} \tag{4.6}$$

A_s = Area of a single stone [m^2]
S = Absolute number of exposed stones [-]
A_{tot} = Total considered area [m^2]

Oysters settle on hard material. The possibility of binding occurring relies on the dimension of the voids between stones. The dimension of these voids scales with the nominal diameter of the stone, d_{n50}, and the packing density, η, which depends on the shape of the stones. As a result, the settling distance that enables an effective binding, e, is a function of the stone diameter. The effective settling distance, e, scales with the radius of the stones, r_s. Specifically, the ratio e/r_s is lower for large stones and higher for small stones (Figure 4.3). The size of an oyster, L_o, is used to determine the settling distance from the edge that enables effective binding (Figure 4.2). L_o is assumed as 6.5 cm which is the average between the average measured width and length of the oyster ((8+5)/2, chapter 5). The settling distance of an oyster, measured from the edge of a stone, that enables effective binding can be written as

$$e = \frac{L_o - ((1-\eta) * d_{n50})}{2}. \tag{4.7}$$

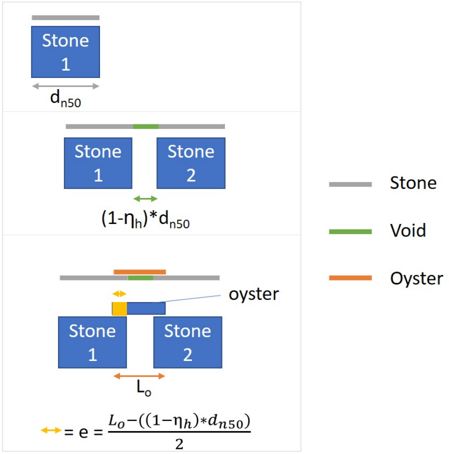

Figure 4.2: Effective settling distance from the edge, side view

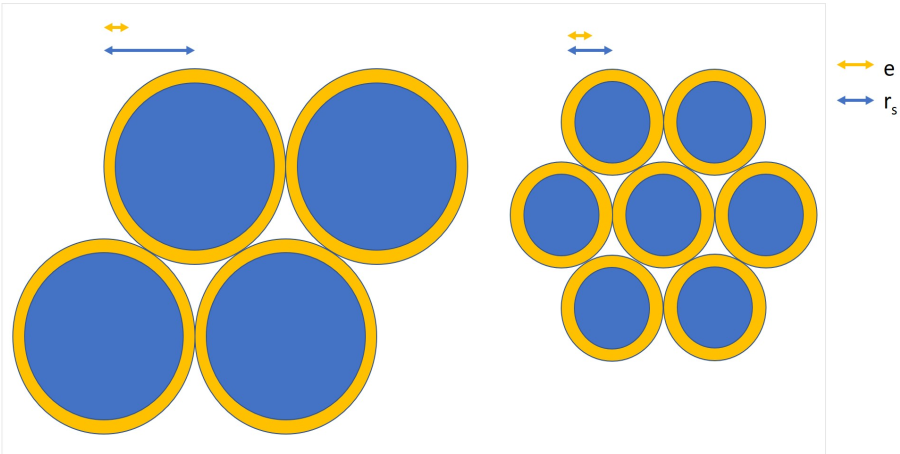

Figure 4.3: Ratio between the total area and the effective settling distance for various stone dimensions, top view

The fraction of settled oysters that will bind stones, is a function of the stone size and can be written as

$$f = \frac{r_s^2 - (r_s - e)^2}{r_s^2}. \tag{4.8}$$

f = Fraction of oysters settling at the edge of stones, leading to binding [-]
r_s = Radius of a stone [m]
e = Settling distance of an oyster that enables effective binding [m]
(measured from the edge of a stone)

This means that 1 in every 1/f oyster will create a new binding. With an increase in the coverage ratio of oysters, r_{CR}, more and more stones are already connected so that more oysters are necessary for a unique binding. For a specified coverage ratio, every stone is connected in some way so more coverage will not lead to extra bindings. Therefore, the effective number of exposed stones, E, can be described through an asymptotically decreasing function. With a and b being the coefficients that describe the shape of the curve.

$$E = 1 + a * (1 - r_{CR})^b \tag{4.9}$$

If there is no coverage by oysters, r_{CR}=0, the effective number of exposed stones will be equal to the absolute number of exposed stones, E=S. On the other hand, a completely covered revetment, r_{CR}=1, will have an effective stone value of E=1 since all stones will be connected. The change in coverage ratio that is necessary for one binding depends on the number of oysters needed for one binding, 1/f,

and the corresponding surface area being covered by those oysters, $A_{o,\,tot}/A_{tot}$. Coefficients a and b can be determined using the boundary conditions described.
E=S for r_{CR}=0, E=1 for r_{CR}=1, and $\frac{dE}{dr_{CR}} = -\frac{1}{f}\frac{A_{o,\,tot}}{A_{tot}}$ for r_{CR}=0.

$$a = S - 1 \tag{4.10}$$

$$b = \frac{A_{tot} * f}{(S-1) * A_o}. \tag{4.11}$$

A_o = Area covered by one oyster [m^2]

For the calculation of A_o, the oyster is considered to have a circular shape with a diameter of 6.5 cm (equal to L_o). Adding coefficients a and b to the formula for the effective number of exposed stones gives a formula for calculating E depending on r_{CR}.

$$E = 1 + (S-1) * (1 - r_{CR})^{\frac{A_{tot}*f}{(S-1)*A_o}}. \tag{4.12}$$

4.2.2. Impact of fully connected stones

The formula for the stability number no longer applies if a revetment is impermeable and is, therefore, acting as a plate. To determine the functioning of an impervious oyster layer, an analogy with asphalt is made, since asphalt is also used to bind stones together. For asphalt grout, the upper limit of the stability increase is a factor of 2. This is the case if 60% of the voids between stones are filled with asphalt. This factor of 2 is also advised for full penetration (more than 60% voids filled), in which case the plate method should be used. This implies that the formula for the stability number is more conservative than the plate method (subsection 2.1.3).

Oysters are assumed to be as porous as asphalt. This is a conservative assumption since it is likely that an oyster layer is more porous than an asphalt layer. Oysters are only expected in the exposed portion of the top layer. The ratio between surface coverage and pore filling of the exposed portion of the top layer is assumed to by 1:1 (Figure 4.4).

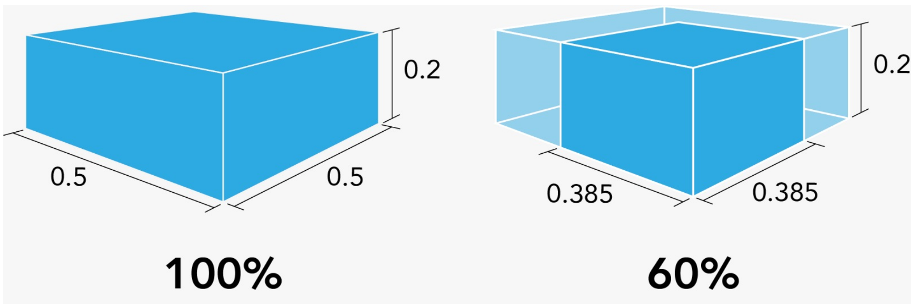

Figure 4.4: Sketch of ratio between surface coverage and pore filling of the exposed portion of the top layer

Initially, the stability upgrading factor that corresponds to a coverage ratio of 0.6 is used as a conservative upper value for the stability increase factor in case of full penetration. Further research could improve this value. Future studies could also reveal whether the formula for the stability number is more conservative than the plate method for oysters as well. Overestimation of the upper value of the coverage ratio may lead to an overestimation of the stability upgrading factor and a revetment that is less stable than assumed. Underestimation may lead to a revetment that is more stable than assumed. Bending stress will impact the revetment at the underside of the layer in case of full penetration. *C. gigas* connect stones mainly on the exterior surface. Therefore, the application of oysters for stability upgrading factors corresponding to coverage ratios higher than 0.6 should be used with caution and should be further studied. The impact of a repeating dynamic load on the attachment strength of oysters is also unknown. Further research should indicate the extent to which the number of wave-impacts and the size of the loading affects the destruction of oysters or damage of an oyster reef.

Hydraulic uplift is an important failure mechanism of an impermeable asphalt revetment. The ratio between the leakage length, Λ, and the characteristic length of the external load, L, determine the head-difference and therefore the moment of uplift which causes failure (TAW, 2003; Schiereck, 2016). Porosity influences the leakage length. A decrease in porosity due to the presence of oysters will lead to an increase in leakage length. At the same time, friction between stones will increase because of the binding of the stones and protruding oyster shells that will prevent movement. This will affect the clamping or friction factor, Γ_1, between elements in the top layer. Measurements showed an increase in the clamping or friction between elements under presence of oysters. A larger clamping or friction between elements in the top layer is beneficial for stability. The exact change in porosity and the clamping or friction factor under oyster presence requires further study.

4.2.3. Results

Merging equation 4.12 and equation 4.4 leads to a relationship between the modeled stability upgrading factor, $\Psi_{d,\ model,\ initial}$, and the coverage ratio, r_{CR} (equation 4.13). Based on the described shift in the model, this formula can be used for coverage ratios from 0 up to and including 0.6 (subsection 4.2.2). The value of the stability upgrading factor for a coverage ratio of 0.6 is assumed to be equal to the stability upgrading factor under larger coverage ratios.

$$\Psi_{d,\ model,\ initial} = \sqrt[3]{\frac{S}{1 + (S-1) * (1 - r_{CR})^{\frac{A_{tot} * f}{(S-1) * A_O}}}} \tag{4.13}$$

Figure 4.5 shows the initial relationship between the coverage ratio and the stability upgrading factor for various standard stone gradings. A refinement of this relationship is explained in subsection 4.3.2. Stones are quickly bound together under low coverage ratios since there is a high chance of each additional binding being a unique connection between stones. The stability upgrading factor is about the same for each stone grading until an oyster coverage ratio of 0.3, because the chance of binding in this initial model is approximately equal for each stone grading. After some time, all stones are effectively connected and a maximum stability upgrading factor will be reached, at which point a higher coverage ratio will not produce a higher stability upgrading factor. The coverage ratio for which this applies is based on findings for asphalt and equals 0.6 (subsection 2.1.3). The corresponding maximum stability upgrading factor depends on the stone size. Smaller stone sizes have the potential for a larger stability upgrading factor compared to larger stone sizes since there are more stones within a specified area that may be bound together. The smaller the stone, the more effect a change in the upper limit has. The dashed lines show how the relationship continuous without any upper limit.

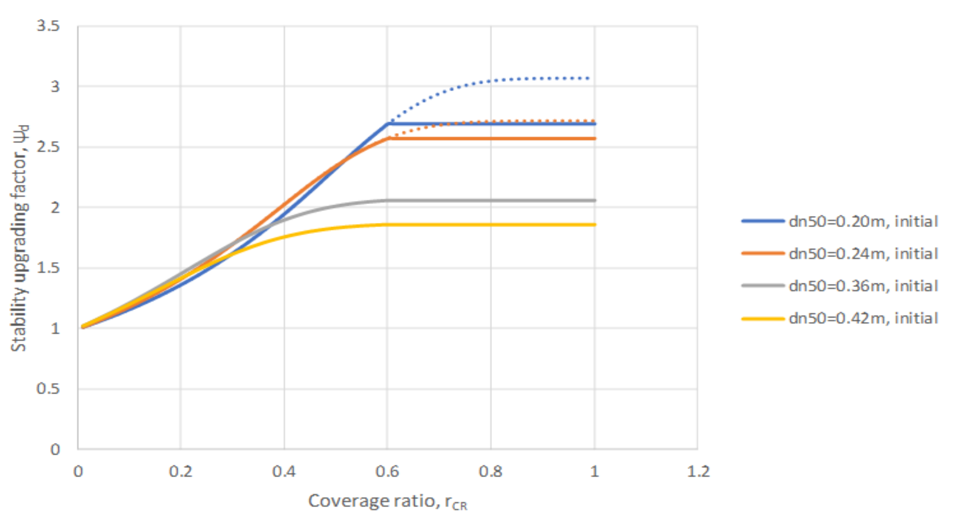

Figure 4.5: Initial relationship between the coverage ratio and the stability upgrading factor for various nominal stone diameters

4.3. Improved connectivity model, multiple oyster connections based on measurements

In the previously described initial model, a single oyster binding was assumed to be strong enough to withstand the forces applied on the stone. This assumption is refuted in this section. To do so, it is necessary to know the attachment strength of oysters. *C. gigas* create a cementation layer when they attach to the surface. The tensile strength of this cementation layer is called the attachment strength. No papers were found regarding the attachment strength of *C. gigas*. An initial study was conducted to generate an estimate (subsection 4.3.1). Results show the number of oysters necessary for the binding of one stone in various standard stone gradings (subsection 4.3.2). Figure 4.5 shows an initial relationship between the coverage ratio and the stability upgrading factor. By adding information about the attachment strength of oysters, an improved relationship between the stability upgrading factor and the coverage ratio has been formulated (subsection 4.3.3).

4.3.1. Measurements of the attachment strength of *C. gigas*

Measurement approach and processing

Measurements of the attachment strength of *C. gigas* were conducted at NIOZ in Yerseke. These tests were designed to determine the tensile strength of oyster cementation. At low water, living oysters were pulled from the surface using a clamp. This clamp was confirmed around the oyster. Appendix F shows pictures of this procedure and a detailed description of the breaking of the oysters. The force required to remove the oyster from the substrate was registered by a tensile force gauge (Model: PCE-HS, max. strength 50 kg, min. strength 200 gr, deviation 20 gr) (Figure 4.6). Forces on the living oysters were applied perpendicular to the direction of cementation. Twenty-four oysters were treated in this manner, of which 20 oysters were attached to a sheet pile and four were attached to stones. Measurements of oysters attached to stones were limited because those oysters were challenging to grab using the clamp since the attachment was very tight.

Figure 4.6: Clamp and tensile force gauge used for pulling *C. gigas* from the surface

Results

Oyster cementation can withstand an average force of 162 N, which can be rewritten as a mass of 16.5 kg. The standard deviation equals 89 N or 9.1 kg (Figure 4.7, Appendix F). The average length of the oysters studied was 8.0 cm, and the average width was 5.0 cm.

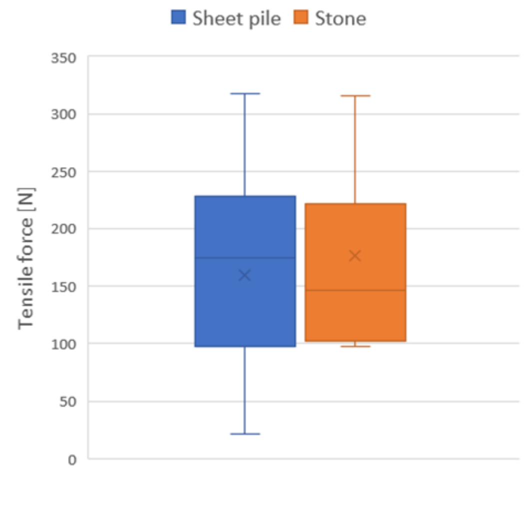

Figure 4.7: Tensile force of *C. gigas* attachment to sheet piles and stones

A rust layer was observed between the sheet pile and the cementation layer of oysters attached to it. Barnacles were observed between the oyster shell and the material surface, both on sheet pile and stone. Measurements showed the strength of the cementation. Some parts of the oyster, like the sphincter (the soft tissue that connects the valves), could be more prone to failure than others, which could negatively affect overall oyster strength. Some observations indicated the strength that the sphincter could withstand (k.11, k.15 in Appendix F, average strength 11.5 kg). Due to time limitations, neither this measure nor the specific strength of particular shell components are considered herein.

4.3.2. Model set up

A maximum force is expected to be applied to the oyster binding when stones are forced out of the revetment. This force is assumed to be equal to the weight of the stones. The tensile strength of *C. gigas* attachment is limited (Figure 4.7). Therefore, multiple oysters are necessary to ensure that stones are bound securely. The average number of *C. gigas* that are necessary for the secure binding of stones, N, depends on the stone class; heavier stones require more oysters. The average force needed to pull an oyster from the surface, F_{po}, is 162 N which equals 16.5 kg.

$$N = \frac{M_{50}\ g}{F_{po}} \tag{4.14}$$

N = Necessary number of *C. gigas* [-]
M_{50} = Median stone weight [kg]
g = Standard gravity (=9.81) [m/s^2]
F_{po} = Average force needed to pull one oyster from a surface [N]

Using this methodology, the value for f should be improved because stones will not bind for every 1 in 1/f oysters but every 1 in N/f oysters (Table 4.1).

$$f_{\text{im}} = \frac{f}{N} \tag{4.15}$$

f_{im} = Improved fraction of oysters settling at the edge of stones, leading to an effective binding [-]

Table 4.1: f_{im} for various standard gradings of light quarry rock material (based on CIRIA et al., 2007)

Standard grading class [kg]	**M_{50} [kg]**	**d_{n50} [m]** (Equation 4.1)	**f [-]** (Equation 4.8)	**N [-]** (Equation 4.14)	**f_{im} [-]** (Equation 4.15)
5 - 40	21	0.20	0.278	2	0.139
10 - 60	37	0.24	0.234	3	0.078
40 - 200	127	0.36	0.160	8	0.020
60 - 300	193	0.42	0.138	12	0.012

4.3.3. Results

The relationship between the coverage ratio of oysters and the stability upgrading factor as obtained in subsection 4.2.3 is improved by using the improved version of f, f_{im} (Figure 4.8). The boundary condition for dE/dr_{CR}, as described in section 4.2, is not valid for this improved value of f. This is because for f_{im} there will not be an immediate opportunity for binding of stones when $r_{CR} = 0$. After all, one single oyster is not sufficient for an effective binding. This means that the model overestimates the effective binding and thus the stability upgrading factor corresponding to a low coverage ratio. The stability upgrading under low coverage ratios should, therefore, be carefully considered in the analysis. Based on the described shift in the model, this formula can be used for coverage ratios from 0 up to and including 0.6.

$$\Psi_{d,\ model} = \sqrt[3]{\frac{S}{1 + (S-1) * (1 - r_{CR})^{\frac{A_{tot} * f_{im}}{(S-1) * A_O}}}} \tag{4.16}$$

Smaller stone gradings have more potential for stability upgrading compared to larger stone gradings because fewer oysters are necessary for one effective binding. A change of maximum coverage ratio by 0.1, either positive or negative, would have a higher effect on the stability upgrading factor for small stone gradings compared to large stone gradings (Table 4.2). The dashed lines in Figure 4.8 show how the relationship runs without an upper limit.

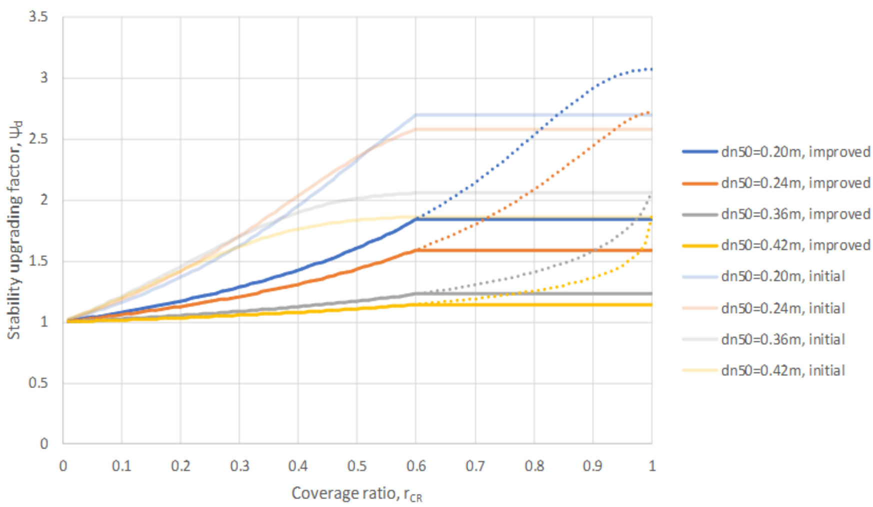

Figure 4.8: Improved relationship between the coverage ratio and the stability upgrading factor for different nominal stone diameters

Table 4.2: Effect of the change in maximum coverage ratio on the upper limit of the stability upgrading factor for different stone gradings. Compared to $r_{CR,\ max} = 0.6$

d_{n50} [m]	Ψ_d [-] $r_{CR,\ max} = 0.6$	Ψ_d [-] $r_{CR,\ max} = 0.5$	Ψ_d [-] $r_{CR,\ max} = 0.7$
0.20	1.84	1.60 (-13.0%)	2.14 (+16.3%)
0.24	1.59	1.43 (-10.1%)	1.80 (+13.2%)
0.36	1.23	1.17 (-4.9%)	1.30 (+5.7%)
0.42	1.14	1.11 (-2.6%)	1.19 (+4.4%)

4.4. Conclusions

C. gigas is considered to have the most promising effect on the stability of loose rock. Oyster coverage leads to binding of stones by *C. gigas* which increases the nominal stone diameter, d_{n50}. To describe this increase in nominal stone diameter, a stability upgrading factor, Ψ_d, has been introduced (Equation 4.4). This factor represents the relative increase in d_{n50} related to the number of stones bound by oysters. The stability upgrading factor has been predicted for various coverage ratios using a connectivity model (Equation 4.13). The exposed portion of the top layer is assumed to become impermeable when the coverage ratio exceeds 0.6, based on an analogy with asphalt. The behavior of an impermeable oyster layer is not well understood, though it stands to reason that an increase in the oyster coverage ratio will not reduce the stability upgrading factor. Therefore, the stability upgrading factor corresponding to a coverage ratio of 0.6 is set as the upper boundary. Combining the connectivity model and the upper boundary resulted in the definition of an initial relationship between the coverage ratio and the stability upgrading factor (Figure 4.5).

This relationship was improved by taking the attachment strength of *C. gigas* into account. The attachment strength of *C. gigas* limits the extent to which they can bind stones. Measurements showed that *C. gigas* attachment could withstand an average force of 162 N. Measurements of *C. gigas* attachment were subject to some uncertainties. One of the uncertainties is the difficulty in grabbing oysters that were very well attached and therefore expected to be stronger, which conceivably led to an underestimation of their true strength.

The number of necessary oysters needed for one binding is assumed to depend on the weight of stones. The value for the number of oysters that are necessary for one binding is therefore improved resulting in a final relationship between the coverage ratio of oysters and the stability upgrading factor,

$$\Psi_{d,\ model} = \sqrt[3]{\frac{S}{1 + (S-1) * (1 - r_{CR})^{\frac{A_{tot} * f_{im}}{(S-1) * A_O}}}}. \tag{4.17}$$

Results show that smaller stone gradings have more potential for stability upgrading than larger stone gradings; fewer oysters are necessary for one effective binding in case of a small stone grading.

5

Validation of the connectivity model with measurements

The oyster coverage ratio, the absolute and effective number of exposed stones were measured at specific locations. The measurement approach and processing are described and results are visualized (section 5.1). More extensive elaboration on safety procedures followed during the measurements can be found in Appendix D. Results from empirical measurements are used to validate the model. Obtained measurement data on *C. gigas* are plotted together with the improved model. The root mean square error (RMSE) is calculated as an indication of the extent to which the model represents the data (section 5.2). This information, combined with the findings from the previous chapter, addresses the third sub-question: *"To what extent can shellfish presence affect the stability of loose rock in revetments in the port area?"*.

