INTEGRATING CORAL HABITAT POTENTIAL AND COASTAL PROTECTION SERVICES IN DESIGN OF ARTIFICIAL REEFS

A CASE STUDY IN ADDU CITY, MALDIVES

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Integrating Coral Habitat Potential and Coastal Protection Services in Design of Artificial Reefs (2023)

by

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Summary

This research contributes to knowledge expansion and tool development for implementing Building with Nature (BwN) approaches in the context of artificial (coral) reefs. It aimed to explore environmental preferences and design tools for coral development emphasizing both coral habitat potential and coastal protection services, and to use this knowledge to optimize artificial reef design for a case study in Addu City, Maldives. This was accomplished through development of both a conceptual and OpenFOAM numerical model that function as dual-purpose design tools in search of a (preliminary) integral design for the case study. To aid in the design process, the first three of five BwN design steps van Eekelen and Bouw [2020] were applied.

A conceptual model is developed after an extensive literature review, representing the critical engineering and ecological variables important in a design process emphasizing both coral habitat potential and coastal protection services. It is applied in the case study as a design tool, aiding in the BwN design process. The conceptual model encompasses physical-chemical, biological, and design variables, and serves as a design tool for practical applications, fulfilling three primary purposes:

1. Identifying physical-chemical and biological variables that require further examination and analysis to explore coral habitat potential of a design.
2. Identifying physical variables that require further examination and analysis to explore coastal protection services provided by a design.
3. Identifying design variables influencing physical-chemical and biological variables that can be modified within a design to explore potential integral solutions.

While OpenFOAM is often used in the field of coastal engineering, it can also serve as a valuable tool in ecological engineering for designing artificial reefs. It is able to accurately model flow and turbulence regimes on any desired scale in the domain, which includes the capability to handle complex geometries and perform three-dimensional (3D) simulations if desired. Flow and turbulence regimes are important for the ecological and biological functioning of coral reefs, as is highlighted in the conceptual model and by many authors [Jokiel, 1978; Dennison and Barnes, 1988; Foley, 2015; Davis et al., 2021; van Gent et al., 2023].

An OpenFOAM numerical model for the case study using the olaFlow [Higuera, 2018] package was set-up, calibrated, and validated for the artificial reef case study using data from physical model tests carried out by DHI Group for average and design wave conditions. For the case study three design alternatives were identified: the traditional alternative with a slope of 2:3, a shallower structure with a slope of 1:3, and a steeper structure with a slope of 3:2, were identified and evaluated using a multi-criteria analysis (MCA) and five criteria. The OpenFOAM numerical model is applied to evaluate the impacts of altering the design variables for two of five important criteria that were evaluated, namely 1) for coral habitat potential through assessing flow regimes around the artificial reefs and 2) for coastal protection value through estimations of (long-term) effects on wave transmission. An artificial

reef with a mild (1:3) slope was eventually pre-selected as an integral solution over the traditional and steeper design, as it best performed in the MCA, taking into account criteria for coastal protection, coral habitat potential, and costs.

The conceptual model and OpenFOAM numerical model developed in this research are flexible dual-purpose design tools that have demonstrated their value in the initial assessment and optimization of artificial reef design in the case study in Addu City. Adhering to the BwN approach, both design tools can aid in the design process of artificial reefs that serve as dual-purpose structures, providing coastal protection and coral habitat potential services.

Preface

In front of you lies the end result of my 9.5-month thesis journey, the product of seven eventful years I devoted to the study of civil engineering, with a particular focus on hydraulic engineering. I still clearly recall my arrival in Delft as an 18-year old young adult, my mind occupied with various concerns of which civil engineering, if I am totally being honest, was not necessarily a top priority.

Over the years, I have developed a deep appreciation for the field of hydraulic engineering as I find it a most valuable and necessary discipline. I believe that us hydraulic engineers, because we possess the capabilities to do so, have a great responsibility to shape a future that is livable and sustainable for all. I feel fortunate to have had the opportunity to contribute to this through my thesis work, especially in light of more sustainable and nature-inclusive solutions. My hope is that my work can be useful and inspiring to you.

I want to thank my supervisors Stefan, Marcel, Martijn, and especially Erik for inspiring me and always providing helpful feedback. The efficiency of these efforts has truly impressed me at times. I would like to express my gratitude to everyone involved in my project at Van Oord, most of all 'colleagues' from the Environmental Engineering department who provided me with support and guidance. I felt very welcome within the company and am grateful for that. I also want to extend a heartfelt thank you to my family and friends for their continuous support, who helped taking away the occasional sense of loneliness throughout the journey.

One lesson that I have learned over the past seven years, both on professional and personal levels, that I would like to share with you is:

*Embrace **possibilities** as they are endless!*

Anne
Rotterdam, July 2023

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1. Introduction

1.1. Relevance

Coastal zones worldwide undergo a constant process of erosion and accretion, leading to continuous shape transformations. Throughout history, humans have recognized the benefits offered by coastal areas (for instance creation of habitable spaces, strategic economic advantages such as harbours, and areas dedicated to recreation and tourism), and have actively managed the movement of these zones to their advantage. Coastal engineers have always played an important role in protecting coastal zones and many coastal protection measures exist such as dikes, seawalls, breakwaters, groynes, and nourishments. At present, the natural dynamics of coastal zones is under additional pressure due to anticipated climate change scenarios, which are associated with rising sea levels and increasing global temperatures. This causes coastal zones to me more prone to erosion and flooding of the hinterland. A climate that is changing, including more frequent and intense extreme events, has caused widespread adverse impacts and related losses and damages to nature and people [IPCC, 2023].

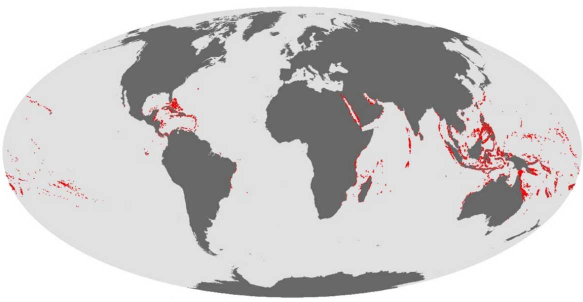


Figure 1.1.: The global distribution of coral reefs [UNEP-WCMC and WRI, 2021]

Figure 1.1 shows the global distribution of coral reefs. Besides human engineered coastal protection measures, natural coastal protection is provided by ecosystems, and it is widely recognized that coral reefs are effective in wave attenuation and coastal protection [Ferrario et al., 2014; Beck et al., 2016; Reguero et al., 2018; Burke and Spalding, 2022]. Especially for low-lying areas in tropical regions such as the Small Island Developing States that face unique social, economic and environmental vulnerabilities [UN, 2022], there is a significant need for coastal protection and restoration of coral habitats, especially in light of climate change. As defined by the Millennium Ecosystem Assessment [MA, 2005], ecosystem services are 'the benefits people obtain from ecosystems'. Coral reef habitat restoration can be effective in enhancing ecosystem-based adaptation and can in response to mean and extreme sea levels deliver habitat gain, biodiversity, carbon sequestration, income for tourism, and improved water quality [Fabian et al., 2013; Brathwaite et al., 2021, 2022; IPCC, 2023].

The use of nature-based solutions has attracted increasing attention in the context of protection against coastal flooding [Saleh and Weinstein, 2016] and there is growing recognition that NbS can be a vital part of adaptation strategies [Turner et al., 2022]. Considering the significance of coastal protection, biodiversity conservation, climate change mitigation, and nature-based solutions, this research focuses on artificial reefs. In the context of this research these concern green-gray solutions, like illustrated in Figure 1.2, specifically solutions C or D. Coral reef ecosystems used in 'hybrid' engineering design provide extra benefits over traditional engineering design since they are highly dynamic in response to physical changes and are able to recover and repair themselves [Spalding et al., 2014].

