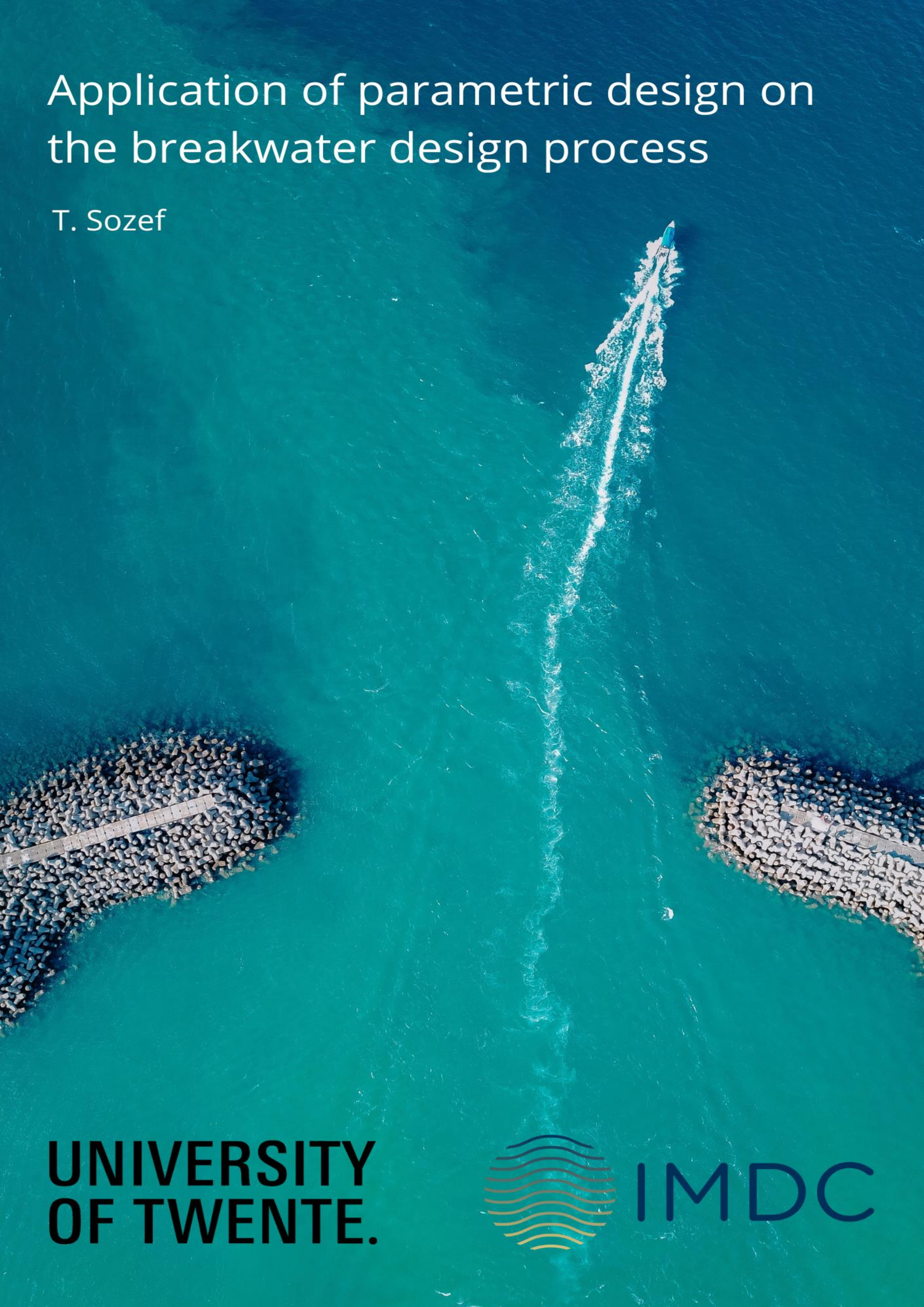
Application of parametric design on the breakwater design process

T. Sozef



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Preface

Before you lies the bachelor thesis research 'Application of parametric design on the breakwater design process'. This thesis is written as part of my graduation from the Bachelor's programme of Civil Engineering at the University of Twente and was commissioned by International Marine & Dredging Consultants (IMDC).

In a brief period of roughly ten weeks, I have learned a lot regarding parametric design, the breakwater design process and of the possibility of the relation between the two. I have learned the aspects of conducting a research single-handily, which brings along more responsibility and organization requirements. I have had the opportunity to conduct part of my research at IMDC's office in Antwerp, which was a nice addition to the research. While I was there, I liked how people became enthusiastic about the possibilities of parametric design. IMDC will continue with the constructed tool as an internal project, which is pleasant to hear.

I would like to give a special thanks to my external supervisors at IMDC, Jaap de Groot and Jonas van Damme. Next to their assistance in conducting my research they have let me in about some of their amazing projects they are conducting. I would also like to thank Leen Baelus and Enrico Di Lauro for their specific knowledge contribution as breakwater experts from IMDC. Next to the people at IMDC I would like to thank my internal supervisor Joost Kranenborg for assisting my research from the University of Twente, from who I have learned a great deal in research practice.

Abstract

Breakwaters are important structures in most ports around the world. They absorb the energy of incoming waves, making these waves less strong, offering port and coastal protection. Next to this a still waterway is created for ships to enter the port. The designing of breakwaters is an expensive and elaborate task as the design must be made fail proof but minimise construction costs as well. The current problem in breakwater designing is the amount of manual labour and time consumption in generating and analysing different breakwater cross-sections. In the early phases of designing, it is important to design multiple cross-sections and analyse them to retrieve the best possible design for the concerning location. Parametric design may be a process that can contribute to the breakwater design process. Parametric design is a form of generative design, this could potentially provide a fast, flexible model and give the designer a visual indication of the generated design.

The first part of this research concerns the investigation of the breakwater design process and its opportunities regarding parametric design. The current design process is investigated through literature research into the design process and an interview which is conducted with an employee that has a history in breakwater designing. To assist in identifying the opportunities of parametric design a survey is constructed and distributed towards breakwater experts regarding their view on parametric design, its application on breakwater designing, and important aspects to keep in mind with development of a potential model. After this an area of application is identified to guide the construction of a model. The next part concerns the development of a parametric design tool. Based off the respondents of the survey, the breakwater experts at IMDC and the advantages of parametric design, model requirements are constructed. These requirements guide the development of the model and during construction further assumptions, design choices, and the structure of the model become apparent. After construction of the parametric design tool verification and validation needs to be performed to assess the functionality of the tool. A validation in calculated rock-grading is conducted by comparing a replicated model of the Elmina port expansion and rehabilitation model to its conceptual design. Next to this a validation in conductibility of a parameter study is performed to assess flexibility of the model. After validation of the model a reflection on the current breakwater design process is done to identify the benefits of the constructed parametric design tool.

The investigation into the breakwater design process and answers to the survey identified a spot in the breakwater design process, in which parametric design can be applied. The cross-section design in the conceptual design phase is an ideal area. Exploration is to be performed to analyse as much as possible potential designs, the flexibility and short computation time of parametric design would contribute to this process. A model suited for this application is therefore constructed and validated. The validation results are promising however there are differences in some results with a high possibility that difference in used theory caused it. The constructed model can improve several steps in the breakwater design process, namely, setting up the functional requirements, the placement of the breakwater, and designing cross-sections.

The parametric design tool developed in this study contributes to the design process of breakwaters. It assists in the cross-sectional design by providing a high amount of flexibility, short computation time and visual interface. To strengthen the conclusion further, application to a real case has been recommended. For the application of parametric design to non-traditional sectors, it can be beneficial if algorithmic processes can be determined, however a cost-benefit analysis and the quantification of results is recommended to investigate if the investment is worth the contribution it brings.

Samenvatting

Golfbrekers zijn belangrijke objecten in de meeste havens wereldwijd. Golfbrekers absorberen energie van inkomende golven en verminderen hierdoor de kracht van deze golven. Dit zorgt voor haven- en kustbescherming. Daarnaast wordt er hierdoor ook een rustig vaarwater gecreëerd voor inkomende schepen. Het ontwerpen van een golfbreker is een duur en uitgebreide opgave. Het ontwerp moet bestand zijn tegen de water condities maar ook zo kost-efficiënt mogelijk zijn. Het huidige ontwerp probleem betreft het genereren en evalueren van golfbreker dwarsdoorsnedes. Dit kost veel handmatig werk en dus ook veel tijd. In het vroege ontwerpstadium is het belangrijk om meerdere verschillende dwarsdoorsnedes te ontwerpen en evalueren om het beste ontwerp te selecteren. Parametrisch ontwerpen is een vorm van generatief ontwerpen, dat voor een snel, flexibel model zou zorgt en de ontwerper een visueel overzicht geeft van het gegenereerde ontwerp.

In het eerste deel van het onderzoek wordt er onderzoek gedaan naar het huidige golfbreker ontwerpproces en de mogelijkheden voor parametrisch ontwerpen. Dit is gedaan door middel van een literatuuronderzoek en een interview met een werknemer van IMDC met golfbreker ervaring. Om het identificeren van de mogelijke toepassing van parametrisch ontwerpen te helpen werd er een enquête gestuurd naar golfbreker experts om hun mening over parametrisch ontwerpen, de toepassing op golfbrekers, en de belangrijke aandachtspunten voor het ontwikkelen van een model gevraagd. Hierna is er een gebied in het golfbreker proces geïdentificeerd waar parametrisch ontwerpen toegepast kan worden. Hierna kan door behulp van het identificeren van dit gebied en de beoogde voordelen van parametrisch ontwerpen een lijst met model vereisten opgesteld worden. Hierna kan er een model ontwikkeld worden, hiermee komen de model aannames, ontwerpkeuzes, en model structuur naar boven die behandeld werden in dit onderzoek. Na het ontwikkeld hebben van het model is er een verificatie en validatie uitgevoerd. Er werd geverifieerd of er aan de vereisten voldaan werd en een validatie aan steen gradering voldaan werd, dit bepaalt de geometrie van een golfbreker. Hiernaast werd er een validatie in flexibiliteit uitgevoerd door middel van de mogelijkheid tot een parameter studie. Na het valideren is er een reflectie uitgevoerd waarin de verbeteringen in het golfbreker ontwerpproces naar boven kwamen door middel van een evaluatiegesprek met golfbreker experts.

Het onderzoek in literatuur en enquête antwoorden betreft parametrisch ontwerpen heeft een plek geïdentificeerd in het golfbreker ontwerpproces waar parametrisch ontwerpen van toepassing kan zijn. Het berekenen van dwarsdoorsnedes in de conceptueel ontwerpfase is het betreffende gebied. In deze fase wordt er veel verkend naar verschillende soorten dwarsdoorsnedes waar een flexibel en snel model een voordeel zou zijn. Een model afgericht op deze fase is hierdoor ontwikkeld en gevalideerd. De resultaten zijn veelbelovend echter maakt het verschil in theorie tussen het model en het nagebootste Elmina golfbreker conceptueel ontwerp het moeilijk om waterdicht te zijn. Het ontwikkelde model verbetert verschillende stappen in het ontwerpproces, namelijk, het opzetten van de vereisten, de plaatsing van de golfbreker, en het ontwerpen van dwarsdoorsnedes.

Het ontwikkelde parametrisch model in deze studie draagt bij aan het ontwerpproces van golfbrekers. Het assisteert in het ontwerpen van dwarsdoorsnedes doormiddel van zijn hoge flexibiliteit, lage berekening tijd, en het visuele overzicht. Om de conclusie te versterken is het aanbevolen om het model te valideren met een echt ontwerpproces. Betreffend het toepassen van parametrisch ontwerpen op andere sectoren is het belangrijk om betreffende processen te onderzoeken en is het goed om een kost-baten analyse uit te voeren en de resultaten proberen te kwantificeren om uit te zoeken of de investering in parametrisch ontwerpen het waard is.

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1. Introduction

In this chapter an introduction is given to breakwaters, the current problems in designing the structures, and the benefits parametric design brings in the designing process. These subjects give context to the need of this research. After this context, the research questions are given along with the scope of this research and the method of research conduction.

1.1. Breakwaters

Breakwaters are structures near the coast that protect an anchorage or port from waves. This type of structure protects these facilities by absorbing the energy of incoming waves. They protect the anchorage from damage that can occur from strong waves, and it can create a still waterway for ships to navigate through (Massie, 1976). This still waterway increases the efficiency and safety of navigation and cargo handling for container ships. Due to the still water created by breakwaters near harbour area, expansion and modification of this area can be performed at lower costs as dredging at exposed areas is relatively expensive. Quays and berms of breakwaters can be combined, making it economic efficient spacing in the harbour area, Figure 1 shows an example of such a breakwater under construction.

Figure 1: Reconstruction of the breakwater of the port of Ericeira (Henriques et al., 2014).

There are several types of breakwaters with two main categories, these are mound and monolithic breakwaters. The mound breakwater existing out of loose elements formed in a slope and the monolithic breakwater is a vertical wall that consists of one element. There is a third type, namely composite breakwaters, which are a combination of the previously mentioned. In Figure 2 different breakwater types are illustrated. For this study, a conventional rubble-mound breakwater is used to restrict the research scope.

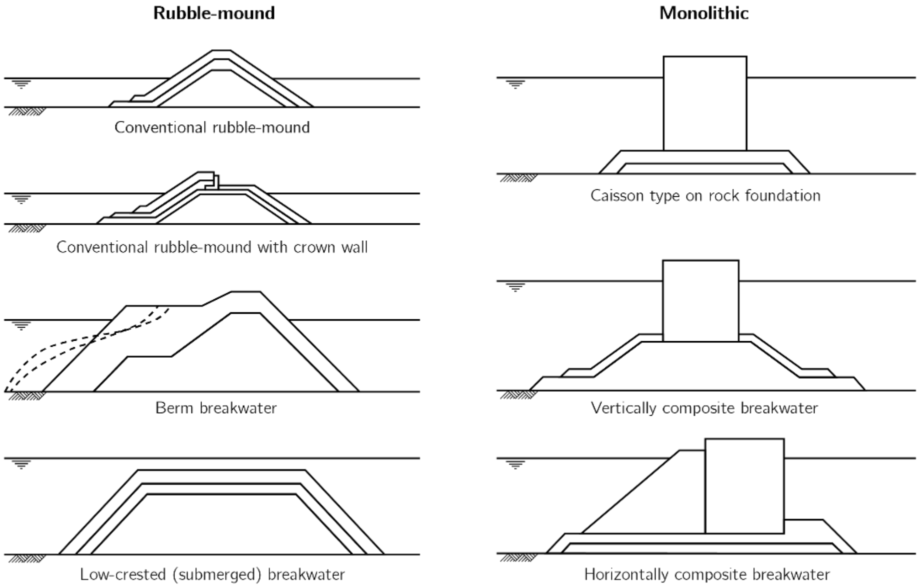


Figure 2: Different breakwater types (Winkel, 2020).

As the mound breakwater will be used in this study it will be elaborated on. Mound breakwaters consist of many loose elements, which are placed in a slope making it have a certain stability. This stability is dependent on the wave strength, height, and size. It is also dependent on the relative density of the loose elements of which the mound breakwater consists of (Verhagen van den Bos, 2017). The advantages of mound breakwater types are the flexibility in change of slope or size of the structure at any time, the dissipation of wave energy and the cost efficiency of the system.

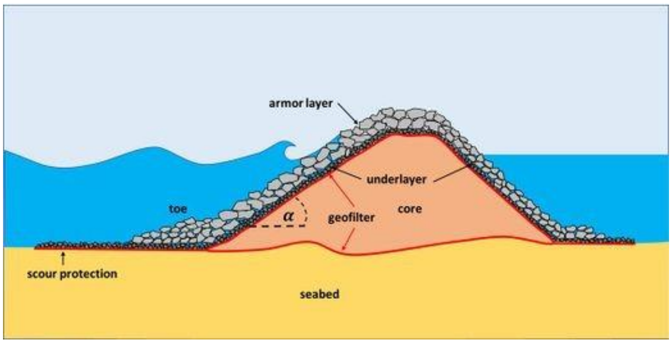


Figure 3: Illustrated rubble-mound breakwater cross-section (Dronkers et al., 2022).

Figure 3 illustrates a conventional rubble-mound breakwater cross-section. A rubble-mound breakwater consists entirely out of rock or in combination with concrete armour units. A rubble-mound breakwater consists out of multiple rock layers of varied sizes to withhold internal stability and follow set permeability and retention criteria (Ciria-Cur, 2007). Starting bottom-up, the first layer is called the 'core'- layer and consists of the finest material for cheap filling of the breakwater. Around this layer a geotextile filter is present to prevent the blending of the core material with the seabed and underlayer. After this an underlayer is placed, this is to follow retention and permeability criteria. On top of the underlayer, a heavy armour layer is placed to prevent erosion of the breakwater elements due to harsh sea conditions. The armour layer is kept in place due to the toe constructed at the end of the slope. The scour protection is a longer thin layer of grading, which is placed to prevent the loss of seabed sediment near the breakwater.

1.2. Parametric design application

Parametric design is a design process that is on the rise in recent years and is getting applied more in a lot of different fields (Kalkan et al., 2018). Parametric designing allows the involvement of difficult algorithms in an early design process by involving computers early (Bialozor et al., 2017) . By implementing parametric design and having optimized solutions early hand, a designer can get a well-established idea of "the best" solution in the preliminary stages of design.

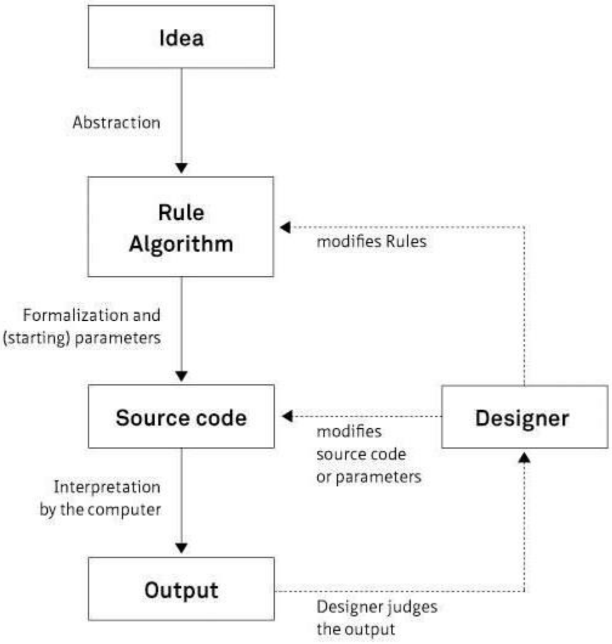


Figure 4: Basic process of algorithmic design (Bohnacker et al., 2009).

Figure 4 visualizes the application and use of a parametric design model. The designer is in control of the design process if the parametric model is constructed well. An idea leads to the creation of a parametric model for a certain system. This model contains source code or standard algorithmic processes of the software, which generates output based on the relationship between set parameters. The designer can judge the generated output and can influence the output via two methods, by changing the parameters or changing the algorithmic processes in use.

With use of parametric designing, calculations are performed, and a corresponding geometric design of a system is generated. This saves a significant amount of time compared to the conventional approach of manually designing the system and performing several iterations. With a parametric design tool, a design is generated based on algorithms and their corresponding input variables and parameters. The output geometry is not fixed and can be changed by altering the parameters. Visual programming languages have boosted the application of parametric modelling as the connections of parameters to processes are visible and model application is easy to conduct (Romaniak & Filipowski, 2018).

One of the first projects where parametric design was incorporated and used within the entire team sharing parametric models and using commercially available CAD products was the designing of the Aviva stadium in Dublin Ireland (Shepherd et al., 2011). Architects and structural engineers were able to share a single parametric model, which allowed rapid development and design changes. The stadium and model are shown in Figure 5 and Figure 6. As a result of this product, more CAD software vendors have included parametric design and the use of it is fast becoming the norm.

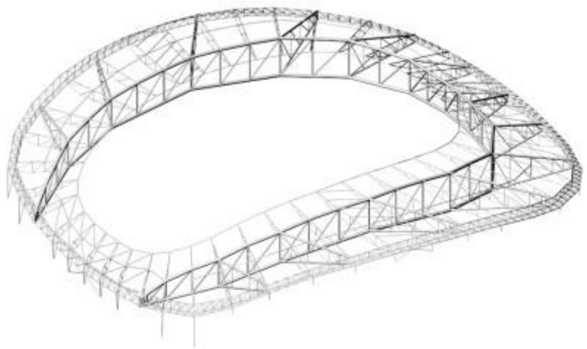


Figure 5: Structural members output of parametric model (Shepherd et al., 2011).