5.1. Quantitative detailed measurements of shellfish presence

5.1.1. Approach

Quantitative research is performed to determine the shellfish presence on loose rock in the port area and the effect of shellfish presence on the stability of stones. The obtained data is used to validate the model. This quantitative research consisted of detailed observations at three different locations in the port area. Observation locations were chosen based on several criteria: the berm of each location had to be accessible, and locations had to be scattered throughout the port area to give a good picture of the port as a whole. In addition, it is aimed that at least one observed location had to meet the requirement of being labeled as +, and one as +- with regards to the predicted presence of *C. gigas* and *M. edulis* (chapter 3). Locations 5, 12, and 15 were chosen based on these criteria (Figure 3.8). At each location, three areas with a width of 1 meter were randomly selected. Random selection of the areas was done by assigning a number to each meter of revetment at every location (Figure 5.1). With the use of a random number generator, numbers were drawn for each location that corresponded to a specified meter of the revetment which was sampled.

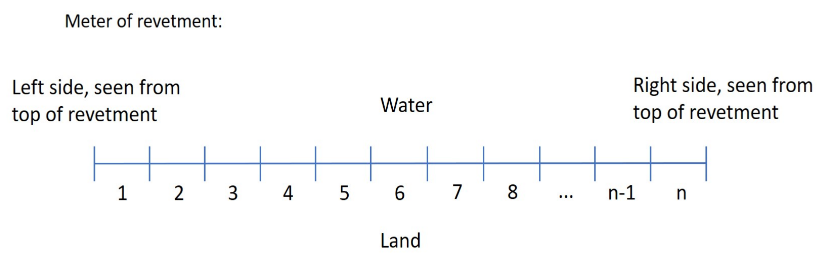

Figure 5.1: Overview of allocation of numbers to areas at a revetment

To get an indication of the shellfish presence in vertical space, three areas at all three locations were divided into five plots at different vertical levels. The highest level was at the significant wave height level, H_{sc}, which is about 1.5 meters above NAP. The lowest level was at 0.5 meters below NAP. This lower value corresponds approximately to the toe of the berm (Figure E.3, Figure E.5, and Figure E.7) and the average water level at low tide (MLW). Each plot had a width and an effective length of 1 m. The bottom lines of the plots are at respectively -0.5, 0, +0.5, +1.0, and +1.5 m in vertical height relative to NAP (Figure 5.2). The plots are labeled as #location_#area_#plot (Figure 5.3).

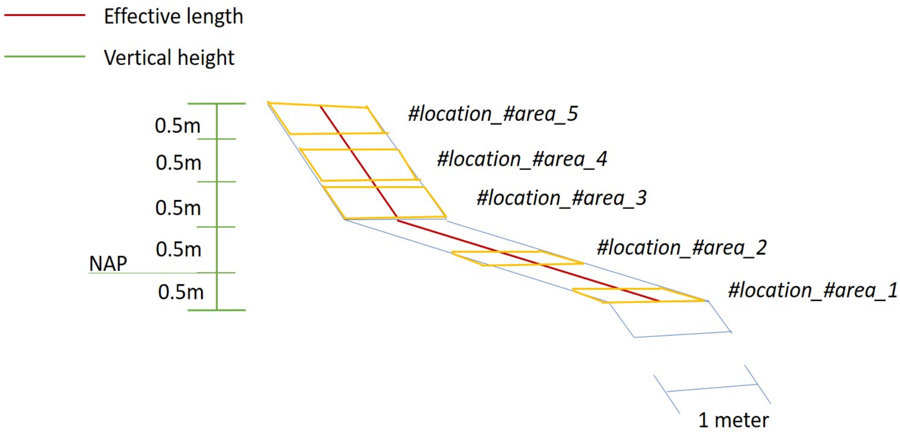

Figure 5.2: Division of an area in plots

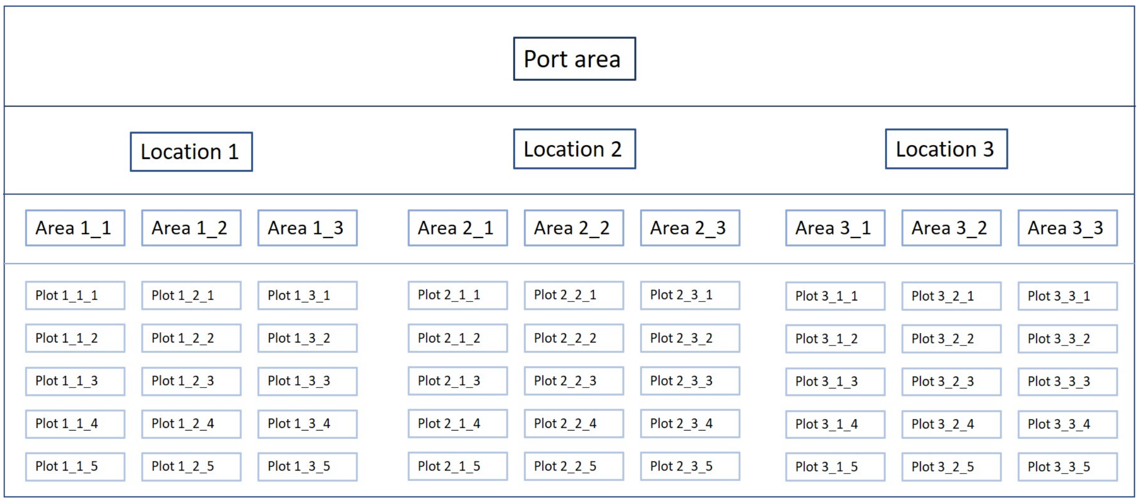

Figure 5.3: Overview of measured locations, areas, and plots

Each plot was sampled using a standard 1 m^2 quadrat that defined the plot area (Figure 5.4). Sampling started at the lowest plot which was determined at NAP -0.5 m. The position of this plot on the vertical was based on the water level and drawings of the revetment. Locations of the other plots were derived from this base level using a measuring tape. To ensure the consistent application of measurement techniques, the same persons were responsible for the same measurement task during each measurement.

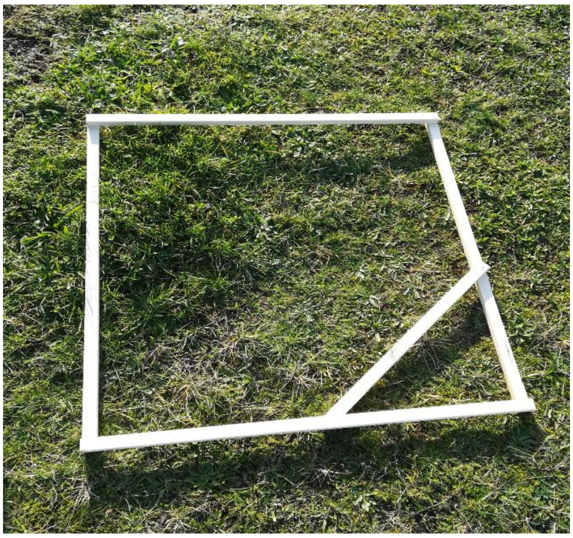

Figure 5.4: Quadrat of 1 m^2, used for observations

Prior to data collection, each observed revetment was compared with technical drawings to see if the type of the top layer and the shape of the revetment corresponded. The observed revetments indeed matched the drawings at every measurement location. The coverage ratio of shellfish and the connection of stones were then observed in different plots over the vertical space of the revetment. The absolute number of exposed stones, the effective number of exposed stones, % coverage of *M. edulis*, % coverage of living *C. gigas*, % coverage of dead *C. gigas*, and % coverage of algal species including *Ulva*, *Fucus*, *Polysiphonia* were recorded for each plot. The time, date, weather conditions, and coordinates of the observation areas were recorded as well. The coverage ratio was estimated as a percentage of the total quadrat area. When dead oysters were present, only those connected to stones were considered. To determine the number of effective stones per quadrat, the exposed portion of the top layer was tested by pulling and kicking the stones to see whether they were bound together. If oysters prevented the movement of one stone relative to the stone next to it, those two stones were considered to be one effective stone.

5.1.2. Data processing

The absolute number of exposed stones, S, the effective number of exposed stones, E, and the coverage ratio for dead *C. gigas* and living *C. gigas* were measured at three different locations in the port area as described in the previous section and are used in this analysis. The stability upgrading factor is calculated as

$$\Psi_{d,\, data} = \sqrt[3]{\frac{E}{S}}. \tag{5.1}$$

The stability upgrading factor is only calculated for locations 5 and 12. Location 15 is not taken into account since asphalt grouting is observed which made it impossible to determine the effective number of exposed stones.

Uncertainties in this research were mainly caused by observational errors. Though each plot was intentionally defined at the same height, across the three locations, there could be some variation caused by imprecision. Human error also could have led to misinterpretation of the coverage ratio or the effective number of exposed stones. All tasks were conducted by the same person to keep this error as small as possible.

5.1.3. Results

An overview of the results for each plot is presented in Appendix E.2. This appendix also contains pictures of each plot. Figure 5.5 shows the coverage ratio of dead and living *C. gigas* at the three locations. For each location, the coverage ratio was averaged over all three areas. The standard deviation is based on the degree of variation between the different areas. Figure 5.6 shows the stability upgrading factor. This factor depends on the absolute number of exposed stones and the effective number of exposed stones and was introduced in section 4.1. The stability upgrading factor is not taken into account at location 15 since asphalt grout is present at that location, which made it impossible to measure the effective number of exposed stones and therefore to calculate the stability upgrading factor.

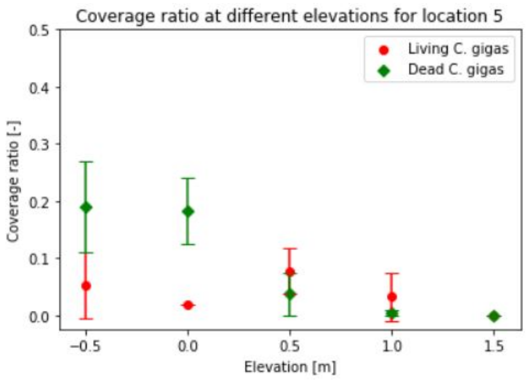

Figure 5.5 (a) Coverage ratio location 5

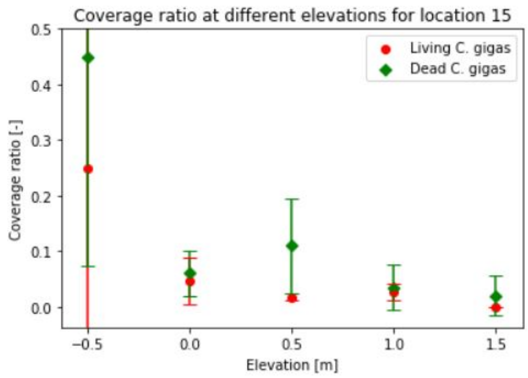

Figure 5.5 (b) Coverage ratio location 12

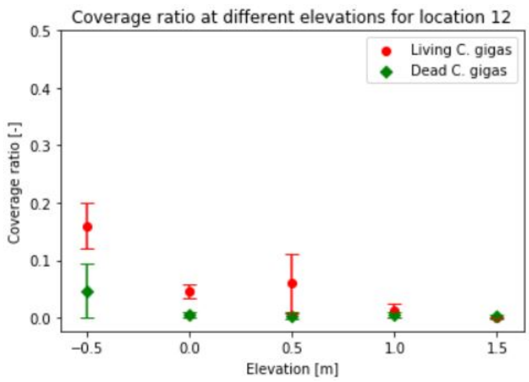

Figure 5.5 (c) Coverage ratio location 15

Figure 5.5: Observed coverage ratios of oysters

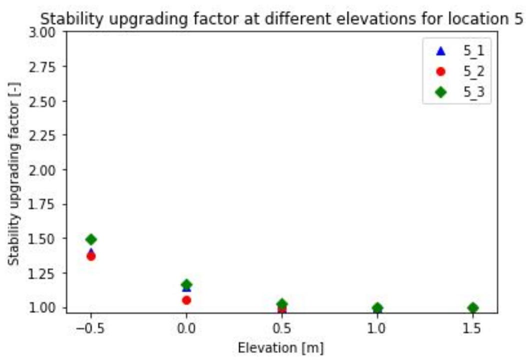

Figure 5.6 (a) Stability upgrading location 5

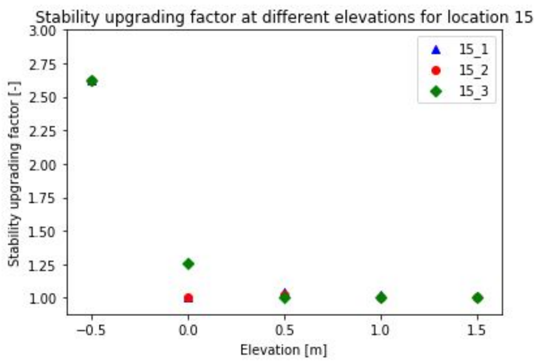

Figure 5.6 (b) Stability upgrading factor location 12

Figure 5.6: Calculated stability upgrading factor from the observed absolute and effective number of exposed stones

Coverage ratio in vertical space
The coverage ratio of shellfish is largest around the lowest plot of the revetment and decreases with progressive distance from the low water line (Figure 5.5). This is likely in response to the harsh environmental conditions in mid- and high-intertidal zones. This pattern was observed in all sampling locations and is in line with predictions regarding shellfish presence in vertical space (chapter 3). The 60%-line in the port area is located around NAP +0.5 m (Rijkswaterstaat, 2020). No shellfish are expected above this line according to chapter 3. Measurements from this study, however, show that there are still shellfish present above this level. Specifically, these data show that *C. gigas* is present until NAP +1.0 m, depending on the location.

Coverage ratio in horizontal space
Based on observations, as described in chapter 3, locations were given a score regarding shellfish presence. Location 5 scored “+-” regarding oyster and “-” regarding mussel presence. Location 12 scored “+” regarding oyster and “+” regarding mussel presence. Location 15 scored “+” regarding oyster and “-” regarding mussel presence. The outcomes of the quantitative measurements in this chapter show that the suitability of the observation method used in chapter 3 is debatable. Location 5 and location 12 show approximately the same cumulative coverage ratio regarding oyster presence, but the method used in chapter 3 came up with different qualifications. Mussel presence is not observed during previous qualitative observations at location 5. Quantitative measurements in this chapter, however, show that mussels are present at location 5. The measurement method used in chapter 3 is prone to false-negative errors; qualitative observations incorrectly indicate no presence. This can be due to circumstances like distance to the observed area and weather which influenced observation conditions. Also, the color of the stones and shellfish can be important, as mussel shells are more similar in color than oyster shells to the color of the stones.

Stability upgrading
The stability upgrading factor is largest around NAP -0.5 m and decreases rapidly with progressive distance from the low water line. An oyster bank was present at location 12. At the same time the effective number of stones, E, was considerably low; all stones were connected at this location. This low value of E resulted in a high stability upgrading factor around NAP -0.5 m.

Others
Fucus vesiculosius L. cover can reduce the recruitment of *C. gigas* (Diederich, 2005). Fucus was mainly present in plot 3 (Fucus coverage averaged over all areas equals 44%) and plot 4 (Fucus coverage averaged over all areas equals 33%) (section E.2). Oyster presence in these plots could potentially be larger if Fucus coverage were lesser. A pilot study can be used to research how and to what extent this coverage can be diminished.

5.2. Validation of the connectivity model with measurement results

Measurements are compared to the connectivity model and the goodness of fit of the connectivity model is determined. Since the cementation of *C. gigas* remains after death of the oyster, the coverage ratio of dead *C. gigas* and living *C. gigas* has been combined to calculate the total coverage ratio of *C. gigas*. The measurement data for coverage ratios of over 0.6 show that the modeled upper limit is a conservative value (Figure 5.7). Further research on stability effects conferred to revetments covered by oyster reefs is necessary to optimize the upper limit.

The d_{n50} of stones in the plots above NAP at location 5 is 0.20 m. Stones in the plots below NAP at location 5 and stones in all the plots at location 12 had a d_{n50} of 0.30 m. The measured data and the predicted improved connectivity model for nominal stone diameter 0.20 m and 0.30 m are plotted in Figure 5.7. The root mean square error (RMSE) between the connectivity model and the data was calculated to determine the quality of the model. The measurement data for coverage ratios of over 0.6 are not included in the calculation of the RMSE since high coverage ratios are conservatively modeled which would result in large errors. The RMSE for a d_{n50} of 0.20 m equals 0.047 while the RMSE for a d_{n50} of 0.30 m equals 0.156. The root mean square error is high when there are large errors. The RMSE differs for both nominal stone diameters because a nominal stone diameter of 0.30 m incurred larger errors than a nominal stone diameter of 0.20 m (Figure 5.8). These larger errors can be the result of the brick that was present at location 12 which may have influenced the measurements. Values for the RMSE can be used to improve the connectivity model if more data is available.

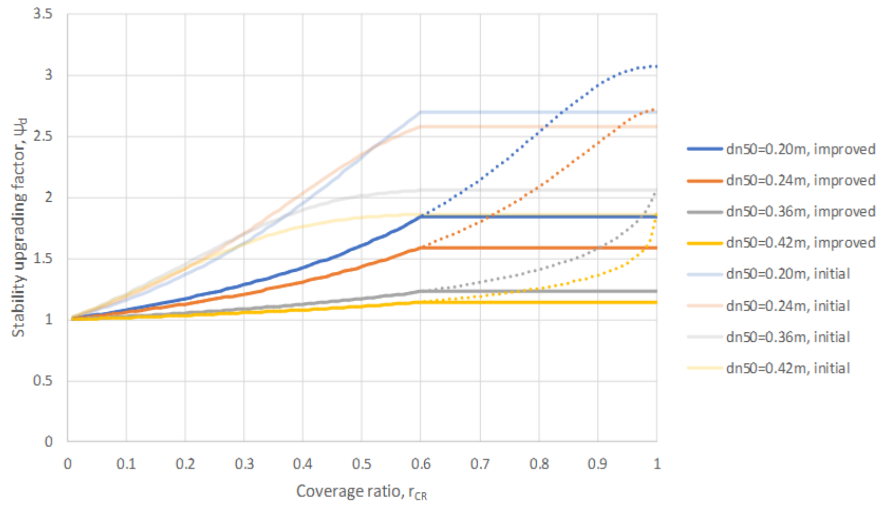

Figure 5.7: Validation of the connectivity model with measurement outcomes for different coverage ratios and a nominal stone diameter of 0.20 m and 0.30 m

The connectivity model seems to overestimate the stability upgrading factor compared to the measurement data for a coverage ratio until 0.12. This was expected since the model overestimates the stability upgrading for an initial coverage ratio. The measurement data for the stability upgrading factor deviates significantly for a coverage ratio between 0.12 and 0.4. A reason for this deviation can be the measurement approach or the variability in the effect of oysters. This implies that the connectivity model should be used with great care for these coverage ratios. More data can help to set an upper limit for the stability upgrading factor within this range of coverage ratio.

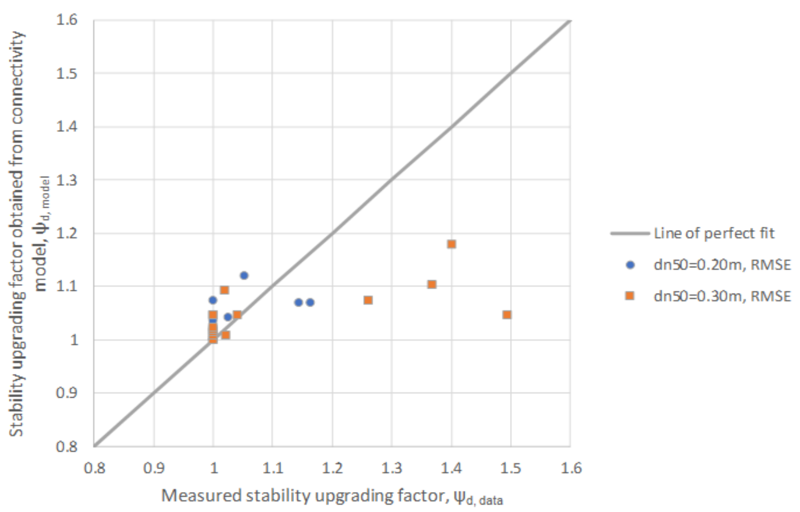

Figure 5.8: Goodness of fit between connectivity model and data

5.3. Conclusions

Quantitative measurements imply that oyster presence does affect the stability of loose rock revetments in the port area. The stability upgrading factor is related to the cumulative coverage ratio of dead and living *C. gigas* because an increase of *C. gigas* coverage is accompanied by an increase of the stability upgrading factor. The extent of the increase of the stability upgrading factor depends on the coverage ratio. The cumulative coverage ratio of dead and living *C. gigas* decreases as one moves up the intertidal zone from the mean low water level. This is in line with the predictions from chapter 3 regarding shellfish presence in vertical space.

The goodness of fit for the improved relationship between the stability upgrading factor and the coverage ratio is calculated by the root mean square error. The RMSE for a d_{n50} of 0.20 m equals 0.047 while the RMSE for a d_{n50} of 0.30 m equals 0.156. The connectivity model predicted the attachment of loose rock with a d_{n50} of 0.20 m more accurately than for a d_{n50} of 0.30 m. Bricks that were present at location 12 may have influenced the measurements, resulting in larger measurement errors for d_{n50} of 0.30 m.

For low coverage ratios, up to 0.12, the effective binding and therefore the stability upgrading factor is overestimated by the connectivity model. The data shows that the stability increased for a coverage ratio of more than 0.12. This counts for each location for which data was collected. This implies that a coverage ratio of approximately 0.12 is the minimum necessary coverage ratio for initial stability upgrading. There is a large deviation of the extent of stability increase between locations with a coverage ratio between 0.12 and 0.6. A reason for this deviation can be the measurement approach or the variability in the effect of oysters. This implies that the connectivity model should be used with great care for these coverage ratios. The calculation of the stability upgrading factor conferred by oyster reefs (high coverage ratio, >0.6) is unknown. For now, an upper limit is used. The effect of a *C. gigas* reef should be studied further to indicate the potential for added stability.

6

Potential and limitations of *C. gigas* populations

This chapter describes potential opportunities for ecological enhancement of *C. gigas* populations within the port area, as well as limitations of the species in this context. The findings from this chapter are used to assess the potential of different strategic applications in the port area (chapter 7).

Physical and physiological characteristics of *C. gigas* are discussed in terms of strengths and weaknesses from an engineering, environmental, and ecological perspective (section 6.1). The primary consideration is that application of *C. gigas* is only possible at locations that are suitable for oyster growth. Characteristics of the port area largely affect physical and environmental conditions across locations and therefore affect their suitability for oyster populations. The implications, both positive (i.e. opportunities) and negative (i.e. threats), of conditions for *C. gigas*, are discussed in section 6.2. Enhancement methods to enhance population growth of *C. gigas* are described in subsection 6.3.1. Based on these analyses, mitigation strategies to address negative consequences of *C. gigas* application on engineered structures are recommended (subsection 6.3.3).

6.1. Strengths and weaknesses

Physical and physiological characteristics of an individual species determine the strengths and weaknesses associated with their application in an engineering design context. The main advantages of increasing *C. gigas* presence and density on engineered structure include: added structural stability; lessened environmental impact of the revetment; and improved potential for overall ecosystem functioning with oysters as a foundation species or ecosystem engineer.