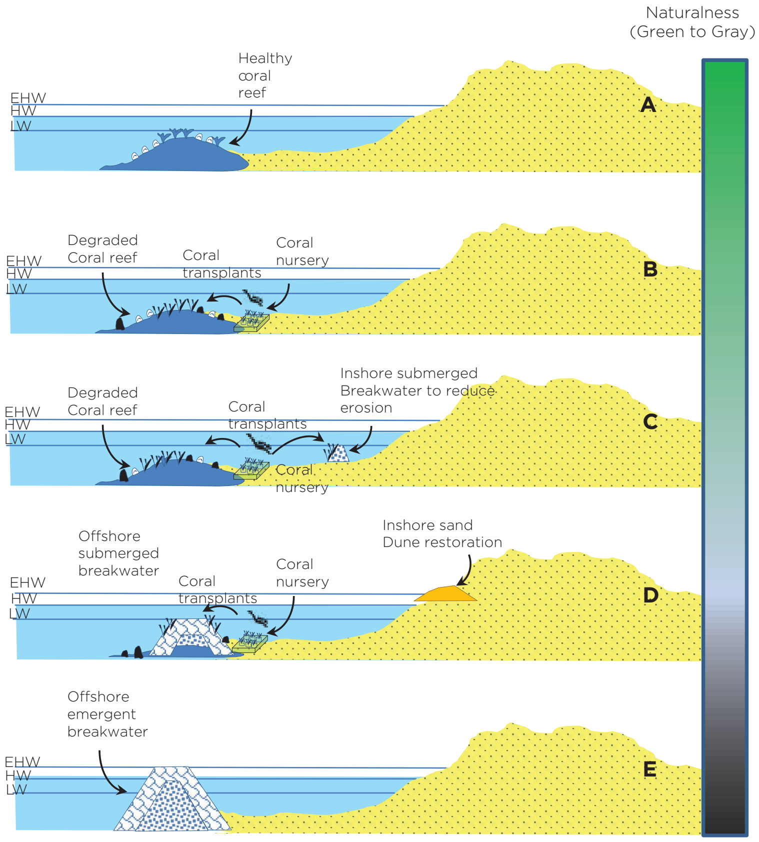


Figure 1.2.: Solutions to wave attenuation in tropical waters, adopted from Beck et al. [2016].

1.2. State-of-the-art

Deltares [2023] calls for marine developments to be designed in a climate-positive way in order to actively boost biodiversity and reduce carbon emissions in projects. Additionally, many authors emphasize that there is an urgent need of conservation and robust action to tackle stressors, threats of climate change and to increase resiliency of coral reefs [Fabian et al., 2013; Ferrario et al., 2014; Beck et al., 2016; Reguero et al., 2018; Jordan and Fröhle, 2022]. Risk reduction through engineered structures is recognized globally, but to date, with the exception of large-scale sand nourishments such the Dutch Sand Motor, little consideration is given to ecosystem-based coastal defense. Spalding et al. [2014] state that is crucial that operational frameworks will be developed for coastal defense planning combining the expertise of ecologists with that of engineers to optimize risk reduction. Research on hydrodynamics and wave attenuation of coral reefs and submerged breakwaters separately is carried out extensively over the past decades, as well as research on coral habitat restoration. Although within these separate fields challenges still remain, research emphasizing both ecological and engineering points of view at the same time is rare.

In recent years, a paradigm shift has been advocated for, known as the Building with Nature (BwN) approach. This approach, pioneered EcoShape [2023], aims to move away from simply building in nature to building with nature. The BwN philosophy continues to grow, and EcoShape [2023] and its contributors strive to serve as knowledge facilitators for engineers, managers, policymakers, and other stakeholders. They have developed 28 concepts to implement BwN solutions and actively participate in the ongoing development and refinement of BwN approaches. The focus of the BwN approach lies on identifying opportunities to incorporate environmental and socio-economic services into traditional approaches. Opportunities emerge in regions requiring coastal protection, particularly in light of climate change, where natural coral reefs occur. One of the 28 BwN Concepts developed by van Eekelen and Bouw [2020]: '*Facilitating coral development*' becomes relevant in the context of tropical regions characterized by sandy coasts and the presence of natural coral reefs. This Concept (Figure 1.3) is intended to provide ecological guidance on habitat requirements that are specifically needed to support coral communities [EcoShape, 2023]. From this point forward, this concept is referred to as **coral development**.

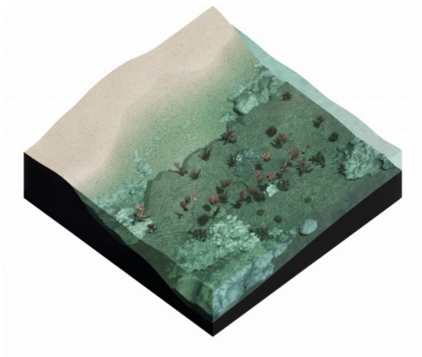


Figure 1.3.: Building with Nature concept: facilitating coral development [EcoShape, 2023]

1.3. Research objective

As recognized by van Gent et al. [2023], a submerged structure can be a traditional coastal defence structure, but the function of dissipating wave energy can also be combined with the function of enhancing marine life by creating an artificial reef. There is a growing recognition of the advantages of nature-inclusive design approaches such as the BwN approach, but further development of frameworks or tools, as well as additional case studies and pilot projects, are needed. This research aimed to contribute to sustainable coastal management, through advancing knowledge and developing tools for coral development within design of submerged breakwaters, from now on referred to as *artificial reefs* emphasizing both coral habitat potential and coastal protection services. This led to the following research objective:

To explore environmental preferences and design tools for coral development emphasizing both coral habitat potential and coastal protection services, and to use this knowledge to optimize artificial reef design for a case study in Addu City, Maldives.

1.4. Research questions

The following research questions have been formulated in order to achieve the research objective:

- **RQ1:** What are the essential engineering and ecological variables in design of artificial reefs, in terms of a conceptual model that can be used as a design tool for coral development?
- **RQ2:** Is it possible to use an OpenFOAM numerical model as a design tool for coral development?
- **RQ3**: Utilizing 1) the conceptual model and the OpenFOAM numerical model as design tools and 2) a Building with Nature design approach, what is a preliminary integral design for the case study?

1.5. Research methodology

This section outlines the systematic approach used to address the research objective and questions of this thesis. First, the case study that is used throughout this thesis is described. Then, the methodology used to reach the research objective and to address the research questions is described.

Case study

The Ministry of National Planning, Housing, and Infrastructure of the Maldives contracted Van Oord to reclaim and create a total of 194 hectares of land in Addu City, Maldives as part of the Addu Development Project. This project is meant to address climate change and to transform Addu City into a fully functional, thriving economic hub and an attractive tourist destination [Van Oord, 2022]. The project is socially driven and aims to enhance the city's physical development by expanding land area for housing and industrial activities. It also supports existing harbor front activities and addresses the residential community's needs. The case study addressed in this thesis is part of the larger Addu Development Project and concerns a reclamation area in Hithadhoo, as shown in Figure 1.4. This area concerns a 40 of the total 194 Ha reclamation area and starts from the approach road to the Hithadhoo Port and extends up to the end of Hithadhoo island near the bridge connecting Hithadhoo to Hankede. The total length of the stretch is about 2.5 km.

Figure 1.4.: Case study area

The case study in Addu City, Maldives concerns a pilot artificial reef project located within the case study area. Two physical model tests, one for average and one for design wave conditions, of the artificial reef have been carried out at DHI Group, Denmark. An on-scale sketch of the average physical model wave flume is shown in Figure 1.5. Here, h is the water, and Wg is an abbreviation for a wave gauge, used to record surface elevations at 10 specific locations in the wave flume.

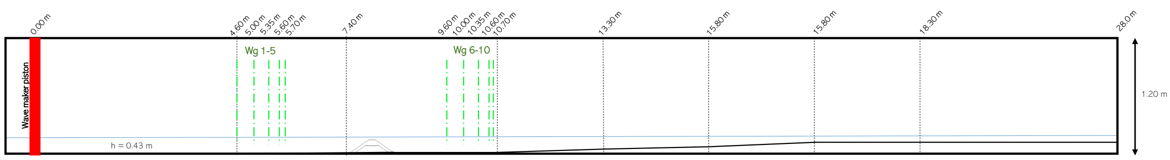


Figure 1.5.: Cross-section (scale 1:20) physical model experiments - average conditions

Methods

The methodology is illustrated in Figure 1.6. At the start of the research, an extensive literature review was conducted. The purpose of this review was twofold:

- To gain a comprehensive understanding of relevant theory that serves as a basis for the rest of the research in the fields of submerged breakwaters, coral reef ecosystems, and numerical modeling.
- To assist in answering the first research question, involving identification of important engineering and ecological variables as well as the development of a conceptual model.