Figure 6: Present view of Aviva stadium (Wikipedia, 2022).

In theory, parametric design could be applied to the breakwater conceptual design process as certain standard rules of thumbs and calculations are applied to give an insight into the initial breakwater configuration (Verhagen van den Bos, 2017). These calculated configurations by the algorithmic processes can then be displayed in the Computer Aided program that is linked to the visual programming tool. The designer can then asses the configurations visually and assess the data output delivered by the model. As a breakwater configuration depends on a substantial amount of input variables and parameters, parametric designing would increase the flexibility in designing significantly. Parametric design has the potential to give the designer a better overview of the impact of parameters and breakwater location on the design.

Traditional location dependent modelling does not support a fast iterative design process, due to the lack of flexibility in workflows (Janssen et al., 2016). Different steps are taken in the design process, in which it is hard to transfer the location specific data and keep an overview. Parametric designing offers a modular workflow in which switching between modelling and analysis is possible. The computer aided design (CAD) offers a visual connection between the iterative data processing and the geographical data and can combine certain workflows in the breakwater design process.

1.2.1. Rhinoceros + Grasshopper

The most common used parametric design software is Grasshopper, which is a Rhinoceros CAD-software plugin that allows the user to create algorithmic functions in a visual programming interface. This software is known for its user-friendliness and is the most common used parametric design software in the last decade for architectural and structural engineering appliances (Shepherd, 2009). Grasshopper is a plugin which has a visual programming interface for the 3D CAD-software Rhinoceros. Rhinoceros uses a NURBS mathematical modelling (non-uniform rational B-splines), which means that it uses points and curves for geometric projection. Grasshopper contains algorithmic processes to generate geometry with parameter relations.

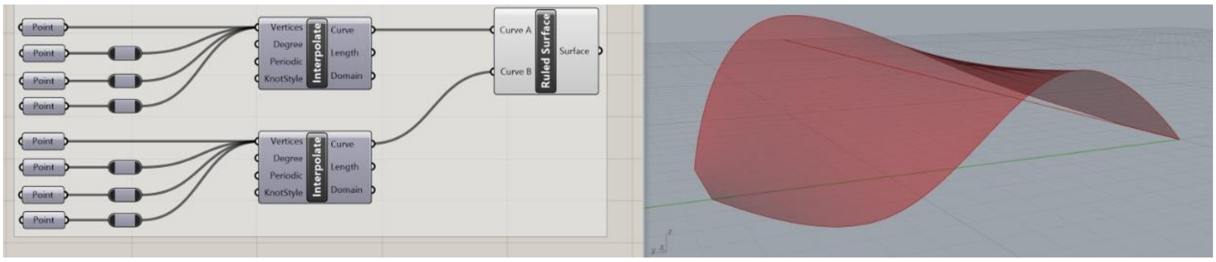


Figure 7: Rhino + grasshopper (Baharmon.github.io, 2022).

In Figure 7 an example is given of a simple model. Points are used to construct two curves which are then connected to create a surface. For a repetitive task with minor changes, it is extremely useful.

1.3. Problem formulation

The problem of the traditional breakwater design approach is the time consumption of testing different breakwater designs in the early design phase. Most breakwater experts have made various tools in the form of excel sheets or MATLAB models. These tools calculate several breakwater configurations to compute the value for the crest height, width, sizes and diameter of different armour layers. To get a best overall design, different breakwater configurations are to be evaluated in these design tools. In this tool the calculations must be initialized manually, and several iterations must be performed to obtain the different conceptual designs. After determining these designs, they have to be drawn on paper or in a CAD (Computer Aided Design) program. This process is time-consuming in a traditional model and therefore expensive. Parametric designing can increase the efficiency in the design process by helping to identify the best type of design in the conceptual design phase fast in order to speed up the conceptual design phase (Abdullah & Kamara, 2013).

Next to the breakwater design process being time consuming, flexibility is an issue. The tools used by designers do not allow a last second change of parameters to explore bold and creative breakwater configurations. Parameters and input variables must be determined prior to configuration calculations. Only after the configurations have been exported can an analysis give insight into the mistakes present in the parameter set-up. A visual parametric design tool can help with this process as changes in input can be made at every step of the process, increasing the flexibility in designing, and a visualisation is present that helps finding mistakes and opportunities (Dino, 2012). With the increase in flexibility an extensive parameter study would be easier to conduct.

The current in-house tools make it difficult to identify the ideal location of the to be designed breakwater. As these tools are programming tools that present little to no visualisation, identifying the ideal place of the breakwater is difficult.

The problems can be summarised shortly into; the generation of different breakwater configurations consuming a large amount of time in unnecessary manual labour, the flexibility of parameters and thus exploration opportunities being limited, and the desired location being difficult to identify in the current breakwater design process.

1.4. Research objective and questions

The objective of this project is to investigate the influence of a parametric breakwater design tool on the design process of breakwaters by creating a parametric breakwater design tool in Rhinoceros + Grasshopper. This objective leads up to the main research question:

Main research question: Is parametric design beneficial in the breakwater design process?
Sub question 1: Which steps of the traditional breakwater design process can parametric design be applied to?
Sub question 2: How well does the generated breakwater of the parametric design tool resemble the conceptual breakwaters designed by experts?
Sub question 2.1: Would the designer be able to use the generated breakwater design to construct a breakwater?
Sub question 3: What aspects does parametric design improve in the breakwater design process?

To meet the objective certain research questions are formed to provide structure. The main question is formed to discover the benefits of parametric designing in the design process of breakwaters. The phenomenon of parametric designing is not widely applied yet in hydraulic engineering and therefore useful to investigate if a shift towards parametric designing would be a possibility to consider.

The first sub question is formed to identify the steps in the breakwater design process, which can potentially be improved by the appliance of parametric designing. In the designing of breakwaters different steps are taken to translate the functional requirements into a final breakwater design.

The second sub question is formed to analyse the practicality of the developed tool in the design process of a breakwater. It is important to investigate if the developed tool generates a design that resembles the final design made by experts. And if the tool allows for a conceptual design of which designers can base the final design off, it could contribute to the design process.

The last sub question is constructed to find out what aspects of breakwater designing are improved due to the parametric design tool. For parametric design to be beneficial in the design process, certain design aspects must be made easier to execute.

1.4.1. Scope

As creating, developing, and validating a model is a time-consuming iterative process, demarcation is applied to ensure a detailed and precise model is constructed opposed to a a universally applicable but incomplete model. The parametric breakwater design model will therefore focus on:

One type of breakwater, namely a conventional rubble mound breakwater, on the conceptual design phase, meaning that the generated design is a rough design set up with existing guidelines. Furthermore, the tool will not include geotechnical data as this is a separate phase in the design process.

This research is applied to one type of breakwater due to the universal nature of breakwater design. Each breakwater has different initial equations to determine the stability and its relationship with waves, however, they can all be translated into an algorithmic process. It is assumed that the answers to the research questions are applicable to all breakwaters but investigating this falls out of scope for this research.

The breakwater design process is expert dependent, meaning that expert judgement and testing comes in play with the design process. A parametric model taking over this task is therefore unlikely and would be untrustworthy. A parametric model is therefore more suitable for the conceptual design phase to be used with an expert analysing the results and making choices consequently.

Geotechnical data is not included in the breakwater design process, as changes due to this data are made after construction of an initial design is constructed based of hydraulic failure. In further research appliance may be useful.

2. Methodology

The objective of this project is to investigate the possible influence of a parametric breakwater design tool on the design process of breakwaters by creating a parametric breakwater design tool in Rhinoceros + Grasshopper.

The methodology of this research describes the methods used to answer the research questions that have been formed. A step-by-step method of answering the research questions is described.

Main research question: Is parametric design beneficial in the breakwater design process?

To answer the main question a variety of different sub questions are constructed. At first the traditional breakwater design process must be dissected to identify the steps at which parametric design can contribute. Together with expert opinions and knowledge a parametric design tool can be constructed. Its practicality and accuracy have to be verified and validated. When this is done the usefulness of parametric design in this design process can be analysed by having used the tool and evaluating the tool and results with hydraulic experts.

Sub question 1: Which steps of the traditional breakwater design process can parametric design be applied to?

To answer this question, several steps are taken. The different steps in the breakwater design process needs to be identified and understood. First literature research is performed to gain insight in the current breakwater design process that is in use. Next to this an interview with a project manager at IMDC with breakwater design experience is conducted, to explain the different steps taken in the design process and what the key elements and models are in it.

This interview aims to identify which computer models/tools are used for the different steps in this process and to complement the breakwater design process retrieved from literature. The used models are then investigated by internet research and information retrieved from the interviewee. To understand these models is important to identify which models/tools can be replaced or skipped by an inclusive parametric design tool. If the tool cannot be replaced or skipped it may be a useful link to the tool, the output of a used model could be an input for the to be developed tool or vice versa.

Furthermore, it is important to know the opinion and knowledge regarding application of parametric design to breakwaters from hydraulic and breakwater experts. This is important as breakwater designing does not follow a standard design procedure, and the most knowledge regarding designing is with experts who have a large resume. To gain this information from a substantial number without inflicting persuasion bias, a survey is constructed. This survey contains questions regarding their view on parametric design, on the appliance of it to breakwater designing and other questions to retrieve requirements and appliances of the potential tool. The constructed survey and respondents can be seen in Appendix A.

The information outlined in the paragraphs above is used to draw a conclusion regarding the applicability of a potential parametric design tool. The steps in the design phase which the model may contribute to, and which models it may replace.

Sub question 2: How well does the generated breakwater of the parametric design tool resemble the conceptual breakwaters designed by experts?

After determining the steps for which a parametric design tool can be developed, which aspects to incorporate, and to keep in mind regarding the development of the tool, this desired tool is constructed.

To develop a tool according to the needs of experts, a list of requirements is set up together with breakwater experts to acknowledge what the model must be able to do. In the development of a tool the design choices and assumptions are tracked and listed together with the model structure and the limitations of the model. The required input and output of the model is also described. These elements tell something about the validity and usefulness range of the model.

To construct a parametric design model, generative processes are required. In breakwater design there are certain design equations used retrieved from design manuals. The manuals used in breakwater engineering are mainly the Rock Manual, the Coastal Engineering Manual, and the Overtopping Manual (Ciria-Cur, 2007; The EurOtop team, 2018; US Army Corps of Engineers, 2012). Next to these manuals some equations from Gerding and van der Meer are used regarding toe stability (Gerding et al., 1993). A literature study is performed to retrieve the useful equations that can functions as an algorithmic process in the parametric design model. The equations and theory used can be seen in Appendix B.

The tool provides internal verification of equation use by producing a warning consisting of the equations of which the validity boundaries are not met, the choice is left with the designer what to do with this information as the equation boundaries are set up conservatively. Furthermore, the tool must meet the requirements, a reflection on these requirements must therefore be made as part of the verification process.

To validate the usefulness of the parametric design tool, the resemblance between a constructed breakwater by IMDC and the designed breakwater by the developed breakwater tool is compared in the form of rock-grading of the breakwater armour layer. The use case for the validation is the Elmina port expansion and rehabilitation project for the Ministry of Transport for the Government of Ghana. Rock size is distinguished in grading as not every piece of rock is the same size. A breakwater layer is constructed out of a range of rock sizes. The standard rock-grading is documented in the European Norm (*EN 13383-1 Armourstone*, 2013). The rock-grading influences the geometrical output of a breakwater as can be seen in Appendix B. With access to the documentation of the breakwater under construction at Elmina harbour, the exact location and input variables can be the same due same data importation used, which should let the tool construct a similar breakwater.

A benefit to the design process of breakwaters would be the increased flexibility, as this is an issue in the current breakwater design process as seen in section 1.3. With this increased flexibility a parameter study is performed with greater ease, which can show the influence of climate change on a breakwater design for example. The flexibility of the tool is validated by assessing the ability of conducting a parameter study and comparing this with the traditional method used.

Sub question 2.1: Would the designer be able to use the generated breakwater design to construct a breakwater?

Having gained information regarding the resemblance between the parametric design tool and a conceptual breakwater design, it is important to gain insight in not only the accuracy of the tool but the usefulness as well. The model may not be the most accurate due to a difference in theory, or early decisions based on construction practicality or expert judgement.

An interview will be conducted with breakwater designers at IMDC to evaluate the usefulness of the tool. The properties and results of the tool will be treated as well as its resemblance with the conceptual breakwater constructed by IMDC.

Sub question 3: What aspects does parametric design improve in the breakwater design process?

After having constructed and validated the parametric design tool, its usefulness must be identified. To investigate if the tool is useful, a reflection is performed on the current breakwater design to identify the addition to or replacement of steps the tool supplies. Together with breakwater designers, the opportunities of the tool in the breakwater design process are identified.

3. Breakwater design process

To gain insight in which part of the breakwater design process has the potential to be improved by a parametric design tool, literature research was performed to gain insight into this process. Together with interviews of breakwater designers, the traditional design process up until the preliminary design selection is described in section 3.1. During the process several models are used in order to aid the designer in the design process, these models and area of application are described in section 3.1.2 to identify, which models can be replaced or skipped. The view of breakwater experts regarding the application of parametric design on the breakwater design process is retrieved via a survey. The outcome of this survey together with the knowledge of the breakwater design process identifies the area of implementation

3.1. Current breakwater designing

To evaluate the potential benefits of parametric design on the breakwater design process, first an insight must be given into the current design process. As breakwaters are designed by different companies across the world, slight differences can be distinguished, however, there is a common systematic approach in the design process laid out by Henk Jan Verhagen in Breakwater Design (Verhagen van den Bos, 2017). In his laid-out approach, the designing starts at setting up the functional description of breakwaters and a system analysis, and ends at the construction phase of breakwater designing, it does not include non-technical aspects, including environmental, social and cultural values as this is hard to express in financial terms universally. Next to the literature research in the breakwater design process an interview is conducted with Jaap de Groot, a project manager at IMDC regarding the breakwater design approach adapted by IMDC and his former employer Arcadis. The breakwater design process is described until the selection of the preliminary design as the process after this does not follow a standard procedure and is location and breakwater dependent.

During the breakwater design process there are separate phases, the phase of which parametric design most likely has the most amount of influence is the preliminary design phase, in which a broad shape is given to the breakwater elements and the functionality and requirements of each element is set. Parametric design will apply to this phase, as in the next design phase choices are being led by expert judgement according to breakwater experts at IMDC. In this phase, optimizations of elements are performed, and physical model testing will indicate the changes necessary. Literature confirms that parametric design is applicable to the conceptual design phase of projects (Abdullah & Kamara, 2013).

In the preliminary design phase, a number of steps are taken in order for the best option to be selected at the end. This phase broadly consists out of an analysis of available data and setting up the functional and structural requirements of the breakwater. Hereafter different conceptual ideas of breakwater alternatives are generated by a design team based on these requirements. These ideas are then worked out in further detail via calculations and modelling. After this an assessment of alternatives is done to determine if they all fit the requirements and to compare the designs based on the costs and benefits. Finally, a decision is made to evaluate the design further for a detailed design.

3.1.1. Breakwater design steps

3.1.1.1. Functional requirements

In this design process, functional and structural requirements are set up by the client or in combination with a consultant. The objective of the design is to meet these set requirements. Within the design, the cost-benefit ratio and social and legal acceptance are factors that are important to include. This is however out of scope for the conceptual models as it can only indicate the cost based on the breakwater and location.

The system design requirements are based off the main purpose of the breakwater. Breakwaters can fulfil a variety of functions (Verhagen van den Bos, 2017). One of the functions of a breakwater is the protection against waves. This protection can be for several reasons, protecting vessels at berth, sailing vessels, port facilities or shore protection. Important is to know the degree of protection needed for these structures. A breakwater function is the guiding of currents, vessels that approach a harbour entrance reduce speed significantly due to the large stopping time required. At this time, the vessels are more vulnerable for currents, which can be guided by a breakwater. Furthermore, a breakwater can offer protection against shoaling. Shoaling is the phenomena where waves increase in height closer to the shore, due to the water level decreasing. A breakwater can protect an area against these waves and protect dredging work at the harbour for example. At last, a breakwater can assist in the provision of dock or quay facilities, in case of a breakwater protecting a harbour it is already quite large and the crest being of significant width. The breakwater can in this case be used for berthing of vessels and for transport of cargo.

Based on the functional requirements and the accompanied failure modes of the to be designed breakwater, the preliminary design phase can start. In Figure 8, the failure modes for a rubble-mound breakwater with crown wall are visualized.

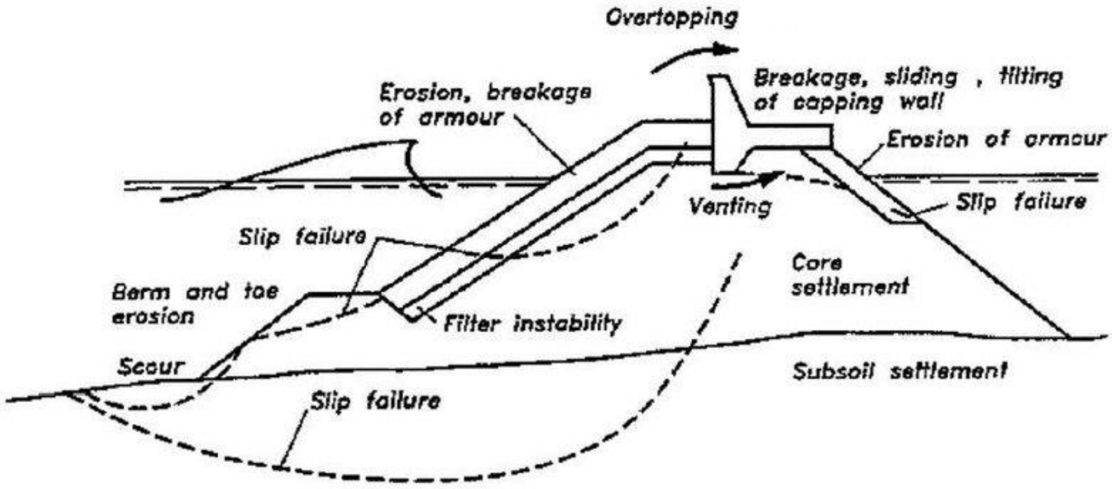


Figure 8: Rubble-mound breakwater failure modes (Burcharth, 1995).

The failure modes illustrated can be divided into different sections. Structural failure occurs with the breakage of armour or the breakage of the crown wall. Hydraulic instability occurs with erosion or filter instability. Hydraulic failure occurs with an overtopping rate that is too high and geotechnical failure occurs with too much settlement or slip failure. These failure modes interact with each other, toe erosion will increase the chances of armour erosion for example (Burcharth, 1995). To assure these failure modes do not occur, design guidelines are constructed making use of conservative empirical equations, these equations can be seen in Appendix B.

3.1.1.2. Wave, hydrological and geotechnical study

To design a breakwater that is structurally safe the wave conditions at the location of construction must be studied. Wave characteristics on short and long term for deep and shallow water are studied. Battjes and Groenendijk (2000) is used to obtain the wave-height distribution and obtain the

2% and significant wave height. In breakwater designing geotechnical stability is a large factor in the design of a breakwater, therefore a look is taken at the potential settlement and the stability of the breakwater slope. Settlements are not a main design driver for a breakwater. However, they may cause the need to add material in the future. To use these studies for the breakwater design phase, data must be collected. Meteorological data, geotechnical data, materials in the area, and hydrological data in the form of bathymetry, tides, storm surges and waves are all used to determine the best fitting design for the area in question.

3.1.1.3. Breakwater placement

After study of the area and the designers having obtained the data that is important for breakwater designing, the location of a breakwater is determined. This decision is based on minimising the costs while complying to the functional requirements. The costs mainly consist out of the breakwater itself, the dredging work required, and land reclamation required for the project. The required breakwater height indicates the size of the breakwater, which is dependent on the seabed level and water depth. These factors are based on the location of the breakwater. A good placement of the breakwater therefore assures that the system meets the functional requirements and minimises the breakwater size and thus costs.

3.1.1.4. Stability

The next step is to ensure the stability of the breakwater by ensuring that the loose elements of which the breakwater exists are stable. Breakwater instability can cause breakwater failure in diverse ways as illustrated in Figure 8. Slip failure, armour erosion, toe erosion, and instability of a breakwater layer are all caused due to lack of stability. A breakwater is constructed mainly out of randomly or uniformly placed rock mounds or concrete armour stones. These are placed on a sloping surface under wave attack, to create the wanted effect while maintaining stability and preventing failure of the system. With the functional requirements and wave characteristics known, the required equivalent cube size of the individual stones can be determined. To make this economically viable a fitting standard rock-grading from the European Norm is selected (*EN 13383-1 Armourstone*, 2013).