6.1.1. Structural

Growth and reproduction of *C. gigas* populations are required to achieve a specified coverage ratio and strength capacity, time must be budgeted for this. The necessary time depends on the desired coverage ratio as a function of the requisite increase in nominal stone diameter. This temporal component is a common consideration in nature-based designs, as living components are dynamic in contrast to structural elements, which are static. This topic is further described in subsection 6.3.3. Presence of *C. gigas* likely provides limited additional stability, as discussed in chapter 5. This is an important consideration for design and an acknowledged limitation of using this species. One advantage is that *C. gigas* presence on loose rock will improve the stability of the stones and therefore reduce maintenance frequency on a revetment. Maintenance is mainly necessary locally in response to unexpected loading. In some cases, port plans result in an expected increase of the load which requires redesigning of the revetment. The additional stability generated with oysters can reduce this redesigning demand. Structural benefits of oysters are provided to the revetment more or less permanently. The shell and cementation remain in place even after the oyster dies (subsection 2.2.3). Many conventional revetment designs are reinforced with asphalt to improve stability. When the revetment is replaced, this asphalt layer is demolished which is a difficult process (M. Minnaard, personal communication, April 16, 2020). If oysters are used instead of asphalt, demolition and reuse of materials may be more readily possible.

6.1.2. Environmental

The environmental impact of a revetment depends on a range of factors, including the greenhouse gas (GHG) emissions associated with construction. The volume of emissions depends on the size of the stones used in construction. Larger stones are obtained using more advanced mining procedures and often must be shipped across longer distances compared to smaller stones because quarries for larger stones are located further away (E.J. Broos, personal communication, September 18, 2019). Additionally, using larger stones means that more cubic meters of stone is needed to achieve the required thickness of the top layer of 1.5-2.0 d_{n50}. Binding of stones by *C. gigas* could enable the use of smaller stones in revetment designs, which decreases the environmental impact of the used material. The extent to which the environmental impact can be decreased depends on the population size and continuity. In addition to affecting material choices during the construction process, *C. gigas* also positively affects the adjacent marine environment on a consistent basis by filtering the water. The filtration capacity of *C. gigas* depends on the speed of the water flow and the size of the oyster (Walne, 1972). This water filtration is a clear benefit to overall water quality and, therefore, for the environment as a whole.

6.1.3. Ecological

Oyster enhancement is also associated with ecological strengths and weaknesses. Oysters are a food source for many species of birds. Previous studies found that birds used *C. gigas* banks slightly more intensively compared to surrounding areas (Scheiffarth et al., 2007; Wijsman et al., 2008).

C. gigas is an exotic species that was introduced in the Netherlands only recently, while the flat oyster (*Ostrea edulis*) is a native species that is threatened in the Greater North Sea area (Beck et al., 2011; OSPAR Commission, 2008). The native *O. edulis* is not considered in this report because this species is not commonly observed in the port area. Interestingly, *C. gigas* can provide substrate to which *O. edulis* can readily attach, which could potentially help to reintroduce this species (Christianen et al., 2018; J.W.M. Wijsman, personal communication, November 22, 2019). Article 11 of the "Gedragscode Flora- en faunawet voor de bouw- en de ontwikkelsector" describes that protected native species should not be disturbed (Bouwend Nederland & NEPROM, 2006). *C. gigas* and *O. edulis* are not listed as protected species; removal of stones covered with *C. gigas* or *O. edulis* is not expected to be a problem (Dijkstra, 2013).

Enhancement of oysters may lead to food scarcity for other species. Competition for food resources may result in a shift in the benthic population if *C. gigas* regularly out-competes other local species (Diederich, 2006; Smaal et al., 2005). Tidal fluctuations and river outflow provide constant salt- and freshwater inputs. The presence of ample nutrient levels in these waters make food resource limitation unlikely.

Physical gaps between loose rocks in revetments can serve as refuge areas for larger species (e.g. fish and lobsters), to recover from the stressful transition from salt to fresh water or vice versa (Groen, 2019). If oyster density is large enough, their presence may eliminate these physical refugia spaces. At the same time, the 3D structure of oyster beds creates topographical complexity and shelter for smaller species (Troost, 2010). Susceptibility of *C. gigas* to diseases like the Herpes virus and predation pressure from local species are additional limitations to take into account (subsection 2.2.2).

Table 6.1: Strengths and weaknesses of *C. gigas*

Strengths	**Weaknesses**
Structural benefits even if oyster dies	Necessary growth and development period
Lessened environmental impact compared to stones	Limited stability capacity
Water filtration	Shift in benthic population due to out-competition
Food source for other species	Potential enhancement of exotic species
May facilitate attachment and growth of native endangered *O. edulis*	
Acts as ecosystem engineer	

6.2. Opportunities and threats

Various opportunities and threats can change the conditions in the port area and affect *C. gigas* fitness and survival. Opportunities and threats are the results of external processes that happen over time. Sources of opportunities and threats for oyster enhancement discussed in this chapter are: global warming, pollution, and future port plans.

6.2.1. Global warming

Global warming is expected to impact future conditions in this system; sea level will rise, and river peak discharges and seawater temperature will increase (IPCC, 2019). *C. gigas* will adapt reasonably well to sea level rise (Fey-Hofstede et al., 2012; Rodriguez et al., 2014), mainly because they prefer locations below MLW (Vismann et al., 2016). Therefore, rising sea levels should not be a problem for oysters.

River peak discharges, however, do pose a threat. Oysters require a certain salinity level for survival which may be diluted by higher river peak discharges that bring more fresh water to the estuary. Figure 3.3 shows the outcome of the OSR model under high river discharge conditions. This spatial model indicates that Maasvlakte 2 and the Calandkanaal will stay saline, while the Beerkanaal becomes fresher due to high river discharge. Before any projects involving oysters are implemented in the Beerkanaal, future freshwater flows should be modeled to determine whether salinity levels remain high enough to support this species.

Seawater temperature in the North Sea is expected to increase by an average of 2 °C in the next 100 years (Mathis & Pohlmann, 2014). Generally speaking, this temperature rise may not be either a threat or an opportunity for oyster populations given that the projected increased temperature still lies within the range that *C. gigas* can tolerate. However, an increase in summer mortality of *C. gigas* may occur. Summer mortality of *C. gigas* is largely, but not only, caused when the water temperature exceeds 20 °C (Child & Laing, 2008; Samain & McCombie, 2008). The extent and effect of this summer mortality should be studied in-depth, particularly if plans for *C. gigas* enhancement extend beyond ten years.

6.2.2. Pollution

Pollution is prevented by strict protocols but can still happen on a structural and an incidental basis. Accidental oil spills, for example, can lead to incidental pollution. Different types of oil spills can occur (e.g., bunker fuel, gasoline). Because oil is lighter than water, it floats on the surface and can come in direct contact with oysters around the mean water line. Previous research indicates that oil appears to alter various biological responses of *C. gigas* (Luna-Acosta et al., 2011). Different types of oil have different impacts. Bunker fuel is extremely viscous and sticky and is persistent in the environment for up to five or six years. Gasoline, on the other hand, is viscous and not very persistent, lasting only days to weeks in the environment. These types of oils also have different levels of toxicity; a measure of the water-soluble compounds in the oil that can cause poisoning of flora and fauna. Bunker fuel oil has a medium level of toxicity while gasoline has a high level of acute toxicity in comparison (Department of Ecology State of Washington, 2019). It is not clear which type of oil could pose the most significant threat to bivalves.

Structural pollution is often caused by industrial parties (KRW, 2019). Surveys in the Western Scheldt estuary showed that *C. gigas* contained: heavy metals, organo-metals, polycyclic aromatic hydrocarbons (PAK), polychlorinated biphenyls, pesticides (Sneekes & Kotterman, 2019). Structural pollution in the port is expected to be similar to the type and levels observed in the Western Scheldt estuary. The vulnerability of oysters to structural and incidental pollution and the effect on the strength of the oyster attachment should be further studied.

Another negative environmental impact from industrial activities is drawing in water for cooling. This process can also suck up and destroy larvae in the vicinity (KRW, 2019). The introduction of oysters should therefore not be situated in close proximity to these systems.

6.2.3. Future port plans

The shipping industry is growing, resulting in larger ships visiting the port. Increasing ship size conceivably increases the size of the waves formed in their wake. Therefore, at some locations, larger stone sizes will be considered necessary in revetment designs. The stone binding efficiency of oysters decreases when larger stones are used (Figure 4.5). Even still, oysters can add valuable strength to the structure and pre-empt future increases in ship size and consequently mitigate any damaging effects from the size of ship waves.

Table 6.2: Opportunities and threats for designing with oysters

Opportunities	**Threats**
Resilient to sea level rise	Increasing river peak discharges
	Pollution
	Water drawing for cooling
	Future port plans

6.3. Measures to improve *C. gigas* potential

To utilize *C. gigas* properties in an engineering context, there must be sufficient certainty that *C. gigas* can provide additional stability within limited time after construction and into the future. Oyster presence can be enhanced on a specific-location basis by stock enhancement (subsection 6.3.1), habitat enhancement (subsection 6.3.2) or food enhancement. Food enhancement is not considered because food is assumed to be abundantly present due to constant nutrient supply from upstream. Proposed enhancement strategies must first be examined in a pilot study (Appendix I). The potential reduction of maintenance costs and additional benefits relative to enhancement costs can determine whether enhancement is wanted. Known current and future risks associated with enhancement activities and structural dependence on oysters can and should be mitigated. Several complementary mitigation measures are described, including allowing sufficient development time, implementing a monitoring protocol, and the placement of extra material if additional stability requirements are not met (subsection 6.3.3).

6.3.1. Stock enhancement

Individual *C. gigas* have limited strength on their own (chapter 5). This limited strength makes multiple oysters necessary for the binding of stones. A positive relationship exists between adult oyster presence and the number of yearly recruits. Therefore, an enhancement strategy that focuses on introducing mature oysters can lead to faster development of oyster coverage (Diederich, 2005). The timing for this type of enhancement is best in early spring before mass spawning takes place to allow both adult oyster growth and recruitment of larvae after reproduction (Didderen et al., 2018). Introduced oysters should be of different ages because different ages indicate different sexes (subsection 2.2.1). Previous pilot studies, at locations without an existing oyster population, aimed for an initial oyster density of 8 oysters/m^2 (Didderen et al., 2019). This can be seen as an upper limit for oyster introduction. The exact introduced oyster density depends on the current oyster presence and should be site-specific determined. Different introduction measures are discussed.

Gluing
Adult oysters can be introduced on the revetment by gluing them to the stones (J. van Poppel, NIOZ, personal communication, June 10, 2020). Ongoing and yet unpublished research in Yerseke (NIOZ) showed that Bison Kit 2K Expert PolyUrethaan is a suitable glue to connect oysters to rubble stone (Figure 6.1). This study also showed that oysters stayed connected to stones for at least 5 months with the help of this glue. Oysters can be glued to stones within the revetment of interest on the part of the stone that is in contact with the water column. 2 hours after gluing, the oysters can be inundated. Further hardening of the glue can take place in the water.

Figure 6.1: Bison Kit 2K Expert PolyUrethaan glue

Racks
Another way of introducing adult oysters is by placing broodstock cages filled with loosely packed living oysters at a location where oyster development is required (Figure 6.2) (Didderen et al., 2018). Previous pilot studies in the North Sea demonstrated a survival rate of 84% for oysters kept in such broodstock cages, clearly indicating that it is a suitable enhancement method (van der Weide et al., 2018). One rack can contain up to 400 oysters (up to 10 baskets with each basket containing 40 oysters). Possible dimensions of the rack are a length of 1 meter, a width of 2 meters, and a height of 1 meter. This shape will provide better stability than a perfect cube. The racks can be placed directly on the berm of the revetment since this offers a stable horizontal location and guarantees enough water flow for feeding and respiration. The effect of these racks on the current and wave dynamics in the port is not considered in this report. Turbulence around the racks may lead to undermining of the construction and need to be further investigated before implementation.

Figure 6.2: Example of basket configuration (van der Weide et al., 2018)

6.3.2. Habitat enhancement

The primary consideration is that application of *C. gigas* is only possible at locations that are suitable for oyster growth. An enhancement strategy that focuses on ameliorating habitat and therefore settlement conditions for this species can lead to faster development. Hard substrate is a requirement for oyster presence and is therefore considered to be present. Additional habitat enhancements are discussed below.

Salinity improvement

Habitat suitability is mainly determined by salinity conditions. These salinity levels can not be influenced on a large scale. Freshwater outlets can, however, lead to reduced local salinity levels. If freshwater outlets are present at a location and if they lower the salinity level, one can relocate these outlets to improve the conditions for oysters. An overview of the current freshwater outlets in the port can be found in Figure 3.2.

Substrate improvement

Another option is to look at the substrate. Oysters tend to prefer certain substrates over others. Potential substrates for oyster attachment are basalton, limestone, concrete, and copper slag (Paalvast, 2017). A previous study showed that *C. gigas* were less present on asphalt and granite (Paalvast, 2017). This information has not been discussed in chapter 3 because it is not yet well-substantiated and should be further studied before application.

Introduction of empty shells

Empty shellfish shells can enhance oyster settlement. The type of shell is only of little importance herein (Didderen et al., 2019; Sas et al., 2019). In previous studies, oysters shells were mainly used as an additive to hard substrate, but it can also serve as an attractive measure for oyster settlement at locations where hard substrate is already present. In the port, hard substrate is widely present. Loose shells can be easily washed away by the tide or be overgrown with marine growth. To reduce these risks, shells should be deposed only shortly before larvae are going to settle which is from June to August in biodegradable nets (Sas et al., 2018). Shells should be clean and not covered by epibionts.

Introduction of algae

Oysters seem to prefer to settle on substrate covered by an algae mixture (A. Cryan, personal communication, January 2020; P. Paalvast, personal communication, December, 2019; Scape, 2020). It is currently unknown how algae can be applied on stones in a revetment. Future research might lead to possibilities.

6.3.3. Mitigating weaknesses and threats

Mitigation of weaknesses and threats can lead to successful enhancement. Mitigation can also ensure that the structural function of the revetment is not undermined. Different mitigation measures are discussed.

Development period

A sufficient development period is required to ensure that *C. gigas* reach a certain strength level. Oysters are not presumed to confer any stability benefits through biological cementation processes during the development period. The duration of this period depends on the development rate and the intended oyster coverage ratio which depends on the desired increase in nominal stone diameter. Oysters are expected to add stability to the structure once they survived the stage of being spat. This means that 6 months after settlement they will start to bind stones and add stability. They are fully grown at 3 years of age, so they are expected to fully bind stones by then (Didderen et al., 2018). If ship waves are normative, the stones that are placed upon initial construction should be able to withstand ship induced waves that occur during this development period. When the specified coverage ratio of oysters has been achieved in a given location, stones can withstand a larger ship wave. The stones placed upon initial construction should be able to withstand the wind wave for a sufficient lifetime to allow development of the oysters. The increased effective stone dimension due to binding by *C. gigas* should be able to withstand wind waves for the remaining lifetime of the structure (Appendix H). If currents are normative, designing with oysters can not be the case since currents can not be postponed.

Monitoring
Oyster-enhanced revetments should be regularly monitored to check the achieved coverage ratio and whether the oysters are healthy. When oysters die, the cause of death should be studied. Monitoring should take place at least once before the shipload increases or before the extension of the lifespan of the structure. If more information is needed, monitoring can be intensified. Surveying once per season (four times per year) can allow for the early observation of diseases or death, which in turn allows time for action. Reinforcement based on monitoring data can mitigate the risk of disease and predation.

Reinforcement
The revetment must be reinforced if the oyster density is not sufficiently high enough prior to the increase of load. This reinforcement can either consist of the placement of additional or larger stones or the placement of asphalt. Reinforcement will mitigate structural risks and ensure that the revetment can withstand the load. However, the physical impact of the placement procedure will lead to the death of shellfish.

6.4. Conclusions

Enhancement of oysters and applications in the design comes with structural, environmental, and ecological strengths and weaknesses (Table 6.1). The conditions in the Port of Rotterdam as a system itself can pose various opportunities and threats for oyster coverage, such as global warming, pollution, and future port plans (Table 6.2). These factors should be taken into account when designing ecological enhancement strategies that utilize oysters.

Enhancement strategies can either focus on stock enhancement or habitat enhancement. Both enhancement measures aim to enhance oyster settlement, growth and reproduction. 6 months after settlement, oysters will begin to bind stones and add stability to the structure. After 3 years, they are full-grown and so they are expected to fully bind stones by then The aim for stock enhancement is to introduce or increase *C. gigas* populations by introducing mature oysters. This can, for example, be done by gluing the oysters to stones in the revetment at the project site. Points of attention for oyster stock enhancement are:

- Enhancement period: early spring
- Age distribution: 50% of oysters < 3 years old, 50% of oysters > 3 years old (to ensure an even sex distribution).

Habitat enhancement aims to improve habitat conditions. A promising habitat enhancement measure is the improvement of the substrate. This can be done by placing sediment types that enhance oyster attachment. Another option for habitat enhancement is to place shells on the revetment. These possible enhancement measures require a pilot study to test the feasibility.

Risks associated with relying on additional stability provided by oysters (subsection 6.1.1) can be mitigated by taking a biologically relevant oyster development period into account during the design phase and by monitoring regularly. If oysters are not able to provide sufficient stability, reinforcement of the revetment can take place by placement of additional or larger stones, or by placing asphalt on the revetment. The possibilities and limitations described in this chapter do not just apply the Port of Rotterdam, but can be used to determine possibilities and limitations at other project sites as well.

7

Applications in the Port of Rotterdam

This chapter answers sub-question: *"What are potential applications of shellfish in revetment designs?"*. Opportunities for *C. gigas* application depend on the suitability of the revetment for oysters' presence. Oysters are naturally present on most of the revetments with potential for *C. gigas*. If oysters are not naturally present on a revetment, enhancement measures can be used to introduce oysters or to improve the suitability of the revetment (section 7.1). Costs and benefits of *C. gigas* applications are considered (section 7.2 and section 7.3) and findings are summarized in a flow chart. This flow chart can be used as a guideline for application in the Port of Rotterdam (section 7.4).

7.1. Opportunities in the port area

This section discusses the opportunities of oyster applications at different locations in the port area. Strategic application of oysters can be used to increase the serviceability limit state (SLS) of the revetment and the ultimate limit state (ULS) of the top layer. To generate these improvements, certain conditions are required.

C. gigas potential

Oysters need certain conditions for survival (subsection 2.2.2). The salinity level mainly determines oyster presence in horizontal space. The salinity level should be at least 16‰ under normal average river discharge (Q_{norm} = 2300 m^3/s) and at least 11‰ under high average river discharges (Q_{high} = 7000 m^3/s) (chapter 3). Locations that meet these requirements are the Maasvlakte 2, Calandkanaal, and a small part of the Beerkanaal (Figure 7.1).

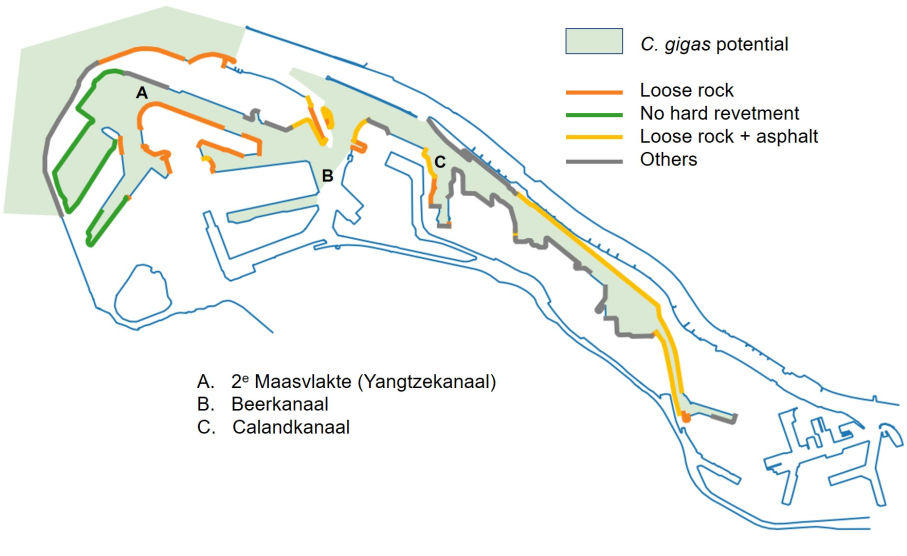

Figure 7.1: Potentially suitable locations for application of oysters in the Port of Rotterdam

Inundation is the limiting condition in vertical space. Oysters need regular inundation for feeding and respiration. This means that oysters are rarely present above NAP +0.5 m. As discussed before oysters need hard substrate for settlement. Therefore their presence in the water column is limited by the presence of hard substrate in the revetment. Sloping hard substrate revetments are normally present until NAP -5 m. This depth is therefore considered as the lower limit of oyster presence. Bed protections can also consist of hard substrate, making them suitable for oysters, but this is beyond the scope of this report. The upper limit of abundant oyster presence is at NAP +0.5 m because of the limited inundation at higher levels. Since oysters settle at a certain part of vertical space, they will affect the stability of the top layer only in this specific vertical range. Normative wind waves are expected to attack the revetment at higher levels due to set up. This results in the greatest wave impact at a location where oysters are not present. Ship waves impact the revetment around the still water level and bow thrusters impact the revetment at an even lower level (subsection 2.1.1). This makes oyster application most promising for a normative ship wave or bow thruster impact.

Top layer

Oysters require hard substrate for settlement. The potential of the effect of oysters depends on the type of revetment. Here, the focus is on the effect of oysters on loose rock.

Asphalt is often used to improve the stability and durability of loose rock revetments. Oyster application can be an alternative to this asphalt penetration. Especially if this application goes hand in hand with ecological and cost-related advantages. When redesigning loose rock revetments that are currently penetrated with asphalt, a combination of loose rock and *C. gigas* can be considered as an alternative. The effect on other types of revetment such as placed rocks is not investigated here and currently unknown. Therefore, oysters can also be used in the design of a new-build revetment or a reconstruction of an existing revetment, but only if loose rock is used in this new design. During the redesigning process, loose rock in combination with stock and habitat enhancement can be an alternative.

***C. gigas* presence**

Oysters offer additional stability to loose rock revetments when the coverage ratio is more than 0.12. While a location can have oyster potential, oysters may be absent or only sporadically present on a revetment. A complete absence of oysters may indicate that there is food scarcity or that there are other reasons why a location is not suitable for oyster growth and survival. The reason for oyster absence should be studied to determine how oysters can be attracted. Sporadic presence of *C. gigas* can be a sign that the habitat is not optimal or that there are not enough larvae in the water column. Enhancement can then be an option. Possible enhancement measures are discussed in the next paragraph.

Possible enhancement measures

The extent of added stability depends on the coverage ratio. The degree of enhancement for existing revetments should depend on the current and aimed coverage ratio and the possibility of occurrence. Enhancement is necessary if the current coverage ratio is less than the aimed coverage ratio. Enhancement will contribute to faster development and therefore improved reliance on oysters.

C. gigas presence can be augmented by stock and habitat enhancement if the coverage ratio is lower than aimed for in the design. If the area is already been identified as one with good conditions for oyster growth, but there are no larvae present in the water column, ecological study should be carried out to show the reason why not. Stock enhancement can improve the *C. gigas* population if there are no reasons for a location not to be suitable for oysters. This should be carefully considered; if larvae are not present in the water column there must be a reason why not. Habitat enhancement is an option if oyster larvae are readily available but do not settle. Different possible stock and habitat enhancement measures are described in section 6.3. Costs associated with promising enhancement strategies are elaborated in the next paragraph. For stock enhancement, the option with glue is elaborated and for habitat enhancement substrate improvement and empty shells application are considered as these strategies are most promising based on subsection 6.3.1 and subsection 6.3.2.

Enhancement measures should be first studied in a pilot study. This pilot study can consist of a combination of habitat and stock enhancement. Surveys should take place at least once per season to monitor the survival and growth of *C. gigas*. Irreparable damage to oysters such as diseases can be devastating to the overall project as loss of coverage will undermine the physical strength of the structure. In the case of a significant loss in oyster coverage, risks to structural stability can be mitigated for example by the placement of additional stones (subsection 6.3.3).