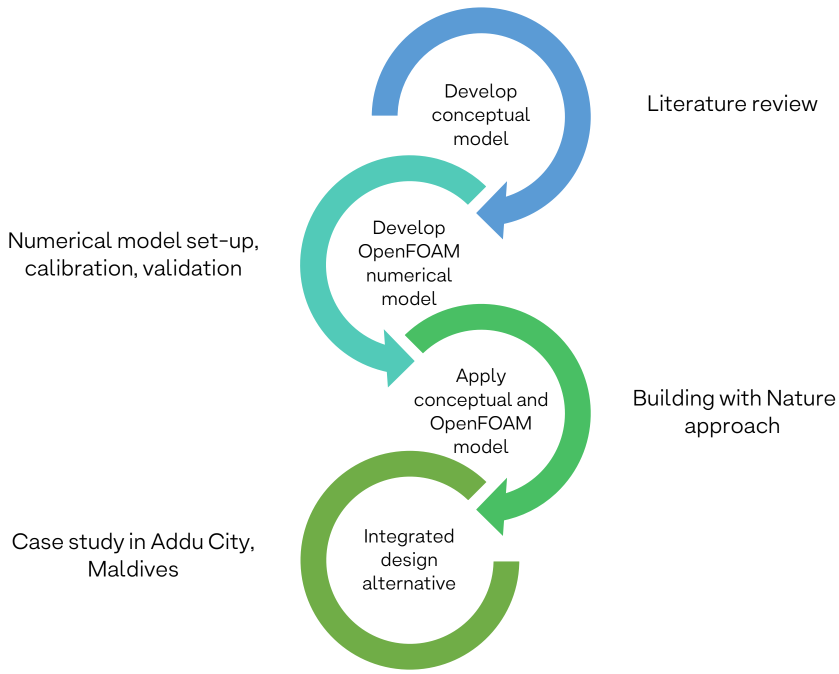


Figure 1.6.: Research methodology

Although OpenFOAM is often used in the field of coastal engineering, it can also serve as a valuable tool in ecological engineering for designing artificial reefs. OpenFOAM is able to accurately model flow and turbulence regimes on any desired scale in the domain and for these reasons, it was decided to explore OpenFOAM as a dual-purpose design tool for artificial reefs. To answer the second research question, an OpenFOAM numerical model has been set-up, utilizing the olaFlow toolbox [Higuera, 2018] for the case study. The data from the physical model tests is used in this research to calibrate (using average conditions) and validate (using extreme conditions) the numerical model.

To be able to reach the research objective and answer the third research question, the conceptual model and OpenFOAM numerical model are explored and used throughout the rest of the research for the initial assessment and decision-making process on a design for the case study. To aid in the design process, the first three of five Building with Nature design steps (Figure 1.7) as formulated by van Eekelen and Bouw [2020] within the BwN approach are applied. Step four and five involve practical considerations such as funding, budgeting, governance, and stakeholder engagement. Due to time, scope, and practicability reasons these are considered not directly applicable or necessary for the purposes of this research.

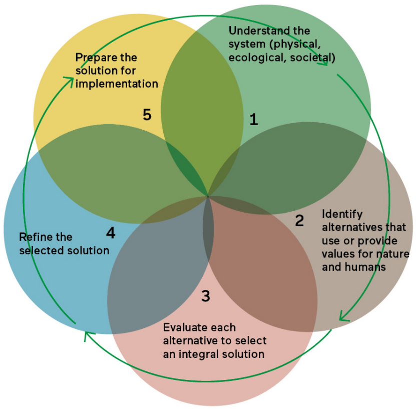


Figure 1.7.: The five Building with Nature design steps [van Eekelen and Bouw, 2020]

1.6. Thesis outline

The structure of this report is presented in Figure 1.8. Chapter 1 first presents significance of the research to the hydraulic engineering field. The chapter outlines the main objective, research questions, and the methodology applied to answer these questions and achieve the research objective. In Chapter 2, relevant basic theory in the fields of submerged breakwaters, coral reefs, and artificial reefs is presented. In Chapter 3 the conceptual model is developed and presented. In Chapter 4 the physical model tests are described and the OpenFOAM numerical model is set-up, calibrated, and validated. In Chapter 5 the first three steps of the Building with Nature five steps approach are applied to the case study resulting in an optimized design for the case study. In Chapter 6 results from Chapter 3, Chapter 4, and Chapter 5 are discussed. Finally, Chapter 7 presents the answers to the research questions, achievement of the research objective, recommendations, and suggestions for further research.

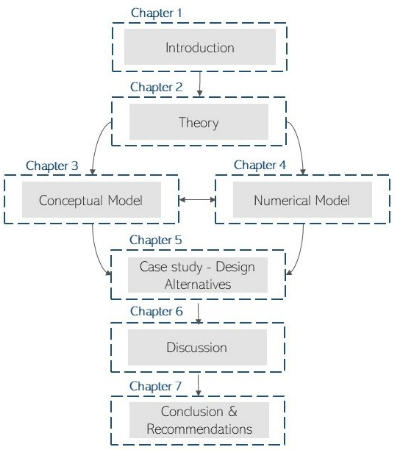


Figure 1.8.: Thesis outline

2. Theory

2.1. The coral reef ecosystem

The coral reef ecosystem is one of the most biodiverse and multi-functional ecosystems in the world. Coral polyps, that show up in various forms, are the animals responsible for the formation and creation of a coral reef ecosystem. Their history is hundreds of years old. The stony or hard corals as we commonly encounter them today are of the order Scleractinia in the phylum Cindaria (aquatic animals in marine environments). They are a group of calcified anthozoan corals, they calcify rapidly and mostly in shallow waters, their success on reefs is related to a symbiotic association with zooxanthellae algae, of which coral reefs are the host organism.

Coral reefs serve a wide array of services, acting as habitats, breeding grounds, shelter and nurseries for fish and other numerous species, thus contributing to global biodiversity. They also play a crucial role in providing regulation services, including water filtration, carbon storage, nutrient cycling, and coastal protection. Additionally, coral reefs hold significant socio-economic value, attracting tourism, supporting fisheries, and offering cultural services, including the conservation of ancestral heritage and provision of spiritual value.

Coral reefs face multiple threats or stressors, particularly from changing climates. These include warming oceans, ocean acidification, and intensified storms, which lead to coral bleaching and structural degradation. Cornwall et al. [2021] highlighted the low likelihood that the world's coral reefs will maintain their functional roles without near-term stabilization of atmospheric CO_2 emissions. Additionally, pollution, overfishing, sedimentation, eutrophication, and the introduction of invasive species pose significant stressors to these ecosystems.

2.2. Submerged breakwaters

A breakwater is a structure built in nearshore waters that protects anything located landward from it from the impact of currents and waves. It can have multiple functions, such as preventing shoreline erosion, facilitating easy access to a harbor for ships and vessels to sail to and from, or serving as a habitat for marine organisms. Many forms and types of breakwaters exist. There are respectively two types of these detached breakwaters, namely emerged (crest level above Mean Sea Level (MSL) or submerged (crest level below MSL). This research focuses on a detached, thus at a certain distance from the coastline, shore-parallel offshore submerged breakwater, with two functions: to protect a beach landward of it from erosion and to serve as a coral habitat substrate. Submerged breakwaters are popular for aesthetic reasons as they do not disrupt views from the beach as opposed to emergent structures.

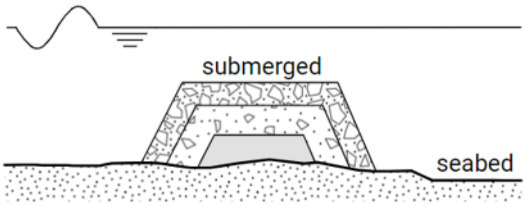


Figure 2.1.: Detached shore parallel submerged breakwater [Bosboom and Stive, 2023]

Wave transmission

Wave transmission refers to the process by which waves pass through or interact with the breakwater structure. It occurs when incoming wave energy interacts with a structure, transferring it to the opposite side where it generates transmitted waves. Waves can travel over the structure (overtopping) or through the structure (porous flow). A submerged breakwater, is continuously overtopped (and allowed), and therefore in general more waves are transmitted to the lee side of the structure compared to emerged structures. For both types of structures, the degree of transmission may vary depending on the design and characteristics of the breakwater. It is common to define wave transmission in terms of the wave transmission coefficient K_t [EurOtop, 2018]:

$$K_t = \frac{H_{s,t}}{H_{s,i}} \tag{2.1}$$

This coefficient in this research is based on the significant wave height H_s and is defined as the transmitted waves $H_{s,t}$ divided by the incoming waves $H_{s,i}$. Since wave heights are related to wave energy, wave transmission is also related to wave energy.

Artificial reefs

Lima et al. [2019] conducted a systematic literature review of artificial reef research including studies from 1962 to 2018. They defined artificial reefs on a broad level as human-made structures installed in aquatic habitats that serve as a substrate and/or shelter for organisms. When serving as a substrate for coral reef or other marine habitats, detached submerged breakwaters are often referred to as artificial reefs. Artificial reefs play imperative roles in coastal ecology and nearshore environments by providing unnatural sheltered habitats and can have noticeable impacts on marine biodiversity [Saengsupavanich et al., 2022]. Many types and forms of artificial reefs exist, ranging from traditional rocky breakwaters to for example complex designed reef balls and 3D printed reef structures.