3.1.1.5. Wave-structure interaction

After the armour stability is determined the interaction between the structure and the waves can be determined. These interactions are measured in several forms: Wave reflection, wave run-up, overtopping, and wave transmission. These wave structure interactions are important to assess to evaluate if the designed breakwater meets the functional requirements. The functional requirements are partly based on the desired wave-structure interactions. One of the reasons could be to decrease wave strength at the port entrance. The reflected waves are the waves that change direction due to colliding with the breakwater, transmitted waves are the waves which have penetrated the structure, wave run-up and overtopping describe the height the waves reach on the breakwater. These interactions are visualized in Figure 9.

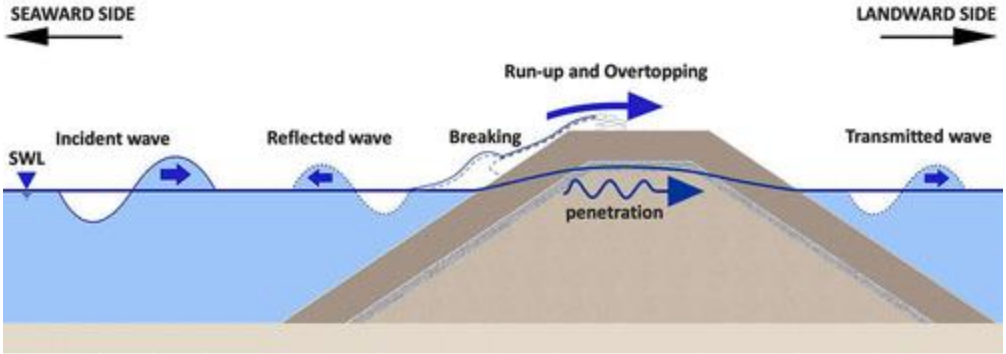


Figure 9: Wave-structure interaction for a rubble-mound breakwater (Vicinanza et al., 2019).

3.1.1.6. Breakwater cross-section designing

Hereafter in breakwater design, choices must be made by the designer while following the guidelines. A choice between a high or low-crest, rock or concrete armour units for example. Next to this the breakwater consists of several elements and for each of these elements, empirical equations or design guidelines are constructed. Figure 3 illustrates a typical cross-section for a rubble-mound breakwater with its elements. For the armour layer, crest, toe, scour protection, under-, filter- and core layers design guidelines are followed to obtain a first breakwater cross-section. The guidelines used are documented and elaborated upon in Appendix B.

3.1.1.7. Preliminary design selection

When multiple breakwater cross-sections have been designed by the breakwater experts with some creative freedom, it is time to select the best conceptual design. For this a trade-off matrix is used to perform a Multicriteria Analysis for the best cross-section to be selected based on certain design elements. Some of these elements are costs and the safety of the design, however the availability of quarry rocks in the area is also a crucial factor to take into consideration. The design that meets the analysis criteria the best will end up being the preliminary design. This design is to be used for the next design phases and sent to a CAD designer to be drawn.

3.1.2. Means to realize approach

In chapter 3.1 the current breakwater design process is sketched. An overview is given of the steps taken by a team to design a breakwater up until the preliminary stage. Design automation and research models are used in these steps to speed up the process and make the designed product more dependable. In an interview with project manager Jaap de Groot, the breakwater design process of IMDC is discussed and the means used to realize this design approach.

To identify at which steps of the current breakwater design procedure, parametric design could come in play, the tools currently used at these steps must be studied. For the different steps diverse types of models are used, most of them specialized in a certain niche. Per step it will be mentioned, what tool is used and why this tool is used at this step. Regarding the use of the models, it is important to implement hindcast modelling to see if the model is valid for the area in past times, and to perform an uncertainty assessment.

Wave study

As discussed in section 3.1.1.2 a wave study at the site where a breakwater is placed is necessary. Wave properties have major influence on the wave-structure interaction and the stability, thus shape and size of the breakwater, as can be seen in Appendix B. The SWAN (Simulate WAves Nearshore) model is used to model the nearshore waves at the site, derived from offshore data (Booij et al., 1996). From this model the wave height, period and direction are important parameters to be retrieved. To gain knowledge of the wave agitation and resonance at harbours before and after breakwater placement, the PHAROS model is used (Kostense et al., 1986). The PHAROS model is used to verify that the designed breakwater meets the functional requirements.

Hydrological study

Next to the study of waves, the hydrological conditions at a site must also be investigated. The reoccurrence and severity of storm surges and weather conditions can cause differences in sediment transport. This phenomenon together with wave-induced currents can be studied with MIKE21, a model that is developed to simulate these conditions (Warren et al., 1992). Next to this the TELEMAC model is used to simulate the nearshore circulation flow of the project area (Hervouet et al., 1991). The bathymetry of the area is studied via a bathymetry map, this is to gain insight in the required height of the breakwater at various locations and possible landfilling required.

Geotechnical study

The geotechnical conditions at a site are significant to be able to account for settlement of soil and the stability of the breakwater. A study into the geotechnical conditions at the site must therefore be performed. Plaxis is used to perform a deformation analysis of soil and rock, which means it is checked if the soil and rock deformation potential imposes any risks (Brinkgreve et al., 2016).

Cross-section design

With the conditions of the site having been studied a good overview is to be made by the breakwater expert. Using this overview certain design choices are made such as the slope, permeability and allowable damage to calculate the stability of the armour layer set in the Rock Manual and Coastal Engineering Manual (Ciria-Cur, 2007; US Army Corps of Engineers, 2012). This determines the rock grading necessary for the breakwater and from this point design choices can be implemented. These choices influence the toe, scour-, under- and filter layers which determines a complete cross-sectional breakwater design. The designer mostly has a self-made excel sheet or Python/MATLAB file with the equations of the breakwater guideline manuals included. Using this tool multiple configurations are designed and exported to be evaluated by the designer. The best constructed designs are then sent to a CAD-specialist that constructs a CAD-drawing of the cross-section.

Physical model testing

After an initial design has been established, it is most likely to be evaluated by undergoing a physical model test. The empirical equations used in the design of the breakwater involve a certain degree of simplification of the true situation. Furthermore, the breakwater is constructed at a unique location with its own bathymetry and wave conditions. If the breakwater to be designed is located at a new location or deviates significantly from the previous design, it is important to eliminate uncertainties. To eliminate the design uncertainties as much as possible the design will undergo physical model testing at a reduced scale. Guidelines for physical model testing have been constructed to universalise this process (Allsop et al., 2007).

3.2. Expert answers on parametric design survey

To gain further insight on the area in the breakwater design process, in which parametric design can be of use, a survey is created for breakwater experts. This survey contains questions regarding the opinion on design automation and parametric design, the potential application of parametric design on the breakwater design process, and the requirements and points of attention which must be kept in mind with the development and use of a parametric design tool. The survey and its respondents can be seen in Appendix A.

3.2.1. Opinion on design automation and parametric design

The overall opinion of experts on design automation is that it is a useful method of speeding up the design processes, making the design process more cost efficient. However, there are certain drawbacks that can occur with the appliance of design automation. One being that unique cases that do not follow the regular circumstances are overlooked and therefore the simplistic rules incorporated in the design automation have not considered all the design realities. Design automation can be extremely useful but must be used cautiously, and the results must be analysed by experts.

3.2.2. Potential application on breakwater design

Parametric design may have room in the breakwater design process according to a share of the breakwater expert respondents. A parametric design tool could help construct an initial design in the conceptual design phase and would be extremely useful to conduct a feasibility study. A cross-section design can be constructed by the tool once the base case and conditions have been derived.

Along with opportunities, there are hazards of the appliance of parametric design in the breakwater design process. It is very unlikely that you will be able to 'teach' the automation software all the reasons for breakwater failure according to an expert. A next hazard is the key decision point of the design tool, the choices made by the tool must be known to the designer for safe operation.

Another hazard that is mentioned is the potential loss of creativity due to a parametric design application. By having a system that generates designs automatically based on parameters, certain optimal parameters may occur for similar projects. Designers may get accustomed to this and not explore different options.

Prof. Van der Meer believes a parametric design tool cannot come up with an optimal design for a breakwater as designing is more than the application of equations. An optimal design saves construction costs, which are more than the costs of designing.

Prof. Allsop and Prof. Van der Meer have both indicated that parametric design application on breakwaters has been done as early as 1984. No documentation is available on constructed models as the models constructed along the years have never been used. Practical implementation was limited with the constructed models as the technology used was not as far developed yet.

3.2.3. Requirements and points of attention for a potential tool

If a parametric design tool is to be constructed for the breakwater design process, there are certain requirements and attention points that must be kept in mind during the development of such a tool. The parametric design tool must allow for a wide range of possible conditions to aid the designer in exploration of different situations. Furthermore, the tool must be easy to use but transparent at the same time. The designer must be in control and know which decisions are made by the parametric design tool. Next to this the designer must know when the parametric design tool gives an answer that may be unreliable for the designer to assess this and not follow it blindly. The parametric design tool must not only be useful for highly repetitive tasks but must also be versatile for different conditions.

3.3. Parametric design opportunities

From section 3.1 and 3.2 a conclusion can be formed regarding the potential of parametric design in the breakwater design process. Having an insight in the current breakwater design process and the view of experts on the application of parametric design has created a window of opportunity to explore the application in this specific field.

The opportunity of parametric design in the breakwater design process lays in the cross-section design phase. The empirical equations from the breakwater design manuals can be incorporated in the tool to construct an initial cross-section design. The parametric design tool can offer high flexibility by offering the ease of changing parameters and short computation time. The geometrical output of parametric designing would then not require the transition of the calculated design by the tool to a CAD-specialist.

The parametric design tool must be constructed for the conceptual design phase. With the equations guiding the initial breakwater configuration and the high flexibility of parametric design, it would be ideal for a parameter study. After the study is conducted an initial breakwater design is constructed for an expert designer to develop further. The tool will therefore not construct an optimised design, but rather an initial design for a designer to work further on.

The parametric design tool must be transparent and easy to use for the designer. It must warn the designer in the case of potential invalidity of the breakwater due to the equations used falling outside its boundary limits. This is to let the designer know when the output of the tool may differ from a real scenario. The importance here is the freedom of designer, in breakwater designing decisions are made with expert judgement due to the water-structure relations being unpredictable and only empirical relations being established (Verhagen van den Bos, 2017). In a research report of S. Winkel (2020) breakwater experts come forward in an interview that with breakwater designing the designer must always be in control of the designing method, and selection of the design to work further on due to the design being heavily dependent on several factors of which the significance is different in each project (Winkel, 2020).

4. Developing a parametric design tool

In Chapter 3, the area of opportunity for a parametric design tool is identified. This has set-up the first step in the development of the tool. This area alone is not enough to construct the parametric design tool and therefore a list of requirements and model assumptions have been constructed in section 4.1. During the development of the model, certain assumptions and design choices are made to further restrict the scope and keep the tool user-friendly. After construction, certain model limitations are identified which are listed in section 4.2.3.

4.1. Model requirements

Based on the parametric design advantages identified in section 1.2, the opportunities for breakwaters identified in chapter 3.3, and with breakwater experts from IMDC, the model requirements for the breakwater design tool are constructed.

1. The parametric design tool shall be able to design a conventional rubble mound breakwater with its required elements.
2. The parametric design tool must be made via visual programming software to let users unfamiliar with programming and the program use the tool.
3. The parametric design tool must allow a breakwater to be placed on inserted terrain data.
4. The parametric design tool must visualize the severest breakwater configuration in 3D, letting the designer opt for the largest equivalent cube length or highest crest freeboard.
5. The parametric design tool must allow change for every parameter and input condition.
6. The parametric design tool must be suitable for application in the conceptual design phase for exploration of different conditions, and locations.
7. The parametric design tool must include coordinate dependent wave characteristics for a suitable configuration to be made at the correct grid point.
8. The parametric design tool must be able to calculate multiple breakwater configurations for different wave conditions and be able export them for analysis.
9. The parametric design tool must show a warning if the requirements for the equations to be valid are not met.
10. The parametric design tool must include the volume of each layer in the breakwater to produce a cost indication.
11. The parametric design tool must allow total freedom of choice to the designer regarding input and parameters.
12. The parametric design tool must include hydraulic failure mechanisms for the design to be generated.
13. The parametric design tool must be well-structured and easy to understand and expand, this is so it can be further developed for more failure mechanisms and breakwater types.
14. The parametric design tool must produce a visual indicating the rock grading and the rate of overtopping at each section of the breakwater.

4.2. Development of tool

The requirements set are yet to be fulfilled by an existing design automation tool. A new tool therefore must be developed. For development, the CAD-software with visual programming plug-in Rhinoceros + Grasshopper is used. This tool is chosen as it is the leading software in parametric 3D-modelling of buildings and structures (Romaniak & Filipowski, 2018).The software gives a graphical visualisation so that the designer can keep up and intervene when designing and it includes a ton of useful scripted plug-ins (Kanaani & Kopec, 2015). During development of the tool, design choices and assumptions are made, the final model structure is defined, and model limitations discovered.

4.2.1. Model assumptions/Further scope

For the construction of a parametric breakwater model certain assumptions are made. Next to this further scope restriction is required to meet the time limit and for the model to be user-friendly. These assumptions are constructed in cooperation with breakwater experts from IMDC.

- The parametric design tool is designed for the conceptual design phase of the breakwater design process.
- The parametric design tool is developed and to be used in Rhinoceros + Grasshopper.
- The parametric design tool mainly uses deterministic equations in order for the computation time to be as little as possible, as this should be a benefit of parametric design.
- The parametric design tool assumes that the leeside is equivalent to the seaside for the designed breakwater.
- The parametric design tool assumes that all breakwaters have a toe at the end of the seaside slope only.
- The assessment of geotechnical failure and structural strength is not included in the parametric design tool.
- The parametric design tool assumes that the roundhead does not have a toe.
- The parametric design tool assumes the wave data for a configuration at a point is the SWAN point closest to the toe at the seaside.

4.2.2. Design choices

During construction of the model several design choices must be made, some are made due to the computation limits, some for user-friendliness, or because an extension of a certain function would have no practical use in the designing procedure. This section states the design choices that are made and motivates the reasoning behind said choice. These design choices are made during construction of the model and in cooperation with breakwater experts from IMDC.

- The equivalent cube length equation used is selected by the design tool dependent on the validity ranges of the equation. If for a certain armour material, the validity is not met the equation will still be used and produce a warning. The designer does not have influence on what equation is selected.
- If the armour layer is chosen to exist out of concrete armour units, no grading is applied to them. The calculated value is the end-result.
- The concrete armour units can only be applied to the armour layer and the roundhead, the filter- and core-layers consist out of rock.
- The local wavelength calculation is an iterative process, in the model the definitive local wavelength is defined if the previous iteration differs less than 1 mm in length. This is found to be a precise but not an extreme time-consuming value.
- The 2D configuration settings in the model are applied to all 2D configurations in the breakwater. Making a distinction between sections would be possible but is not implemented in this model.
- The rock grading selected for a layer of the breakwater configuration is based on the median mass lower limit from the EN-13383-1 European guideline (*EN 13383-1 Armourstone*, 2013). The designer cannot select a diverse selection method unless they alter the coding.
- The model shows the entire breakwater from top to bottom instead of showing only the section above water level. This may look unnatural due to the satellite image as background.

4.2.3. Model limitations

During construction and testing of the model certain limitations come forward. These limitations are necessary to describe for the user of the tool to acknowledge the model limits. Some important model limitations are:

- Exporting the 2D configurations neat and in order is only possible via a programming plug-in, in this case python. This is due to certain parameters being consistent for every configuration and certain parameters being different. This python plug-in uses Ironpython 2.7, which cannot import pandas, the most used python data analysis tool. Due to this the configurations are saved in a nested dictionary and exported to a .csv file. In a CSV file, multiple sheets are not possible and therefore it is chosen to export the input configurations separate from the output.
- The data must be converted to a dictionary to be able to be structured and exported for multiple configurations. Therefore, data needs to be prepared after exporting to manually remove the brackets for the first and last parameter before statistical analysis can be performed.
- The parametric design tool uses SWAN-data as input to generate a breakwater. This data is however first converted by an in-house tool to present the data in an excel format, after which it can be conveniently imported.
- The starting z-value for the modelled breakwater is set in the middle of the breakwater cross-section. The starting height of the breakwater is retrieved from the nearest grid point. The breakwater will therefore not match perfectly with the bathymetry used in the model.
- The model uses a function called closest point, which searches the closest point to the designed curve and takes the sea characteristics of that point. This closest point function takes the severest Dn50/Rc characteristics of one point and is therefore as accurate as the grid resolution. If the grid-resolution is too big, calculations may be an inaccurate representation.
- The parametric design tool can compute a significant amount of data at a fast rate, however there is a limit number after which the model crashes. The model calculates the configurations within one second up until around 1000 configurations. In case of a SWAN output file with a considerable number of configurations manual filtering is necessary for the parametric design tool to operate efficiently.
- The parametric design tool only takes a single grid point into consideration for its configuration calculation. This while another grid point may be almost as close. The wave characteristics used may therefore differ from a real case scenario.
- The parametric design tool is only able to design one breakwater at a time. This is opted for due to the time restriction in this research. If the parametric design tool is to be applied for a port development project, it would be extremely useful to design multiple breakwaters in the same interface. The Elmina port expansion and rehabilitation project consists of two breakwaters for example.
- The parametric design tool allows import of a coastal boundary shape file of the location at which the breakwater is to be designed. The imported satellite image and SWAN grid points are then manually scaled to fit the coastal boundary. A slight scaling error may therefore be present, however, if done correct, will not be significant.

4.3. Model structure

To effectively build a model, the structure must be clear to the model creator. To create the parametric design tool, an illustration of the internal structure has been made, which fits the requirements set in section 4.1. During the process of creating the model this overview will assist in the implementation of processes and parameters. Figure 10 shows the block diagram of the structure.

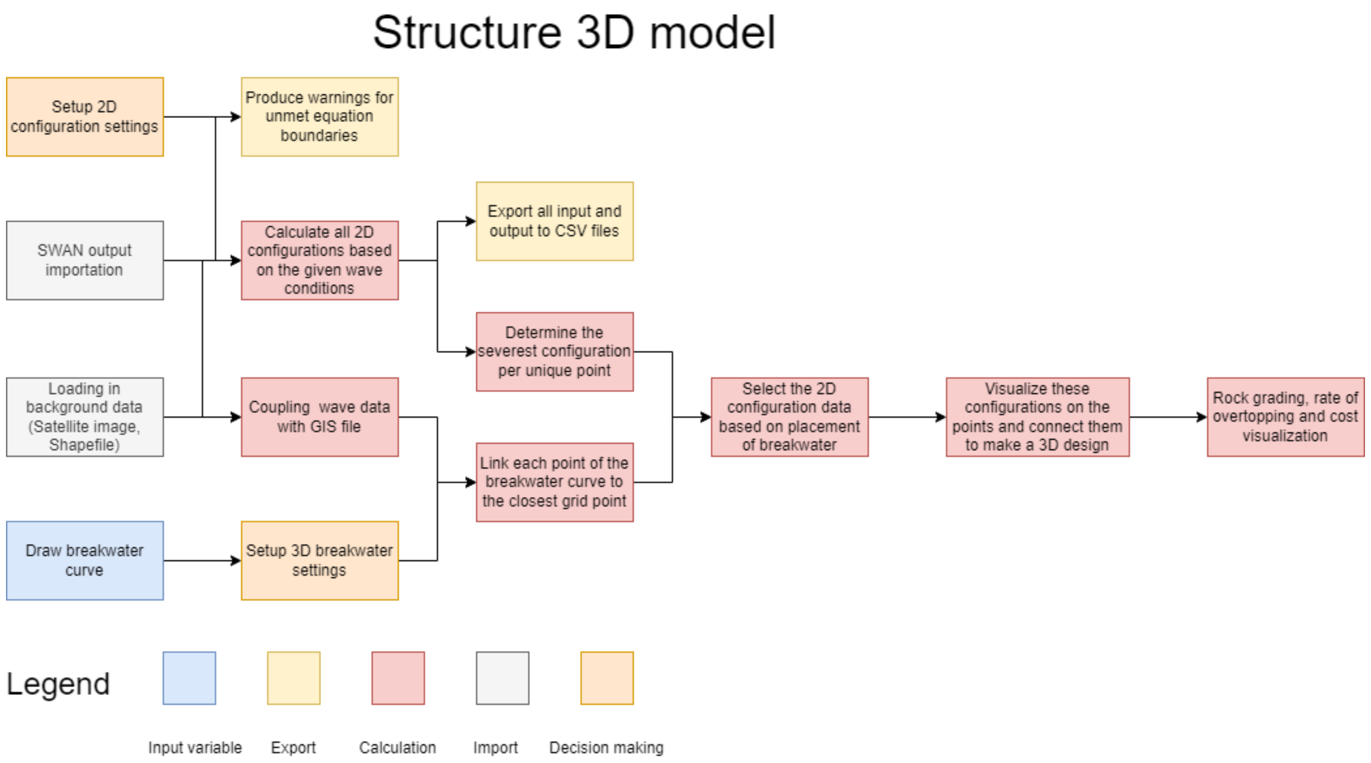


Figure 10: Block diagram representing the parametric breakwater model structure.