7.2. Costs

Various quantitative and qualitative costs are discussed. Quantitative costs include those associated with construction, monitoring, and enhancement. Maintenance costs can not be quantified due to large variability and a lack of data and are therefore qualitative. There is a large variability in maintenance demand throughout the port area, maintenance is not performed regularly, but only if needed. Total enhancement costs are not quantified since they depend on the final enhancement strategy.
A revetment with a length of 100 m and an effective width of 6 m (area = 600 m^2) is used as a basis for all cost calculations. The lifetime of the structure is set to 50 years. Future costs may be higher than current costs as a result of inflation, but this is not considered in these preliminary calculations.

Construction costs
The price of loose rock used for the top layers of revetments is EUR 35 per square meter for stone class 5-40 kg and EUR 40 per square meter for stone class 10-60 kg. This includes both material and construction costs (E. Broos, personal communication, June 22, 2020).

$$Construction\ costs\ 5-40\ kg = 35\ €/m^2 * 600\ m^2 = €21,000 \tag{7.1}$$

$$Construction\ costs\ 10-60\ kg = 40\ €/m^2 * 600\ m^2 = €24,000 \tag{7.2}$$

Monitoring costs
Monitoring may be performed on foot from land (LS) or a vessel from water (WS). Usually monitoring activities should be performed once a year from land, and once every two years from water. When the physical stability of the structure relies on a functioning oyster layer, surveys should take place at least once per season (four times per year) from land to carefully monitor the condition and coverage of the oyster population. Data collection and processing costs are included in the monitoring costs. Monitoring from land takes approximately 5.7 hours per km of revetment. The costs of one labor-hour are assumed to be EUR 80. Monitoring can be done from a vessel at a speed of 1 hour per km of revetment, the corresponding costs are EUR 440 per hour (R. Duvaloois and M. Minnaard, personal communication, April 16, 2020). Monitoring costs for a standard revetment (SR) are calculated as well as additional monitoring costs that are needed to check the condition of the oysters in case of reliability on *C. gigas*.

$$Monitoring\ costs,\ LS = 0.57\ h\ per\ 100m\ of\ revetment * 80€/h * 50\ year = €2,280 \tag{7.3}$$

$$Monitoring\ costs,\ WS = 0.1\ h\ per\ 100m\ of\ revetment * 440€/h * 50 year * 0.5\ times\ per\ year = €1,100 \tag{7.4}$$

$$Total\ monitoring\ costs,\ SR = Monitoring\ costs,\ LS + Monitoring\ costs,\ WS = 2,280 + 1,100 = €3,380 \tag{7.5}$$

$$Additional\ monitoring\ costs,\ LS,\ to\ check\ the\ condition\ of\ oysters\ = 3 * €2,280 = €6,840 \tag{7.6}$$

Enhancement costs
Stock enhancement, gluing
The goal of stock and habitat enhancement is to enhance *C. gigas* presence. Stock enhancement costs,

corresponding to placement using glue, are derived based on information from J. van Poppel (NIOZ, personal communication, June 10, 2020). The costs for *C. gigas* equal EUR 1 per oyster if purchased in bulk (>500 oysters). This adds up to EUR 600 in case one oyster is introduced per m^2. The costs for Bison Kit 2K Expert PolyUrethaan, the glue that can be used for the introduction of oysters, equals EUR 35-40 per 900 grams. 1-3 grams of glue is necessary per oyster. Glue costs add up to EUR 50 in case one oyster is introduced per m^2 ((37.5/(900/2))*600). Daily costs of deployment, maintenance, and monitoring activities by 4 workers equal EUR 4,000. 600 oysters can be introduced per day by these four workers. Total enhancement costs depend on the number of oysters that are needed per m^2.

$$\begin{aligned} Stock\ enhancement\ costs &= (600€ + 50€ + 4,000€) * number\ of\ oysters\ necessary\ per\ m^2 \\ &= 4,650€\ per\ 600\ oysters. \end{aligned}$$

Habitat enhancement, substrate

Costs, associated with habitat enhancement, can be incorporated in the construction costs for renovated or new-build revetments; the top layer will be made of the most suitable substrate. The exact costs depend on the most promising substrate. Habitat enhancement is not expected to increase the construction costs of a revetment substantially. Existing revetments can be improved by placing a layer of substrate on top of the revetment. These costs will equal half of the construction costs, depending on the material, since half a top layer is needed (1*d_{n50}). This makes habitat enhancement an expensive option for existing revetments, which should carefully be considered.

Habitat enhancement, shells

Clean shell material will cost around EUR 100 per m^3 (Groen, 2019). A layer of 5 cm used in previous pilot studies (Sas et al., 2018) would lead to 30 m^3 of necessary clean shell material (600 m^2 * 0.05 m). This will add up to EUR 3,000 (EUR 100 * 30 m^3). Nets that can be stretched over these oysters will cost about EUR 200. Placement can consist of one employee with machinery leading to an estimated cost of EUR 2,000. Total costs equal EUR 5,200.

Maintenance costs

Maintenance costs are difficult to preemptively quantify because they are highly variable throughout the port area. The reduction in maintenance costs depends on the maintenance demand at the location of interest. An average value would not give a good impression of the site-specific costs. Since it is not expected that the whole revetment needs maintenance, maintenance costs are expected to be a fraction of the construction costs. Oyster coverage results in the binding of stones and thus in increased stability. This increased stability will result in a revetment that can withstand a higher load before failure. This will reduce the maintenance demand for the structure. Therefore, oyster presence is expected to reduce maintenance costs.

Calculation example

Structural

To ensure that stones within stone class 5-40 kg can provide the same stability as stones within stone class 10-60 kg, their nominal diameter should effectively increase from 0.20 m to 0.24 m (Appendix G). This means that Ψ_d should be at least

$$\Psi_d = \frac{d_{n50\ new}}{d_{n50\ original}} = \frac{0.24}{0.20} = 1.2 \tag{7.7}$$

Stone class 5-40 kg reaches the same nominal stone diameter as stone class 10-60 kg for a value of the stability upgrading factor of 1.2. This value is reached for a coverage ratio of 0.23 (Figure 4.8).

Financially

For this financial calculation example, a revetment is considered where loose rock with a d_{n50} of 0.24 m is needed. This requirement can be met with stones of grading class 10-60 kg. Another option could be to use stones of grading class 5-40 kg in combination with an additional minimum oyster coverage ratio of 0.23 as calculated above. This last option is only possible if oysters are naturally present or if enhancement is expected to lead to additional oyster coverage. At the same time, this last option also requires postponing of load and makes additional monitoring necessary (Table 7.1).

Total costs will largely depend on whether and to what extent enhancement is needed. The enhancement strategy depends on locally available larvae in the water column, the quantity of necessary oysters, and available development time. Oyster presence can have a positive effect on maintenance costs. Local financial, structural, environmental, or ecological interests should indicate whether these costs are justified concerning the advantages.

Table 7.1: Life cycle costs of loose rock revetment with a length of 100 m and an effective width of 6 m. (based on R. Duvaloois and M. Minnaard, personal communication, April 16, 2020)

Variable	**No enhancement 10-60 kg**	**No enhancement 5-40 kg**	**Enhancement 5-40 kg**
Oysters present	yes	yes, $r_{CR} > 0.23$	depends, $r_{CR} < 0.23$
Construction	Loose rock 10-60 €24,000	Loose rock 5-40 €21,000	Loose rock 5-40 €21,000
Monitoring	No additional monitoring €3,380	With additional monitoring €10,220	With additional monitoring €10,220
Enhancement	No enhancement	No enhancement	Enhancement costs*
Maintenance	Lower maintenance demand	Lower maintenance demand	Lower maintenance demand

* The range in enhancement costs per 600 m^2 depends on the type of enhancement. For habitat enhancement, additional costs will range between EUR 0 - EUR 10,500 (half of the construction costs). For stock enhancement, costs will range between EUR 4,650 (1 oyster/m^2) - EUR 37,200 (8 oysters/m^2).

The total cost of a loose rock revetment with grading class 10-60 kg are equal to EUR 31,220. The total costs of a loose rock revetment with grading class 5-40 kg are equal to EUR 27,380. The increase in enhancement costs and reduction in maintenance costs, determine the optimal option.

7.3. Benefits

Ecological and environmental impacts of *C. gigas* are not included in this report in financial terms. Qualitative impacts are assigned a value of -, +, or 0 (Table 7.2). "-" represents a disadvantage, "+" represents a benefit, and "0" means there is neither a disadvantage nor benefit. The situation with oysters is compared to a scenario without oysters (score set at "0" for each variable). Table 7.2 shows the benefits of using oysters. Chapter 6 is used as a reference for table 7.2.

Clearly many variables show benefits from oyster application. Emissions during construction will diminish (subsection 6.1.2), and water quality will be increased. One disadvantage is the reduced refuge area for larger species. The extend of the positive and negative impacts of the other variables depend on the number of oysters present. Introduction depends on local financial, structural, environmental, and ecological interests. Decisions can be made using this overview and cost information.

Table 7.2: Benefits of different oyster applications on a loose rock revetment

Variable	Using oysters in the design
Development time (+=shorter)	0 or - (0 if oysters are already present, - if oysters need to be enhanced)
Emissions during construction (+=less)	+
Water filtration (+=more)	+
Biodiversity (+=more)	+
Stimulate return of native species (+=more)	+
Refuge area for large species (+=more)	-
Refuge area for small species (+= more)	+

7.4. Flowchart

All considerations are combined in a flowchart that can be used to determine the potential of structural dependence on *C. gigas* and the corresponding costs and benefits (Figure 7.2). Figure 7.1 shows the location of the discussed revetments types throughout the port area at locations that have *C. gigas* potential.

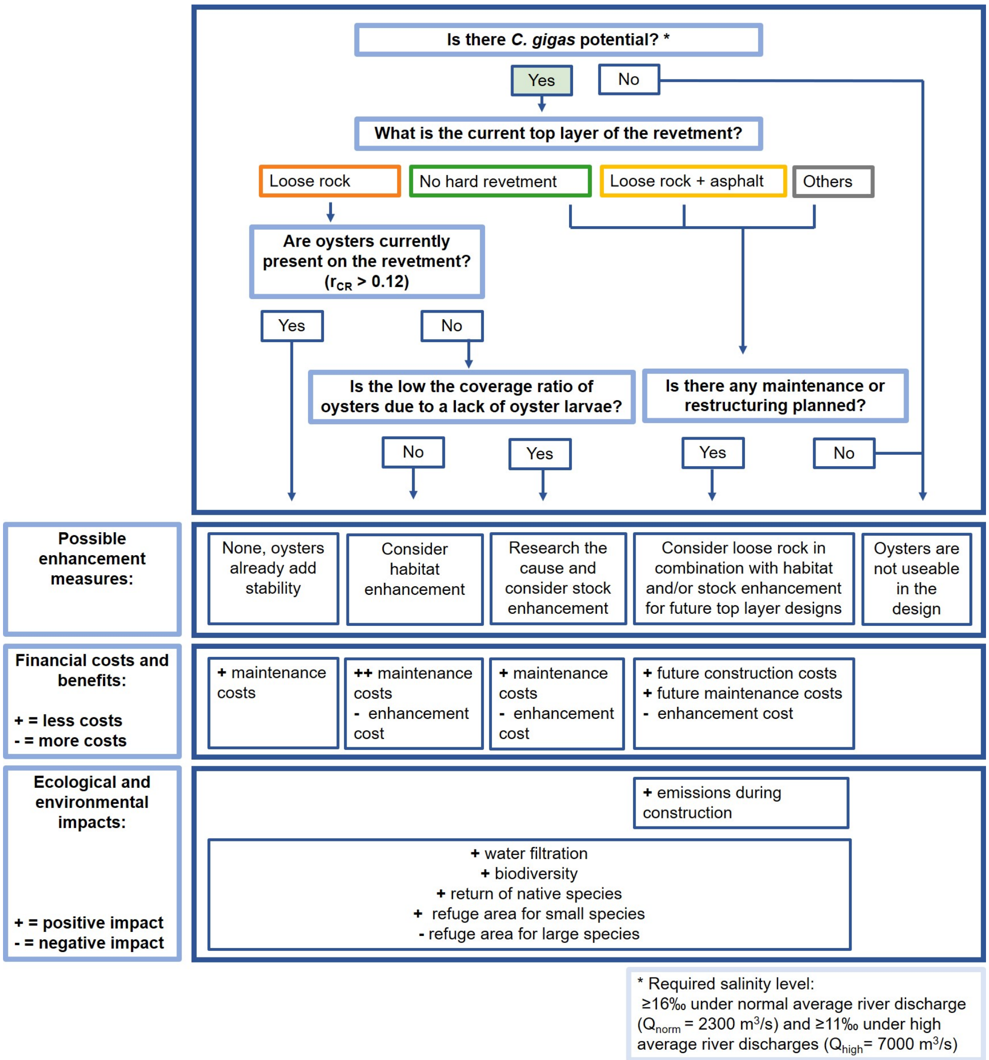

Figure 7.2: Flowchart for application of oysters in the Port of Rotterdam

7.5. Conclusions

Possibilities for applying *C. gigas* in the design are studied. The location of possible application should meet the requirements for oyster presence. The main requirement is that the salinity level should be higher than 16‰ under normal discharges. *C. gigas* application is most promising when ship wave or bow thruster impact are normative because oysters are mainly found up to NAP +0.5 m. Oysters are already present at some revetments where they add to the stability.

If oysters are not present at loose rock revetments or only in small coverage ratios, oyster enhancement may be a solution. Enhancement strategies can consist of habitat or stock enhancement and can be directly applied to loose rock revetments. If the area has already been identified as one with good conditions for oyster growth, but there are no larvae present in the water column, ecological study should be carried out to show the reason why not. Stock enhancement can augment the *C. gigas* population if there are no reasons for a location not to be suitable for oysters. This should be carefully considered; if larvae are not present in the water column there must be a reason why not. A possible proposed stock enhancement method is the gluing of mature oysters to stones in the revetment. This will lead to the natural production of more larvae and thus to an increase in the oyster population. If larvae are abundantly present, but settlement is limited, habitat enhancement can be proposed. Possible habitat enhancement methods are improvement of the substrate or introduction of empty shells. Enhancement strategies in combination with loose rock are only suitable at locations with another type of top layer if maintenance or restructuring is planned.

The effect of oysters should be better substantiated before the actual application of oysters. This can be done by conducting a pilot study in the port area in which *C. gigas* enhancement can be applied to determine how quickly specified coverage ratios can be achieved. A possible stock enhancement method is gluing oysters to stones in the revetment. Habitat enhancement can consist of substrate improvement. Enhancement strategies will lead to an increase in total costs while, as a result, maintenance costs can decrease. Costs can be balanced by additional structural, ecological en environmental benefits. Positive and negative impacts and additional costs must be carefully weighed before application.

8
Discussion

Research findings are discussed in this chapter. Limitations of the research and the outcomes are described in section 8.1. The sensitivity of the assumptions made in this report is analyzed in section 8.2.

8.1. Limitations

The limitations involved in answering the sub-questions are described in this section. Limitations are divided into measurement limitations, model limitations, and limitations associated with the application.

8.1.1. Measurements

Qualitative observations of shellfish presence

The number and quality of observations of the current presence of shellfish species in the port were limited by the inaccessibility of revetments. Many revetments in the port area were not accessible for various reasons during the qualitative observations. This resulted in a limited overview of shellfish presence in the port area. The degree of accessibility of the observed revetments differed. Having different observation distances made observation consistency complicated. The extent of mussel presence, in particular, was difficult to determine because they were the same color as the stones and because they were relatively small compared to oysters. Using the rating (+, +-, -), results could be made as objective as possible. For future observations, it is suggested to make the observation distance equal for each location to make the observations more consistent.

Measurements of the attachment strength of *C. gigas*

The attachment strength of oysters that were tightly connected to the substrate was impossible to measure. This was mainly the case for oysters connected to stones, these oysters were firmly attached to the surface so that it was impossible to put the clamp around most of the oysters. Leaving those firmly attached oysters out of the measurements may have led to a conservative strength measure. The measured attachment strength of oysters showed a large standard deviation. This shows the variability in natural elements which is a limitation for the reliability of oyster strength.

Quantitative detailed measurements of shellfish presence

Binding of stones by oysters is assumed to prevent stones from being washed out of the revetment. The shape of oysters or stones can hold stones in place as well. This could have led to an overestimation of the binding of stones by shellfish. Stones may have been unmovable although there was no cementation. Quantitative measurements of the coverage ratios and the absolute and effective number of exposed stones were only conducted at locations where oysters and mussels were present at least around MWL. Locations without shellfish were not observed in the detailed measurements although, such a location could have functioned as a control area. A control area should at least demonstrated the effect of the prevention of movement by stones themselves. A comparison of observed plots with and without shellfish showed that a lack of shellfish presence is associated with almost no binding of stones (Figure 5.7). The chance that the stability factor has been overestimated by the absence of a control area is present, but not plausible.

8.1.2. Model

One of the boundary conditions for the improved model implied that there was a possibility of stability upgrading for an initial coverage ratio. This is an overestimation since binding requires multiple oyster connections; there is no possibility of binding for initial oyster settlement. Thus this boundary condition caused an overestimation of the effective binding of stones and therefore of the stability upgrading factor associated with low coverage ratios. The model should, therefore, be used with great care for an initial coverage ratio. In this study, it is believed that stone bonding increases stability. This has not been investigated, but is logically motivated and requires further investigation.

8.1.3. Application

Exposed stones

One of the main limitations of oysters is that they only connect stones in the exposed portion of the top layer of the revetment. This means that only the exposed portion of the top layer is improved while normally the top layer has a thickness of 1.5-2.0 d_{n50}. An increased load might result in damage to this upper layer, exposing the bottom layer of the top layer. If the bottom layer of the top layer can withstand common load this should not be a problem. If the load increases again or if the load is permanently increased this might pose a threat and can result in the bottom layer being washed out and therefore the complete top layer being undermined.

Shape

The binding of stones will result in stones that are more rectangular instead of squared, this can change the stability behavior. Bending stress will impact the revetment at the underside of the layer in case of full penetration, Shellfish connect stones mainly on the exterior surface. This will cause large stress on the oysters. Stones are placed close together so initially, the stones will intercept these bending stresses. Ultimately, the increased stress can lead to the failure of oysters in the oyster coverage.

Development time

The development time that is needed for a certain oyster coverage to develop is a limitation for the application. Oysters need some time to settle and grow before they are effective in the design and before they are reproductive. After a certain period (approximate 6 months after fertilization) the first signs of oyster coverage should be found. After 3 years, oysters coverage is optimal. Asphalt, on the other hand, almost immediately provides additional strength and stability. Further studies should investigate how the development of oyster coverage can be accelerated.

8.2. Sensitivity analysis

The research results are influenced by the assumptions made. The sensitivity of these assumptions is described. Assumptions are divided into measurement assumptions, model assumptions, and assumptions associated with the application.

8.2.1. Measurements

Qualitative observations of shellfish presence

Phytoplankton is assumed to be abundantly present in the port area. As a result, food is expected not to be a limiting factor for shellfish presence in the port area. Therefore, salinity is used to predict the shellfish presence. Unexpected food limitations might lead to locations being less suitable for shellfish growth. Before enhancing oysters, it is best to make an inventory of the fauna, observed species give an estimation of the conditions at a location and will indicate whether oysters can occur at a location.

Qualitative observations from a distance were used as a first indication of the presence of shellfish in a given location. These measurements were assumed to provide a good overview of shellfish presence. This was not necessarily the case, as observation distances differed depending on the accessibility of a location. Sometimes the berm was accessible, resulting in more detailed observations compared to other locations where only the top of the revetment could be reached. This led to various degrees of accuracy and false-negative errors. It cannot be excluded that shellfish were not observed while they were present, this is especially true for mussels. Measurements results, therefore, showed a conservative level of shellfish presence.

Quantitative detailed measurements of shellfish presence
During the quantitative detailed measurements, the mobility of stones was measured by kicking and pulling the stones. These measurements show a value for the effective number of exposed stones, E. However, there may have been other reasons for the immobility of those stones. Tools needed to get those stones out were not present. Kicking and pulling were limited by the ability of the observer. This limitation could have led to an overestimation of the effective number of exposed stones, E, and thus of the stability upgrading factor, Ψ_d. An underestimation of E due to this sensitivity is not expected.

8.2.2. Model

The assumed packing density determines the stability upgrading. Dense packing leads to more opportunities for oyster connectivity and therefore a greater stability upgrading compared to loose packing. The packing density of 0.9 is probably chosen too large. The packing density has a large effect on the potential for stability upgrading. If the packing density is less dense, around 0.75, oysters only affect the stability upgrading for smaller stone gradings like 5-40 kg and 10-60 kg. For larger stone gradings, the voids are too large for any potential binding of stones. The smaller the packing density, the smaller the degree of stability upgrading (Figure 8.1).

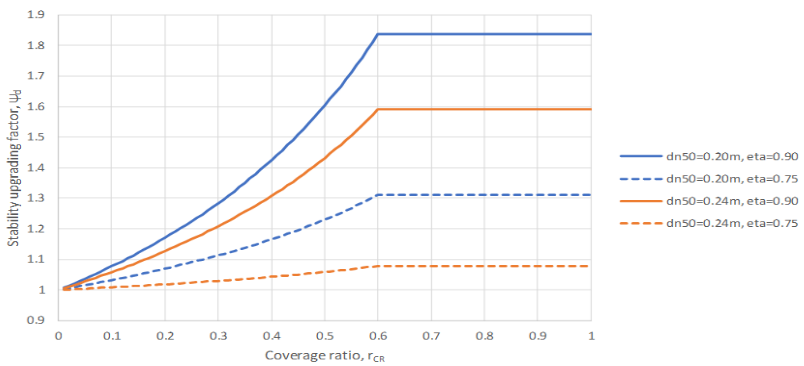

Figure 8.1: Different packing densities

For the development of the model, it was assumed that oysters connect stones if they settle close enough to the edge of stones. Based on this assumption, the fraction of oysters that will lead to binding of stones equals $1/f_{im}$ with f_{im} depending on the stone size. The fraction of $1/f_{im}$ will change if not every oyster connects stones when settling on the edge or if the edge is smaller than assumed. If only a percentage of oysters connect stones when they settle on the edge more oysters are needed for an effective binding and the stability upgrading will be lower (Figure 8.2). If the effective settling distance is smaller, meaning that oysters only bind stones if they are settled closer to the edge of stones, fewer stones are expected to be connected (Figure 8.3). The effective distance is limited by the oyster length and is therefore not expected to be greater than assumed in the model.