2.3. OpenFOAM

Some basic theory on numerical modelling and the toolbox used in this thesis is presented in this section and serves as a basis for Chapter 4. Numerical modelling is a preferred tool for many engineering applications since it is in general more efficient and less time consuming than experimental or physical modelling methods. Following the numerical modelling procedure that uses computer algorithms to solve mathematical equations describing physical phenomena allows for insights in the behaviour of complex systems.

Various numerical modeling approaches are available for wave-structure interaction processes, including nonlinear shallow water (NLSW) models, Boussinesq potential flow models, Eulerian Reynolds-Averaged Navier-Stokes (RANS) models, and Volume-Averaged Reynolds-Averaged Navier-Stokes (VARANS) models. The Navier-Stokes (NS) models have the capability to simulate intricate phenomena such as wave breaking and complex flow processes within porous media, unlike potential flow modeling.

Open Source Field Operation And Manipulation (OpenFOAM) is a computational fluid dynamics (CFD) C++ library that operates under the GNU General Public License. It is able to solve the Reynolds-Averaged Navier-Stokes (RANS) equations to model fluid flow. In combination with the olaFlow toolbox, which solves the Volume-Averaged Reynolds-Averaged Navier-Stokes (VARANS) equations, the foam-extend 3.1 toolbox within OpenFOAM is employed in this thesis. olaFlow [Higuera, 2018], previously known as olaFoam and a continuation of the IHFOAM project, is an open-source initiative developed within the OpenFOAM framework. It builds upon the work of Higuera [2015] and enables the simulation of wave and porous structure interactions in the coastal and offshore fields. This toolbox provides a range of utilities, solvers, and boundary conditions to actively generate and absorb water waves at boundaries and simulate their interaction with porous structures.

2.3.1. Flow through porous media

VARANS equations

OlaFlow uses finite volume discretization to solve the 3D VARANS equations. The Volume of Fluid (VOF) technique [Hirt and Nichols, 1981] is used to represent complex configurations of free surfaces by tracking two incompressible phases: water and air. Furthermore, turbulence modelling is introduced by different approaches and a number of available models. The VARANS equations describe flow through porous media. The RANS equations for incompressible fluids, are capable of describing the motion of a fluid. Difficulties are encountered though in solving the equations with regards to turbulent flow. Turbulence small-scale fluctuations of random or chaotic nature that cause challenges in solving the equations, giving rise to closure problems. Volume-Average RANS equations, as the name implies, account for the effects of turbulent flow in a porous medium in a volume-averaged sense. The VARANS equations are represented by the continuity (2.2a) and momentum (2.2b) equations that link pressure and velocity. The momentum equations involve additional closure terms ([CT]) to account for the effects of turbulence, and are in that way able to represent flow inside porous media:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{2.2a}$$

$$\frac{1+C}{\phi}\frac{\partial \rho u_i}{\partial t} + \frac{1}{\phi}\frac{\partial}{\partial x_j}\left[\frac{1}{\varphi}\rho u_i u_j\right] = -\frac{\partial (p^*)^f}{\partial x_i} - g_j X_j \frac{\partial \rho}{\partial x_i}$$
$$+ \frac{1}{\phi}\frac{\partial}{\partial x_j}\left[\mu_e \frac{\partial u_i}{\partial x_j}\right] - [CT] \tag{2.2b}$$

where u_i is the velocity vector and x_i the position vector. ϕ is the porosity, p^* the pseudo-dynamic pressure, g_i is gravitational acceleration ($g_i = 9.81 m/s^2$), μ_e the effective dynamic viscosity ($\mu_e = \mu + \rho\nu_{turb}$), ν_{turb} being the turbulent kinetic viscocity given by a turbulence model. C is related to acceleration of porous flow. The closure terms as proposed by Forchheimer [1901] and Engelund [1953], revised by Van Gent [1995] and applied by Burcharth and Andersen [1995] are represented with linear and nonlinear drag force resistance coefficients A and B:

$$[CT] = Au_i - B\sqrt{u_j u_j} u_i \tag{2.3}$$

$$A = \alpha \frac{(1-\phi)^3}{\phi^3}\frac{\mu}{D_{50}^2} \tag{2.4a}$$

$$B = \beta \left(1 + \frac{7.5}{KC}\right)\frac{1-\phi}{\phi^3}\frac{\rho}{D_{50}} \tag{2.4b}$$

where D_{50} is a median or average particle size of the porous medium, and KC the Keulegan-Carpenter number which quantifies additional friction as a result of flow-induced oscillations. Here, α and β are empirical drag coefficients. They are are essential for ensuring the model behaves in accordance with the underlying principles of physics.

VOF technique

The VOF technique describes the movement of two phases: water and air. Since in many coastal engineering applications only water and air are relevant, this assumptions results in the need of only the following equations to solve this problem, α being the indicator (VOF) function:

$$\begin{cases} \alpha = 0 & \text{Air} \\ 0 < \alpha < 1 & \text{Free Surface} \\ \alpha = 1 & \text{Water} \end{cases} \tag{2.5}$$

If $\alpha = 1$ the cell is full of water and If $\alpha = 0$ the cell is full air, and in other cases it concerns the free surface. This way density is computed via:

$$\rho = \alpha\rho_{water} + (1-\alpha)\rho_{air} \tag{2.6}$$

And the final advection-diffusion equation that is solved is given by:

$$\frac{\partial \alpha}{\partial t} + \frac{1}{\phi}\frac{\partial u_i \alpha}{\partial x_i} + \frac{1}{\phi}\frac{\partial u_{c_i}\alpha(1-\alpha)}{\partial x_i} = 0 \tag{2.7}$$

For a detailed decsription of this method the reader is referred to Rusche [2003].

Turbulence model

OlaFlow is able to solve modified versions of the k-ϵ and k-ω SST turbulence models to simulate correctly multi-phase systems, which mitigates excessive wave height damping due to turbulence build-up [Higuera, 2018]. The k-ϵ model is widely applied as a turbulence model [Shaheed et al., 2018] and is applied in this research, solving turbulent kinetic energy k, and turbulent kinetic energy dissipation rate ϵ.

2.3.2. Solving procedure

In OlaFlow, the two step method solving the VARANS equations is called PIMPLE, a combination of PISO (Pressure Implicit with Splitting of Operators) and SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithms. Equation 2.7, an advection-diffusion equation is solved with a specially designed solver called MULES (Multidimensional Universal Limiter for Explicit Solution). From version 2.3.0, this technique includes a new semi-implicit variant, which combines operator splitting with application of the MULES limiter to an explicit correction rather than to the complete flux. In principle this is advantageous, as it will enhance the stability for larger Courant numbers [Higuera, 2018].

3. Conceptual model

In this chapter, a conceptual model is presented illustrating critical engineering and ecological variables important in artificial reef design serving both coral habitat restoration and coastal protection services. The conceptual model is the result of an extensive literature review in the fields of coral reefs, submerged breakwaters, and artificial reefs. Main conclusions from the literature review are presented first, resulting in a set of physical-chemical (Section 3.1), biological (Section 3.2), and design variables (Section 3.3). Some variables in the model specifically address coral habitat potential services, some concern coastal protection services, and some variables are important for both. These distinctions are elaborated on in the respective sections. In Section 3.4, interrelations and practicability of the model are discussed, followed by an elaboration on how the conceptual model is applied in this research to the case study in Addu City, Maldives in Section 3.5.

3.1. Physical-chemical variables

Physical-chemical variables important in artificial reef design serving both coral habitat restoration and coastal protection services are presented in Figure 3.1. Three essential groups of physical-chemical variables are established as a result from the literature review: water quality, light availability, and water motion.

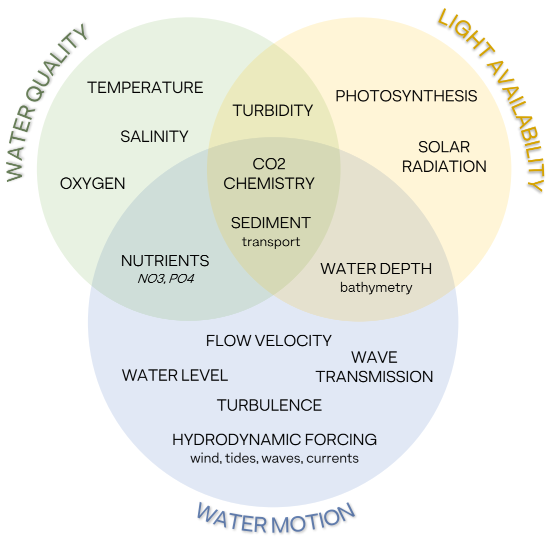


Figure 3.1.: Physical-chemical variables that influence coral habitat restoration (water quality, light availability, water motion) and coastal protection (water motion) services.