4.3.1. Import/Input variable.

SWAN output importation

In the model a CSV file must be imported containing output data of a SWAN (Simulating WAves Nearshore) model that is constructed based on the location of the project. This file must contain the water level, spectral significant wave height, wave periods and wave direction. These variables are all required to compute a valid breakwater cross-section design at the project location.

Background data

A satellite image is imported and linked to the coordinates of the SWAN data to create visual support for the designer. This layer gives an overview of the potential placing of a breakwater and allows the designer to place the breakwater precisely. GIS data in the form of coastal boundary shape file is imported as well to import the correct scale of the project area and fit the grid and satellite image to this boundary layer.

4.3.2. Setup

Draw breakwater curve

After having completed the previous steps, it is important to draw a breakwater curve at the desired location. This curve must be drawn in the Rhinoceros interface and matched to the curve parameter in Grasshopper.

Setup 2D configuration settings

To calculate a 2D breakwater configuration, a lot of calculations need to be performed that require data regarding wave characteristics, materials and geographical input. In the breakwater model it is important to setup the breakwater configuration settings correctly to project your desired result. An overview of 2D configuration parameters can be found in Appendix B.

3D breakwater setup

Next to 2D, 3D settings must be initialized, these are to distinguish the sea and lee side of the breakwater and the amount and placement of roundheads. Next to this a choice can be made regarding the severest configuration, whether it is based on the highest crest freeboard or largest equivalent cube length, and the number of meters between the 2D configurations can be chosen.

4.3.3. Calculations

2D calculating configurations

The SWAN output data delivers multiple wave characteristics per point as the same conditions do not apply every time of the day. For each scenario at every point a configuration is calculated.

Finding severest configuration

The most interesting configuration to visualize in Rhinoceros is the most extreme configuration, which means the largest equivalent cube length or highest free crest board, which translates into the largest armour layer and width. For the unique locations, the calculated scenarios must be analysed and the severest configuration for that point is selected.

Finding nearest points

As the breakwater curve is drawn and is divide in an x number of points separated by the distance chosen between configurations. The location of these points defines the 2D configuration of that point. The closest SWAN grid point is searched for this point and the most severe wave conditions are selected for this point to be visualized at this location.

4.3.4. Model output

Configuration export

The 2D configurations, which are calculated in the model can be exported by the model as well. The output of a configuration will be exported to a spreadsheet file. This data is then ready to be used for statistical analysis.

3D visualization

The 2D configurations are linked to each other by extrusion, the height of all the configurations is the same as this is dictated by the maximum required height of one location. The armour and filter layers differ in size per section. The difference in size is filled by the core layer as this consists of the cheapest material.

Breakwater indicators

Next to the visualization, important characteristics are visualized in the rhino viewport, for the designer to see immediately. These characteristics are the rock grading, rate of overtopping per section, and the total volume per layer of the breakwater.

5. Applying a breakwater design tool

In this chapter the constructed parametric design tool is applied to a case. This case is a port project executed by IMDC in Elmina, Ghana. In this chapter the use case is described shortly, a demonstration of the tool is given, and the results of the verification and validation are evaluated.

5.1. Context of breakwater case

The project that is used for the validation case is the Elmina fishing port rehabilitation and expansion project. It is assigned by the Ministry of Transport of the Government of Ghana and is currently being executed by IMDC. A small context is given in this chapter to give a representation of the calculations and breakwater case used for the demonstration and validation of the parametric design tool. The information of this project is provided by IMDC via personal communications.

5.1.1. Reason of project

For every project that is to be conducted, several constraints and opportunities can be translated to the design requirements. These design requirements are then worked out in more detail, based on these requirements several conceptual designs can be made.

5.1.1.1. Constraints

Small-scale or artisanal fishing and related activities provide to Elmina considerable direct and indirect employment, engaging residents as well as migrants and incorporates subsistence and commercial fishing. According to the local Fisheries Association, the fishing industry would be responsible for over 60% of the employment in Elmina. However, the town has lost employment opportunities to neighbouring cities as Cape Coast and Takoradi where bigger vessels and more modern equipment are deployed. Deep sea and tuna vessels with freezer can currently not operate form Elmina harbour.

Figure 11: Elmina, Ghana located in Africa (Google, 2022)

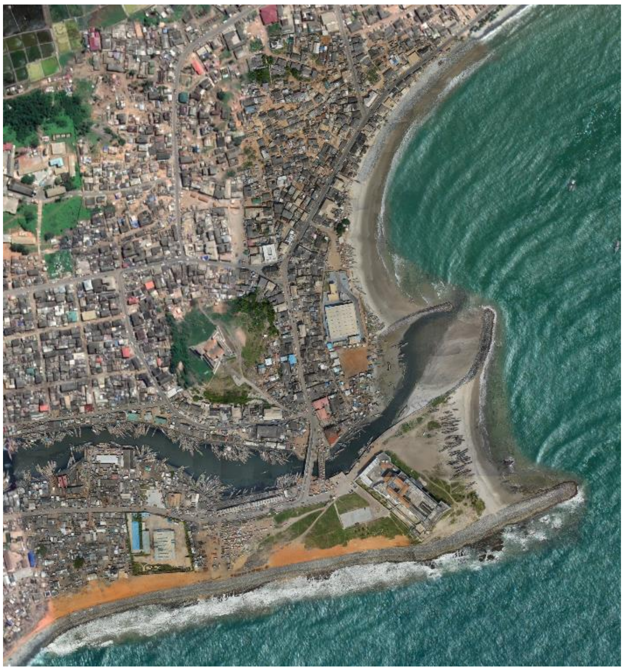


Figure 12: Satellite image of Elmina port prior to expansion and rehabilitation project (IMDC, 2021)

Next to the current constraints in the Elmina harbour environment, opportunities of (economic) growth can be identified. Elmina remains a town with pre-existing aesthetic appeal, and huge development potential. The fishing industry will benefit from added port development, and the heritage and living culture evident in town hold enormous potential to make Elmina a major tourism destination.

The provision of a new port outside of the river mouth will set up a second node of fishing trade and support activities. In effect there will be a dual harbour: the original fishing harbour within the lagoon, serving predominantly the traditional canoes and a new outer harbour with capacity to serve not only canoes, but also larger vessels. The new outer harbour also provides an opportunity to modernise the fishing industry, with access to improved trading and processing opportunities, and added support infrastructure for the manufacture of boats and the maintenance of boats and nets.

5.1.1.2. Port layout

The constraints and the opportunities are used to set up the requirements regarding the rehabilitation of Elmina fishing port, these requirements are determined by IMDC and documented in the concept design report.

The layout of a port is to a significant extent determined by its water area. This includes the orientation and alignment of the approach channel, the manoeuvring areas within the breakwaters, anchorage, turning circle/basin and port basin for the actual berths. These dimensions are of importance because they constitute a major part of the overall investment and because they are difficult to modify after once the port has been built. The port basin can be defined as the protected water area, which should provide safe and suitable accommodation/berthing for vessels. In Figure 13 one of three conceptual designs of the Elmina port layout can be seen.

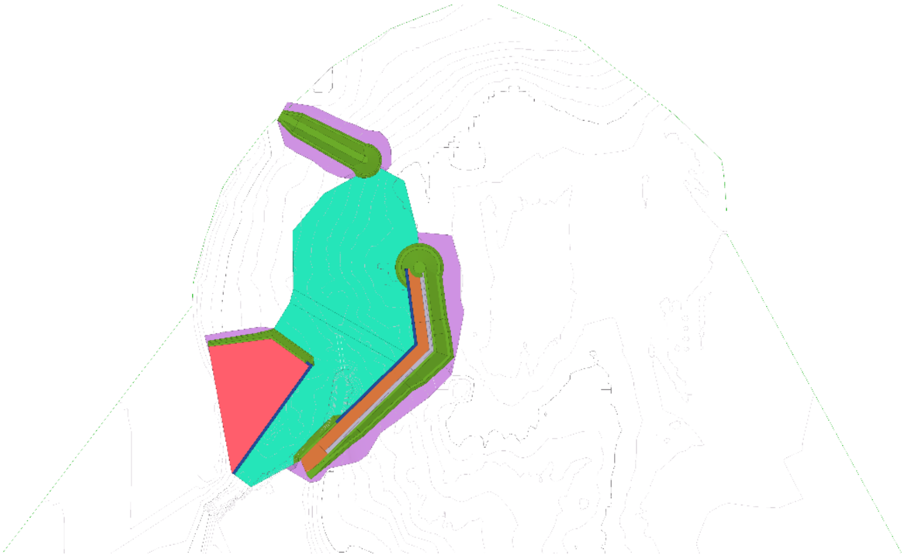


Figure 13: Top view of a conceptual port layout design (IMDC, 2021)

5.1.2. SWAN model

For the Elmina case, a SWAN model is used to simulate the nearshore waves at the lagoon (Booij et al., 1996). The settings, input and boundaries are project specific and therefore mentioned in this section for context.

SWAN (Simulating WAves Nearshore) is a model frequently used in the study of waves near coastal areas. SWAN Is a realistic wave model that computes nearshore wave parameters based on given wind-, bottom-, and current data. It Is a third-generation wave model based on the wave balance equation incorporating losses (Booij et al., 1996).

In this research SWAN is used to retrieve several location specific wave data which are listed below:

- Spectral significant wave height, H_{m0}.
- Bathymetry, d.
- Water level, h.
- Peak wave period, T_p.
- Mean wave period, T_m.
- Spectral wave period, $T_{m-1,0}$.
- Mean wave direction, (°).

SWAN wave modelling using 2008 bathymetry data has been undertaken for the conceptual design phase. The modelling has provided 100-year joint probability wave and water level conditions at the toe of the structures.

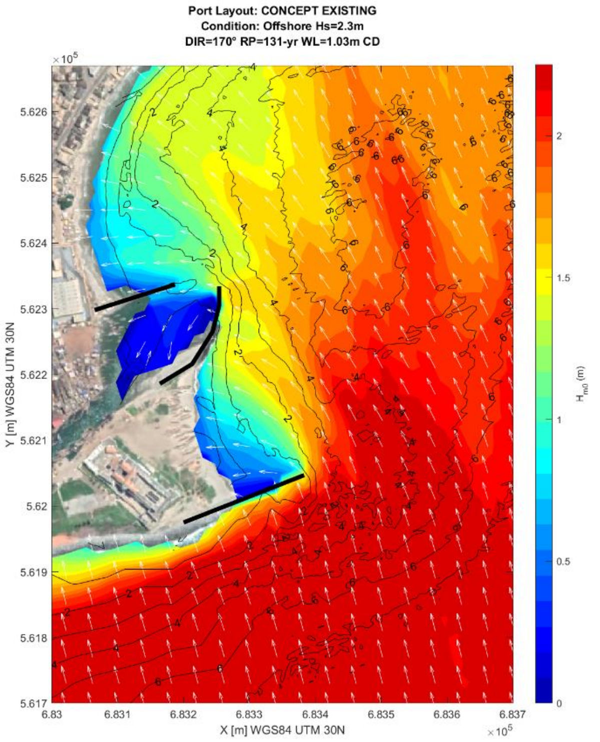


Figure 14: Existing port layout modelled in SWAN (IMDC, 2021)

In Figure 14 the old port layout is modelled in SWAN roughly to get an idea regarding the waves nearshore in the Elmina harbour. As a detailed wave agitation analysis into the harbour is pending, during conceptual design phase a minimum significant wave height Hm0 of 0.5 m is considered for the inner side of the harbour structures.

5.2. Demonstration of parametric design tool

In this section, a demonstration of the constructed parametric design tool is given. In Figure 15, Figure 16, and Figure 17, The output of the model is visualized in Rhinoceros CAD-software. The distinction between sections of the breakwater is visible with notable differences between them.

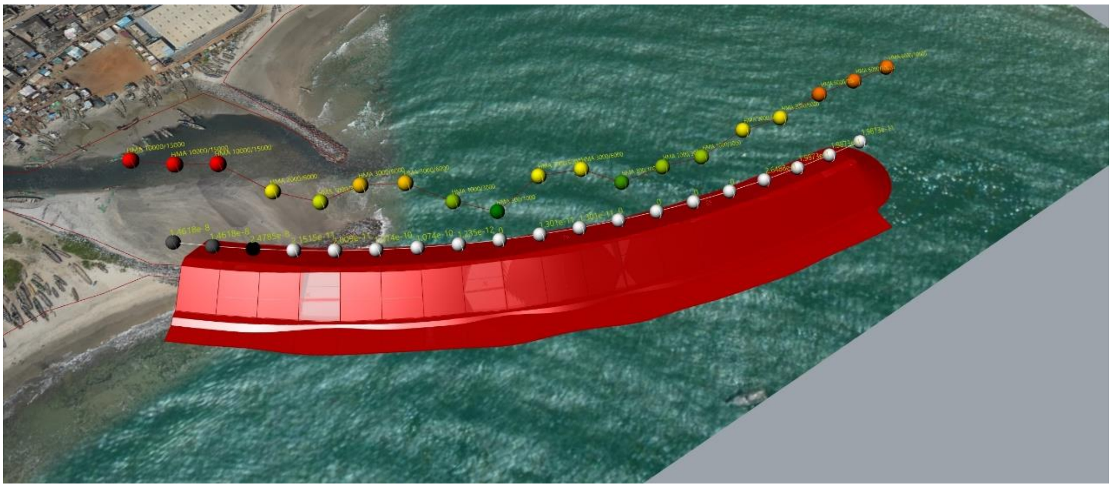


Figure 15: Close-up of projected breakwater design.

In Figure 15 a generated breakwater design can be seen. Above the breakwater two graphs are shown to directly communicate two important design characteristics to the designer. The top graph indicates the rock-grading at each cross-section ranging from green being the smaller grading and red a heavier grading, this gives the designer an impression of the costs and geometry of each breakwater section. The bottom graph presents the rate of overtopping at each section of the breakwater indicating its safety.

Figure 16: Top-view visualized output.

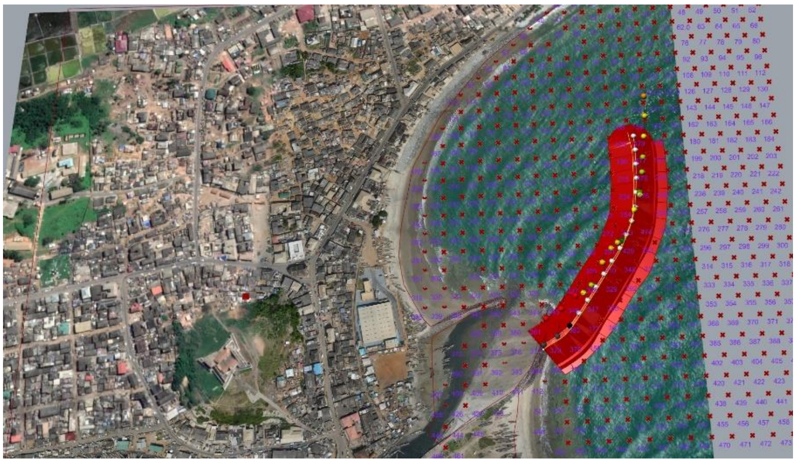


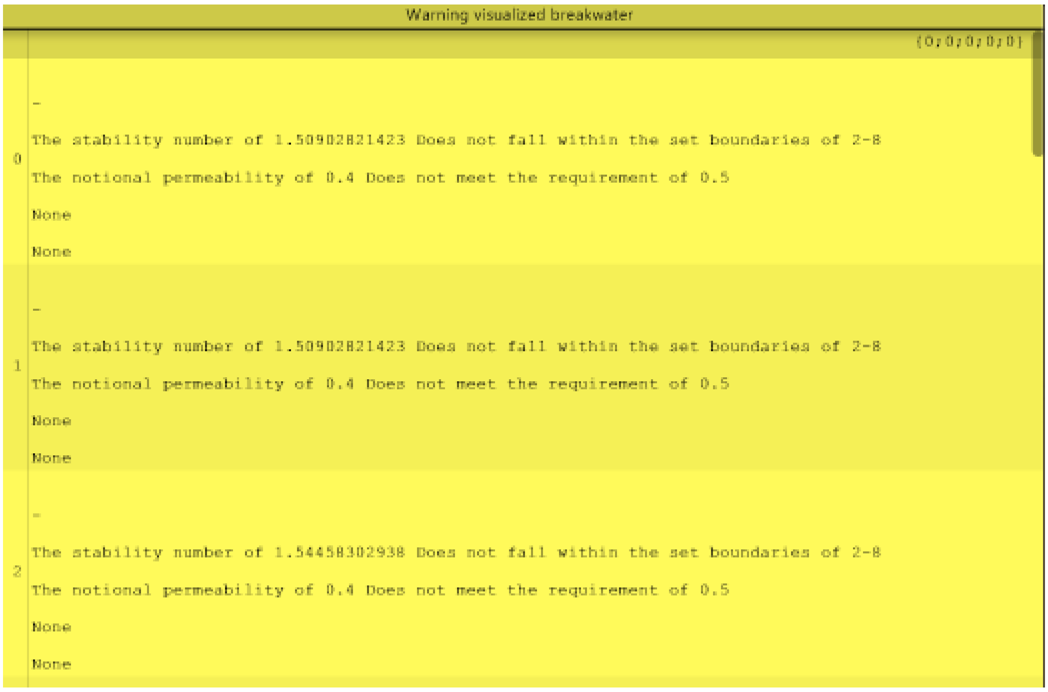
Figure 17: Angled-perspective visualized output with SWAN-grid.

5.3. Model verification

For a model to be utilized, it must fulfil the requirements, which are set beforehand, in this case set in section 4.1. The model must not limit the designer. However, it must produce a warning to aid the designer in the design process. This will be discussed in subsection 5.3.1. The fulfilment of requirements will be assessed in subsection 5.3.2.

5.3.1. Internal warnings

Per calculated section of the breakwater a warning is generated. This warning presents the boundaries of the equations used in the algorithmic process, which are not met. In Figure 18 an example of the generated warnings is given. These warnings are visualized in the canvas of the model. The designer can therefore see the warnings at the moment of designing. These warnings do not interfere with the design process, it is the choice of the designer to respond based on these warnings. These warnings are customizable for location specific requirements if necessary.



```
  -
  The stability number of 1.50902821423 Does not fall within the set boundaries of 2-8
0
  The notional permeability of 0.4 Does not meet the requirement of 0.5
  None
  None

  -
  The stability number of 1.50902821423 Does not fall within the set boundaries of 2-8
1
  The notional permeability of 0.4 Does not meet the requirement of 0.5
  None
  None

  -
  The stability number of 1.54458302938 Does not fall within the set boundaries of 2-8
2
  The notional permeability of 0.4 Does not meet the requirement of 0.5
  None
  None
```

Figure 18: Generated warnings regarding breakwater cross-section design.

5.3.2. Verification of requirements

At this section, a reflection is done on the requirements set up at section 4.1, to verify the functionality of the constructed parametric design tool.

1. **The parametric design tool shall be able to design a conventional rubble mound breakwater with its required elements.**

   The parametric design tool can generate a rubble mound breakwater with rock and multiple concrete armour units as armour layer. The equations and parameters used to complete this can be seen in Appendix B .

2. **The parametric design tool must be made via visual programming to let users unfamiliar with programming and the program use the tool.**

   The parametric design tool is constructed via a visual programming tool named Grasshopper. This tool helps regarding the structure and simplicity of the parametric design tool. The canvas for the programming can be seen in Appendix C.2.

3. **The parametric design tool must allow a breakwater to be placed on inserted terrain data.**

   The parametric design tool can only be used with a SWAN-grid inserted containing terrain related data. In Figure 17 the model output can be seen with numbered grid points containing terrain specific data in the background.