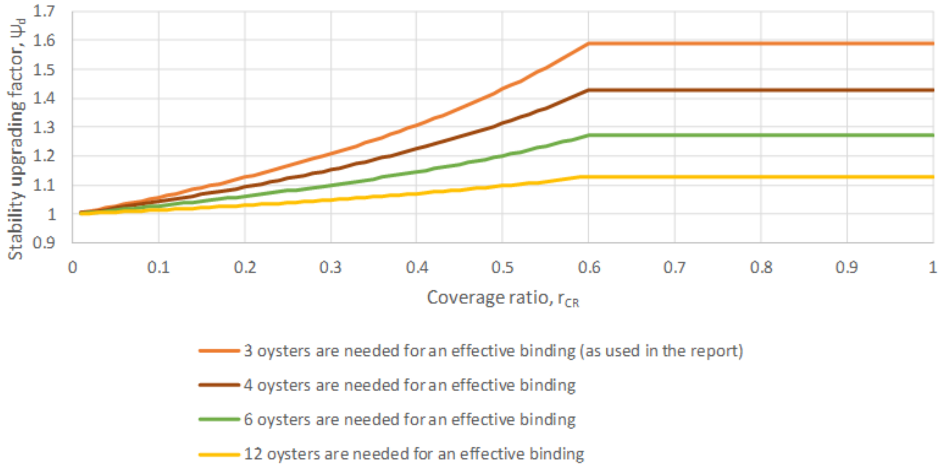

Figure 8.2: Effect of different numbers of binding oysters on the relationship between the coverage ratio and the stability upgrading factor for stone grading 10-60 kg

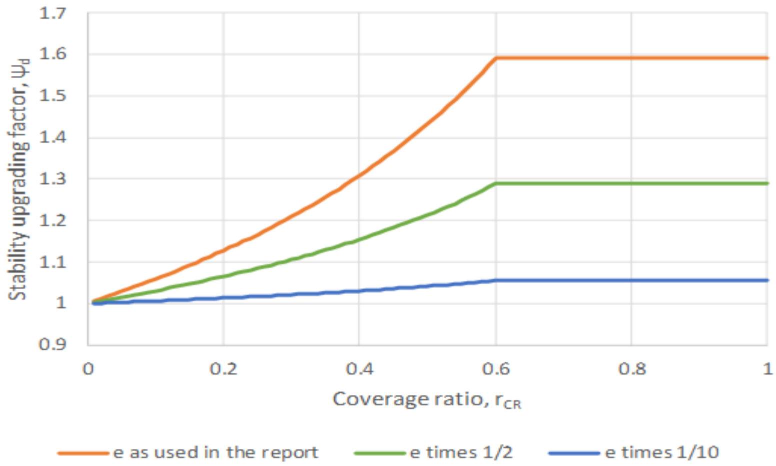

Figure 8.3: Effect of different effective settling distances of oysters on the relationship between the coverage ratio and the stability upgrading factor for stone grading 10-60 kg

The average size of an oyster, Lo, in the Eastern Scheldt is assumed to be equal to the size of an oyster in the Port of Rotterdam. This assumption has led to a value for the effective settling distance in the connectivity model because the effective settling distance is based on the oyster size. A larger oyster size will lead to a greater effective settling distance and thus to a larger fraction of oysters that will lead to the binding of stones. A smaller oyster size will lead to a smaller effective settling distance and thus to a smaller fraction of oysters that will lead to the binding of stones (Figure 8.3).

It is also assumed that the average measured strength of an oyster connection in the Eastern Scheldt is equal to the average strength of an oyster connection in the Port of Rotterdam. The number of oysters required for the binding of stones in the connectivity model is based on the measured strength of these oyster connections in the Eastern Scheldt. Greater resistive strength will result in fewer oysters needed for effective binding. A lower resistive strength will result in more oysters needed for effective binding of stones (Figure 8.2). A deviation between the two locations is not expected since the conditions in the Port of Rotterdam are comparable to the conditions in the Eastern Scheldt. This means that values used in the model for application in the Port of Rotterdam are not sensitive to these assumptions. It is assumed that the maximum force applied to the oyster connection is equal to the weight of the median nominal stone weight. If the maximum force exerted on the oyster is greater, more oysters are necessary for 1 binding. This will change the relationship between the stability upgrading factor and the coverage ratio (Figure 8.2).

8.2.3. Application

It is assumed that the stability does not increase after impermeability of the top layer is reached, which is assumed to be the case for a coverage ratio of 0.6. The stability upgrading factor corresponding to a coverage ratio of 0.6 is therefore considered as the upper limit for stability upgrading. Stability is not expected to decrease after permeability is reached, based on design criteria for asphalt. An additional failure mechanism can be hydraulic uplift. It is important to note that the effect of impermeability on stability is unknown and that stability can increase even under impermeable conditions, making stability increase more promising than described in this report. More oysters will connect the stones under impermeable conditions, resulting in increased strength. The assumption described here can, therefore, be seen as a safe indication. Additional research should indicate whether stability increases further and to what extent. If impermeability is achieved for a lower coverage ratio, the associated maximum stability upgrading factor is smaller. If impermeability is achieved for a higher coverage ratio, the corresponding maximum stability upgrading factor is larger depending on the stone grading (Figure 4.8). Smaller stone gradings are more sensitive to a change in the upper limit of the coverage ratio than larger stone grading.

Observations in a particular area are decisive for oyster occurrence over the entire stretch of that revetment (i.e oysters are assumed to be uniformly present in horizontal space). As a result, it is expected that oysters can be used as a structural addition to a stretch of the revetment once the coverage ratio exceeds 0.12 on any part of that stretch. Oysters can be more or less abundant present, making a location more suitable than expected or less suitable than expected. Not being aware of this possible change in presence can result in sudden failure of the revetment if oysters are expected, but not uniformly present.

The average measured strength of an oyster connection is assumed to be representative of the failure of the oyster connection. The number of oysters needed for the binding of stones in the connectivity model is therefore based on the measured strength of oyster connections. If another part of the oyster, (e.g. the sphincter) is prone to faster destruction, a lower strength will lead to failure. A lower resistance strength results in more oysters needed for effective binding of stones (Figure 8.2).

8.3. Conclusion

This research aims to determine the effect of shellfish presence on the stability of loose rock. Discussion points with the most relevant and significant effect on the outcome of the model and measurements are listed.

Model

This report provides a relationship between the presence of oysters and the binding of stones on one hand and a relationship between the binding of stones and stability upgrading on the other. The relationship between the binding of stones and stability upgrading is mainly based on reasoning and is not further substantiated in this report. This should be better investigated, for example using a wave flume study (chapter 10). The relationship between oyster presence and binding of stones is measured and modeled. Input parameters for the determination of the binding of stones can vary depending on local conditions and characteristics of oysters. The effect of this range on the stability upgrading factor is described (Table 8.1).

Table 8.1 clearly shows that stability upgrading factors will range depending on the chosen parameter values. Further research is necessary to narrow this range. Currently used parameter values gave results that supported measurement results best.

Table 8.1: Likely variability and effect of this variability on modeled maximum stability upgrading factor corresponding to stone class 10-60 kg

Factor	Current input	Input range	Current outcome, Ψ_d	Outcome range, Ψ_d
Packing density	0.9	0.6 - 0.9	1.59	0 - 1.59
Number of oysters necessary for effective binding	3	3 - 12	1.59	1.13 - 1.59
Effective settling distance, e	e (based on L_o)	0.1 times e - e	1.59	1.06 - 1.59

Measurements
An estimate is made whether a limitation led to an underestimation or an overestimation of a specified effect. Measurement results with the most significant overestimation and underestimation are:

- The impact of oysters on the immovability of stones, observed using quantitative detailed measurements, is probably overestimated due to a lack of control area. The effective number of stones in the exposed portion of the outer layer may have decreased not only due to oyster binding, but the decrease may also be due to other factors. This might have led to an optimistic stability upgrading factor.

- Leaving firmly attached oysters out of the measurements to the attachment strength has led to an underestimated value for the attachment strength.

9 Conclusions

The main objective of this thesis is to increase the understanding of the effect of shellfish presence on the stability of loose rock revetments and to investigate the possibilities in the design. The Port of Rotterdam is used as a research area because many hard bank protections are located throughout the port area in Rotterdam, including 202.0 kilometers of sloping bank protections. Literature, a spatial salinity model, and qualitative observations of shellfish presence were used to determine the shellfish presence at the horizontal and vertical space in the port area. A connectivity model was created to understand the effect of shellfish on the stability of loose rock. Results from the connectivity model were compared to quantitative detailed measurements of shellfish presence in the port. Based on these findings, the research questions were answered and advice was formulated for the authority of the Port of Rotterdam.

9.1. Effect and potential of shellfish in the design

Effect

C. gigas is the shellfish species with the most promising effect on the stability of loose rock within revetments. The presence of oysters leads to the binding of stones. This binding of stones increases the effective nominal stone diameter which positively effects the stability of a revetment. The extent of the binding of stones, and thus the stability upgrading, depends on the cumulative coverage ratio of oysters (i.e. summation of coverage ratio of dead *C. gigas* and living *C. gigas*) and the stone grading.

A cumulative oyster coverage of over 0.12 results in an initial stability increase of the exposed portion of the top layer of a revetment. The stability upgrading factor corresponding to a cumulative coverage ratio of 0.6 is considered to be a conservative upper limit for added stability. Smaller stone gradings will experience a greater stability increase compared to larger stone gradings under the same coverage ratios because smaller stone gradings require fewer oysters for effective binding.

Potential

Oysters can survive in locations with a minimum salinity level of 16‰ under normal discharges. Oysters are mainly found up to NAP +0.5 m which makes the resulting stability upgrading only applicable for normative ship wave or bow thruster impact. Once present, oysters add stability to the structure and will reduce the maintenance costs of the revetment.

Oysters are naturally present on most of the revetments with potential for *C. gigas* and will there add to the stability and reduce maintenance costs. If *C. gigas* is not already present on the stones in the revetment, presence can be augmented by stock and habitat enhancement. Stock enhancement can augment the *C. gigas* population if there are no reasons for a location not to be suitable for oysters. If the area has already been identified as one with good conditions for oyster growth, but there are no larvae present in the water column, ecological study should be carried out to show the reason why not. Stock enhancement should then be carefully considered; if larvae are not present in the water column there must be a reason why not. A possible proposed stock enhancement method is the gluing of mature oysters to stones in the revetment. This will lead to the natural production of more larvae and thus to an increase in the oyster population. If larvae are abundantly present, but settlement is limited, habitat enhancement can be proposed. Possible habitat enhancement methods are improvement of the substrate or introduction of empty shells. The effect of these enhancement measures should be further studied in a pilot study. The application of *C. gigas* is associated with structural, ecological, and environmental benefits. Additional enhancement costs are approximately equal to the expected reduction in maintenance costs. Exact costs and benefits depend on the application and need to be weighed. Mitigation measures will reduce the risks involved, while extensive monitoring is required to estimate the moment when mitigation is required.

9.2. Findings

9.2.1. Revetment designs and characteristics of shellfish species in the port area

The stability of typical loose rock revetments is characterized by a balance between the strength and the load. The strength is based on the density and the size of the stone, while the load comes from ship waves, wind waves, or currents. For permeable top layers on slopes, this balance between strength and load can be described by the stability number. Penetration with asphalt results in a stability increase until the top layer becomes impermeable (pore filling >0.6).

The Pacific oyster (*Crassostrea gigas*) and the blue mussel (*Mytilus edulis*) are the shellfish species commonly found living on these revetments. *C. gigas* cement their valve to the substrate which makes them not lose their connection to the surface after they die; this in contrast to *M. edulis* that are known to lose their connection to the surface. *M. edulis* can also move relatively easily and are therefore not reliable as an addition to the structure. Therefore, *C. gigas* is the shellfish species with the most promising effect on the stability of loose rock. A sufficient salinity level, water temperature, phytoplankton ratio, and submersion time for daily feeding and respiration are important for *C. gigas* survival.

9.2.2. Current presence of shellfish and prediction

Salinity is used as the most important factor for the prediction of shellfish presence in horizontal space. The ratio of phytoplankton to suspended material and the water temperature in the Port of Rotterdam are expected to be suitable for shellfish growth throughout the port area. Salinity is commonly measured and many ports including the port of Rotterdam have a spatial salinity model. A spatial salinity model acts as an estimated guess for shellfish presence.

In this study, oyster presence was investigated at 20 locations. Oyster presence was correctly predicted at 19 out of 20 locations according to a comparison of expectations regarding the spatial salinity model and measurements of oyster presence. They were found in large quantities in Maasvlakte 2, Beerkanaal, and the Calandkanaal. They require hard substrate for settlement and are not present on sandy revetments. *C. gigas* is uniformly present over an area.

In vertical space, requirements regarding submersion time are considered. *C. gigas* require water flow for daily feeding and respiration. They should be submerged at least 40% of the time based on literature findings. The line until which shellfish presence is expected is called the 60%-line in this report. Quantitative measurements that were conducted in the port area showed that shellfish were also present in small numbers until 0.5 m above the 60%-line. The 60%-line will nevertheless serve as a conservative upper limit of occurrence.

Required conditions for oyster presence:

- In horizontal space: the salinity level should be larger than 16‰ under normal average discharges and larger than 11‰ under high average discharges;
- In vertical space: location should be inundated for 60% of the time. For the Port of Rotterdam, this means that oysters are only present below NAP +0.5 m. Oyster presence is studied until NAP -0.5 m. Oysters presence below NAP -0.5 m is expected, but not studied in this report;
- Hard substrate.

9.2.3. Effect of shellfish on the stability of loose rock

Oysters create a cement layer between their valve and the surface. This results in the binding of stones when oysters settle close enough to the edge of a stone. Coverage of stones by oysters leads, therefore, to an increase in the nominal stone diameter. The binding process and increase in nominal stone diameter result in a stability upgrading. A stability upgrading factor, Ψ_d, is introduced to describe this increase in nominal stone diameter. Binding of stones by *C. gigas* increases the nominal stone diameter, d_{n50}. The stability upgrading factor represents the relative change in d_{n50} related to the number of stones bound by oysters.

$$\Psi_d = \frac{d_{n50,\ oysters}}{d_{n50,\ original}} = \frac{H_{D,\ oysters}}{H_{D,\ original}} = \sqrt[3]{\frac{S}{E}}. \tag{9.1}$$

The strength of an oyster connection is measured in a small preliminary study. Measurements showed that *C. gigas* attachment can withstand an average force of 16.5 kg with a standard deviation of 9.1 kg. The oysters observed had an average length of 8.0 cm and an average width of 5.0 cm. The maximum force exerted on an oyster connection is expected to be equal to the weight of the stones to which they are attached. The number of oysters required for one binding is calculated for various stone classes based on the strength of the oyster connection and the median nominal stone weight.

The relationship between the stability upgrading factor, Ψ_d, and the coverage ratio, r_{CR} was predicted using a connectivity model. This model describes the stability upgrading factor as a function of the coverage ratio. An upper boundary for the stability upgrading factor is set at a coverage ratio of 0.6. A coverage ratio of over 0.6 is assumed to result in an impermeable exposed portion of the top layer. The revetment is supposed to behave differently regarding stability for such an impermeable exposed portion of the top layer. The stability increase under a larger coverage ratio is supposed to stay at least equal to the stability increase corresponding to a coverage ratio of 0.6.

$$\Psi_{d,\ model} = \sqrt[3]{\frac{S}{1+(S-1)*(1-r_{CR})^{\frac{A_{tot}*f_{im}}{(S-1)*A_O}}}}. \tag{9.2}$$

for $0 \le r_{CR} \le 0.6$.

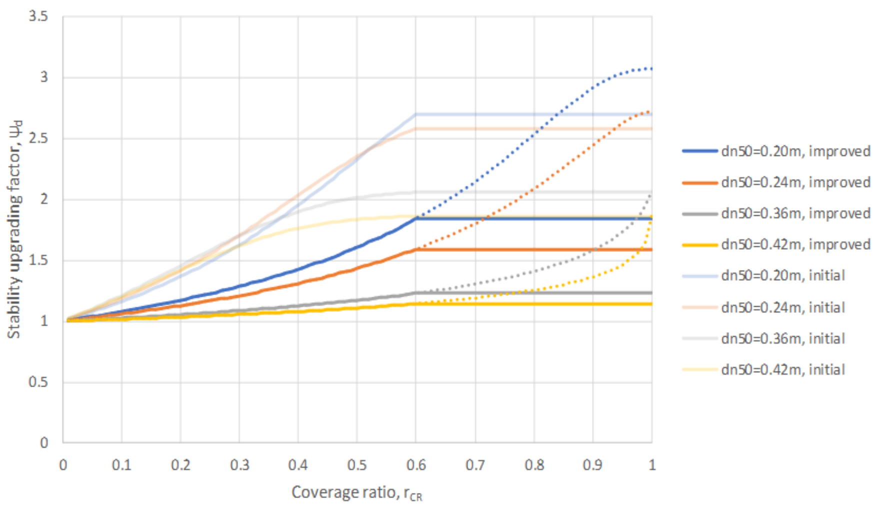

Figure 9.1: Improved relationship between the coverage ratio and the stability upgrading factor for different nominal stone diameters. With dashed lines showing the model without upper limit

Quantitative measurements are conducted in the port area to validate the model. These measurements showed that the presence of oysters does affect the effective number of exposed stones in the top layer of the revetment. Measurements showed a relationship between the cumulative oyster presence (i.e. summation of coverage ratio of dead *C. gigas* and living *C. gigas*) and the effective number of exposed stones in the top layer of the revetment. Measurement outcomes were implemented in Equation 9.1, leading to corresponding stability upgrading factors. These values showed that oyster presence affects the stability of loose rock revetments in the port area, given the relationship between stability upgrading and stone diameter.

The connectivity model is validated for measurement results. The extent of the effect of oyster presence on the effective number of exposed stones in the top layer of the revetment depends on the coverage ratio of oysters and the stone size. Smaller stone gradings will experience a greater stability increase compared to larger stone gradings under the same coverage ratios because smaller stone gradings require fewer oysters for effective binding. The connectivity model overestimated the effect of oysters until a coverage ratio of 0.12. Measured coverage ratios ranging from 0.12 to 0.6 were accompanied by deviating stability upgrading factors in the range from 1.0-1.5 (Figure 9.2). More research is needed to improve and understand the relationship between oyster coverage and binding of stones and between the binding of stones and stability increase. This will help to understand the causes of the deviation in the results.

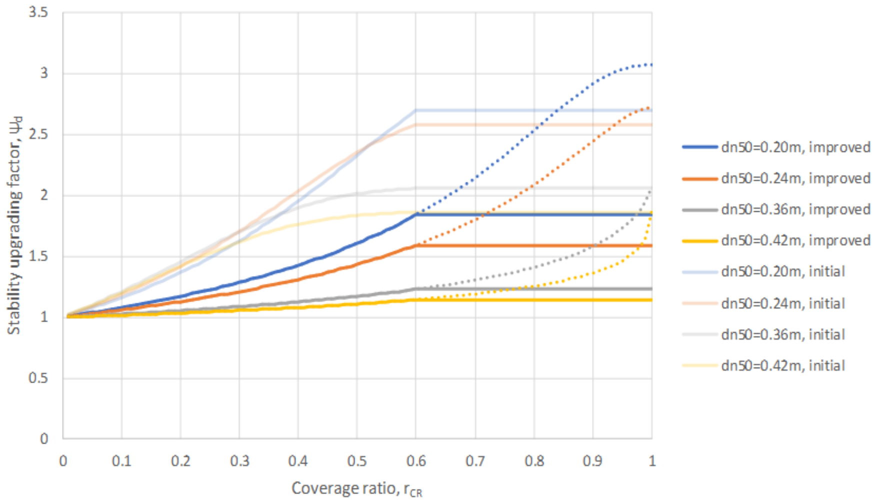

Figure 9.2: Validation of the connectivity model with measurement outcomes for different coverage ratios and a nominal stone diameter of 0.20 m and 0.30 m

Effect of oyster coverage on stability increase:
- Cumulative oyster coverage of over 0.12 results in initial stability increase of the exposed portion of the top layer of a revetment (Figure 9.2);
- Stability increase deviates for coverage ratios between 0.12 - 0.6 (Figure 9.2). Values depend on the stone grading, Ψ_d ranges from 1.0-1.6 for stone grading 10 - 60 kg (Figure 9.1);
- Stability increase corresponding to a coverage ratio of 0.6 is considered as an upper limit. Values depend on the stone grading, $\Psi_{d,\,max}$ = 1.6 for stone grading 10-60 kg (Figure 9.1);
- For smaller stone classes the stability increase is more significant than for larger stone classes (Figure 9.1).

9.2.4. Application of shellfish in revetment designs

Stability upgrading, resulting from the binding of stones by oysters can be used in the design practice. For this to be possible, it is important to understand the strengths and limitations of oysters and the opportunities and threats of the system. Strengths and limitations of oysters are structural, environmental, and ecological in nature. Opportunities and threats of the system should be considered at the same time, such as global warming, pollution, and future port plans.

C. gigas application is most promising when normative bow thruster or ship wave impact are normative because oysters are mainly found up to NAP +0.5 m. The location of application should meet the requirements for shellfish presence including a salinity level larger than 16‰. Freshwater outlets should be investigated before the application of oysters, to determine if the required salinity levels are met. Locations in the port area with oyster potential are visualized in Figure 9.4.

The effect of oysters should be better substantiated before the actual application of oysters. This can be done by conducting a pilot study in the port area. Stock and habitat enhancement can be applied to enhance oyster presence as quickly as possible after the start of the pilot study. Enhancement strategies can consist of habitat or stock enhancement and can be directly applied to loose rock revetments (Figure 9.3). If the reason for a low coverage ratio is a lack of oyster larvae the cause of this lack of larvae should be studied and depending on the outcome, stock enhancement may be an option. A possible stock enhancement method is gluing oysters to stones in the revetment. Habitat enhancement is particularly effective if larvae are present in the water column, but there is a lack of optimal places for them to settle. This type of enhancement can consist of substrate improvement or the introduction of empty shells. Enhancement costs are approximately equal to the gains as a result of a reduction in maintenance costs. Impacts and costs must be carefully weighed before application. Weaknesses and threats should be mitigated by the placement of stones on a revetment if monitoring shows that the applications do not work out as expected.