The determination of these variables is mainly based on a classification of Huang et al. [2011] of environmental variables depicting major aspects of marine environment that influence benthic biota at fine to broad spatial scales, an extensive study carried out by Haywood [2007] that characterised key biotic and physical attributes of benthic species among which corals, and a practical guide for establishment and management of artificial reefs by Tinto [2015].

Light availability

Coral habitat restoration service

Corals, just as plants, other algae, and some bacteria, are **photosynthetic** organisms, meaning that they capture energy from sunlight and use that energy to convert carbon dioxide and water into organic compounds. Corals build their calcium carbonate structures with the help of photosynthesis. They are able to grow and remain healthy for specific ranges of quality, duration, and exposure of light. Corals have a symbiotic relationship with microscopic single-celled photosynthetic algae called zooxanthellae that are located within the coral tissue. These zooxanthellae produce oxygen through photosynthesis, which is used by corals for carrying out their critical physiological processes. Chlorophyll is the pigment that allows zooxanthellae to absorb light and carry out photosynthesis and **solar radiaton** determines the amount of light availability. Solar radiation in the visible range (photosynthetically active radiation, PAR: 400–700 nm) is vital to photosynthetic organisms such as the algal symbionts that live within the tissue of reef-building corals [Bouwmeester et al., 2023].

Naturally, **water depth** influences the amount of light available for corals and zooxanthellae, and different types of coral species prefer different water depths [Foley, 2015]. As water depth increases, less light can penetrate through the water column. An important stressor for coral reefs is coral bleaching, where corals lose their colour. One of the causes of coral bleaching is when corals are exposed to high levels of light availability for too long, which causes this symbiotic relationship between corals and zooxanthellae to break down.

Water quality

Coral habitat restoration service

Adequate water quality ensures growth, survival, and propagation of corals and is essential for their health and resilience. Water quality varies significantly around the world, and corals flourish in areas where their preferred water quality is met. If the water quality in these areas deteriorates, it could cause stressors to coral reefs, such as sedimentation or excessive nutrients, ultimately threatening their survival. Appropriate salinity, temperature, nutrient, and sedimentation levels should be ensured since they are of influence to metabolic rates, reproductive success and immunity.

Reef corals and coral reefs can encounter a large range of **salinities**, but are sensitive to them. If salinity tolerances are exceeded, sub-lethal changes in coral reef metabolism can occur. Salinity levels are important for osmoregulation and other physicological processes necessary for coral growth, and coral reefs prefer to grow where high evaporation and low precipitation and freshwater input produce salinities much higher than world average [Coles and Jokiel, 1992].

18 to 31 °C is the generally accepted range of water **temperature** for coral reef development worldwide [Tinto, 2015]. As mentioned earlier an important stressor to corals is coral bleaching, which occurs with rising global water temperatures.

Zooxanthellae produce **oxygen** through photosynthesis, which is used by corals for carrying out their critical physiological processes. Disturbed oxygen levels can disturb these processes and again deteriorate a coral's health. Furthermore, nitrate and phosphate are essential **nutrients** necessary for the formation of coral tissue and development of their skeletal structures, the process of calcification [Haywood, 2007; Huang et al., 2011]. Excess nutrients can lead to eutrophication, where growth of algae and other organisms that compete with corals is promoted.

CO_2 chemistry here refers to the process of regulating pH of ocean waters and coral skeleton building processes. CO_2 dissolves in seawater, which could lead to a process called ocean acidification due to a decrease in pH (or due to rising temperatures). Coral reefs are sensitive to changes in pH levels referring to acidity or alkalinity and these changes could have negative effects on carbonate accretion and calcification. CO_2 chemistry in seawater directly affects the availability of inorganic carbon for photosynthesis in coral reefs.

Corals prefer clear, clean waters with low levels of **sedimentation** [Martin et al., 2005; Fabi et al., 2015; Reguero et al., 2018], where sandy particles settle and accumulate in a water column, and **turbidity**, the cloudiness of water caused by the suspended particles. Too high levels of these processes can bury the corals or prevent them from successful photosynthesis and nutrient intake. For example, sediment deposition prevents coral larvae from settling on a surface and strongly impacts post-recruitment survival of corals [Jayanthi et al., 2020].

Water motion

Coral habitat restoration service

Wind, tides, and variations in temperature and salinity are external factors that act as **hydrodynamic forcing**, causing wave and current patterns in oceans and seas. These mechanisms result in hydrodynamic energy and water motion that induces variations in **turbulence**, **velocities** and **water levels** in the water column. Water motion or flow has been recognized for a long time to be of great importance for the health and growth of marine ecosystems, and coral growth and reef development are influenced by the metabolic responses of corals to water motion over and around coral reefs [Jokiel, 1978; Dennison and Barnes, 1988]. Water motion is induced by hydrodynamic energy and serves a variety of functions such as delivering nutrients, supplying oxygenated water, removing sediment from the water column, increasing respiration rates of coral tissue, and better elimination of waste products such as carbon dioxide. The interaction of coral reefs, both chemically and physically, with the surrounding seawater is governed by flow—at the large scales by tides, mesoscale currents, and waves and at the smallest scales by turbulence [Davis et al., 2021].

Kuffner [2002] found that the effect of water motion on the calcification rate of the scleractinian reef coral *Porites compressa* was investigated. The study found that water motion was the only significant factor affecting calcification rate. One study carried out by Dennison and Barnes [1988] found that net photosynthesis and respiration were significantly reduced in unstirred conditions compared with stirred conditions. Jokiel [1978] also observed variations in coral growth patterns with respect to higher water motion regimes. As noted by Adams [2006], the study of water motion and its impact on coral growth establishment is a complex and multifaceted field. Turbulence plays an important role in the mixing of momentum and diffusing nutrients, metabolites, and larvae around coral reefs [Huang et al., 2011; Huang, 2015]. Hydrodynamic energy critically affects coral and substrate composition through sediment transport and (sea)bed shear stress as it affects substrate composition through sediment transport which controls benthic community composition and imparts temporal variation within the system [Jackson-Bue et al., 2022]. Again, suspended sediment at high concentrations can adversely affect a variety of reef organisms via light attenuation and smothering [Pomeroy et al., 2017].

Coastal protection service

Within the physical-chemical variables, water motion naturally plays a vital role in coastal engineering and the design of coastal protection measures, specifically in relation to hydrodynamic parameters. The interaction between physical and chemical variables in coastal areas is influenced significantly by the **hydrodynamic energy** and forces. These forces affect the stability of structures, and coastal defenses are constructed to dissipate wave energy and manage **sediment transport**, thereby minimizing erosion and safeguarding both the coasts and the hinterland. Bathymetry or water depth of above reef surfaces or breakwaters is a critical factor in determining amounts of wave attenuation [Koch et al., 2009; Ferrario et al., 2014; Beck et al., 2016].

3.2. Biological variables

Figure 3.2.: Biological variables that influence coral habitat restoration services

Coral habitat restoration service

Important biological variables are presented in Figure 3.2, involve living organisms, and are important for coral habitat restoration purposes. Coral growth and survival are influenced by a variety of interconnected and -dependent biological variables and are interdependent on many physical chemical variables. **Invasive species** compete with native coral reefs for nutrients, light, and space, can become abundant due to for example prolonged high nutrient levels [Jayanthi et al., 2020]. A natural balance between native and invasive species exists, yet the balance can be disturbed due to for example the abundance of prolonged high nutrient levels. Successful recruitment of corals and colony growth is influenced by the succession of **larval settlement** and the availability of new recruits.

An important stressor to this is sedimentation, since sediment deposition may hinder coral larvae settlement and significantly impact post-recruitment survival of corals, as noted by Jayanthi et al. [2020] in their study on perforated trapezoidal artificial reefs.