4. **The parametric design tool must visualize the severest breakwater configuration in 3D, letting the designer opt for largest equivalent cube length or highest crest freeboard.**

   The parametric design tool processes the different wave conditions per point and selects the severest breakwater configuration to visualize as seen in section 4.3.3.

5. **The parametric design tool must allow change for every parameter.**

As can be seen in the model documentation in Appendix B, all input and parameters can be changed by the designer. The local wave characteristics imported into the model can be varied as well via the implementation of a multiplication factor.

6. **The parametric design tool must be suitable for application in the conceptual design phase for exploration of different conditions, and locations.**

   The parametric design tool is universally applicable due to the use of local wave characteristics. These characteristics are imported via a SWAN output file. Together with the option of satellite image and shapefile import which can be seen in Figure 17, This tool can be set up for every location.

7. **The parametric design tool must include coordinate dependent wave characteristics for a suitable configuration to be made at the correct grid point.**

   The parametric design tool makes use of a SWAN-output file containing a point grid. This point grid has xyz-coordinates along with the wave characteristics used in the tool. The wave-characteristics used can be seen in Appendix B, section 1.

8. **The parametric design tool must be able to calculate multiple breakwater configurations for different wave conditions and export them for analysis.**

   As seen in section 4.3.3, the parametric design tool can calculate a configuration for each individual set of wave conditions and export them to a spreadsheet file to use for further analysis.

9. **The parametric design tool must show a warning if requirements for the equation to be valid are not met.**

   The parametric design tool produces warnings if boundary conditions of the equations used are not met as can be seen in section 5.3.1.

10. **The parametric design tool must include the volume of each layer in the breakwater to produce a cost indication.**

    The parametric design tool includes a calculation of the volume per layer over the entire breakwater as can be seen in the model canvas in Appendix C.2. and in the model structure at section 4.3.4.

11. **The parametric design tool must allow total freedom of choice to the designer regarding input and parameters.**

    The model does not make any choice of parameter and input of the breakwater configuration except for the rock grading, which it automatically chooses based on requirements set by the designer. This process can be seen in Appendix B, section 2.2.

12. **The parametric design tool must include hydraulic failure mechanisms for the design to be generated.**

    The parametric design tool uses hydraulic failure mechanisms to determine the acceptable geometrical design output based on a requirement set by the designer. The hydraulic failure mechanisms for which the model bases its output on can be seen in Appendix B.

13. **The parametric design tool must be well-structured and easy to understand and expand, this is so it can be further developed for more failure mechanisms and breakwater types.**

The parametric design tool is structured according to the set-up model structure in section 4.3. This set-up makes a clear distinction between import, set-up, calculations and output and can be seen realized in the model canvas in Appendix C.2.

14. **The parametric design tool must produce a visual output indicating the rock grading and the rate of overtopping at each section of the breakwater.**

    As can be seen in section 4.3.4 and Figure 15, a graph is projected above the breakwater indicating the rock grading and rate of overtopping at each section.

5.4. Model validation

A validation of the parametric design tool is necessary to conclude if the tool functions well and can be used in the practice of breakwater designing. The validation aims to identify if the parametric design tool projects a valid result. This is investigated by checking if the rock-grading the tool projects is the same as the inhouse tool projects which is used by IMDC. Furthermore, the flexibility will be investigated by comparing the conductibility of a parameter study with a current method used by IMDC.

5.4.1. Model validation set-up

To validate the parametric design tool, the conceptual breakwater design designed by IMDC for the Elmina rehabilitation and port expansion project must be replicated in the tool. In Figure 19 the SWAN grid used for the Elmina project can be seen, each grid point is numbered to distingusih them. In Figure 20 the grid points with identification number are shown, which are closest to the breakwater's seaside toe. Due to the SWAN grid export file missing some points, the identification numbers from the parametric design tool will not correspond with the grid points visualized in Figure 19. The correct breakwater curve must be identified manually to replicate the Elmina breakwater in the parametric design tool.

Figure 19: Elmina SWAN grid with breakwater outline (IMDC, 2021).

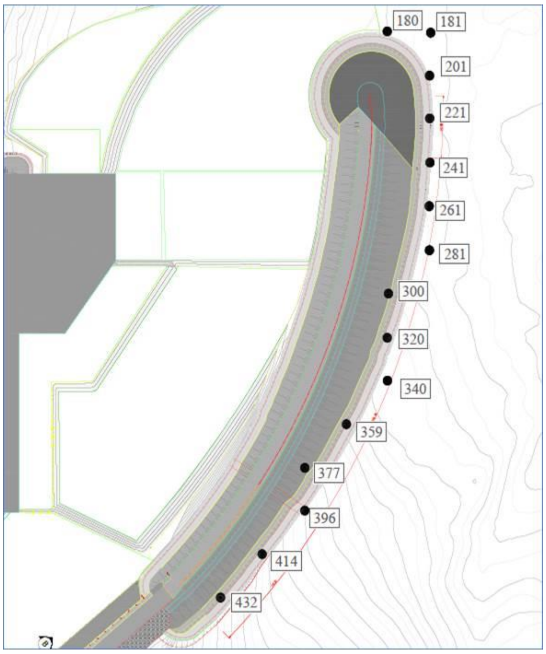


Figure 20: Breakwater design with closest SWAN point to the seaside toe (IMDC, 2021).

With the breakwater sketched in the tool, the 2D configuration parameters must correspond to those used in the breakwater design process of the Elmina project. In Table 1 the parameters used in the conceptual design of the Elmina breakwater are listed.

Table 1: Parameters conceptual design Elmina breakwater.

Parameter/Input	Value
Rate of overtopping (q)	1 $l/s/m$
Number of filter layers	1
Permeability factor (P)	0.4
Storm duration (D)	12 hours
Density of stone (ρ_s)	2650 kg/m^3
Density of water (ρ_w)	1030 kg/m^3
Damage level (S)	2.0
Plunging and surging coefficient shallow water conditions (C_{pl}, C_s)	7.25, 1.05
Plunging and surging coefficient deep water conditions (C_{pl}, C_s)	5.5, 0.87
Ratio armour layer/ underlayer	10 - 15

With the set-up being finalized, the breakwater configurations are calculated and the severest configuration per point is identified. The configurations are projected and connected to form a 3D breakwater.

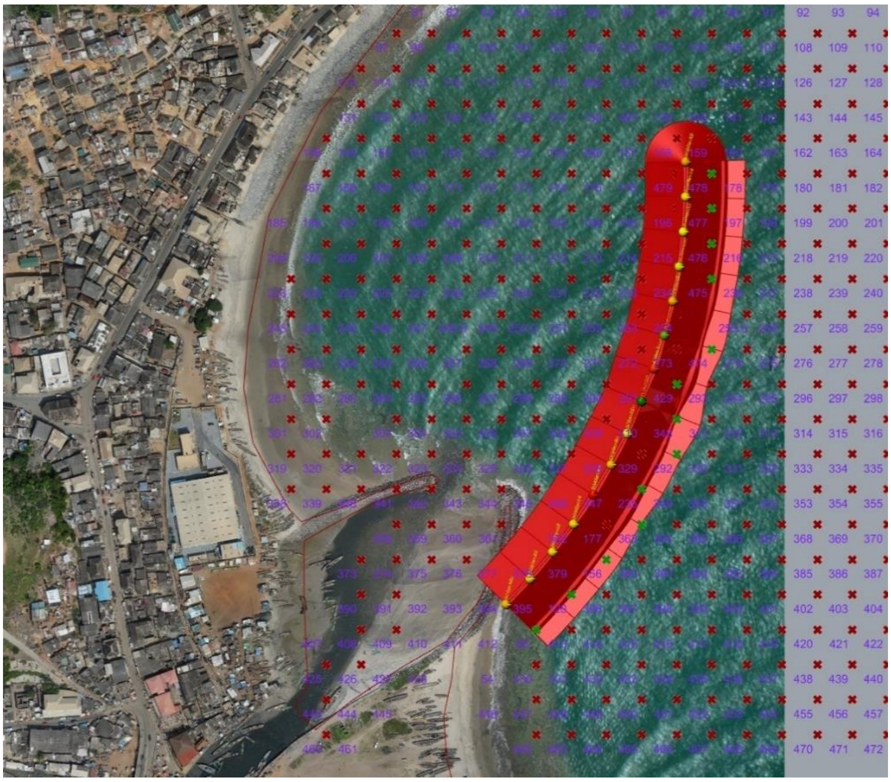


Figure 21: Replicated breakwater in the parametric design tool.

In Figure 21 the replicated breakwater can be seen. The closest points of the SWAN grid, which the by IMDC designed breakwater reaches are also reached by breakwater designed by the parametric design tool.

5.4.2. Rock grading

A form of validation is to investigate the similarity of the rock grading between the in-house tool of IMDC and the result of the parametric design tool. If the theory is consistent, the resulting rock grading must be similar. Figure 22 shows the replicated breakwater with the corresponding rock-grading per cross-section.

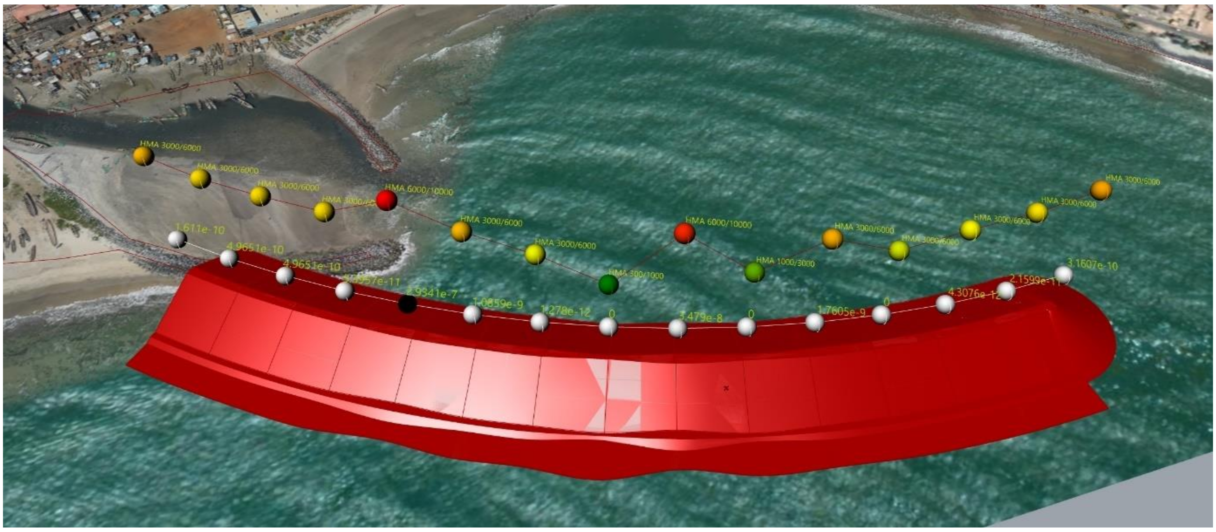


Figure 22: Replicated Elmina breakwater with visualized Rock-Grading per section.

The theory used in the conceptual design of the breakwater designed by IMDC differs slightly from the theory used in the parametric design tool. The difference cannot be stated in this report due to the Elmina project being under construction during this research. Having obtained the rock-grading per cross-section of the parametric design tool it can be compared to the rock grading per SWAN grid-point calculated by the in-house tool of IMDC, which is documented in the conceptual design report of IMDC.

Table 2: Rock-grading similarity.

Point (SWAN –Excel)	Rock grading IMDC	Rock grading tool	Valid
85 - 88	3-6T	3-6T	✓
120 - 307	3-6T	3-6T	✓
156 - 1215	3-6T	3-6T	✓
363 - 915	3-6T	6-10T	✗
235 - 595	3-6T	3-6T	✓
292 - 737	3-6T	3-6T	✓
348 - 877	0.3-1T	0.3-1T	✓
429 - 1066	3-6T	6-10T	✗
474 - 1173	2-4T	1-3T	✗
475 - 1175	3-6T	3-6T	✓
476 - 1178	3-6T	3-6T	✓
477 - 1180	3-6T	3-6T	✓
478 - 1183	3-6T	3-6T	✓

As seen in Table 2, the rock-grading calculated by the in-house tool yields results similar to the parametric design tool. The rock-grading is measured in weight with the ‘T’ being an abbreviation for ton. Three out of thirteen results do not correspond well, this is to be explained by the difference in model theory, however, some results are overestimated by the parametric design tool and some results are underestimated, making it difficult to pinpoint the exact cause.

The rock grading retrieved from the parametric design tool might differ from the result of IMDC in their conceptual design. The SWAN data was filtered before use in the parametric design tool as the tool cannot manage the amount of data points provided. This matter does not influence the rock-grading validation in this section.

5.4.3. Parameter study

The flexibility of the parametric design tool is important. A supposed benefit of parametric designing is the increased flexibility of the tool, allowing for more parameters and input values to change as mentioned in section 1.2. The ease to conduct a parameter study is an effective way of measuring this flexibility.

5.4.3.1. Current parameter study

The current method of a parameter study is via excel sheets. An excel sheet is used to compute certain breakwater output, to conduct a parameter study these sheets are copied and these outputs are calculated for different parameters and the output can be compared. This parameter study can only be conducted however per cross-section and therefore it is most likely that a single cross-section will be varied by the change of a parameter. Expanding it to multiple cross-sections would end up in a lot of sheets to be used and requires a substantial amount of manual labour. A typical traditional parameter study would end up in a graph like the one displayed in Figure 23.

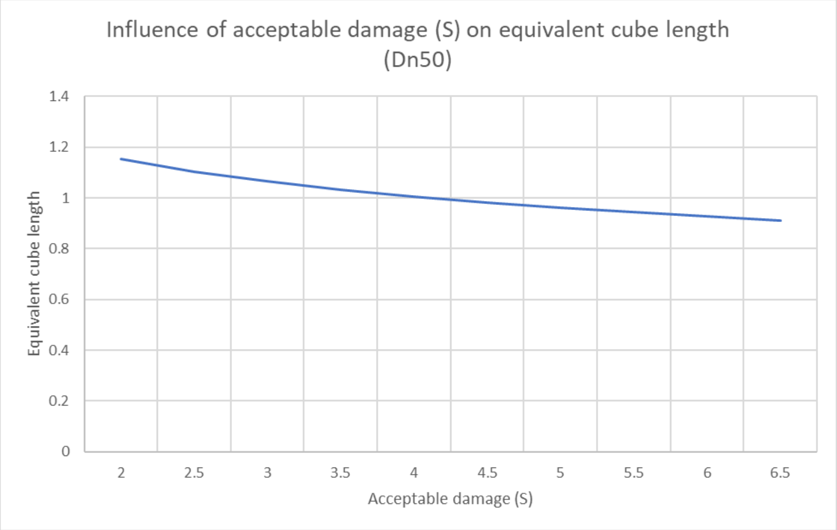


Figure 23: Traditional parameter study.

The graph presents the relation between the equivalent cube length of the armour layer (Dn50) against the acceptable damage (S) of a breakwater cross-section. In this case a single cross-section based on a SWAN-grid point is analysed.

5.4.3.2. Parameter study by parametric design tool

The parametric design tool allows for quick generation of designs and the change of every parameter as confirmed in section 5.3.2. The parametric design tool produces all the configurations in rows below each other and the versions of these configurations in the same row, producing a matrix containing different versions of configurations based on a parameter. The data export structure is shown in Table 3.

Table 3: Structure of parametric design tool data export for parameter study

	Parameter 1	Parameter 2	Parameter 3
Configuration 1	Output 1.1	Output 1.2	Output 1.3
Configuration 2	Output 2.1	Output 2.2	Output 2.3
Configuration 3	Output 3.1	Output 2.3	Output 3.3

This data structure can then be used for an extensive parameter study by analysing the change in the output of multiple configurations. In Figure 24 the equivalent cube length of the amour layer (Dn50) against the acceptable damage (S) of a breakwater cross-section is projected similar to the traditional method, however, the parametric design tool allows this to be performed for multiple configurations of a constructed breakwater.

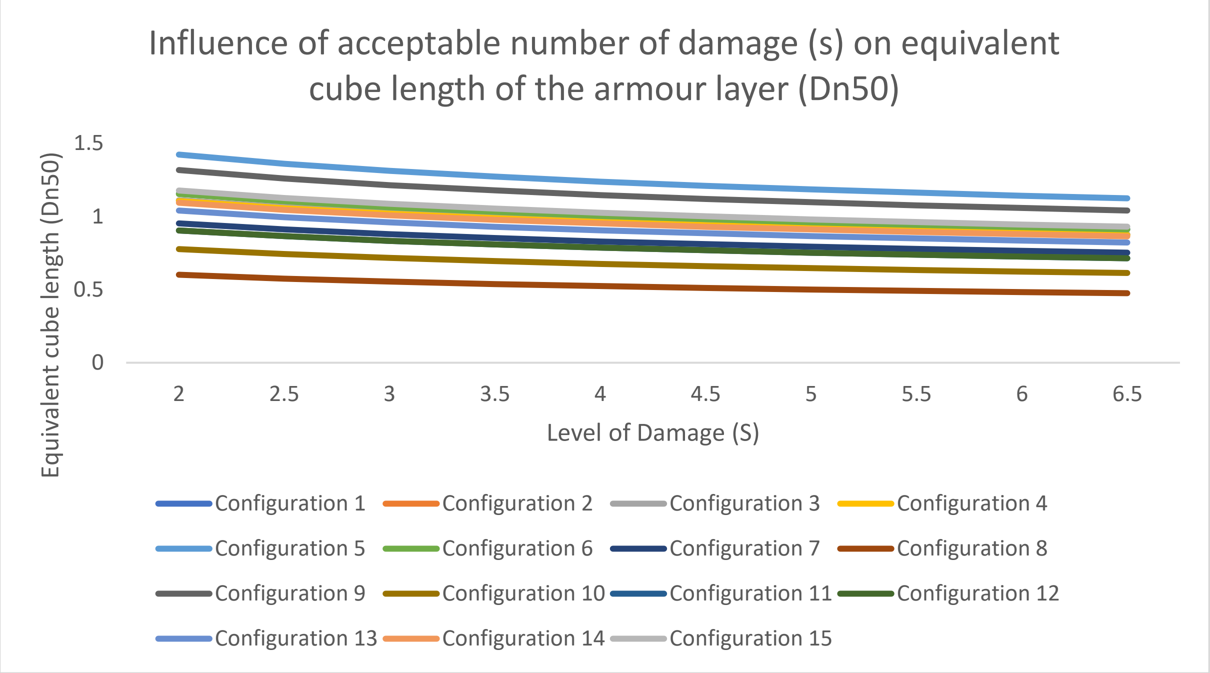


Figure 24: Parameter study via parametric design tool.

Due to the flexibility of the parametric design tool, every parameter used in the calculations can be used in the parameter study. The effect of the combination of multiple parameters can be studied as well in the constructed tool.

6. Design process improvement

This chapter aims to identify the value of parametric design and the constructed parametric design tool to the breakwater design process. To identify if it will contribute to the process, a follow-up interview is done with designers to evaluate the current use and the potential it has to improve the breakwater design process. The improvements identified by designers are then reflected upon the current breakwater design process laid out in section 3.1.

In this chapter a reflection is performed on the current breakwater design process. The elements of the steps which the parametric design tool contributes to are presented in tables. Below the tables a short elucidation is given on the improvements.

Functional requirements

Table 4: Improvement of constructed tool on functional requirements

Process
• Translating desires into functional requirements along with client. • Set up additional requirements of the project. • Investigate the feasibility of the project. • Make an indication of the costs of the project.
Improvement by parametric design tool
• Improved technical communication with client. • Check the feasibility at location of requirements and cost. • Cost indication based on bathymetry location and volume. • Overview necessary rock-grading and thus required rock availability in the area.

Together with a client the functional requirements are constructed to meet the demands set by the client. The constructed parametric design tool improves the communication with the client by communicating with help of a visual interface which can show the potential of the project. The tool helps to determine the feasibility of the proposed requirements by delivering output regarding certain wave-structure interactions for the breakwater at different potential locations. An indication of costs and the rock-grading at sections are presented indicating the amount of rock needed near the project.

Wave-, Hydrological, and Geotechnical studies

Table 5: Improvement of constructed tool on location studies

Process
• Study the wave conditions in detail near site. • Study the bathymetry and hydrological conditions in the project area. • Study geotechnical conditions in detail in project area.
Improvement by parametric design tool
• -

The models used are detailed and data heavy models, which cannot be replaced by the tool. Currently the output of SWAN, which is one of the wave study models is used as input for the parametric design tool and in the future more links to models may be useful for a more detailed design output of the parametric design tool.