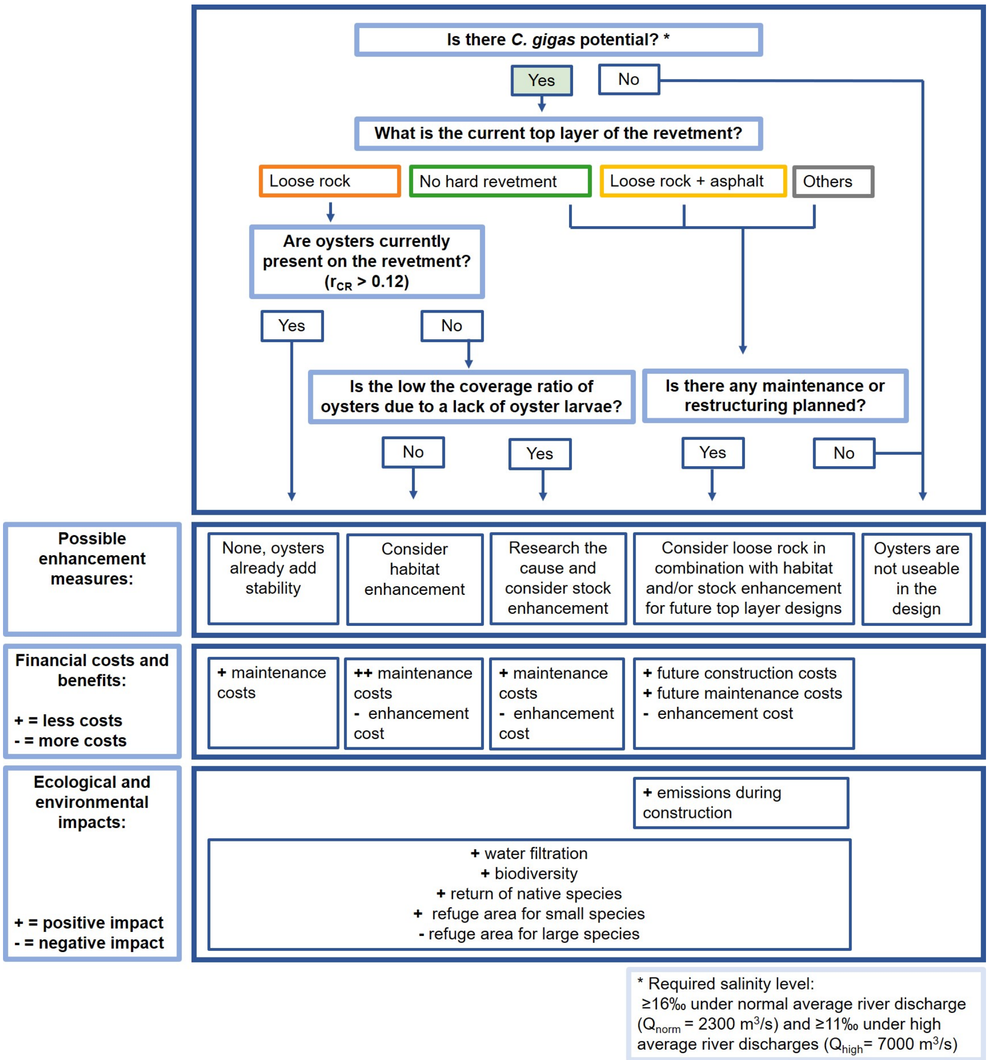

Figure 9.3: Flowchart for application of oysters in the Port of Rotterdam

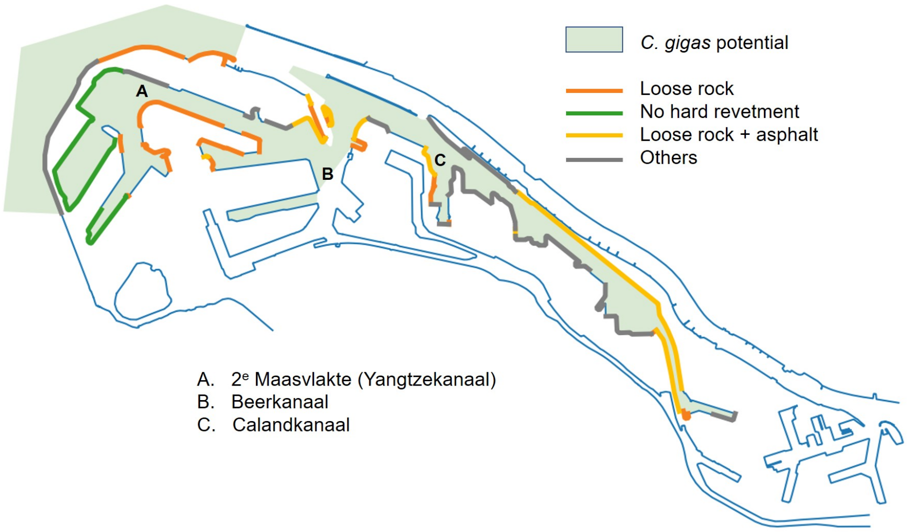

Figure 9.4: Potentially suitable locations for application of oysters in the Port of Rotterdam

9.3. Relevance

The findings presented in this report are relevant to the hydraulic engineering field; the interaction between oysters and hard substrate had not been studied before from a civil engineering point of view. This report can be used as a guideline on the design with natural elements. Building with Nature asks for another approach than conventional designs. Nature requires patience and is difficult to steer. The benefits and limitations of designing with shellfish are presented in this report. This will contribute to a substantiated decision whether or not to design using oysters. The presented flowchart offers possibilities for further research in the Port of Rotterdam (Figure 9.3). Insights obtained in this report can also lead to better collaboration between ecologists and engineers.

10 Recommendations

10.1. Further research

Through observations and modeling, a substantial amount of relevant information was obtained. Certainly, a complete evaluation of the biotechnical aspects of the effect of oysters on hard substrate needs further study to progress knowledge. Further research regarding the following aspects, in particular, is recommended:

Necessary study before the implementation of oysters:

- Gather more data of the
  - relationship between oyster presence and binding of stones
  - relationship between binding of stones and stability upgrading
- Research the uniformity of oyster presence on a revetment.

Additional study to improve knowledge about the interaction between oysters and hard substrate:

- Research the cementation process of oysters to hard substrate and determine how the binding of stones works.
- Study the effect of large coverage ratios on the stability of stones.
- Research the strength and behavior of different parts of the oyster.
- Research how long it takes for the oyster cementation to break down after mortality of the oyster.

The recommended studies can be performed in several ways. Depending on the objective, further study can be through a pilot study, a laboratory study, or a numerical study. The pilot study is the most useful study to substantiate application and can consist of different enhancement strategies (Appendix I). A laboratory or numerical study can be useful to improve knowledge.

Pilot study
A pilot study can be used to gather additional data that can help to improve and substantiate the model and to give additional insight into the relationship between oyster coverage and the stability of stones. An initial pilot study design is given in Appendix I. Data obtained through this pilot study will help to set clear requirements for oyster presence. Attention should be paid to the effect of oyster attachment under high loading. High loading can be obtained by sailing close to the revetment at high speed.

Laboratory study
Laboratory research can be used to study the effect of the binding of stones in the exposed portion of the top layer on the stability of the stones. This can be studied using a wave flume study. A restriction for laboratory research can be the necessary saline environment that could damage the devices. Pilot studies and laboratory research require significant financing. Costs for laboratory research depend on the objective and time frame of the research.

Laboratory research, can on the other hand, be used to study the effect of oyster coverage on the increase in nominal stone diameter. Laboratory research can give a thorough understanding of the detailed characteristics of oysters and can be used to study the attachment of oysters to hard substrate. This research can look to what extent shellfish connect stones with their cement-layer and to what extent they merely protect stones from moving due to their shape. It is unknown which part of the oyster is crucial for the attachment besides the cementation layer. Therefore, laboratory research can be used to indicate which part of the oyster is the weakest regarding the connection of stones. At the same time, the maximum force that can be applied to this part of the oyster should be studied to determine its limitations. Further research must reveal the reason for the large standard deviation in oyster attachment strength. The variation in attachment strength between living and dead oysters should be tested as well.

Numerical study
Large coverage ratios of oysters or reefs (>0.6) are not that common and the creation of reefs requires time. A numerical study is an alternative to study these oyster reefs and their effect on the stability of stones. Oysters create a layer of oyster over the stones which will probably alter the stability of the stones in a different way than studied in this report. Knowledge about attachment can enable the preparation of a numerical study. This type of study can also be used to research the effect of the roughness of oysters on the turbulence around the stones and therefore on the stability of stones. Other potential benefits of oyster application such as the associated decrease in wave impact are also interesting topics to study further.

10.2. Application

Application within the area of the Port of Rotterdam is discussed in chapter 7. Application requires a pilot study, a pilot study will result in better substantiation for the application of oysters. A potential pilot study design can consist of different enhancement strategies (Appendix I). Application at other ports or other locations where shellfish and stones interact is possible. The same preconditions remain for shellfish occurrence. A location must be saline enough. Since inland waterways are too fresh, this application better suits ports close to the sea or other locations with saltwater conditions. In addition to the recommendations given in chapter 7, the following points must be taken into account.

Beerkanaal
Application in the Beerkanaal requires further research compared to the more saline Maasvlakte 2 and Calandkanaal. It is seen that the Beerkanaal receives a larger freshwater outflow. The extent of this freshwater outflow should be predicted for various discharge scenarios. Water temperature increase and the effect of this increase on summer mortality of oysters should be further investigated if oysters application is required for a period longer than 10 years.

Bed protections
One of the other locations inside the port where stones and shellfish interact is the underwater toe protection at quay walls. Research on the effect of shellfish underwater was accompanied by practical limitations and is, therefore, not studied herein. Applications underwater may be even more promising than around MWL. Since saline water is heavier than fresh water, saline water will flow beneath the fresh water, resulting in higher salinity parameters at the bottom of the water column. Model outcomes did confirm this assumption. Underwater monitoring is difficult and therefore a pilot study to this application will become expensive. Consideration will have to be made between benefits and costs.

Monitoring
Future application of oysters requires regular monitoring of the oyster coverage. Individuals will certainly give various values regarding the coverage ratio. Monitoring should, therefore, be conducted according to a protocol. The spread in observed coverage ratio can be calculated by listing the obtained coverage ratios for a specified plot observed by different ecologists. The average degree of variation in observed coverage ratio should be taken into account in the design.

10.3. Interdisciplinary approach

This study was conducted in different disciplines. Designing with shellfish is a civil engineering issue on the one hand and an ecological one on the other. This requires good cooperation between the different fields. The civil engineer needs to understand the limitations of nature and the ecologist needs to understand the requirements of the structure. It is important to constantly discuss the intention of the research interdisciplinary and to describe the ways to get there and the limitations involved in both fields. Often the objective is clear for both parties, but the way of thinking is different. This can be used as an opportunity since combining both ways of thinking can result in surprising solutions. One aspect encountered in this study was the reluctance of the ecologists regarding Building with Nature. They did not understand that a load can be diminished by for example using a smaller initial lifetime of a structure as described in this report. On the other hand, the author of this report did not understand the limitations and unpredictability of nature. This shows the importance of describing thoughts and discussing options.

References

Alferink, N. (2016). *Modeling the influence of mussels and oysters on hydrodynamics and sediment transport (PhD thesis)*. University of Twente, Enschede. Retrieved from `https://essay.utwente.nl/69491/`

Almada-Villela, P. C., Davenport, J., & Gruffydd, L. D. (1982). The effects of temperature on the shell growth of young Mytilus edulis L. *Journal of Experimental Marine Biology and Ecology*, *59*(2-3), 275–288. http://doi.org/10.1016/0022-0981(82)90121-6

Bayne, B. L. (1964). Primary and Secondary Settlement in Mytilus edulis L. (Mollusca). *Journal of Animal Ecology*, *33*(3), 513–523. Retrieved from `https://www-jstor-org.tudelft.idm.oclc.org/stable/pdf/2569.pdf`

Bayne, B. L. (1965). Growth and the delay of metamorphosis of the larvae of Mytilus edulis (L.). *Ophelia*, *2*(1), 1–47. http://doi.org/10.1080/00785326.1965.10409596

Beck, M. W., Brumbaugh, R. D., Airoldi, L., Carranza, A., Coen, L. D., Crawford, C., … Guo, X. (2011). Oyster reefs at risk and recommendations for conservation, restoration, and management. *BioScience*, *61*(2), 107–116. http://doi.org/10.1525/bio.2011.61.2.5

Borsje, B. W., van Wesenbeeck, B. K., Dekker, F., Paalvast, P., Bouma, T. J., van Katwijk, M. M., & de Vries, M. B. (2011). How ecological engineering can serve in coastal protection. *Ecological Engineering*, *37*(2), 113–122. http://doi.org/10.1016/j.ecoleng.2010.11.027

Bouwend Nederland, & NEPROM. (2006). *Gedragscode flora- en faunawet voor de bouw- en ontwikkelsector*.

Bower, S. M., & Figueras, A. J. (1989). Infectious diseases of mussels, especially pertaining to mussel transplantation. *World Aquaculture*, *20*(4), 89–93.

Bower, S. M., McCladdery, S. E., & Price, I. O. (1994). Synopsis of infectious diseases and parasites of commercially exploited shellfish. *Annual Review of Fish Diseases*, *4*, 1–199. http://doi.org/10.1016/0959-8030(94)90028-0

Brinkman, A. G. (2013). *Modelling the effects of seed mussel collectors on the western Dutch Wadden Sea ecosystem*. (No. C061/13). Wageningen: IMARES. Retrieved from `https://library.wur.nl/WebQuery/wurpubs/450852`

Child, A. R., & Laing, I. (2008). Comparative low temperature tolerance of small juvenile European, Ostrea edulis L., and Pacific oysters, Crassostrea gigas Thunberg. *Aquaculture Research*, *29*(2), 103–113. http://doi.org/10.1046/j.1365-2109.1998.00934.x

Christianen, M., Lengkeek, W., Bergsma, J., Coolen, J., Didderen, K., Dorenbosch, M., … van der Have, T. M. (2018). Return of the native facilitated by the invasive? Population composition, substrate preferences and epibenthic species richness of a recently discovered shellfish reef with native European flat oysters (Ostrea edulis) in the North Sea. *Marine Biology Research*, *14*(6), 590–597. http://doi.org/10.1080/17451000.2018.1498520

CIRIA, CUR, & CETMEF. (2007). *The Rock Manual. The use of rock in hydraulic engineering (2nd edition)*. London: C683, CIRIA.

Cirkel, J., van Dam, C., van den Akker, E., & Nell, J. W. (2015). *Handreiking Dijkbekledingen: Asfaltbekledingen*. Deltares. Retrieved from `http://publications.deltares.nl/Deltares125.pdf`

Climate-data.org. (2020). *Water temperatuur Hoek van Holland (Noordzee).* Retrieved 2020-01-25, from `https://nl.climate-data.org`

D'Angremond, K., Span, H. J. T., van der Weide, J., & Woestenenk, A. J. (1970). Use of Asphalt in Breakwater Construction. *12th International Conference on Coastal Engineering*, 1601–1627.

Dankers, N., & Fey-Hofstede, F. E. (2015). *Een zee van Mosselen. Handboek ecologie, bescherming, beleid en beheer van mosselbanken in de Waddenzee*. Stichting ANEMOON.

Dare, P. J., Davies, G., & Edwards, D. B. (1983). *Predation on juvenile Pacific oysters (Crassostrea gigas Thunberg) and mussels (Mytilus edulis L.) by shore crabs (Carcinus maenas L): Fisheries research technical report*. (No. 73) Lowestoft, UK: Ministry of Agriculture, Food, and Fisheries. Retrieved from `http://ci.nii.ac.jp/naid/10012363630/en/`

De Looff, A. K., Hart, R. T., Montauban, C. C., & Van De Ven, M. F. (2006). Golfklap a model to determine the impact of waves on dike structures with an asphaltic concrete layer. In *Coastal engineering* (pp. 5106–5115). http://doi.org/10.1142/9789812709554$_0$427

De Looff, A. K., Versluis, A., & Montauban, C. C. (2002). *Technisch rapport asfalt voor waterkeren*. Den Haag: DWW, Rijkswaterstaat. Retrieved from `http://publicaties.minienm.nl/documenten/technisch-rapport-asfalt-voor-waterkeren`

Demers, A., & Guderley, H. (1993). Acclimatization to intertidal conditions modifies the physiological response to prolonged air exposure in Mytilus edulis. *Marine Biology*, *118*, 115–122. http://doi.org/10.1007/BF00699225

Department of Ecology State of Washington. (2019). *Focus on: environmental harm from oil spills* (No. September). Washington. Retrieved from `www.ecy.wa.gov/programs/spills`

de Vriend, H., & van Koningsveld, M. (2012). *Building with nature: Thinking, acting and interacting differently* (No. 1). Dordrecht: EcoShape. Retrieved from `https://www.ecoshape.org/uploads/sites/3/2016/06/ECOSHAPE_BwN_WEB.pdf`

Didderen, K., Lengkeek, W., Bergsma, J. H., Van Dongen, U., Driessen, F. M. F., & Kamermans, P. (2019). *WWF & ARK Borkum Reef Ground oyster pilot. Active restoration of native oysters in the North Sea*. (No. 19-227). Culemborg: Bureau Waardenburg. Retrieved from `https://www.wwf.nl/globalassets/pdf/wwf-and-ark-borkum-reef-ground-oyster-pilot.pdf`

Didderen, K., Lengkeek, W., Kamermans, P., Deden, B., & Reuchlin-Hugenholtz, E. (2018). *Pilot to actively restore native oyster reefs in the North Sea*. (No. 19-013). Culemborg: Bureau Waardenburg, Zeist: WWF. Retrieved from `https://www.ark.eu/sites/default/files/media/Schelpdierbanken/Report_Borkumse_Stenen.pdf`

Diederich, S. (2005). Differential recruitment of introduced Pacific oysters and native mussels at the North Sea coast: Coexistence possible? *Journal of Sea Research*, *53*(4), 269–281. http://doi.org/10.1016/j.seares.2005.01.002

Diederich, S. (2006). High survival and growth rates of introduced Pacific oysters may cause restrictions on habitat use by native mussels in the Wadden Sea. *Journal of Experimental Marine Biology and Ecology*, *328*(2), 211–227. http://doi.org/10.1016/j.jembe.2005.07.012

Dijkstra, S. (2013). Bekendmaking lijsten beschermde inheemse diersoorten. *Staatscourant*(8498), 1–21. Retrieved from `https://zoek.officielebekendmakingen.nl/stcrt-2013-8498.html`

Elston, R. A. (1993). Infectious diseases of the Pacific oyster, Crassostrea gigas. *Annual Review of Fish Diseases*, *3*, 259–276. http://doi.org/10.1016/0959-8030(93)90038-D

Fey-Hofstede, F. E., Rippen, A. D., Dankers, N., & Smit, C. (2012). Growing with sea level rise - Deltaprogram Wadden progress Report inventory mussel beds 2011: cluster 3 Sediment. Retrieved from `https://library.wur.nl/WebQuery/titel/1985171`

Frölke, G. (2018). *Nature enhancing opportunities for an artificial North Sea island (MSc thesis)*. Delft University of Technology, Delft. Retrieved from `http://resolver.tudelft.nl/uuid:47c4598f-0100-4eb4-97a3-75266b0162bd`

Gercken, J., & Schmidt, A. (2014). *Current Status of the European Oyster (Ostrea edulis) and Possibilities for Restoration in the German North Sea*. Federal Agency for Nature Conservation. Retrieved from https://www.bfn.de/fileadmin/BfN/meeresundkuestenschutz/Dokumente/2015-06-02_Auster_Machbarkeitsstudie-barrierefrei-english.pdf

Gosling, E. (2004). *Bivalve Molluscs. Biology, Ecology and Culture*. Fishing News Books Ltd.

Groen, O. D. (2019). *Nature-enhancing design of scour protection for monopiles in the North Sea (MSc thesis)*. Delft University of Technology, Delft. Retrieved from http://resolver.tudelft.nl/uuid:f612bc90-785c-4706-90e6-b7116f4b8077

Grüne, J. (1988). Wave-induced shock pressures under real sea state conditions. *Proceedings 21st International Conference on Coastal Engineering*, 2340–2354. http://doi.org/10.1061/9780872626874.174

Guo, X., Hedgecock, D., Hershberger, W. K., Cooper, K., & Allen, S. K. (1998). Genetic determinants of protandric sex in the Pacific oyster, Crassostrea gigas Thunberg. *Evolution*, *52*(2), 394. http://doi.org/10.2307/2411076

Harper, E. M. (1992). Post-larval cementation in the ostreidae and its implications for other cementing bivalvia. *Journal of Molluscan Studies*, *58*(1), 37–47. http://doi.org/10.1093/mollus/58.1.37

IPCC. (2019). *Special report on the Ocean and Cryoshphere in a Changing Climate* (H. O. Portner et al., Eds.). In press.

Jamieson, G. S., Neish, I. C., & Clarke, C. S. L. (1975). *Perspectives and development prospects of mussel cultivation in Maritime Provinces of Canada*. Nova Scotia: Mar. Ecol. Lab.

Kang, D. H., Kim, S. J., & Choi, K. S. (2004). Microscopic observations of larval Ostrea Circumpicta (Bivalve: Ostreidae) in brood chambers. *Journal of Shellfish Research*, *23*.

Koehn, R. K., Milkman, R., & Mitton, J. B. (1976). Population genetics of marine pelecypods. IV. Selection, migration and genetic differentiation in the blue mussel Mytilus edulis. *Evolution*, *30*, 2–32. http://doi.org/10.2307/2407669

KRW. (2019). *Waterlichaam: Nieuwe Waterweg*. Factsheet behorende bij Stroomgebiedbeheerplan SGBP2 2015-2021.

Letendre, J., Chouquet, B., Manduzio, H., Marin, M., Bultelle, F., Leboulenger, F., & Durand, F. (2008). Tidal height influences the levels of enzymatic antioxidant defences in Mytilus edulis. *Marine Environmental Research*, *67*(2), 69–74. http://doi.org/10.1016/j.marenvres.2008.11.003

Luna-Acosta, A., Kanan, R., Le Floch, S., Huet, V., Pineau, P., Bustamante, P., & Thomas-Guyon, H. (2011). Enhanced immunological and detoxification responses in Pacific oysters, Crassostrea gigas, exposed to chemically dispersed oil. *Water Research*, *45*(14), 4103–4118. http://doi.org/10.1016/j.watres.2011.05.011

Lützen, J., Faasse, M., Gittenberger, A., Glenner, H., & Hoffmann, E. (2012). The Japanese oyster drill Ocinebrellus inornatus (Récluz, 1851) (Mollusca, Gastropoda, Muricidae), introduced to the Limfjord, Denmark. *Aquatic Invasions*, *7*(2), 181–191. http://doi.org/10.3391/ai.2012.7.2.004

MacDonald, J., Freer, A., & Cusack, M. (2010). Attachment of oysters to natural substrata by biologically induced marine carbonate cement. *Marine Biology*, *157*(9), 2087–2095. http://doi.org/10.1007/s00227-010-1476-7

Mathis, M., & Pohlmann, T. (2014). Projection of physical conditions in the North Sea for the 21st century. *Climate Research*, *61*, 1–17. http://doi.org/10.3354/cr01232

Menzel, W. (2017). *Estuarine and Marine Bivalve Mollusk Culture*. CRC Press.

Nehls, G., & Thiel, M. (1993). Large-scale distribution patterns of the mussel Mytilus edulis in the Wadden Sea of Schleswig-Holstein: Do storms structure the ecosystems? *Journal of Sea Research*, *31*(2), 181–187. http://doi.org/10.1016/0077-7579(93)90008-G

Nehring, S. (2011). *NOBANIS–Invasive Alien Species Fact Sheet–Crassostrea gigas.* Retrieved 2019-11-28, from `www.nobanis.org`

Nunuk, D. (2013). *Pacific Oysters.* Retrieved from `https://fineartamerica.com/featured/pacific-oysters-david-nunuk.html`

Ó Foighil, D., & Taylor, D. J. (2000). Evolution of parental care and ovulation behavior in oysters. *Molecular Phylogenetics and Evolution*, *15*(2), 301–313. http://doi.org/10.1006/mpev.1999.0755

OSPAR Commission. (2008). *OSPAR List of Threatened and/or Declining Species and Habitats*. (No. 2008-6).

Paalvast, P. (1998). *Ecologische waardering van de oevers in het Rotterdamse Havengebied*. Vlaardingen: Ecoconsult. http://doi.org/10.13140/RG.2.1.3456.6003

Paalvast, P. (2017). *Ecologische beoordeling van de oevers in het Rotterdamse havengebied een eerste aanzet*. (No. 201704). Vlaardingen: Ecoconsult.

Pauley, G. B., van der Raay, B. M., & Troutt, D. (1988). Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (Pacific Northwest): Pacific oyster. *U.S. Fish Wildl. Serv. Biol. Rep.*, *82*(11.85).

Port of Rotterdam. (2019). *All about our themes.* Retrieved from `https://www.portofrotterdam.com/en/our-port/all-about-our-themes`

Quayle, D. B. (1969). *Pacific oyster culture in British Columbia*. Fisheries Research Board of Canada.

Rajagopal, S., van der Velde, G., Jansen, J., van der Gaag, M., Atsma, G., Janssen-Mommen, J. P., … Jenner, H. A. (2005). Thermal tolerance of the invasive oyster Crassostrea gigas: Feasibility of heat treatment as an antifouling option. *Water Research*, *39*(18), 4335–4342. http://doi.org/10.1016/j.watres.2005.08.021

Reise, K. (1998). Pacific oysters invade mussel beds in the European Wadden Sea. *Senckenbergiana Maritima*, *28*(4-6), 167–175. http://doi.org/10.1007/BF03043147

Remane, A., & Schlieper, C. (1971). *Biology of Brackish Water*. New York: Wiley-Interscience.