A crucial component of the coral **food chain** is the symbiotic relationship between corals and a type of microalgae called zooxanthellae. Zooxanthellae live within the coral tissues and provide corals with a significant portion of their energy needs through photosynthesis. The **surrounding habitat** is mentioned because, when searching for a suitable location to place an artificial reef, the chances of succession are higher in areas where existing reefs are already thriving. The benthic community's recruitment, composition, and abundance may be impacted by the typology of the surrounding habitats [Tinto, 2015]. When an artificial reef is designed, it is crucial to consider the **life history of target species** and their migratory patterns [Fabi et al., 2015]. Finally, corals can contract several **diseases** due to viruses, parasites, bacteria from pollution and other environmental stressors. It is likely that due to sea water warming diseases greatly contributed to coral degradation globally [Reguero et al., 2018]. Where light availability is limited, corals and other organisms may experience reduced growth rates, lower reproductive success, and increased susceptibility to disease and **predation**.

3.3. Design variables

In this section, design variables that influence the physical-chemical and biological variables are presented that can be adjusted in design of artificial reefs. The design variables are divided into two principal groups resulting from the literature review: *substrate* and *structural* and are illustrated in Figure 3.3. Both affect coral habitat restoration and coastal protection purposes.

Substrate

Coral habitat restoration service

A suitable type of hard substrate is an essential requirement for coral establishment, attachment, growth, and survival [Tinto, 2015; Strain et al., 2018; Burt and Bartholomew, 2019; Margheritini et al., 2021; Brathwaite et al., 2022; Jackson-Bue et al., 2022].

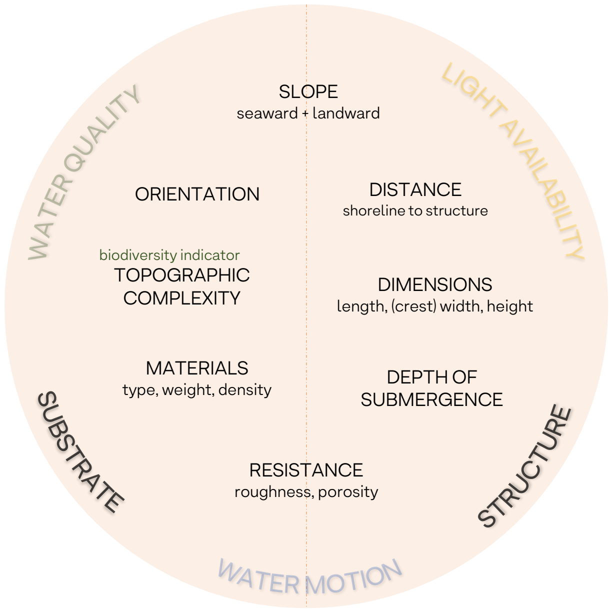


Figure 3.3.: Design variables that influence coral habitat restoration and coastal protection services in design of artificial reefs.

One key requirement for success is to incorporate a certain amount of **topographic complexity**, or habitat, or structural complexity for the corals to settle on. Whalan et al. [2015] argue that surface complexity plays an important role in larval settlement of coral reef sessile invertebrates. When looking at naturally occurring hard substrates that coral reefs have settled on, these are not simple flat and smooth surfaces in their natural state, but have complex features that allow coral reefs to thrive. Natural substrates on which coral reefs settle are characterized by a diverse range of features such as small holes, grooves, ripples, and pits. These features provide shelter for a variety of marine organisms and contribute to the overall biodiversity of the reef ecosystem. Incorporating certain features, such as small cavities and narrow spaces, into coastal defense structures can improve coral colonization and survival. These features are best included during the construction phase, but retrofitting can also be done for existing structures [Burt and Bartholomew, 2019].

In relation to topographic complexity, the type of **material** chosen in the design of an artificial reef is a crucial variable in serving as a hard substrate for coral establishment and is of influence on the settlement of coral larvae. Furthermore, the positioning of the substrate or **orientation**, with respect to the incoming wave direction and the structure's **slope** are important, as this affects water motion, light exposure and sedimentation.

Coastal protection service

Also in relation to coastal protection, **topographic complexity** and the type of **material** chosen in the design of an artificial reef is a crucial variable as it influences both the coastal defense function of the structure. Material type affects how waves are transmitted over (roughness) and through (porosity) the structure and relates to resistance parameters. More topographic complexity and therefore rougher surfaces for instance result in more resistance offered by the structure which contributes to more wave energy reduction.

Structure

The variables associated with the structure are the primary considerations when designing coastal defense. For the purposes of designing an artificial reef, these variables should be carefully considered through an ecological lens as well.

Coral habitat restoration service

From an ecological point of view, it is important to take the **slope** and (partial) shading into account. Light availability can be affected, and also differences in wave exposure can affect the type of sediments that are deposited on the breakwater surface, resulting in distinct benthic communities in exposed versus sheltered areas [Burt et al., 2012]. As mentioned **resistance**-related parameters of a structure representing roughness and porosity, in relation to materials and topographic complexity, play a crucial role in coral settlement. Compared to smooth surfaces, rough surfaces reduce the risk of dislodgment and damage from water motion or other disturbances because corals can anchor and build their base more effectively. The dimensions and positioning of a coastal defense structure have a significant impact on water motion in its vicinity. This factor becomes crucial in the context of coral habitat restoration design since different coral species have specific preferences for water motion regimes [PIANC, 2010].

Coastal protection service

The mode of shoreline response to a submerged breakwater, unlike an emergent breakwater resulting in accretive or erosive patterns, is influenced greatly by hydrodynamic conditions, the distance from structure to shoreline, the natural surf zone width and the geometry of the structure, regardless of the wave angle of incidence [Ranasinghe and Turner, 2006; Ranasinghe et al., 2010]. Together with the significant wave height, the **depth of submergence** of the structure is considered to be the most important variable affecting the wave transmission over submerged structures [Bleck, 2006; Srineash et al., 2020; Kim et al., 2021]. Besides the depth of submergence, naturally the **dimensions** of the structure (length, width, height) and the distance from **shoreline to structure** influences amounts of wave transmission and sediment transport. The less porous and more rough the structure, the more waves are transmitted.

3.4. Interrelations and practicability

The complete conceptual model is presented in Figure 3.4 as a result of the extensive literature review. The conceptual model functions as a comprehensive framework, illustrating the essential variables that impact both the objectives of coastal protection and coral habitat restoration of an artificial reef. It serves as a design tool for practical applications, fulfilling three primary purposes:

2. Identifying physical variables that require further examination and analysis to explore coastal protection services provided by a design.
3. Identifying design variables influencing physical-chemical and biological variables that can be modified within a design to explore potential integrated solutions.

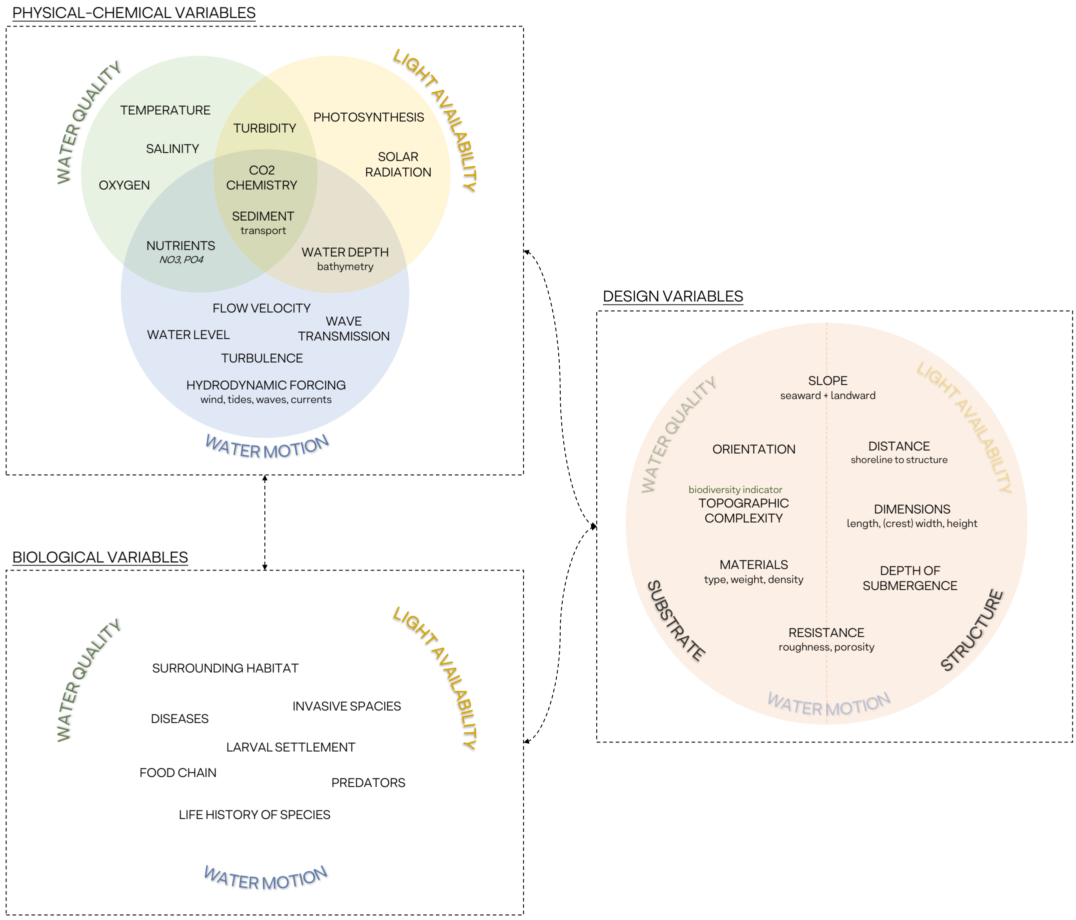


Figure 3.4.: A conceptual model that can be used as a tool for analysis and design of an artificial reef delivering both coral habitat restoration and coastal protection services.