Breakwater placement

Table 6: Improvement of constructed tool on the breakwater placement

Process
• Check functional location and shape of breakwater. • Assess costs for locations. • Asses non-technical impact of locations on project area. • Choose locations to develop further.
Improvement by parametric design tool
• Assist in exploration study by freedom of parameter selection and ease of parameter study. • By giving visualization of structure, helps the assessment of locations.

The constructed parametric design tool can help to determine the costs of taking on the project by analysing it within the model quickly and indicating the rough costs of the breakwater based on a volume estimate. The high flexibility of the tool makes it easy to study the effect of different breakwater locations on the functional requirements and on the material volume costs. The direct visual indication helps the designer to assess the impact of a location on the project area.

Stability

Table 7: Improvement of constructed tool on the stability analysis

Process
• Calculate equivalent cube length according to location. • Match rock grading to calculated equivalent cube length.
Improvement by parametric design tool
• Exploration of alternative armour units. • Rock grading matched automatically.

The calculation of stability of the breakwater is improved by the constructed parametric design tool. The tool includes the selection of eight different armour units as seen in Table 12. This makes exploration of different units appealing and easier. Within the tool the rock-grading is matched automatically to the different cross-sections along the breakwater, making the stability process of the entire breakwater a lot easier. This is opposed to the calculations of a single cross-section at a time.

Wave-structure interaction

Table 8: Improvement of constructed tool on the wave-structure interaction analysis

Process
• Calculate wave-structure interactions different conditions.
Improvement by parametric design tool
• Wave-structure interactions per cross-section for entire breakwater. • Parameter study helps analysing the optimisation between costs and requirements.

The wave-structure interaction analysis is improved by the parametric design tool. The tool allows analysis of different cross-sections along the entire breakwater instead of a single cross-section at a time. The option to parameter study improves the analysis of meeting the functional requirements of the project while minimising costs.

Cross-section design

Table 9: Improvement of constructed tool on the cross-section designing

Process
• Compute different cross-sections based on different possible choices (concrete vs rock armour unit for example). • Analyse potential best configurations with a parameter study and uncertainty analysis.
Improvement by parametric design tool
• Compute multiple cross-sections simultaneously. • No limitations to parameter selection. • Short computation time. • Compute breakwater based on cross-section. • Internal warnings. • Parameter study of entire breakwater instead of a single configuration (section 5.4.3).

The cross-section designing is improved by having no limitations to the selection of parameters in the model. The parametric design tool can calculate up to 1000 configurations within a second to be exported for analysis. Furthermore, the model produces warnings indicating the cross-sections which do not comply with the boundary conditions set in the used design guidelines. Warning the designer can indicate the necessity for a potential uncertainty analysis. The parameter study, which can be conducted analyses the cross-sections of the entire breakwater instead of a single cross-section aiding the designer of the influence of a parameter on the entire structure.

Preliminary design selection

Table 10: Improvement of constructed tool on the preliminary design selection

Process
• Multicriteria analysis to select best design to develop further. • Chosen design sent to CAD-designer for drawing.
Improvement by parametric design tool
• Visual interface presenting each breakwater and potential impact. • Chosen design assists in detailed drawing.

The parametric design tool has a visual interface, presenting the to be implemented configuration over the entire breakwater. The designer does not assess a single cross-section, but also its impact over the entire structure analytically and visually. The chosen design has an accompanied visual interface and acts as clear communication for the detailed drawing.

7. Discussion

The main research question of this thesis is regarding the potential benefit of parametric design in the breakwater design process. During this research certain points of discussion have occurred concerning the constructed design tool, the conducted research, its limitations, and discussion points regarding parametric design

7.1. Parametric design tool

The constructed parametric design tool is useful for designers in the conceptual design phase. With the tool the Elmina port expansion and rehabilitation projects has served as use case to validate the breakwater design tool. The validation of rock grading in section Table 2 yields results which indicate that the parametric design tool matches the in-house tool of IMDC for a greater share of the used grid points. There are however certain points on the breakwater, of which the results of the parametric design tool do not match with the in-house tool. There are two potential causes of this problem, the theory of the parametric design tool does not match the theory used in the in-house tool, or the processes used in the parametric design tool are incorporated incorrectly. The first cause is true, the theory in the parametric design tool does differ from the theory used by IMDC for the conceptual design of the breakwaters for the Elmina project. The difference can however not be shown as the conceptual design report of the project in question is restricted. This is due to the breakwater being under construction during the conduction of this research. With the model theory being different does not mean that the theory used in the model is used correctly, however this could not be investigated in this research due to the restriction in time.

Another process in the tool which needs to be discussed is the nearest point selection. Currently the breakwater cross-section at a certain point of the drawn breakwater is determined by the closest SWAN-grid point. This closest grid point can be just a fraction closer than a different grid-point, which has more severe conditions. A better solution may be selecting more than one grid point in a proximity range and determining the breakwater cross-section based on the severest point.

7.2. Research limitation

During the research that has been conducted certain discussion points have risen that will be addressed in this section.

In section 3.1 the traditional breakwater method is described based off literature and an interview. There is limited literature available on the management of a breakwater design process opposed to the plentiful resources on a technical design process. The limited literature together with the interview being conducted with a designer from IMDC, may not give as much of an indication on the universal breakwater design process as wished for.

The constructed breakwater tool has undergone a validation process, which partly consists of the comparison of parameter study. It is now validated by explaining the ease of parameter exploration of this tool opposed to the traditional method used. This can be seen as subjective as this is a non-quantified validation. Although it may look easier and more elaborate there is a lack of proof in a quantifiable form such as time or costs.

In this research a use case has been applied to the constructed parametric design tool. The project used is based in Elmina and is a modern project, which is ongoing during the conduction of this research. A new method of wave study has been applied, in which an elaborate investigation of data is performed at different moments in time. SWAN data is in this project processed in a different model, and the processed file is imported in the constructed parametric design tool. This means that no additional use case was available for validation of the parametric design tool. Making it an uncertainty if the tool is applicable to other cases as it has not been evaluated.

In this research a conclusion is formed in section 3.3 that parametric design is most applicable to the breakwater design process in the conceptual design phase. This conclusion is based off literature research and input from breakwater experts. In parametric design literature regarding construction engineering, it is concluded that parametric design is best applied to optimization studies and for solving problems that arise during the design process (Kalkan et al., 2018). This being the most argued case for parametric design application does not mean it is not applicable to other design stages. Abdullah and Kamarah (2013) argue that parametric design is applicable to the conceptual design phase to assess predefined criteria, site constrains, and construction costs (Abdullah & Kamara, 2013). The breakwater design process being a complicated and location dependent process in later stages make parametric design application more useful in the conceptual design phase. Although this can be debated through the best application method of parametric design.

7.3. Parametric design

Parametric design is a useful and powerful method for generative design especially for repetitive tasks. There is however a certain downfall to parametric design. Developing an elaborate parametric design model takes time. The designer wanting to learn parametric design most likely has to get familiar with the software program and develop a complicated tool. This takes a substantial amount of time and for a company this is translated into labour costs. The cost-benefit ratio must therefore be explored before the development of a tool. An investigation must be conducted to find if the contribution of the developed tool outweighs the investment costs. A cost-benefit analysis would have been an interesting insight for this research.

A hazard that is mentioned regarding parametric design is the limited amount of design freedom. Due to algorithmic processes being predetermined, a potential hazard would be that a parametric model would make decisions for the designer, which the designer would not know of. Therefore, the tool constructed in this research is developed with total designer freedom, leaving every process in the model influenced by the designer. In such a complicated system as a breakwater it is important for the designer to know all the choices made. However, if all choices in a model are to be made by the designer, several systems would not benefit as much from parametric design. The right balance must be found by the designer between choices made by the designer and choices, which can be made by the model. The designer should know the choices made and the variables the choices are always based on.

8. Conclusion

The objective of this project is to investigate the possible influence of a parametric breakwater design tool on the design process of breakwaters by creating a parametric breakwater design tool in Rhinoceros + Grasshopper.

Based on the objective, research questions are constructed with the main question worded as follows:

> *"Is parametric design beneficial in the breakwater design process?"*

To answer this main research question, four sub-questions are formed and when answered bottom-up will work towards answering the main research question. A conclusion regarding the sub questions will be drawn at first to answer the main research question after.

8.1. Application of parametric design

Sub question 1: Which steps of the traditional breakwater design process can parametric design be applied to?

Through literature research, interviews and conducting surveys it became apparent that parametric design is specifically suitable for the conceptual design phase of breakwater designing. Conceptual design phase is an early phase in the design process in which multiple potential solutions are explored to retrieve the best design(s) for further exploration. Parametric design can assist in this breakwater design phase due to its great flexibility in parameters, short computation time, direct visualization of the product, and convenience in performing a parameter study.

The cross-section design of breakwaters follows empirical equations retrieved from design manuals to construct an initial breakwater design. These equations can be transformed to generate geometrical output of a breakwater and can therefore be applied to a parametric model. This parametric design model can assist in generating and exploring different cross-section designs of a breakwater.

8.2. Resemblance of model output

Sub question 2: How well does the generated breakwater of the parametric design tool resemble the conceptual breakwaters designed by experts?

After a parametric design tool has been constructed, it has been verified and validated in order to identify the resemblance it has with the conceptual breakwater designed by experts from IMDC. The tool constructs a conventional rubble-mound breakwater, similar to one designed by IMDC in the Elmina port and rehabilitation project. Geometrical output of a breakwater is largely dependent on the rock-grading of the armour layer, which has influence on the height, width, layer thickness and toe of the structure. A similar rock grading will thus result in a similar breakwater.

A validation in rock grading has been performed in this report, comparing the rock grading of the breakwaters at different cross-sections dependent on the location. The rock-gradings of the tools are similar with ten out of thirteen rock-gradings of the armour layer being the same, two are larger and one is smaller estimated by the parametric design tool in comparison with the in-house tool. This is to be explained by the difference in theory used by the models, however a validation of the tool using the same theory has not been performed and may yield different results.

8.2.1. Assistance of model

Sub question 2.1: Would the designer be able to use the generated breakwater design to construct a breakwater?

This question is aimed at the usefulness of the constructed tool for the breakwater designer. The constructed tool should provide improvement in the designing of breakwaters, by generating designs that meets the requirements and minimises costs.

The constructed tool generates a detailed design within a brief period providing the designer with a visual design in a separate interface. This allows the designer to see a visual link between parameters and the breakwater design with an option of conducting a parameter study to analyse different breakwater concepts.

With the breakwater theory included to the desire of the designer, the tool contributes to the breakwater design process.

8.3. Improvements by constructed model

Sub question 3: What aspects does parametric design improve in the breakwater design process?

To analyse which aspects of the breakwater design process can be improved by parametric design, a review on the traditional breakwater design process is performed and a follow-up interview with designers that have experience in breakwater designing is conducted.

The constructed parametric design tool can assist in the feasibility study of a project, by delivering output regarding the wave-structure interactions varied due to the location, wave-characteristics, and placement of the breakwater. Next to this it also assists the designer in the choice of breakwater placement, together with the material costs indication, and high flexibility of the tool.

The main aspect of improvement the constructed tool brings is the cross-section design of a breakwater. The parametric design tool allows the designer to generate a cross-section design fast and review this visually via the visual interface and data analytically via exportation to a spreadsheet. It allows the designer to evaluate and change the design quick according to their liking. This assists the designer to construct and choose a preliminary breakwater design.

8.4. Addition to design process

Based on the aforementioned aspects it is possible to draw an overall conclusion for the main research question of this research, which was stated as:

> *"Is parametric design beneficial in the breakwater design process?"*

Parametric design is beneficial to the breakwater design process. The short computation time, visual interface, and freedom of parameters give great benefits to the design process of breakwaters. In this research, a tool is developed that assists the designer in the design of cross-sections in the conceptual design phase. The tool allows for generation of different cross-sections based on imported coordinate dependent wave data. An exploration study of different breakwater designs can be executed by varying the dependent parameters for a particular location. These designs can afterwards be analysed through the accompanied visual interface and an exported spreadsheet containing all output data. The tool can be modified containing the desired processes of the designer. Additionally, the tool aids in the conduction of a feasibility study and the exact placement of a breakwater. Parametric design is beneficial in the breakwater design process, however, there is still an expert needed to analyse the results projected by parametric design and making decisions based off these results.

9. Recommendations

In this chapter recommendations are suggested to improve the research and overcome its current assumptions and limitations. The recommendations are separated in three sections, in the first section recommendations are given regarding the constructed parametric design tool as part of this research. The improvements, which can be made and possible expansion opportunities of the tool. Hereafter, in next section recommendations are suggested regarding the verification and validation of the developed parametric design tool. In the section recommendations are presented regarding parametric design application to fields outside of architecture and structural engineering, and the further research into parametric design implementation in the breakwater industry.

9.1. Parametric design tool

In this research a parametric design tool has been developed to aid an expert designer in the conceptual phase of the breakwater design process. Before and during the conduction of this research and development of the parametric design tool certain assumptions and design restriction have been made to make it feasible in the proposed research time. If the tool is to be further developed certain improvements can be done to minimise the restrictions and to expand the tool into a wider applicability range. The following recommendations are suggested:

The expansion of the parametric design tool such that it can design multiple breakwaters at the same time. Currently the parametric design tool can design one breakwater at a time, however at most port projects, the works consist out of several separate breakwaters. Expanding the parametric design tool can allow the designer to work out a port project of multiple breakwaters within the tool.

The expansion of the parametric design tool such that several breakwater types can be analysed in the tool. The parametric design tool developed in this research is only capable of designing a rubble-mound breakwater, this limits the exploration possibility of several types of breakwaters. If this current tool is to be used, a decision is to be made beforehand that the to be designed breakwater is a rubble-mound breakwater. If multiple breakwater types are implemented in the parametric design tool, more options are to be explored in the conceptual design phase, benefiting the quality of the final design.

The parametric design tool can be improved to make a distinction between the seaside and lee side of the rubble-mound breakwater, which in a real case is always the case. This is due to the lee side being exposed to waves that are far less severe. There are certain rules of thumb set up by designers although these are acquired from old references (Massie, 1976).

The parametric design tool currently imports a shape file of a coastal boundary of a location at scale to supply background context and for scaling opportunity. A potential expansion of the parametric design tool could be to include more shape files into the model and modifying it to use the tool as a port development tool in the conceptual design phase. This multidisciplinary tool could include and modify building shapes and could therefore allow designers to develop a conceptual design of a port project.

The parametric design tool currently only corresponds with a singular location study model namely SWAN. The parametric design tool could be improved in accuracy by linking other models used in the design process directly with it. It must be done cautiously not increasing the computation time too much.

9.2. Verification and validation of the parametric design tool

The recommendations upon the further improvement of the verification and validation process are described in this section. With further improvement in verification and validation the conclusion regarding the application of parametric design and the parametric design tool are more trustworthy. The recommendations are as follows:

The verification can be improved by verifying that the hydraulic failure equations implemented in the parametric design tool are the same as one used in real case breakwater design process. By verifying this fact, the validation of the tool is also improved due to the rock grading calculation being the same in theory and a valid comparison between models can be made.

To improve validation the tool must be used in real case designing. A tool can save work in theory but if it is difficult to understand or difficult to use for the designer it does not contribute to the design process.

To improve the validation of the flexibility of the tool a form of quantification should be found. Either in time, costs or in both, a quantifiable analysis should be done of the improvement in flexibility, however this can only be done by a designer with breakwater experience.

9.3. Parametric design application and research

The recommendations regarding the further research and application of parametric design in engineering are documented in this section. With the application of parametric design in a field, which does not follow strict guidelines for the final design, this research has showed that it has the potential to help the designer in the initial stages of the design process. The recommendations suggested are the following:

It is important to investigate the cost-benefit ratio from parametric design application. Parametric designing may be useful in the design process; however, it is useful to know if the benefits of a parametric design tool outweigh the research and construction costs and time it brings with it. If the benefits do not outweigh the investment costs, the option for parametric design must not be made until more developments have been made in the field of parametric design.

it is useful for designers to explore the possibility of parametric design in their work field, even though it is not traditionally linked to parametric design. If a small part of the design process is a repetitive process it is most likely open to a parametric design application and may be beneficial long term.

For researchers and developers, it is beneficial to develop more plug-ins to broaden the accessibility of parametric design. The possibility of the parametric design tool constructed in this report was only possible due to certain plugins such as GHPython were made available for the program. Investment does not go without reward. Useful plugins sell licenses against profitable prices.

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Appendices

A. Expert interview regarding parametric design

A.1. Survey questions

1. What is your name and job title?
2. What is your project history in the field of breakwaters?
3. Would it be all right for me to include your name, title, and project history in my thesis?
4. What is your opinion of design automation?
5. Do you see any dangers in the application of design automation in the engineering field? If so what dangers?
6. Do you think parametric design is an effective way of implementing design automation?
7. Do you think that parametric design can be applied to the breakwater design process? Why or why not?
8. Are there any dangers in applying parametric design to the breakwater design process in particular?
9. A which stage of the breakwater design process can parametric designing be applied?
10. At which step in the breakwater design process would you apply parametric design?
11. What should be kept in mind when developing this parametric design tool?
12. What are the most important requirements for this tool?
13. What would you use the described parametric design tool in the previous question for?
14. Would you think the investment in the forms of time and money in designing a parametric design tool to the breakwater design process is worth it from an organization standpoint? Why or why not?

A.2. Survey respondents

In this appendix the respondents of the survey and their credentials are stated in order to substantiate section 3.2 of the report.

Respondent 1:

William Allsop, Director / Principal of William Allsop Consulting Ltd. Up to 2018 I was a Technical Director at HR Wallingford.

Experience:
I have worked in hydraulic engineering since 1969. I have specialised in coastal / shoreline structures since 1977. I now have in excess of 50 years' experience of analysis and testing of breakwaters (rubble mound, vertical and composite), sea walls, revetments, piers / jetties and coastal / shoreline structures, engineering works or renewable energy systems in tidal estuaries, and rivers, in sand and cohesive sediment transport, of river structures, outfalls and oil booms, and performance and certification of temporary flood protection devices. I have supervised testing in large facilities in UK, France, Germany, Italy, Spain, Turkey. I developed a series of innovative test rigs for flood protection devices, and I devised the UK's first laboratory Tsunami Simulators which have tested tsunamis at 1:50 scale.

I have been responsible for research for breakwaters and coastal structures in collaboration with other UK and European researchers, particularly in VOWS, Big-VOWS, PROVERBS, CLASH and Floodsite. I have served on ICE Maritime Board, PIANC working groups, and has contributed to PIANC, BSI, ISO and ICE working groups, the Rock Manual, Revetment and Exposed Jetties Manuals, and revisions to BS6349. I chaired the ICE Breakwaters Conference from 1998 to 2013, and I routinely review conference and learned journal papers.

I have taught more than 120 courses / workshops / seminars since 1994, regularly teach at ESITC Caen. I have co-supervised 12 PhD theses, 14 Master's theses and examined 3 PhD's since 1991. In 2014, I was appointed Honorary Professor at University College London.

Respondent 2:

Ali Dastgheib, Senior Coastal Engineer and Associate professor in Coastal Engineering and Port Development.

Experience:
Designing several rouble mound breakwaters with rock and concrete armour, design of reshaping berm breakwaters, teaching design of breakwaters.

Respondent 3:

Prof. Jentsje van der Meer, Principal of Van der Meer Consulting BV and Emeritus Professor Coastal Structures and Ports at IHE Delft

Experience:
Van der Meer Consulting provides independent and specialized consultancy services in the field of coastal engineering since 2007. This consultancy is based on more than 40 years of experience in both research (16 years at Delft Hydraulics, now Deltares) and consultancy (10 years at Infram). In January 2014 Van der Meer became full professor Coastal Structures and Ports at IHE Delft for one day per week (0.2 fte).

In June 2010, during an induction ceremony in Shanghai, Dr Van der Meer was granted the status of Diplomate in Coastal Engineering by ACOPNE, the Academy of Coastal, Ocean, Port & Navigation Engineers from the USA.

Main areas of Van der Meer Consulting are:

- Independent expert witness in arbitration
- Breakwaters and coastal structures
- Hydraulic design conditions
- Hydraulic simulators
- Flood risk assessment
- Manuals and guidelines

B. Documentation Breakwater model

1. Hydraulic boundary conditions

1.1. Wave height computation

IMDC utilizes the SWAN-model (Simulating WAves Nearshore) that computes the waves at a specific location and delivers H_{m0}, T_p and T_m. With the H_{m0}, the spectral significant wave height, the 2% run up wave height $H_2\%$, and significant wave height H_s can be calculated. These values characterize the waves at a particular location and are necessary for certain calculations regarding breakwater designing.