Renault, T., Bouquet, A. L., Maurice, J. T., Lupo, C., & Blachier, P. (2014). Ostreid herpesvirus 1 infection among Pacific oyster (Crassostrea gigas) spat: Relevance of water temperature to virus replication and circulation prior to the onset of mortality. *Applied and Environmental Microbiology*, *80*(17), 5419–5426. http://doi.org/10.1128/AEM.00484-14

Renault, T., Le Deuff, R., Cochennec, N., Chollet, B., & Maffart, P. (1995). Herpes-like viruses associated with high mortality levels in larvae and spat of Pacific oysters, Crassostrea gigas: a comparative study, the thermal effects on virus detection in hatchery-reared larvae, reproduction of the disease in axenic larvae. *Veterinary Research*, *26*(5-6), 539–543.

Rijkswaterstaat. (2020). *Waterhoogte astronomisch Tennesseehaven.* Retrieved from `https://waterinfo.rws.nl`

Rodriguez, A. B., Fodrie, F. J., Ridge, J. T., Lindquist, N. L., Theuerkauf, E. J., Coleman, S. E., … Kenworthy, M. D. (2014). Oyster reefs can outpace sea-level rise. *Nature Climate Change*, *4*(6), 493–497. http://doi.org/10.1038/nclimate2216

Rodriguez-Perez, A., James, M., Donnan, D. W., Henry, T. B., Møller, L. F., & Sanderson, W. G. (2019). Conservation and restoration of a keystone species: Understanding the settlement preferences of the European oyster (Ostrea edulis). *Marine Pollution Bulletin*, *138*, 312–321. http://doi.org/10.1016/j.marpolbul.2018.11.032

Samain, J., & McCombie, H. (2008). *Summer mortality of Pacific oyster Crassostrea gigas: the Morest Project* (Ifremer, Ed.). Versailles.

Sas, H., Didderen, K., van der Have, T. M., Kamermans, P., van den Wijngaard, K. A., & Reuchlin, E. (2019). *Recommendations for flat oyster restoration in the North Sea*. Retrieved from https://www.ark.eu/sites/default/files/media/Schelpdierbanken/Recommendations_for_flat_oyster_restoration_in_the_North_Sea.pdf

Sas, H., van der Have, T. M., Kamermans, P., & Lengkeek, W. (2018). *Flat oyster pilot design in North Sea offshore wind farm.* Retrieved from https://edepot.wur.nl/473135

Scape. (2020). *Oyster-tecture.* Retrieved 2020-03-19, from https://www.scapestudio.com/projects/oyster-tecture/

Scheiffarth, G., Ens, B., & Schmidt, A. (2007). What will happen to birds when Pacific oysters take over the mussel beds in the Wadden Sea? *Wadden Sea Newsletter*, *1*, 10–14.

Schellekens, T., Wijsman, J. W. M., & v.d. Brink, A. (2012). *A habitat suitability model for Pacific oysters (Crassostrea gigas) in the Oosterschelde*. (No. C057/11). Wageningen: IMARES. Retrieved from https://library.wur.nl/WebQuery/wurpubs/428298

Schiereck, G. J. (2016). *Introduction to Bed, bank and shore protection* (2nd ed.; H. J. Verhagen, Ed.). Delft: VSSD.

Segarra, A., Pépin, J. F., Arzul, I., Morga, B., Faury, N., & Renault, T. (2010). Detection and description of a particular Ostreid herpesvirus 1 genotype associated with massive mortality outbreaks of Pacific oysters, Crassostrea gigas, in France in 2008. *Virus Research*, *153*(1), 92–99. http://doi.org/10.1016/j.virusres.2010.07.011

Smaal, A. C., Ferreira, J. G., Grant, J., Petersen, J. K., & Strand, Ø. (2018). *Goods and services of marine bivalves*. Springer.

Smaal, A. C., van Stralen, M. R., & Craeymeersch, J. (2005). Does the introduction of the Pacific oyster Crassostrea gigas lead to species shifts in the Wadden Sea? In R. F. Dame & S. Olenin (Eds.), *The comparative roles of suspension-feeders in ecosystems* (pp. 277–289). Springer.

Sneekes, A. C., & Kotterman, M. J. J. (2019). *Biotamonitoring Rijkswateren t/m 2018: Deel I: Toetsing en trends*. (No. C106/19). IJmuiden: Wageningen Marine Research. http://doi.org/10.18174/507702

Spencer, B. E. (1990). *Cultivation of Pacific Oysters*. Lab. Leafl., MAFF Direct. Fish. Res., Lowestoft, (63). Retrieved from https://www.cefas.co.uk/publications/lableaflets/lableaflet63.pdf

Sukhotin, A., Abele, D., Pörtner, H., Sukhotin, A. A., Abele, D., & Pörtner, H. (2006). Ageing and metabolism of Mytilus edulis: populations from various climate regimes. *Journal of Shellfish Research*, *25*(3), 893–899. http://doi.org/10.2983/0730-8000(2006)25[893:aamome]2.0.co;2

TAW. (1984). *Leidraad voor de toepassing van asfalt in de waterbouw*. 's-Gravenhage.

TAW. (2003). *Technisch rapport steenzettingen (achtergrondinformatie & onderbouwing)*. (No DWW-2003-097). Retrieved from http://publicaties.minienm.nl/documenten/technisch-rapport-steenzettingen

Troost, K. (2010). Causes and effects of a highly successful marine invasion: Case-study of the introduced Pacific oyster Crassostrea gigas in continental NW European estuaries. *Journal of Sea Research*, *64*(3), 145–165. http://doi.org/10.1016/j.seares.2010.02.004

Tydeman, P. (1996). *Ecologisch profiel van de wilde litorale mosselbank (Mytilus edulis L.)*. (No. RIKZ-96.0.26). Den Haag: Rijksinstituut voor Kust en Zee.

Utting, S. D. (1988). The growth and survival of hatchery-reared Ostrea edulis L. spat in relation to environmental conditions at the on-growing site. *Aquaculture*, *69*(1-2), 27–38. http://doi.org/10.1016/0044-8486(88)90183-4 van der Weide, B. E., Sas, H., Kamermans, P., van der Have, T. M., Christianen, M. J. A., Coolen, J. W. P., … van der Pool, J. (2018). *Shellfish bed restoration pilots Voordelta, Netherlands*. (Annual report 2018). Bureau Waardenburg, WMR, Sas Consultancy. Retrieved from https://www.ark.eu/sites/default/files/media/Schelpdierbanken/Annual_report_Voordelta_2018.pdf

Verhagen, H. J., D'Angremond, K., & van Roode, F. (2009). *Breakwaters and closure dams* (2nd ed.). Delft: VSSD.

Vismann, B., Wejlemann Holm, M., Davids, J. K., , & others Dolmer, P. (2016). Field clearance of an intertidal bivalve bed: relative significance of the co-occurring blue mussel Mytilus edulis and pacific oyster Crassostrea gigas. *Aquatic Biology*, *25*, 107–119. http://doi.org/10.3354/ab00661

Waite, J. H. (1992). The formation of mussel byssus: anatomy of a natural manufacturing process. In *Structure, cellular synthesis and assembly of biopolymers* (pp. 27–54). Heidelberg: Springer.

Walne, P. R. (1972). The influence of current speed, body size and water temperature on the filtration rate of five species of bivalves. *Journal of the Marine Biological Association of the United Kingdom*, *52*(2), 345–374. http://doi.org/10.1017/S0025315400018737

Walne, P. R. (1979). *Culture of bivalve molluscs: 50 years experience at Conwy* (2nd ed.). Farnham, Surrey: Fishing News Books Ltd.

Weerman, E. J., Eriksson, B. K., Olff, H., & van der Heide, T. (2014). Predation by native brown shrimp on invasive Pacific oyster spat. *Journal of Sea Research*, *85*, 126–130. http://doi.org/10.1016/j.seares.2013.04.010

Wijsman, J. W. M., Dubbeldam, M., De Kluijver, M. J., van Zanten, E., van Stralen, M., & Smaal, A. C. (2008). *Wegvisproef Japanse oesters in de Oosterschelde*. (No. C063/08:1-95). Yerseke: IMARES.

Wolff, W. J. (1973). *The estuary as a habitat an analysis of data on the soft-bottom macrofauna of the estuarine area of the rivers Rhine, Meuse, and Scheldt*. (No. 106). Yerseke: Delta Institue for Hydrobiological Research.

Yamaguchi, K. (1994). Shell structure and behaviour related to cementation in oysters. *Marine Biology*, *118*(1), 89–100. http://doi.org/10.1007/BF00699222

Young, G. A. (1985). Byssus-thread formation by the mussel Mytilus edulis: effects of environmental factors. *Marine Ecology Progress Series*, *24*(1972), 261–271. http://doi.org/10.3354/meps024261

Zenz, R. (2006). *Miesmuscheln: Seitlich, von der Underseite aus.* Retrieved from https://commons.wikimedia.org/wiki/File:Miesmuscheln-2.jpg

A

Personal communication

A.1. Erik Broos / 18-09-2019

Designs of bank protections in the Port of Rotterdam are often over-dimensioned. Design formulas are used to come up with a stone diameter, d_{n50}, that would fulfill. Stones come in ranges. If a specified stone dimension is not available, often larger stones are used to guarantee safety. Another option could be to use a somewhat smaller stone diameter and monitor the area more often. This has also a positive environmental effect since the collection of smaller stones is easier compared to the collection of larger stones resulting in a smaller loss of nature at the quarry location. The Port of Rotterdam normally gets its stones from a quarry in Norway.

A.2. Robin Duvaloois / 01-10-2019

Different slopes do exist in the port. The top layer is typically made of asphalt, rubble stone or paving stone. The underwater slope is not steeper than 1:3. The lifespan of a slope is normally 50 years. For paving stone 40 years of lifespan is normal. Monitoring of the slope above NAP is done visually, approximately once a year. Under NAP monitoring takes place with small vessels. First, an echo sounding survey is conducted during high water level. The second measurement, a slope scan, takes place at low water level. The combination of the two measurements gives an outline of the slope. When slopes are built, a theoretic slope line is measured. This functions as a baseline for further monitoring. The monitor vessel will measure the change of the slope compared to this baseline measurement. This measurement takes place approximately once a year, depending on the location. If the measurement differs ”too much” from the baseline measurement intervention takes place. ”Too much” is determined based on experience and logical reasoning of the staff. First of all, the cause of the damage will be analyzed to determine if something has to change. For example, if erosion is caused by vessels, the cause of the damage can be addressed by mooring the vessels differently. However, maybe the designed stone dimension is too small resulting in an addition of larger stones. Intervention depends on the type of revetment and the cause of the damage. For a rubble stone revetment, intervention usually means placing extra stones at the location where the damage occurs. For a paving stone revetment, stones have to be relocated.

B
Habitat requirements

B.1. *C. gigas*

Salinity
Optimal salinity levels for the growth of *C. gigas* range between 25-35‰. Permanent salinity levels lower than 16‰ lead to higher mortality rates (Nehring, 2011; Pauley et al., 1988). Although, *C. gigas* can reduce its metabolic activity and can, therefore, survive short periods of freshwater supply up to 11‰ (Reise, 1998).

Temperature
Populations can adapt to local water temperatures. Nonetheless, an optimum survival rate is found between 6-30 °C. *C. gigas* can withstand lower temperatures but for a limited amount of time. Especially juvenile oysters are sensitive to lower temperatures. High mortality occurs if the oyster is kept 3-7 weeks in water with a temperature of 3 °C (Child & Laing, 2008). Air temperatures of -4 °C can be tolerated during exposure (Quayle, 1969). *C. gigas* is sensitive to high-temperature water. From temperatures of 30 °C onwards mortality will occur. *C. gigas* can better tolerate high temperatures than *M. edulis*. However, exposure to temperatures of 42 °C for one hour is lethal (Rajagopal et al., 2005). Mass mortality during summer is a phenomenon linked to temperature. If water temperatures rise above 20 °C after oysters had just spawned, increased mortality is observed especially among female oysters (Child & Laing, 2008).

Water depth
C. gigas survive from locations that are 60% of the time wet until depths of about 40 meters (J.W.M. Wijsman, personal communication, November 22, 2019).

Suspended particle concentration
Oysters need a certain optimum organic and non-organic suspended particle concentration. Utting (1988) showed that a higher concentration of suitable phytoplankton leads to a higher growth rate. Suitable phytoplankton is phytoplankton that is not too large or too small because very large or small phytoplankton is difficult to be filtered out (Brinkman, 2013). At the same time, non-organic suspended material suppresses the growth (Utting, 1988).

Predators
Some predators like the common starfish (*Asterias rubens*), the common whelk (*Buccinum undatum*), the dog whelk (*Nucella lapillus*), the green shore crab (*Carcinus maenas*) and the brown shrimp (*Crangon crangon*) prey for oysters (Dare et al., 1983; Spencer, 1990; Lützen et al., 2012; Weerman et al., 2014). Among birds, only the herring gulls (*Larus argentatus*) and oystercatchers (*Haematopus ostralegus*) prey for *C. gigas*. This local predation at low rates will not lead to large mortality (Troost 2010). European oysters are less of prey for birds, crabs, and fish if the shell diameter of the oyster is larger than about 3 cm, this is also assumed to be the case for *C. gigas*. (Gercken & Schmidt, 2014).

Whelks are also called sea snails, they do not migrate a lot. However, if they reach an oyster reef, they can have a lethal effect depending on the relative number of snails and the dynamics of the snails themselves. Currently, sea snails do appear in the Eastern Scheldt. Observations showed that the snail mainly migrates through sandy material. Therefore, oysters are placed on steel racks in the Eastern Scheldt region. (J.W.M. Wijsman, personal communication, November 22, 2019).

Diseases
C. gigas is not affected by as many diseases as other oyster species. However, some diseases still do occur and pose a risk. Diseases that occur in the North Sea area among *C. gigas* are Herpes-like infections which can result in mass mortality (Elston, 1993; Renault et al., 1995; Renault et al., 2014; Segarra et al., 2010).

B.2. *M. edulis*

Salinity
M. edulis can survive salinity rates of about 16‰ during normal river discharge at high tide. During high river discharge and high tide, conditions of 4 to 6‰ are limiting. Occasionally mussels can be found in the brackish parts of the estuary. However, during high discharges in winter and early spring, species will not survive at those locations (Remane & Schlieper, 1971; Wolff, 1973). According to Jamieson et al. (1975), salinity levels over 40‰ lead to a reduced growth rate.

Water temperature
The optimal water temperature for *M. edulis* lies between 3-20 °C. With possible adaptation to higher temperatures. However, high temperatures increase the oxygen reduction in the sediment. This leads to the production of toxins like ammonium and sulfide which can become dangerous for the mussel (Dankers & Fey-Hofstede, 2015). Temperatures above 29 °C are lethal. Between 3-5 °C, no new feces are produced. (Almada-Villela et al., 1982).

Water depth
The optimal water depth lies between the intertidal area and circa 20-25 m below MWL (Tydeman, 1996). *M. edulis* can survive exposure to air for over 60% of the time during a tidal cycle (Letendre et al., 2008).

Suspended particle concentration
M. edulis have the same habitat requirement regarding suspended particle concentration as *C. gigas*.

Predators
One of the main predators of the mussel is the Eider. This bird mainly hunts for subtidal mussels. The effect of this predator on the survival of a mussel bed is only moderate (Dankers & Fey-Hofstede, 2015; Nehls & Thiel, 1993). Other predators are the common starfish (*Asterias rubens*) which can consume mussels in the subtidal zone. For a temperature of 10 °C, the common starfish can consume 0.34 grams of mussels per day per gram of starfish. Salinity, temperature, current velocity, and the size of the mussel can lead to different rates of consumption (Dankers & Fey-Hofstede, 2015). In the Eastern Scheldt, mussels are mainly prey to shrimps (J. Barbe, personal communication, November 22, 2019). Older mussels are prone to predation by birds like the oystercatcher (*Haematopus ostralegus*) or the European herring gull (*Larus argentatus*). This can lead to starvation if there is no accretion of mussel larvae. Enough accretion of young larvae will normally result in the survival of mussel beds (Dankers & Fey-Hofstede, 2015).

Diseases
In contrast to oysters, mussels are not likely to experience mass mortality due to diseases when grown in high densities (Bower & Figueras, 1989). Different diseases can occur however, none of them is lethal on a large scale (Bower et al., 1994).

C

Previous measurement points

Predicted shellfish presence in horizontal as well as vertical space in the port area is compared to previous in-situ observations by Paalvast (1998). Observations by Paalvast are relatively outdated because they were taken before the construction of Maasvlakte 2. Nonetheless, the information can be used to inform at least a rough estimate of shellfish presence at similar locations.

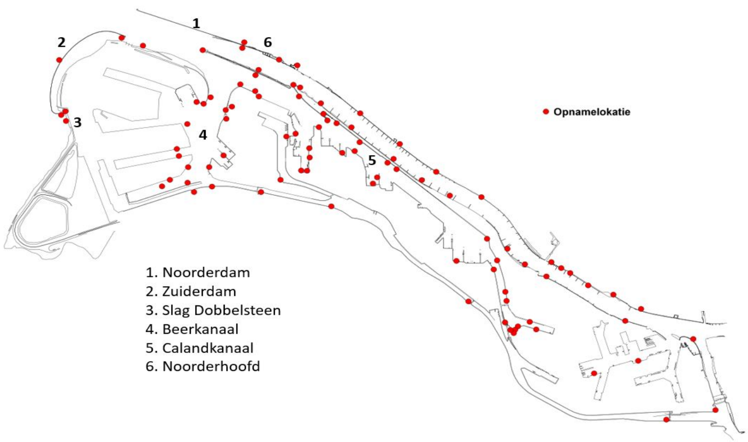

Figure C.1: Observation points of the previous study by Paalvast (1998)

D

Safety procedures

Table D.1: Possible risks and appropriate measures to avoid hazardous situations during measurements

Possible risks	Measures taken
Accidents	Never go into the port alone, always work together with another person Always take a phone with you while visiting the port
Sharp oysters	Wearing gloves Wearing working boots
Extreme weather	Check forecast before the start of measurements. If the wind force is higher than 4 on the scale of Beaufort measurements are canceled.
Working close to waterline *	Wearing a life vest

* This risk only applies to the quantitative observations.

E

Measurement results of shellfish presence

E.1. Qualitative observations

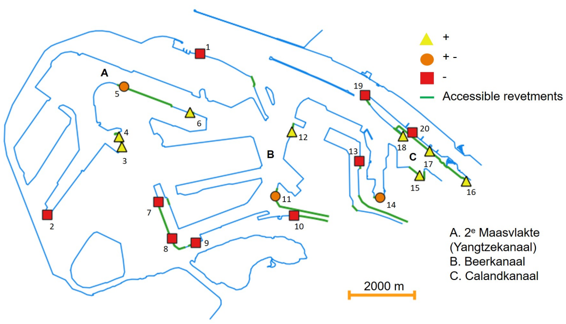

Figure E.1 (a) *C. gigas*

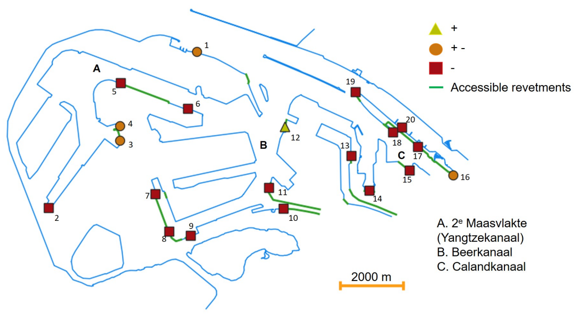

Figure E.1 (b) *M. edulis*

Figure E.1: Overview of results of qualitative observations

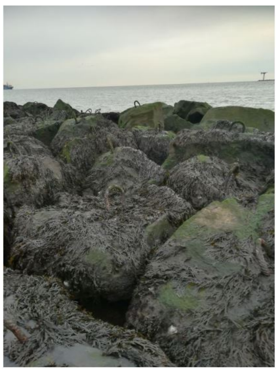

Figure E.2 (a) Location 1

Figure E.2 (b) Location 2

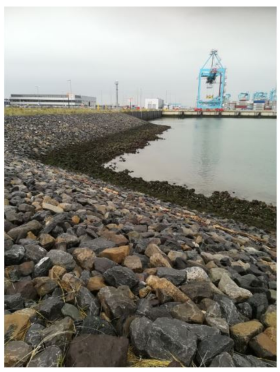

Figure E.2 (c) Location 3

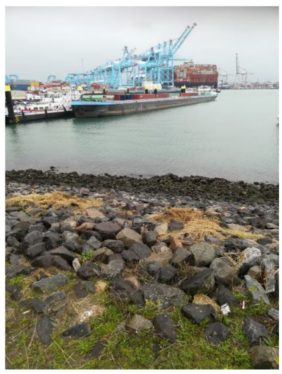

Figure E.2 (d) Location 4

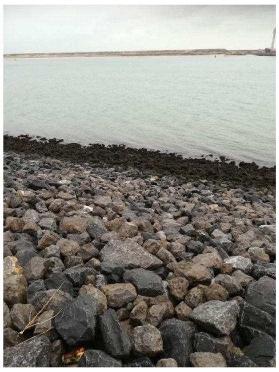
Figure E.2 (e) Location 5


Figure E.2 (f) Location 6

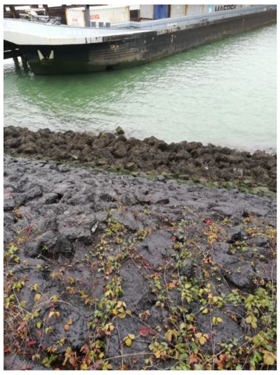
Figure E.2 (g) Location 7


Figure E.2 (h) Location 8


Figure E.2 (i) Location 9


Figure E.2 (j) Location 10

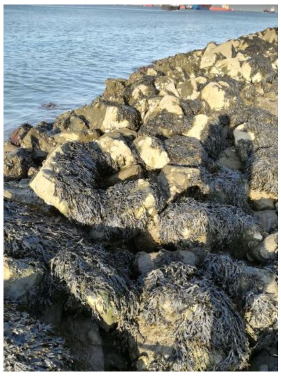
Figure E.2 (k) Location 11

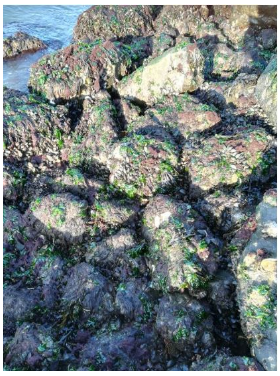
Figure E.2 (l) Location 12

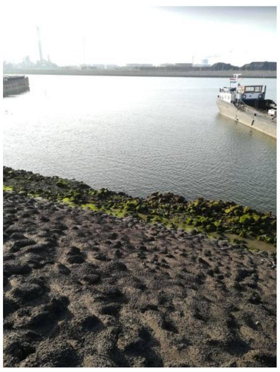
Figure E.2 (m) Location 13


Figure E.2 (n) Location 14

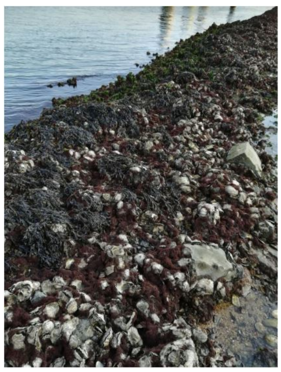
Figure E.2 (o) Location 15


Figure E.2 (p) Location 16


Figure E.2 (q) Location 17


Figure E.2 (r) Location 18

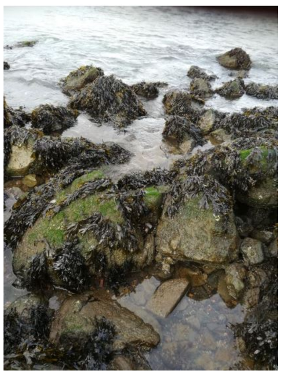
Figure E.2 (s) Location 19

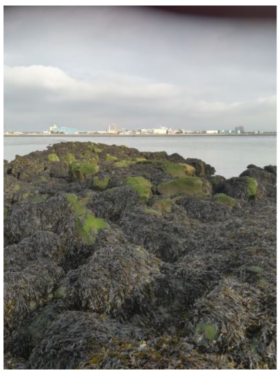
Figure E.2 (t) Location 20

Figure E.2: Pictures taken during qualitative observations

E.2. Quantitative measurements

E.2.1. Location 5

Table E.1: Measurement results at location 5

Area	Elevation [m]	# stone	# effective stone	% coverage *M. edulis*	% coverage living *C. gigas*	% coverage dead *C. gigas*	% coverage *Fucus*
5_1_1	-0.5	22	8	18	12	25	6
5_1_2	0.0	21	14	4	2	15	20
5_1_3	0.5	12	12	1	3	2	33
5_1_4	1.0	17	17	0	2	0.5	40
5_1_5	1.5	22	22	0	0	0	5
5_2_1	-0.5	23	9	15	2	22	8
5_2_2	0.0	7	6	0.5	2	25	25
5_2_3	0.5	10	10	0	10	8	30
5_2_4	1.0	10	10	0	8	1	50
5_2_5	1.5	21	21	0	0	0	2
5_3_1	-0.5	20	6	3	2	10	8
5_3_2	0.0	11	7	0.5	2	15	12
5_3_3	0.5	14	13	0	10	1	35
5_3_4	1.0	21	21	0	0	0	15
5_3_5	1.5	20	20	0	0	0	1

Area 5_1 observed on 13 January 2020. 09:11 AM - 10:03 AM. Weather: partially cloudy, Bf3. Coordinates of area in decimal degrees: 51.972830,4.018514.
Area 5_2 observed on 13 January 2020. 00:05 PM - 01:31 PM. Weather: foggy, Bf3. Coordinates of area in decimal degrees: 51.972235,4.021043.
Area 5_3 observed on 13 January 2020. 11:00 AM - 11:25 AM. Weather: sunny, Bf3. Coordinates of area in decimal degrees: 51.971357,4.024823.