The literature review revealed that many variables within the conceptual model are interrelated. The physical-chemical variables are visible in the boxes displaying biological and design variables, illustrating this interplay. Essentially, all variables within the conceptual model exert mutual influence on one another. The combined story of coral habitat restoration and coastal protection is interdisciplinary, and highly site- or case-specific. This results in a complex interplay between all variables. There is no single optimal design or one-size-fits all solution that can be applied universally and for every case. Many researchers expressed diverse perspectives, and the absence of definitive design rules further emphasizes the complexity of the subject.

The framework provides a valuable starting point for initial assessments and serves as a broad guide rather than a prescriptive blueprint. Through identifying, understanding, and deeper analysis of interrelationships, the model can provide insights into the complex dynamics of coral habitats and guides decision-making in design processes focusing on integral artificial reef solutions that emphasize both coral habitat restoration and coastal protection services. In terms of practicability of the model, several methods exist for deeper analysis and are often applied, ranging from extensive and time-consuming methods to quicker methods for initial assessments. In general the following methods are highlighted:

- Desk research
- In-situ measurements or field observations
- Laboratory works or experiments
- Analytical methods or (empirical) design guidelines
- Physical modeling
- Numerical modeling

For each set of variables specific methods for the purposes of coral habitat restoration and coastal protection services are recommended. Some important interrelations are summarized in this section together with additional guidelines for practicability.

Physical-chemical variables

Interrelations

Adequate water quality, sufficient light availability, and a suitable water motion regime are **necessary** factors for coral growth potential. The relationship between coral reefs and the surrounding seawater, involving both chemical and physical aspects, is shaped by the movement of water. This movement occurs on different scales, with larger-scale factors like tides, mesoscale currents, and waves influencing the interaction, while at smaller scales, turbulence becomes the key factor governing these processes. Water motion is generated by hydrodynamic energy and has long been recognized as an important factor affecting growth and development of coral reefs [Dennison and Barnes, 1988]. For example, water motion and light penetration are both negatively correlated with depth and positively correlated with each other [Jokiel, 2008]. Optimal levels of water motion facilitate sediment removal and promote coral recruitment and growth [Stender et al., 2021]. It affects nutrient availability, light penetration, and temperature and salinity changes [Nakamura, 2010]. Corals rely on wave- and current induced fluid advection to supply the input of nutrients and dissolved gasses required for calcification, metabolism, and photosynthesis, and fluid motion drives waste removal, larval transport, and mitigation of absorbed solar irradiance to alleviate thermal-induced bleaching [Stocking et al., 2018].

Due to presence and growth of corals, an increase of skin friction and form drag explain an increase in turbulence around corals [Lowe et al., 2005, 2007]. Drag, which includes skin friction, influences the energy expenditure and feeding efficiency of corals due to the resistance experienced during water flow. Turbulent mixing determines vertical transport of heat, food, pollutants, pathogens, larvae, and nutrients to or from the coral community Davis et al. [2021]. Studies have shown that nutrient uptake is positively correlated with the bottom shear stress and water velocity Huang [2015].

Practicability

In order to analyze **water quality** and **light availability** variables, several approaches are possible. If time and resources allow for it, in-situ measurements or field observations can be conducted, which provide direct and real-time data on for example temperature, salinity and nutrient levels in the area of interest. These measurements can be carried out using specialized instruments and sampling techniques at specific locations within the study area. For quicker assessments, desk research can be conducted by referring to for example existing Environmental Impact Assessments (EIA) or other relevant studies that have already examined quantitative values of water quality in an area of interest.

Typically in practice, the analysis and study of **water motion** variables involves a combination of desk research, analytical, physical modeling, and/or numerical modeling methods. One common approach to analyze hydrodynamic forcing data such as wave and climates is to gather existing data from coastal monitoring programs, scientific publications, and historical records. Also, hydrodynamic forcing parameters, may involve field measurements using instruments like wave buoys and gauges. Different types of coral species prefer different hydrodynamic regimes. For quick assessment of growth and environmental tolerances and preferences in terms of wave energy, sedimentation, and location preference the reader is referred to Appendix A. Quantyfing interrelations is often complex, but examples of interrelations between biological and physical-chemical variables, are the ones derived by Hearn et al. [2001], who found that a nutrient-uptake coefficient, S, is proportional to energy dissipation rate (turbulence) to the 0.25 root, to bottom shear stress to the 0.4 root, and to current speed to the 0.75 root.

Analytical models, physical model tests, and numerical (hydrodynamic) models are frequently employed to analyze variables in greater detail. These methods provide valuable insights into the spatial and temporal variations of water motion variables, particularly for the purpose of coastal engineering. By integrating these approaches, a more thorough analysis can be conducted to guide effective coral habitat potential and coastal protection strategies. Numerical models, depending on the software utilized, have the capability to analyze various hydrodynamic variables effectively for both purposes. These variables include flow fields, wave heights, turbulence, pressures, and sediment transport, within the desired spatial and temporal scales.

Optimal levels of water motion facilitate sediment removal and promote coral recruitment and growth [Stender et al., 2021]. Analyzing sedimentation for exploring coral habitat potential and sediment transport for coastal protection purposes involves a combination of field measurements, numerical modeling, and desk research. Field measurements, including sediment sampling and traps, provide data on sediment characteristics and deposition rates. Desk research supplements the analysis by accessing existing data on sedimentation trends and factors influencing sediment transport. Sediment resuspension and turbidity dynamics are important factors on the design of a submerged breakwater to promote coral settlement and growth. Sediment suspension grealty differs by 'large roughness' created by canopies of corals and reef organisms, but 'large roughness' is rarely taken into account into hydrodynamic models. Both macro- and microstructural elements need to be reflected in a design of a submerged breakwater to facilitate optimal water flow and circulation while minimizing sediment deposition and resuspension to facilitate colonization and growth of symbiotic corals [Jayanthi et al., 2020].

Biological variables

Interrelations

Biological variables are influenced by physical-chemical processes. For instance, species engage in competition with native coral reefs for nutrients, light, and space. Corals maintain a symbiotic relationship with microscopic single-celled photosynthetic algae known as zooxanthellae, which reside within the coral tissue. These zooxanthellae conduct photosynthesis, generating oxygen that is vital for the corals' essential physiological functions. Consequently, photosynthesis enables corals to construct their calcium carbonate structures, which are associated with the chemistry of carbon dioxide (CO_2). Excessive sedimentation and turbidity levels can lead to the burial of corals or hinder their ability to carry out successful photosynthesis and nutrient absorption. Furthermore, coral health and resilience are closely linked to water temperature. Elevated water temperatures can cause coral bleaching, which disrupts the symbiotic relationship with zooxanthellae and can lead to coral mortality. While projections for gradual warming are of concern, it is the marked increase in temperature that occurs in marine heatwaves that are most damaging [Fellowes et al., 2022].

Practicability

In order to achieve coral habitat restoration or preservation, it is important to consider the biological variables during the design process. If resources and time allows it, variables can be assessed through field evaluations and monitoring conducted in and around the construction site, with a focus on existing species. Additionally, it is important to consider physical and chemical conditions such as temperature, nutrient levels, and sedimentation rates, as these factors influence the biological variables. Collaboration with experts and conducting extensive literature research and data collection are also valuable in gaining a better understanding of the biological variables and the design process.