Using Battjes and Groenendijk, different wave characteristics can be calculated making use of empirical data (Battjes & Groenendijk, 2000). To calculate the characteristic height the non-dimensional transitional wave height H_{tr}must be computed first.

$$H_{tr} = (0.35 + 5.8tan\alpha)h \qquad \textit{Equation 1}$$

With a is the bed slope of the sea bottom, and h the water depth as input.

The root mean square (rms) wave height H_{rms} is computed to calculate the non-dimensional transitional wave as a result.

$$H_{rms} = \left[0.6725 + 0.2025\left(\frac{H_{m0}}{h}\right)\right] Hm0 \qquad \textit{Equation 2}$$

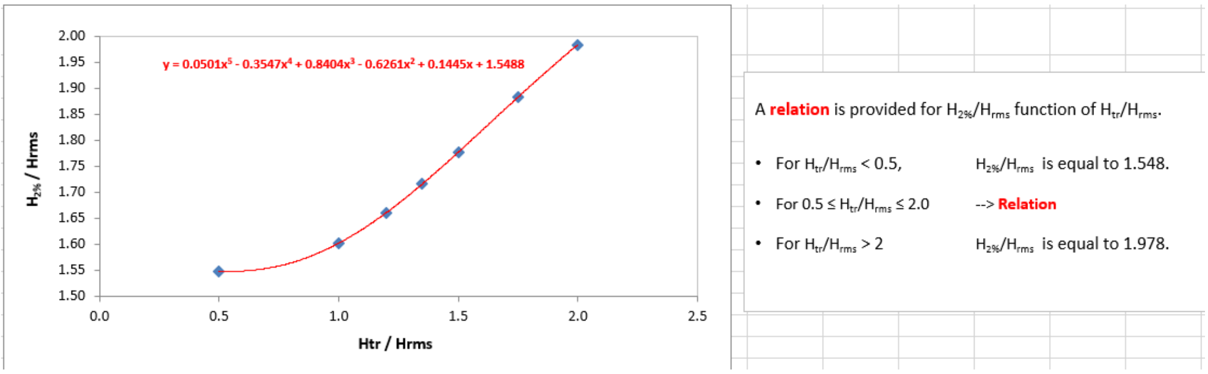
With H_{m0} the spectral significant wave height and h the water depth.

In Table 11 the relation between the average of the highest third of the waves, the highest 2% of the waves $H_2\%$ and the rms wave height is indicated. For this model, a common assumption is made that the significant wave height H_s is equal to the average of the highest third of the waves $H_{\frac{1}{3}}$.

Table 11: Relation between characteristic heights and the non-dimensional transitional wave (Battjes & Groenendijk, 2000)

Characteristic height	Non-dimensional transitional wave H_{tr}/H_{rms}									
	0.05	0.50	1.00	1.20	1.35	1.50	1.75	2.00	2.50	3.00
$H_{1/3}/H_{rms}$	1.279	1.280	1.324	1.371	1.395	1.406	1.413	1.415	1.416	1.416
$H_2\%/H_{rms}$	1.548	1.549	1.603	1.662	1.717	1.778	1.884	1.985	1.978	1.978

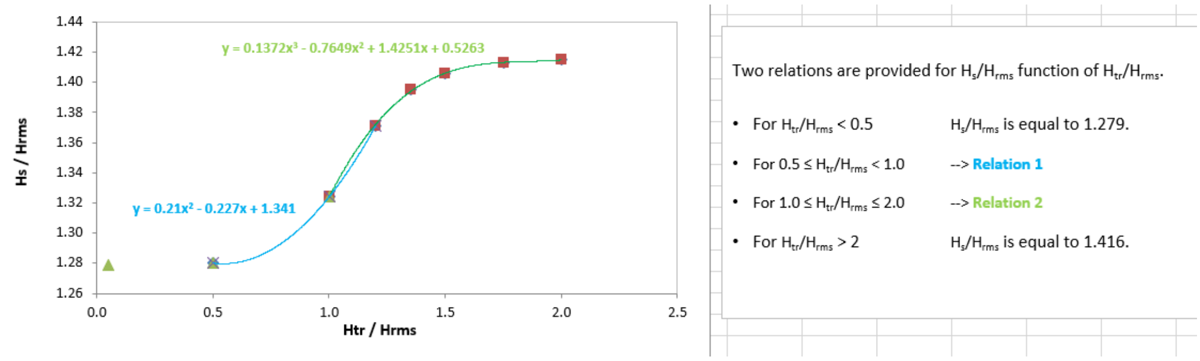
At IMDC a relation is formed between the data points by fitting a line between these characteristic heights and the non-dimensional transitional wave. This relation is used to compute H_s and $H_2\%$.



A **relation** is provided for $H_{2\%}/H_{rms}$ function of H_{tr}/H_{rms}.

- For $H_{tr}/H_{rms} < 0.5$, $H_{2\%}/H_{rms}$ is equal to 1.548.
- For $0.5 \leq H_{tr}/H_{rms} \leq 2.0$ --> **Relation**
- For $H_{tr}/H_{rms} > 2$ $H_{2\%}/H_{rms}$ is equal to 1.978.

Figure 25: A relation formed between H2%/Hrms and Ht/Hrms based on Battjes en Groenendijk (2000)



Two relations are provided for H_s/H_{rms} function of H_{tr}/H_{rms}.

- For $H_{tr}/H_{rms} < 0.5$ H_s/H_{rms} is equal to 1.279.
- For $0.5 \leq H_{tr}/H_{rms} < 1.0$ --> **Relation 1**
- For $1.0 \leq H_{tr}/H_{rms} \leq 2.0$ --> **Relation 2**
- For $H_{tr}/H_{rms} > 2$ H_s/H_{rms} is equal to 1.416.

Figure 26: A relation formed between Hs/Hrms and Ht/Hrms based on Battjes en Groenendijk (2000)

The relations formed in Figure 25 and Figure 26 are used to compute the wave height characteristics in the parametric design tool. In some cases, H_s is given by the client as well and does not have to be calculated, in such a case it can be inserted in the model separately.

1.2. Transform periods

To calculate more wave characteristics such as wavelength and steepness, wave periods must be known, there are three to be distinguished with each having a ratio with each other.

- T_p, the peak wave periods
- T_m, the average wave periods
- $T_{m-1,0}$, the spectral wave periods

All three wave periods are preferably derived from the wave record. However, they can also be calculated from the spectrum (The EurOtop team, 2018).

$$T_{m-1,0} = 0.9\, Tp \quad \text{Equation 3}$$

$$T_m = 0.71 - 0.82\, Tp \text{ (PM Spectrum)} \quad \text{Equation 4}$$

$$T_m = 0.79 \; to \; 0.87\, Tp \text{ (JONSWAP Spectrum)} \quad \text{Equation 5}$$

In the model a choice can be made between the fact that all the data is retrieved from the SWAN data, or one period is imported, and the other period use the conversion factor of the spectrum.

1.3. Wave characterisation

Wave steepness is the relation of wave height and wavelength, and indicates the type of sea, this is important to supply context for a project and to define what equations to use in the breakwater design.

There are two types of wave lengths, the deep-water wavelength, which are waves that are not interfered by coast conditions, and the local wave length, which are wave lengths at a certain point characterised by the water depth h.

The deep-water wavelength.

$$L_{m,0} = \frac{g * T_x^2}{2\pi}$$ Equation 6

The local wavelength is an iterative equation:

$$L_x = \frac{g * T_x^2}{2\pi} * \frac{\tanh(2\pi * h)}{L_x}$$ Equation 7

With g = gravitational acceleration, h water depth, and T_x the wave period.

In the model a for loop is used, where if the difference between the old local wavelength and new local wavelength after iteration is smaller than 0.001 meter, the for loop stops and the last iterated value is used.

The wave steepness is calculated by dividing the spectral significant wave period by the appropriate wavelength.

$$S_x = \frac{H_{m0}}{L_x}$$ Equation 8

2. Material selection

With the wave characteristics known, a material can be selected for the outer layer of the breakwater. There is a choice between natural rocks and manufactured concrete armour units.

For every material chosen holds that the material has to have sufficient hydraulic stability which is expressed as shown in Equation 9

$$N_s = \frac{H_s}{\Delta * D_{n50}}$$ Equation 9

2.1. Armour unit

For several type of armour units, empirical equations have been formed to calculate the required median equivalent cube length of the material. The model contains several armour unit choices which are listed in Table 12.

Table 12: Armour unit types included in the model

Armour unit type
Rocks
Xbloc
Cubes
Tetrapods
Dolos
Accropode
CORE-LOC
Tribar

2.1.1. Rocks

Rock is a natural material, which is commonly used for the design of breakwaters and is therefore included in the model. A distinction needs to be made between deep and shallow water conditions, and between surging and plunging waves (Ciria-Cur, 2007).

2.1.1.1. Deep water equations

The rock armour layer is designed with the aid of the equations for plunging and surging waves in deep water (van der Meer, 1988). Deep water is determined by the water depth h being equivalent to or larger than three times the significant wave height H_s.

Plunging

$$\frac{H_s}{\Delta D_{n50}} = C_{pl} * P^{0.18}\left(\frac{S}{\sqrt{N}}\right)^{0.2} (\xi_m)^{-0.5}$$

Equation 10

Surging

$$\frac{H_s}{\Delta D_{n50}} = C_s * P^{-0.13}\left(\frac{S}{\sqrt{N}}\right)^{0.2} \sqrt{cot\alpha} * (\xi_m)^{P}$$

Equation 11

Where $C_{pl} = 5.5, C_s = 0.87$, P is the permeability factor, N is the number of waves during a storm, α the angle of the breakwater slope, Δ the relative density, D_{n50} the median equivalent cube length and ξ_m is the surf similarity parameter.

2.1.1.2. Shallow water equations

The shallow water equations are applied when the water depth is smaller than three times the significant wave height H_s.

Plunging

$$\frac{H_s}{\Delta D_{n50}} = C_{pl} * P^{0.18}\left(\frac{S}{\sqrt{N}}\right)^{0.2} * \left(\frac{H_s}{H_{2\%}}\right) * \xi_{s-1,0}^{-0.5}$$

Equation 12

Surging

$$\frac{H_s}{\Delta D_{n50}} = C_s * P^{-0.13}\left(\frac{S}{\sqrt{N}}\right)^{0.2} * \left(\frac{H_s}{H_{2\%}}\right) * \sqrt{cot\alpha} * \xi_{s-1,0}^{P}$$

Equation 13

Where $C_{pl} = 7.25, C_s = 1.05$, and $H_{2\%}$ is the wave height that 2% of the waves reach.

A distinction between plunging and surging waves has to be made. This is done by calculating the surf similarity parameter and the critical value of this parameter. If $\xi_{cr} > \xi_m$ then the formula for plunging waves is used in order to obtain correct results. If $\xi_{cr} < \xi_m$ the formula for surging waves is used. The model makes a distinction between these wave types automatically.

With:

$$\xi_m = \frac{tan\alpha}{\sqrt{\left(\frac{2\pi H_s}{gT_m^2}\right)}}$$

Equation 14

And:

$$\xi_{cr} = \left[\frac{C_{pl}}{C_s} P^{0.31} \sqrt{tan\,\alpha}\right]^{\left(\frac{1}{P+0.5}\right)}$$ *Equation 15*

Equation 11, 12, 13 and 14 are rewritten to calculate the required median equivalent cube length D_{n50} based on the allowable damage, wave conditions and permeability.

2.1.2. Concrete armour units

As an alternative to rock, concrete armour units may be used for slope protection of the breakwater. Due to the uniformity of the elements and therefore its predictability, separate equations describe its behaviour. An often-reoccurring formula for concrete elements is the Hudson equation seen in Equation 16 (Hudson, 1974). The stability coefficient K_D varies for distinct types of armour unit.

$$\frac{H_s}{\Delta * D_{n50}} = \left(K_D * \frac{1}{\tanh(\alpha)}\right)^{\frac{1}{3}}$$ *Equation 16*

Where H_s is the significant wave height, α the angle of the breakwater slope, Δ the relative density and D_{n50} the median equivalent cube length.

2.1.2.1. Xbloc

For Xbloc the Hudson equation is used with the stability coefficient $K_D\ =\ 16$ and a set slope of 1:1.33.

Cubes

For Cubes there are multiple equations describing its behaviour. Van der meer and hudson equations describe this element (Hudson, 1974; van der Meer J, 1999).

$$\frac{H_s}{\Delta * D_{n50}} = \left(6.7 * \frac{N_{od}^{0.4}}{N_z^{0.3}} + 1\right) * s_m^{-0.1}$$ *Equation 17*

With N_{od} the number of damage, N_z the wave steepness and s_m the deep water mean wave steepness.

The van der Meer equation described in Equation 17, has certain requirements:

- Hs/H <0.55
- Slope = 1:1.5
- 3<ξ_m<6

The Hudson equation is applied for slopes between 1:2 and 1:3, with the stability coefficient K_D between 6.5 and 7.5 for breaking and non-breaking waves.

2.1.2.2. Tetrapod

For tetrapod there are multiple equations describing its behaviour. Van der Meer and Hudson equations describe this element(Hudson, 1974; van der Meer J, 1999)

$$\frac{H_s}{\Delta * D_{n50}} = \left(3.75 * \frac{N_{od}^{0.5}}{N_z^{0.25}} + 0.85\right) * s_m^{-0.2}$$ *Equation 18*

With N_{od} the number of damage, N_z the wave steepness and s_m the deep water mean wave steepness.

The van der Meer equation described in Equation 18, has certain requirements:

- Hs/h <0.55

- Slope = 1:1.5
- 3.5<ξ_m<6

For depth-limited waves, Hs/h >= 0.55, Equation 19 is used.

$$\frac{H_s}{\Delta * D_{n50}} = 1.4 * \left(3.75 * \frac{N_{od}^{0.5}}{N_z^{0.25}} + 0.85\right) * s_m^{-0.2}$$

Equation 19

The Hudson equation (Equation 16) is applied for a slope of 1:2, with the stability coefficient K_D between 7 and 8 for breaking and non-breaking waves.

2.1.2.3. Dolos

Regarding Dolos an equation describing its behaviour has been formed by Burcharth & Liu (Burcharth & Liu, 1992).

$$\frac{H_s}{\Delta * D_{n50}} = (47 - 72 * r) * \varphi_{n=2}^{\frac{2}{3}} * N_{od}^{\frac{1}{3}} * N_z^{-0.1}$$

Equation 20

In which r is the dolos waist ratio ranging from 0.32 to 0.42, and $Phi_{n=2}$ is the packing density ranging from 0.61 to 1. The breaker parameter must range between 2.9 and 11.7 for the equation to be valid.

2.1.2.4. Accropode

For accropode the Hudson equation (Equation 16) is applied for a set slope of 1:1.33, with the stability coefficient K_D between 12 and 15 for breaking and non-breaking waves.

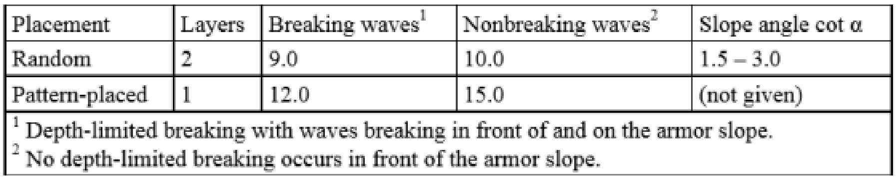
2.1.2.5. CORE-LOC

For CORE-LOC the Hudson equation (Equation 16) is applied, with the stability coefficient K_D of 16.

2.1.2.6. Tribar

For Tribar, the Hudson equation (Equation 16) is applied for a slope varying between 1:1.5 and 1:3.0. The stability coefficient is dependent on if the unit is random placed or pattern-placed and on the type of waves. The values can be seen in Table 13.

Table 13: Stability coefficients for tribars



Placement	Layers	Breaking waves[1]	Nonbreaking waves[2]	Slope angle cot α
Random	2	9.0	10.0	1.5 – 3.0
Pattern-placed	1	12.0	15.0	(not given)

[1] Depth-limited breaking with waves breaking in front of and on the armor slope.
[2] No depth-limited breaking occurs in front of the armor slope.

2.2. Rock-Grading

When the required equivalent cube length is calculated, a standard rock grading is chosen that fits this cube length. As not all rocks are the same size, a grading is chosen. These gradings have an upper and lower size and a median size. Having these standard rock gradings in the breakwater instead of custom ones lower the cost significantly (Ciria-Cur, 2007).

Table 14: Rock gradings used by IMDC

Grading	[-]	CP 32/90	CP 45/125	CP 63/180	CP 90/250	LMA 5/40	LMA 10/60	LMA 40/200	LMA 60/300	HMA 300/1000	HMA 1000/3000	HMA 3000/6000	HMA 6000/10000
Rock density	[kg/m³]	2650				2650							
							6	5	5	3.33	3	2	
ELL	[mm] or [kg]	16	22.4	31.5	45	1.5	2	15	30	200	700	2000	4000
NLL	[mm] or [kg]	31.5	45	63	90	5	10	40	60	300	1000	3000	6000
NUL	[mm] or [kg]	90	125	180	250	40	60	200	300	1000	3000	6000	10000
EUL	[mm] or [kg]	125	180	250	360	80	120	300	450	1500	4500	9000	15000
Mem,LL	[kg]	-	-	-	-	10	20	80	120	540	1700	4200	7500
Mem,UL	[kg]	-	-	-	-	20	35	120	190	690	2100	4800	8500
< 50%	[mm]	45	63	90	125	-	-	-	-	-	-	-	-
M50/Mem	[-]	-	-	-	-	1.386	1.352	1.269	1.243	1.163	1.099	1.054	1.024
nRRM	[-]	1.06	1.09	1.06	1.09	1.74	2.02	2.25	2.25	3.00	3.29	5.22	7.08
nRRD	[-]	3.19	3.28	3.19	3.28	5.22	6.06	6.74	6.74	9.01	9.88	15.65	21.24
M_{50}	[kg]	0.4	1.0	2.8	7.7	20	33	117	176	671	2083	4767	8440
$M_{50,LL}$	**[kg]**	**0.1**	**0.4**	**1.1**	**3.1**	**14**	**27**	**102**	**149**	**628**	**1868**	**4427**	**7680**
$M_{50,UL}$	[kg]	-	-	-	-	28	47	152	236	802	2308	5059	8704
M_{15}	[kg]	0.1	0.3	0.7	2.0	9	16	61	92	414	1341	3610	6877
M_{85}	[kg]	0.9	2.4	7.3	19.4	36	55	183	275	938	2829	5781	9730
M_{99}	[kg]	2.1	5.5	16.7	43.7	60	85	272	408	1260	3703	6852	11029
D_{n50}	**[mm]**	**51**	**71**	**102**	**143**	**196**	**232**	**354**	**405**	**633**	**923**	**1216**	**1471**
$D_{n50,LL}$	[mm]	38	53	76	105	174	217	337	383	619	890	1187	1426
$D_{n50,UL}$	[mm]	-	-	-	-	219	261	386	447	672	955	1241	1486
D_{50}	**[mm]**	**61**	**85**	**122**	**170**	**234**	**276**	**421**	**482**	**753**	**1099**	**1448**	**1752**
$D_{50,LL}$	[mm]	45	63	90	125	207	258	401	456	737	1060	1413	1697
$D_{50,UL}$	[mm]	-	-	-	-	260	311	459	532	799	1137	1477	1770
D_{15}	[mm]	39	55	77	109	177	217	340	389	641	949	1320	1636
D_{85}	[mm]	83	116	167	231	283	326	489	560	842	1217	1544	1837
D_{99}	[mm]	110	152	220	303	336	378	558	638	929	1331	1634	1915

In Table 14 the rock grading table can be seen that IMDC uses for its breakwaters, and it is derived from the European Standard rock armour stone gradings (*EN 13383-1 Armourstone*, 2013).

The selection method of the grading to use with a certain equivalent cube size is as followed. The mass of the calculated equivalent cube length is calculated and compared to the lower limit median mass of each grading. The calculated mass must be lower than the lower limit median mass of the rock grading. The rock grading in which the difference of the two masses is the least, is selected.

2.2.1. Mass

The mass of the armour layer can be calculated due to the relation of the mass and the equivalent cube length (Ciria-Cur, 2007).

$$M_{50} = \rho_a * D_{n50}^3 \qquad \text{Equation 21}$$

The mass is calculated as it gives an input for the composition of the filter and core layers which can be seen further in this report.