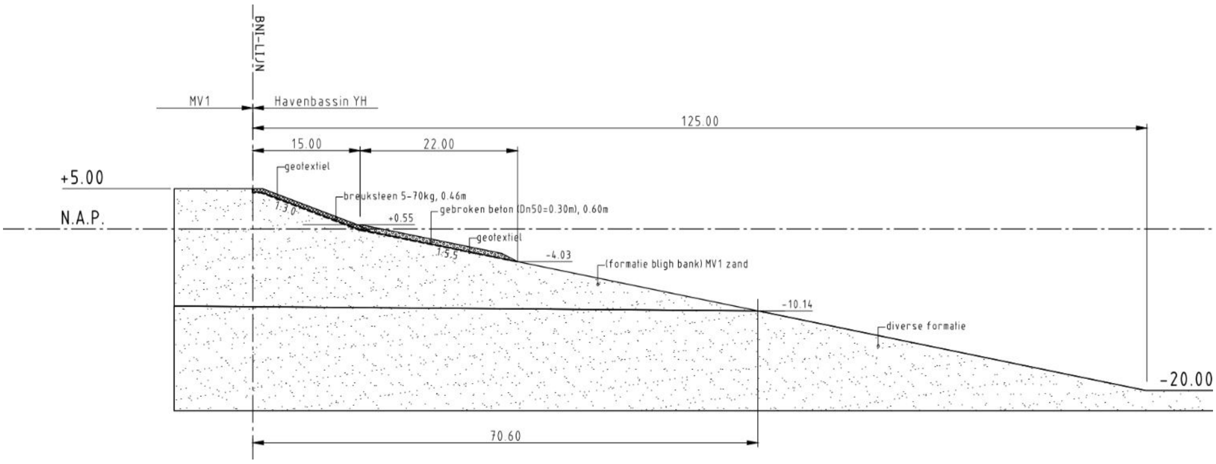

Figure E.3: Schematic overview of the revetment at location 5


Figure E.4 (a) 5_1_1

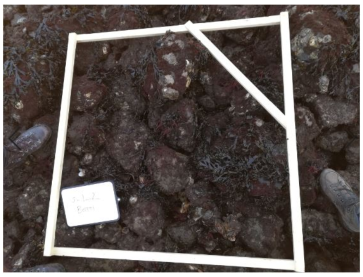
Figure E.4 (b) 5_1_2


Figure E.4 (c) 5_1_3

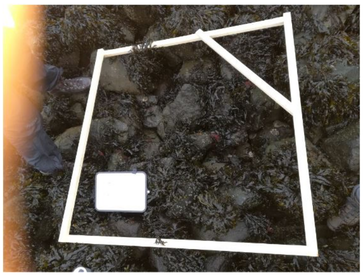
Figure E.4 (d) 5_1_4

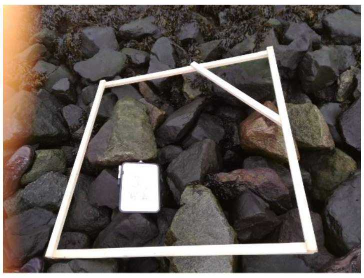
Figure E.4 (e) 5_1_5


Figure E.4 (f) 5_2_1


Figure E.4 (g) 5_2_2

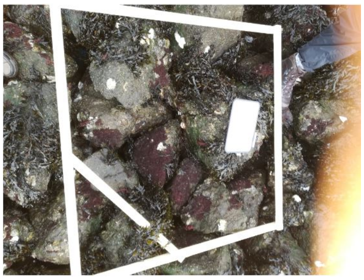
Figure E.4 (h) 5_2_3


Figure E.4 (i) 5_2_4


Figure E.4 (j) 5_2_5


Figure E.4 (k) 5_3_1


Figure E.4 (l) 5_3_2


Figure E.4 (m) 5_3_3


Figure E.4 (n) 5_3_4


Figure E.4 (o) 5_3_5

Figure E.4: Pictures taken at measurement location 5

E.2.2. Location 12

Table E.2: Measurement results at location 12

Area	Elevation [m]	# stone	# effective stone	% coverage *M. edulis*	% coverage living *C. gigas*	% coverage dead *C. gigas*	% coverage *Fucus*
15_1_1	-0.5	18	1	5	15	50	2
15_1_2	0.0	3	3	1	6	6	18
15_1_3	0.5	18	16	0	2	10	25
15_1_4	1.0	16	15	0	1	0.5	4
15_1_5	1.5	18	18	0	0	0	0
15_2_1	-0.5	18	1	2	2	85	12
15_2_2	0.0	1	1	0	0	2	20
15_2_3	0.5	18	17	0	2	20	40
15_2_4	1.0	18	18	0	3	2	10
15_2_5	1.5	17	17	0	0	0	0.5
15_3_1	-0.5	18	1	5	65	10	3
15_3_2	0.0	6	3	1	8	10	10
15_3_3	0.5	5	5	0	1	3	50
15_3_4	1.0	17	17	0	4	8	25
15_3_5	1.5	15	15	1	0	6	0

Area 12_1 observed on 16 January 2020. 10:58 AM - 11:28 AM. Weather: sunny, Bf3. Coordinates of area in decimal degrees: 51.950957,4.144582.
Area 12_2 observed on 16 January 2020. 11:33 AM - 11:50 AM. Weather: sunny, Bf3. Coordinates of area in decimal degrees: 51.950712,4.144803.
Area 12_3 observed on 16 January 2020. 11:56 AM - 00:17 PM. Weather: sunny, Bf3. Coordinates of area in decimal degrees: 51.950660,4.145052.

Remark: An oyster reef is present around the low water level at location 12

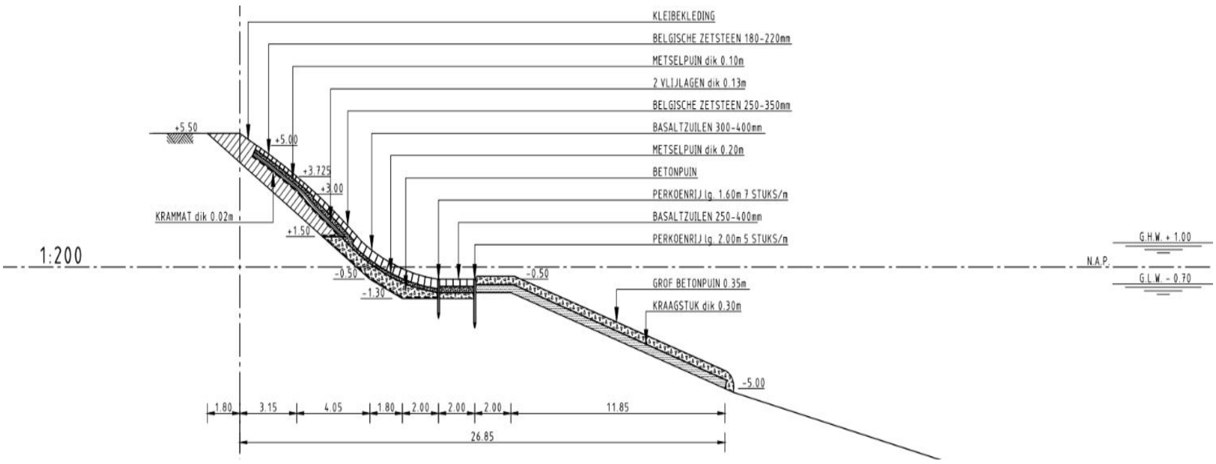

Figure E.5: Schematic overview of the revetment at location 12

Figure E.6 (a) 12_1_1

Figure E.6 (b) 12_1_2

Figure E.6 (c) 12_1_3

Figure E.6 (d) 12_1_4

Figure E.6 (e) 12_1_5

Figure E.6 (f) 12_2_1

Figure E.6 (g) 12_2_2

Figure E.6 (h) 12_2_3

Figure E.6 (i) 12_2_4

Figure E.6 (j) 12_2_5

Figure E.6 (k) 12_3_1

Figure E.6 (l) 12_3_2

Figure E.6 (m) 12_3_3

Figure E.6 (n) 12_3_4

Figure E.6 (o) 12_3_5

Figure E.6: Pictures taken at measurement location 12

E.2.3. Location 15

Table E.3: Measurement results at location 15 (AG=Asphalt grout)

Area	Elevation [m]	# stone	# effective stone	% coverage *M. edulis*	% coverage living *C. gigas*	% coverage dead *C. gigas*	% coverage *Fucus*
12_1_1	-0.5	8	8	50	12	10	15
12_1_2	0.0	12	AG	15	6	1	25
12_1_3	0.5	18	AG	2	3	0	65
12_1_4	1.0	AG	AG	0.5	0	0	70
12_1_5	1.5	AG	AG	0	0	0	10
12_2_1	-0.5	1	1	30	16	1	10
12_2_2	0.0	14	AG	15	4	1	8
12_2_3	0.5	17	AG	0.5	12	1	55
12_2_4	1.0	22	AG	1	2	0.5	45
12_2_5	1.5	20	AG	0.5	0	0	35
12_3_1	-0.5	3	3	50	20	3	15
12_3_2	0.0	17	AG	8	4	0.5	85
12_3_3	0.5	17	AG	10	3	0	65
12_3_4	1.0	18	AG	4	2	1	35
12_3_5	1.5	15	AG	0	0	0.5	0.5

Area 15_1 observed on 16 January 2020. 01:04 PM - 01:20 PM. Weather: sunny, Bf3. Coordinates of area in decimal degrees: 51.961664,4.090455.
Area 15_2 observed on 16 January 2020. 01:22 PM - 01:42 PM. Weather: sunny, Bf3. Coordinates of area in decimal degrees: 51.962009,4.090626.
Area 15_3 observed on 16 January 2020. 01:52 PM - 02:09 PM. Weather: sunny, Bf3. Coordinates of area in decimal degrees: -.

Remark: Algae seems to grow on stones and less on asphalt at location 15

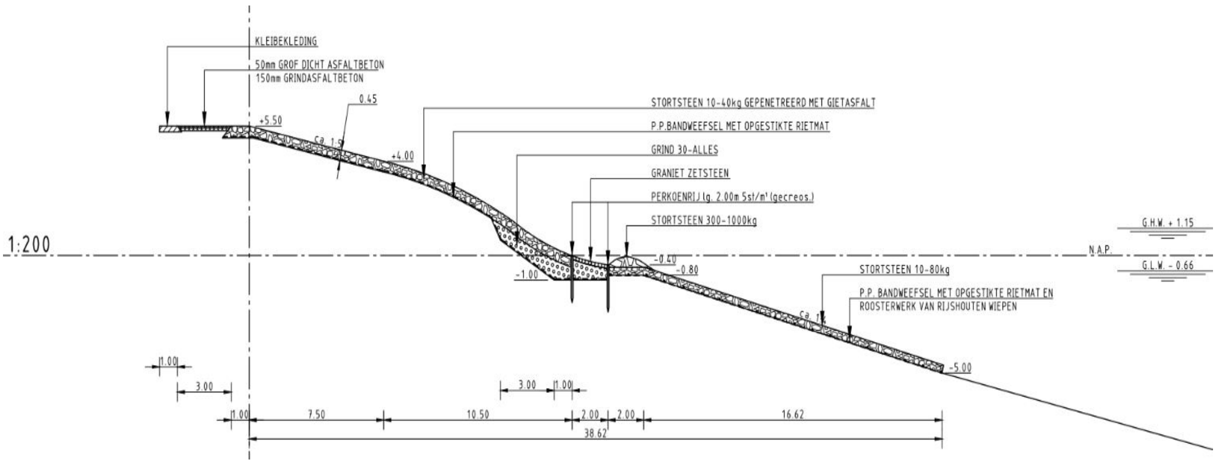

Figure E.7: Schematic overview of the revetment at location 15


Figure E.8 (a) 15_1_1


Figure E.8 (b) 15_1_2


Figure E.8 (c) 15_1_3


Figure E.8 (d) 15_1_4


Figure E.8 (e) 15_1_5


Figure E.8 (f) 15_2_1


Figure E.8 (g) 15_2_2


Figure E.8 (h) 15_2_3


Figure E.8 (i) 15_2_4


Figure E.8 (j) 15_2_5


Figure E.8 (k) 15_3_1


Figure E.8 (l) 15_3_2


Figure E.8 (m) 15_3_3


Figure E.8 (n) 15_3_4


Figure E.8 (o) 15_3_5

Figure E.8: Pictures taken at measurement location 15

F

Measurement results of the strength of oyster attachment

Table F.1: Measurements results of oyster attachment

Oyster	Force [kg]	Length [cm]	Width [cm]	Height [cm]	Description
k.1	26.52	7	3	-	lo
k.2	10.92	7.5	5	-	lo
k.3	5.44	6.5	4	-	so
k.4	23.43	7.5	5	2.5	lo
k.5	11.70	7.5	3	2	lo
k.6	12.00	7	4	2	lo
k.7	20.18	8.5	5	1.5	sb
k.8	2.18	8	6	1	lo
k.9	20.78	7	6	1.5	lo
k.10	10.92	6	7	1.5	lo
k.11	5.38	8.5	4	3	spb
k.12	23.80	11	6	3.5	lo
k.13	20.78	10	6	3	lo
k.14	30.28	7.5	4	1.5	sb
k.15	17.62	10	5	3	spb
k.16	23.2	8	5	-	sb
k.17	19.38	8	4.5	2	lo
k.18	9.96	7	4	2	lo
k.19	32.16	9	6	2	lo
k.20	10.56	7	6	2	so
s.1	2.72	9	5	2.5	lo
s.2	32.4	7	6	-	cllo
s.3	18	8.5	5	2.5	lo
s.4	6.94	-	-	-	lo

The first column indicates where the oyster was located: K. = sheet pile, S. = stone. The last column specifies what happened during the measurement. “Lo” means that the oyster got disconnected from the surface, the cementation broke and the shell came off the surface. “So” means that the shell opened. “Sb” means that the shell broke. “Spb” means that the sphincter broke so that the upper shell was detached from the other shell. “Cllo” means that the clamp came loose, from the shell.

Figure F.1 (a) k.1

Figure F.1 (b) k.2

Figure F.1 (c) k.3

Figure F.1 (d) k.4

Figure F.1 (e) k.5

Figure F.1 (f) k.6

Figure F.1 (g) k.7

Figure F.1 (h) k.8

Figure F.1 (i) k.9

Figure F.1 (j) k.10

Figure F.1 (k) k.11

Figure F.1 (l) k.12

Figure F.1 (m) k.13

Figure F.1 (n) k.14

Figure F.1 (o) k.15

Figure F.1 (p) k.16

Figure F.1 (q) k.17

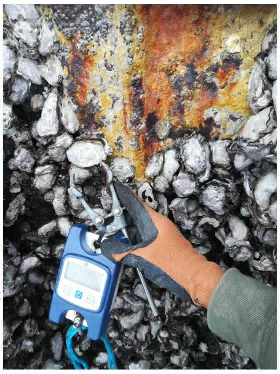

Figure F.1 (r) k.18

Figure F.1 (s) k.19

Figure F.1 (t) k.20

Figure F.1 (u) s.1

Figure F.1 (v) s.2

Figure F.1 (w) s.3

Figure F.1 (x) s.4

Figure F.1: Pictures taken during measurements of oyster attachment

G
Stone grading

Table G.1: Standard grading of light quarry rock material (based on CIRIA et al., 2007)

Grading class	**M_{50}**	**d_{n50}**
5 - 40 kg	21 kg	0.20 m
10 - 60 kg	37 kg	0.24 m
40 - 200 kg	127 kg	0.36 m
60 - 300 kg	193 kg	0.42 m

H

Time-dependent load of wind waves

H.1. Normal design wave condition

Necessary stone dimensions are calculated using a design wave height if the wave load is normative. The design wave height is related to local wave conditions and the lifetime of the structure (Verhagen et al., 2009). The acceptable probability of failure during the lifetime of a structure depends on the structural demands and the reliability level of the structure. An acceptable probability of failure during the lifetime of the structure is 5%. Revetments are normally designed for 50 years (Appendix A.2). The Poisson distribution gives the probability of failure during the lifetime of the structure

$$p = 1 - exp(-fT_L). \tag{H.1}$$

p = Probability of occurrence of an event one or more times in period T_L
f = Average frequency of the event per year
T_L = Considered period (i.e. lifetime of the construction) in years

A calculation example for normal design wave conditions gives

$$f = -\frac{1}{T_L} ln(1-p) \tag{H.2}$$

$$f = -\frac{1}{50} ln(1-0.05) = \frac{1}{1000}. \tag{H.3}$$

H.2. Design wave condition for applications

Building with Nature solutions need some time to develop before providing the required strength. Therefore, the lifetime of the structure is split into two periods. The first period is the development period and the other period is the final period. Suppose that oysters need a development period of three years before providing the required stability. The wave frequency for the development period becomes

$$f = -\frac{1}{3} ln(1-0.05) \approx \frac{1}{60}. \tag{H.4}$$

The wave frequency of the final period will be equal to equal to the normal design wave conditions.

H.3. Difference in required d_{n50}

Lower wave frequencies correspond to a lower design wave and thus a lower necessary nominal stone diameter, d_{n50}. The extent to which the d_{n50} can be lowered during the development period depends on local wave conditions and should be calculated for each specific application. To get an indication of the order of magnitude, halving the design wave height leads to a reduction of the nominal stone diameter by 50% when using the formula for the stability number (Equation 2.1).

Initial pilot study design

At present, the development rate of *C. gigas* is difficult to predict. A reliable projection of the development time and the increase in coverage ratio is relevant for application in future designs. Since the effect of enhancement methods is unknown, several promising methods should be tested in a pilot study. A pilot study in the Port of Rotterdam should answer "*how well and how quickly oysters develop on a revetment under various enhancement strategies*". The outcome of this study can indicate the best enhancement method and how successful recruitment will be.

The most promising stock enhancement is the gluing option. Racks can undermine the stability of the revetment because they can cause turbulence (subsection 6.3.1). The most promising habitat enhancement can be expected from introducing suitable substrates and the introduction of empty shells (subsection 6.3.2).

Design
A pilot study is proposed in which several promising habitat and stock enhancement measures are studied. The proposed pilot study requires three different locations with *C. gigas* potential in the port area (Figure 7.1). Regarding stock enhancement, oysters of different ages are glued to the exposed part of the stones in the revetment. Each location will have a different degree of stock enhancement. Complete enhancement of 8 oysters/m^2 is not expected to be necessary as there are already larvae in the water column, therefore the following introduction values are used: location 1 will have no stock enhancement, location 2 will have 3 oysters introduced per m^2 and location 3 will have 6 oysters introduced per m^2. Oysters should be placed below NAP +0.5 m to ensure sufficient water flow for feeding and respiration. Concerning habitat enhancement, the effect of different substrates can be studied. At each location, 3 different substrates should be introduced at a stretch of 10 meters each. Potential substrates for oyster attachment are basalton, granite, greywacke, basalt, concrete, copper slag (subsection 6.3.2).

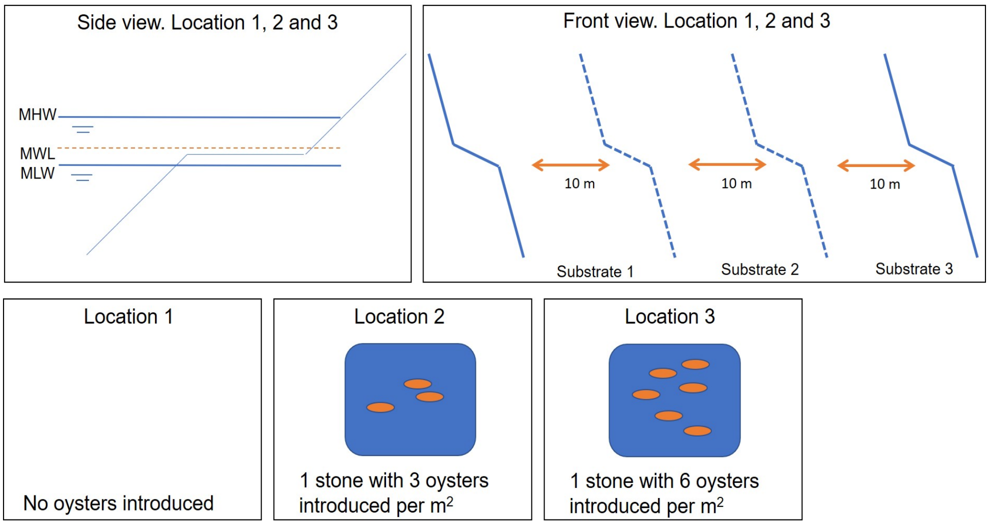

Figure I.1: Proposed pilot study

Phasing plan

1. Find three loose rock revetments that are accessible and have a small stone grading (10-60 kg or 5-40 kg), preferably locations that are known to be damaged relatively often.
2. Check the suitability of an area regarding oyster survival. Salinity levels should always be larger than 16‰ under normal average discharges and greater than 11‰ under high average discharges.
3. Investigate the current coverage ratio of living and death oysters as well as the absolute and effective number of exposed stones. This information can be used as a benchmark.
4. Order oysters, glue, and substrate.
5. Place substrate and glue the oysters to the stones.
6. Monitor the coverage ratio of living and death oysters, the absolute and effective number of exposed stones, and the uniformity of oyster presence on a revetment in the enhanced areas at least once per season (four times per year). Regular monitoring efforts should generate data to compare the extent of increase of oyster coverage on the different substrates and under different degrees of stock enhancement.

Autumn-early spring (Oct-March)	Spring (April-May)	Summer (June-July)	Summer (Aug-Sept)
Phase 1, 2	Phase 3, 4, 5	Phase 6	Phase 6

Figure I.2: General planning of a pilot study