2.2.2. Layer thickness

Having calculated the median equivalent cube length, the thickness of the armour layer can be calculated (US Army Corps of Engineers, 2012). The number of layers in the armour layer is chosen by the designer.

$$r = n * k_{\Delta} * \left(\frac{W}{w_a}\right)^{\frac{1}{3}} \qquad \text{Equation 22}$$

The thickness of the layer is dependent on the shape of the armour unit, this is translated to the layer coefficient k_{Δ}, which is seen in Table 15, the number of layers n, the Unit weight W, and the specific weight w_a.

Table 15: Layer coefficient for random placed armour units (US Army Corps of Engineers, 2012).

Typer of armour unit	**Layer coefficient ($\boldsymbol{k_{\Delta}}$)**
Rocks	1
Xbloc	1.4
Cubes	1.1
Tetrapod	1.02
Dolos	0.94
Accropode	1.29
CORE-LOC	1.516
Tribar	1.02

3. Berm width

Regarding the berm width three methods are applicable.

- A general rule of thumb: B = 3 * Dn50 (Ciria-Cur, 2007).
- The thickness formula also used for layers: $B = n * k_{\Delta} * \left(\frac{W}{w_a}\right)^{\frac{1}{3}}$ (US Army Corps of Engineers, 2012).
- A manual width can be chosen for example if the berm of the breakwater has a multifunctional use.

With a chosen berm width wider than the necessary an overtopping reduction factor can be calculated and implemented on the relative crest freeboard calculation (The EurOtop team, 2018).

$$C_r = 3.06 \exp\left(-\frac{1.5B}{H_{m0}}\right) with\ maximum\ C_r = 1 \qquad \text{Equation 23}$$

With B the width of the berm, and H_{m0} the spectral significant wave height.

In the model this reduction factor is inserted in the overtopping equation, Equation 24. This model has multiple options of design choices to assure high flexibility.

4. Crest height

The height of the crest is determined by two methods, namely the EurOtop overtopping equation for rubble mound breakwater (The EurOtop team, 2018), and the rule that the core of the breakwater must be at least one meter above water level if the breakwater is constructed with land-based equipment (US Army Corps of Engineers, 2012). The larger of the two methods dictates the crest height. Within the model the designer can choose to opt for the maximum breakwater height, the height based on the overtopping manual or to set a manual height.

For the overtopping equation of a probabilistic breakwater design (The EurOtop team, 2018). With the design amount of overtopping, wave height, and wave incidence and roughness factor, the relative freeboard can be computed.

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0.1035 * \exp\left(-1.35 * \frac{R_c}{H_{m0} * \gamma_f * \gamma_\beta}\right)^{1.3} \qquad \text{Equation 24}$$

Deriving this equation to calculate the relative crest freeboard and incorporate the crest reduction factor the equation results in:

$$R_c = \left(-\ln\left(\frac{\frac{q}{C_r}}{0.1035 * \sqrt{gH_{m0}^3}}\right)\right)^{\frac{1}{1.3}} * \left(\frac{-H_{m0} * \gamma_f * \gamma_\beta}{1.35}\right) \qquad \text{Equation 25}$$

According to the overtopping manual this equation suffices for steep slopes ranging from 1:1.33 to 1:2.

This exact equation is used in the model, with the necessary input being the design rate of overtopping q, the wave incidence angle β and the material and number of layers of the armour layer.

The influence of the wave incidence angle can be determined by use of Equation 26 (The EurOtop team, 2018).

$$\gamma_\beta = 1 - 0.0063|\beta| \; for \; 0° \leq |\beta| \leq 80° \qquad \text{Equation 26}$$

Where γ_β is the oblique wave influence factor and β is the angle of wave attack.

For distinct types of armour units and layer compositions roughness coefficients are retrieved from empirical data measurement. These layer compositions and roughness coefficients can be seen in Table 16.

Table 16: Armour layer compositions and roughness factors (The EurOtop team, 2018).

Type of armour unit	**Roughness coefficient (γ_f)**
Smooth impermeable rock	1.00
Rocks 1 layer impermeable	0.60
Rocks 1 layer permeable	0.45
Rocks 2 layers impermeable	0.55
Rocks 2 layers permeable	0.40
Cubes 1-layer random positioning	0.50
Cubes 2 layers random positioning	0.47
Accropode	0.46
Xbloc	0.45
CORE-LOC	0.44
Tetrapods	0.38
Dolos	0.43

For surf similarity parameters higher than 5.0 the roughness coefficient increases linearly to 1 for a surf similarity value of ten. For armour units with impermeable core the roughness coefficients increase to 1 and for units with a permeable core it rises to 0.6. The linear increase is described in Equation 27 (The EurOtop team, 2018).

$$\gamma_{f\ mod} = \gamma_f + \left(\xi_{m-1,0} - 5\right) * (1 - \gamma_f)/5.0$$

Equation 27

5. Toe

5.1. Toe construction

The bottom of the sea is vulnerable to scour and instability and therefore a toe is constructed for most breakwaters. The armour units used can rest on this toe if displaced, increasing the overall stability of the structure (Gerding et al., 1993).

The toe is designed by an iterative process, at first a minimum hydraulic stability number is set by the designer. The hydraulic stability equation can be seen in Equation 9. All the rock gradings available and their respective equivalent cube length are used to calculate the stability for that grading. The grading that is the closest but larger than the set hydraulic stability is selected.

The thickness of the toe is determined by multiplying the equivalent cube length of the rock grading used for the toe by 2-3 times. The width of the toe can be determined by the designer as well. However, it is recommended for it to be 3-5 times the equivalent cube length (Ciria-Cur, 2007).

5.2. Scour protection

For scour protection the choice can be made in the model to generate a scour layer, the length and height is left to the designer as there are no guidelines for this, as it is very location dependent.

6. Filter and core layer

6.1. Median mass

With the median mass of the armour units calculated this weight can be applied to weight ratios to identify the median weight and median equivalent cube length of the filter layers and core layer. These weight ratios are customizable by the designer but will first stay at the ratios set by the coastal engineering manual (US Army Corps of Engineers, 2012).

$$\frac{W_{armour}}{W_{filter1}} = 10\ \& \frac{W_{armour}}{W_{filter2}} = 200\ \& \frac{W_{armour}}{W_{core}} = 4000$$

Equation 28

6.2. Material selection

A selection of material and its grading must be made. There are standard gradings available in En-13383-1 that are based off the Rosin-Rammler curves (*EN 13383-1 Armourstone*, 2013). The Rosin- Rammler curves are implemented in the model to give the designer the option to use standard gradings or custom grading if desired and to determine if the grading meets the filter criteria.

$$M_y = M_{50} * \left(\frac{-\ln(1-y)}{0.693}\right)^{\frac{1}{nRRM}}$$

Equation 29

Where:

$$M_{50} = \frac{NLL * \left(\frac{\ln(1-y_{NLL})}{-0.693}\right)^{-\frac{1}{nRRM}} + NUL * \left(\frac{\ln(1-y_{NUL})}{-0.693}\right)^{-\frac{1}{nRRM}}}{2} \qquad \text{Equation 30}$$

$$n_{RRM} = \frac{\log\left(\frac{\ln(1-y_{NUL})}{\ln\,(1-y_{NLL})}\right)}{\log\left(\frac{NUL}{NLL}\right)} \qquad \text{Equation 31}$$

Where, y is the fraction passing value, M_y is the mass corresponding to fraction y. n_{RRM} is uniformity index, NLL/NUL the nominal lower and nominal upper limit mass of a grading. $y_{NLL\,/NUL}$ is the fraction corresponding to NLL/NUL.

These fractions are evaluated against the different filter criteria determined in the rock manual (Ciria-Cur, 2007). These criteria assess the permeability, retention, and internal stability of the layers.

To prevent loss of materials of underlying layers through the voids that are created in the top layer, retention criterion is set.

$$\frac{d_{15(filter)}}{d_{85(foundation)}} < (4\ to\ 5) \qquad Retention\ criterion \qquad \text{Equation 32}$$

To prevent pressure build-up within the structure, the gradient across the structure should provide sufficient permeability.

$$\frac{d_{15(filter)}}{d_{15(foundation)}} > (4\ to\ 5) \qquad Permeability\ criterion \qquad \text{Equation 33}$$

To prevent loss of the finer particles within a layer due to significant differences in grain size an internal stability criterion is set.

$$d_{60(filter)}/d_{10(filter)} < 10 \qquad Internal\ stability \qquad \text{Equation 34}$$

6.3. Layer thickness

Having calculated the median equivalent cube length for the filter layer, the thickness of the layer can be calculated. The number of layers in the filter layer is chosen by the designer.

$$r = n * k_{\Delta} * \left(\frac{W}{w_a}\right)^{\frac{1}{3}} \qquad \text{Equation 35}$$

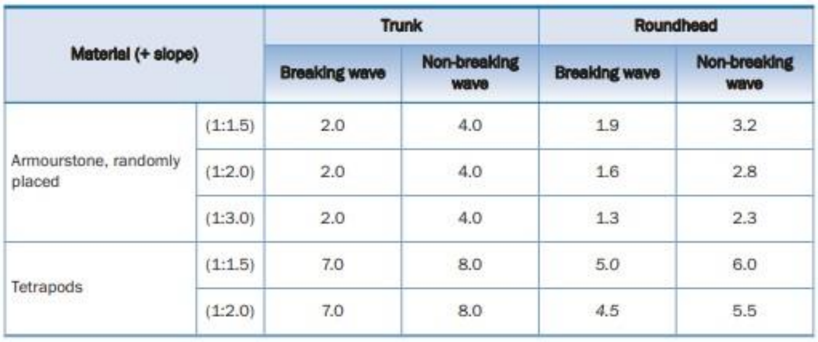
The thickness of the layer is dependent on the shape of the unit, this is translated to the layer coefficient $k\Delta$, which is seen in Table 15, the number of layers n, the Unit weight W, and the specific weight w_a.

The core layer fills the breakwater area that is not used by the armour or filter layers.

7. Roundhead

Breakwaters often have one or two roundheads dependent on the location and placement of the breakwater. The roundhead is exposed to high wave forces and velocities. For the roundhead to obtain the same stability as the trunk, the mass of the armour stones is increased at this section.

Table 17: Hudson stability coefficients K_D, for no damage and minor overtopping (Ciria-Cur, 2007).



Material (+ slope)		Trunk		Roundhead	
		Breaking wave	Non-breaking wave	Breaking wave	Non-breaking wave
Armourstone, randomly placed	(1:1.5)	2.0	4.0	1.9	3.2
	(1:2.0)	2.0	4.0	1.6	2.8
	(1:3.0)	2.0	4.0	1.3	2.3
Tetrapods	(1:1.5)	7.0	8.0	5.0	6.0
	(1:2.0)	7.0	8.0	4.5	5.5

The stability of the roundhead is related to the stability of the trunk and can be identifiable via the Hudson coefficient K_D. In Table 17 a distinction is made between breaking and non-breaking waves, knowing the wave condition and slope that is used for the breakwater the ratio between the Hudson coefficients for the trunk and roundhead must be multiplied with the median mass of the armour at the place of the roundhead to identify the required median mass of the armour stone at the roundhead.

$$M_{50_{Roundhead}} = \frac{K_{D_{Trunk}}}{K_{D_{Roundhead}}} * M_{50} \qquad \text{Equation 36}$$

8. Wave transmission

A valuable coefficient to know in the design of a breakwater is the wave transmission coefficient. The wave transmission coefficient indicates the ratio of waves hitting the breakwater which will pass through the medium. This coefficient is important to know due to assess if the breakwater meets the intended function.

$$\begin{cases} K_t = -0.4\left(\frac{R_c}{H_i}\right) + 0.64\left(\frac{B}{H_i}\right)^{-0.31}\left(1 - e^{-0.5\xi}\right) & for\,\frac{B}{H_i} < 8 \\ K_t = -0.006\left(\frac{B}{H_i}\right)^{-0.65} + 0 & for\; 8 < \frac{B}{H_i} < 12 \\ K_t = -0.35\left(\frac{R_c}{H_i}\right) + 0.51\left(\frac{B}{H_i}\right)^{-0.65}\left(1 - e^{-0.41\xi}\right) & for\,\frac{B}{H_i} > 12 \end{cases} \qquad \text{Equation 37}$$

The wave transmission coefficients are calculated by different equations which are dependent on the width of the breakwater and the wave height. Van der Meer has described this relation and used interpolation to create a relation for all cases (van der Meer et al., 2005).

9. Wave reflection

Another wave-structure relation important to assess is the wave reflection coefficient, this indicates the number of waves that bounce of the breakwater and thus changes direction. This is important to evaluate and keep in mind when designing.

$$K_r = 0.14\xi_{0p}^{0.73} \qquad for\ \xi_{0p} < 10$$ *Equation 38*

Equation 38 is set by the Rock Manual to describe the relation between the breaker parameter and wave reflection (Ciria-Cur, 2007).

C. Model structure

C.1. 2D configuration structure

In section B the model documentation is given regarding the calculation of a 2D conceptual breakwater configuration. The input and output of these separate calculations are often linked to other calculations or choices made. In Figure 27 the relations between parameters and geometrical output are given in a block diagram to offer a visual overview of the relationships.

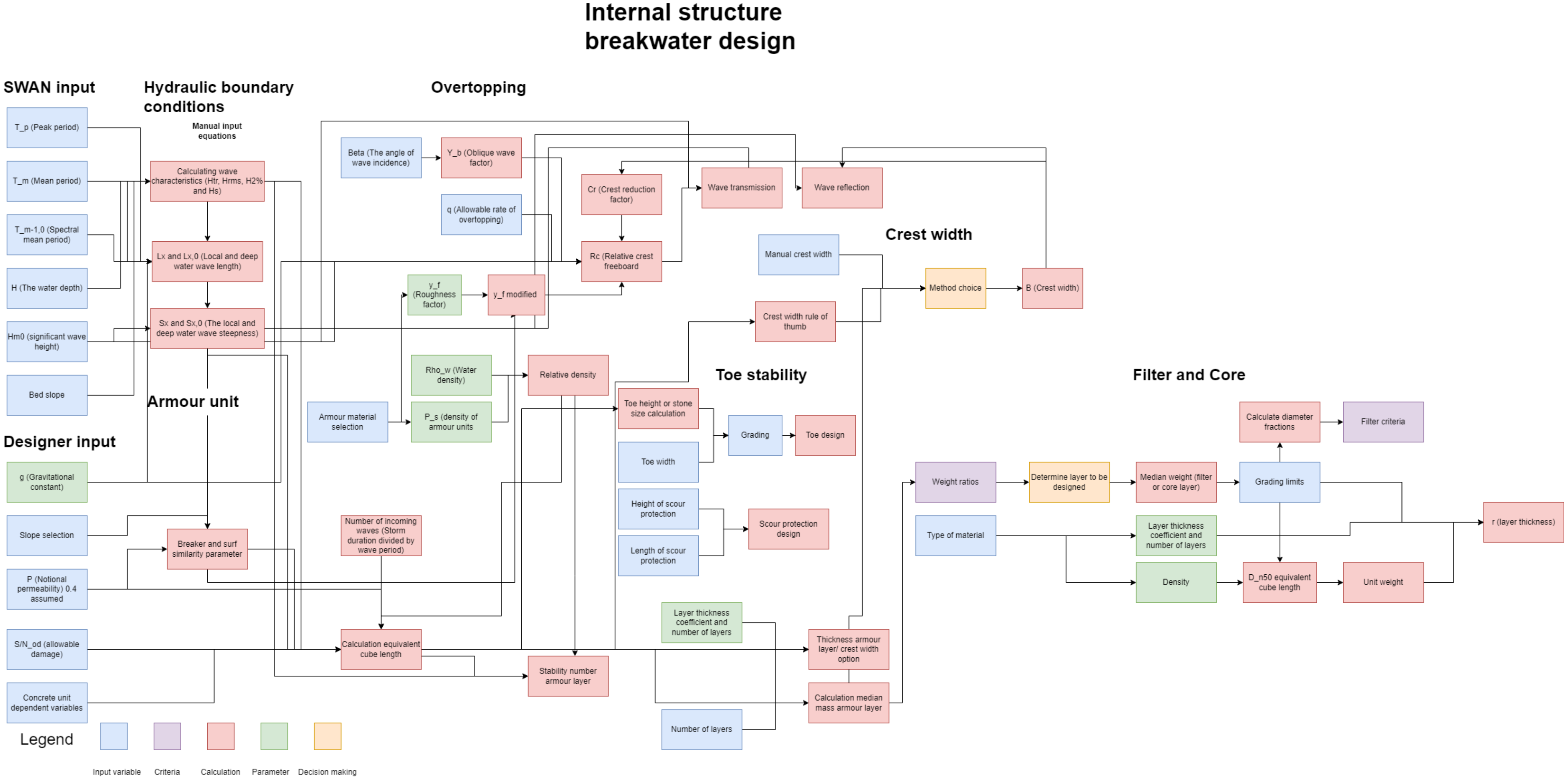


Figure 27: 2D-configuration calculation structure.

C.2. Model canvas structure

The model structure described in section 4.3 is translated to the software grasshopper to obtain a functioning model. In Figure 28 the canvas of the parametric design tool can be seen, structured in as described in the model structure. This to make it a user-friendly model for a designer to use.

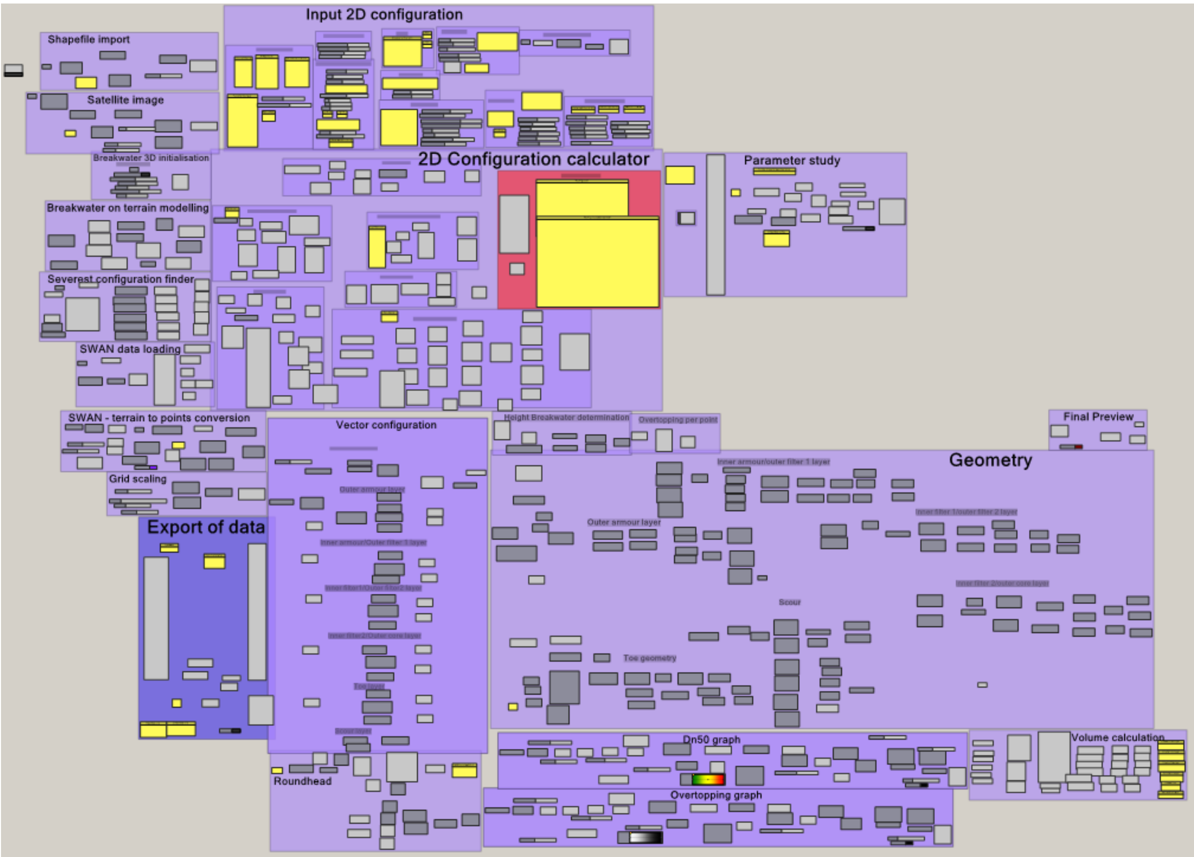


Figure 28: Grasshopper canvas of parametric design tool.