If the circumstances permit it, various comprehensive methods can be employed, such as the removal and chemical treatment of invasive species, or the enhancement of larval settlement. Restoration methods such as direct transplantation, coral gardening, larval enhancement, or substratum enhancement or addition can be considered [Boström-Einarsson et al., 2020]. Boström-Einarsson et al. [2020] conducted a systematic review of current methods, successes, failures and future directions of coral restoration. They emphasized the importance of addressing key challenges in the field, such as a lack of clear and achievable objectives, a lack of appropriate and standardized monitoring and reporting, and poorly designed projects. Overcoming these challenges is crucial for successfully scaling up restoration projects and maintaining public trust in restoration as a tool for resilience-based management.

Design variables

Interrelations

In search for integral solutions, the design variables can be adjusted, influencing the physical-chemical and biological variables. Manipulating design variables can have an impact on hydrodynamic energy regimes both around and at distance from the structure, impacting coral habitat potential and coastal protection services. One example of how altering a design variable influences physical-chemical and biological variables is the modification of material (resistance) variables. Structures with reduced porosity and a rougher surface transmit fewer waves. leading to a more substantial decrease in wave energy. Moreover, these design characteristics can also influence the settlement preferences of coral species, as they exhibit a tendency to favor rough substrates for colonization. Furthermore, diverse substrates attract various species, extending beyond corals.

Practicability

Identifying design variables that can be modified within a design suggests an opportunity to incorporate principles such as user-centered design or experimentation in the search for integrated solutions. In the design of submerged breakwaters, analytical methods or design guidelines, such as those found in references like the Rock Manual [CIRIA et al., 2007] or the Manual on wave overtopping of sea defences and related structures [EurOtop, 2018], are commonly used. Additionally, physical model tests are currently applied in the field of coastal engineering in wave flumes to study wave-structure interactions, hydrodynamics, and/or sediment transport, while numerical modeling is often utilized to study hydrodynamics, wave mechanics, and sediment transport and morphology. These methods provide insights into the system's behavior and allowing for optimization and analysis of various design alternatives.

Considering the **structure** variables (Figure 3.4), to aid in coastal engineering purposes the key geometrical properties governing shoreline response of a submerged breakwater are shown in Figure 3.5, and wave characteristics and structural variables involved in the wave transmission phenomenon are shown in Table 3.1.

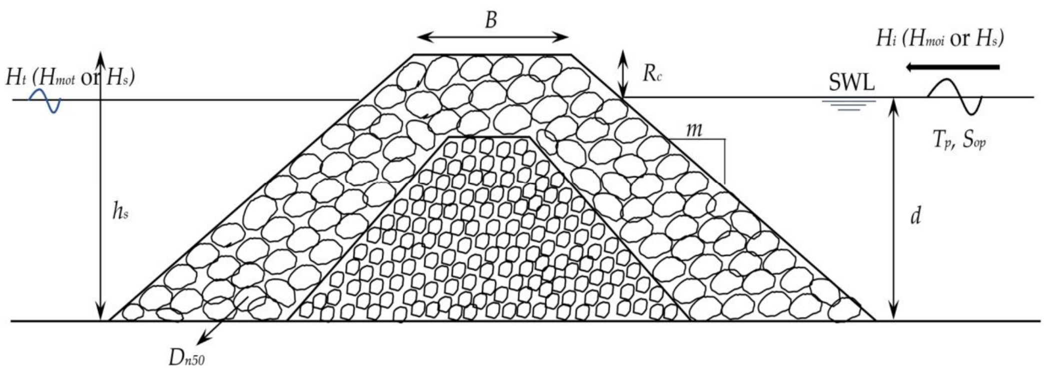


Figure 3.5.: Important variables for wave transmission for rubble mound breakwaters (emerged, $R_c > 0$ or submerged, $R_c < 0$), adapted from Hassanpour et al. [2023].

Table 3.1.: Wave characteristics and structural parameters involved in the wave transmission phenomenon [Hassanpour et al., 2023].

Symbol	Unit	Definitions
H_i	(m)	Incident significant wave height
H_t	(m)	Transmitted significant wave height
T_p	(s)	Peak wave period
L_p	(m)	Peak wave length
m_0	(m^2)	Zeroth-order moment of the wave spectrum
$T_{m-1,0}$	(s)	First negative moment of the energy spectrum
$T_{m-0,2}$	(s)	Zero-crossing period or mean zero-crossing period
h_s	(m)	Breakwater height
d	(m)	Water depth at toe of breakwater
R_c	(m)	Crest freeboard
B	(m)	Crest height
m	(-)	Seaward slope
$S_o p$	(-)	Wave steepness ($S_{op} = \frac{2\pi H_i}{g T_p^2} = \frac{H_i}{L_p}$)
$\xi_o p$	(-)	Surf similarity parameter $\xi_o p = \frac{m}{\sqrt{(S_{op})}}$)
$D_{n,50}$	(m)	Nominal diameter of armour rock

The depth of submergence d' or crest freeboard R_c is often argued to be the dominant parameter influencing wave transmission [Ranasinghe et al., 2010; Kim et al., 2021; van Gent et al., 2023], followed by wave height and wave period [Ranasinghe et al., 2010; Kim et al., 2021]. When the crest is closer to the MWL (about 0.5 m below MWL), wider crest widths would minimise the risk of shoreline erosion in the lee of a SBW in comparison to narrower crest widths [Kim et al., 2021]. To estimate wave transmission over low-crested structures, many empirical formulas have been developed as design guidelines. In their paper providing tips on literature formulae performance for estimating wave transmission over rubble-mound breakwaters Hassanpour et al. [2023] argued as the most reliable formulae for wave transmission of submerged breakwaters are the formulae developed by d'Angremond et al. [1996] and Van der Meer et al. [2005]. Kurdistani et al. [2022] proposed a formula for submerged homogeneous rubble mound breakwaters based on a large data-set and numerical modelling and concluded that their formula outperforms other empirical relations. Design rules for wave transmission of artificial reefs or submerged breakwaters deviating from common rubble mound breakwater structures are lacking, yet recently an empirical formula is developed by van Gent et al. [2023] that can be used in design of artificial reefs with respect to wave transmission. This formula is mentioned here for practicability:

$$K_t = c_1 \tanh\left(-\frac{R_c}{H_{m0}} + c_2\left(\frac{B}{L_{m-1,0}}\right)^{c_3} + c_4\right) + c_5 \tag{3.1}$$

where the crest height R_c is made non-dimensional using the spectral significant wave height H_{m0} and the crest width B is made non-dimensional using the wave length based on the spectral wave period: $L_{m-1,0} = (g/2\pi)T_{m-1,0}^2$. The five coefficients relate to the type of artificial reef structure, see Table 3.2.

Table 3.2.: Coefficients for wave transmission formula for artificial reefs as in Equation 3.1 from van Gent et al. [2023]

Structure type	c_1	c_2	c_3	c_4	c_5
Impermeable structure	0.47	3.1	0.75	0	0.5
Permeable structure (rubble mound)	0.43	3.1	0.75	-0.25	0.5
Perforated structure	0.13	3.1	0.75	-0.15	0.82
Perforated structure with screen	0.40	3.1	0.75	-0.15	0.5
Perforated structure with perforated screen	0.17	3.1	0.75	-0.15	0.76

Considering the **substrate** variables, while certain material such as rocks may be preferred for optimal delivery of coastal defense, they may not necessarily be the best choice for coral attachment. This means that the selection of materials should be carefully balanced to ensure that the artificial reef provides adequate resistance whilst also facilitating the establishment and growth of coral colonies. Over time, artificial reef materials of many types have been implemented already. Common artificial reef modules applicable to coastal defence are for example Reef Balls^{TM}, constructed of concrete (often pH-neutral), Ecoreefs^{TM} made from ceramic, and BioRock^{TM} constructed of steel with added electro-deposition [Beck et al., 2016; EcoShape, 2023].

Although still under development, more recent technologies are emerging such as 3D printing of artificial reef structures, that mimic naturally occurring reefs. A case study from Yoris-Nobile et al. [2023] is highlighted here. The study presents the manufacture of artificial reefs by 3D printing, proposing designs with a combination of prismatic and random shapes, with different external overhangs as well as inner holes. The development of artificial reef design alternatives was established utilizing criteria provided by marine biologists, as well as the results obtained from a numerical simulation using ANSYS to analyze the stability of the reefs on the seabed. This is a good example where multiple methods are used to find integral solutions.

For coral habitat potential purposes, horizontal, more shallow surfaces are generally more favorable than vertical ones for corals to attach on [Beck et al., 2016; Stender et al., 2021]. In their case study on a multipurpose perforated trapezoidal artificial reef, Jayanthi et al. [2020] observed that the leeward side of the breakwater exhibited lower coral cover, smaller coral size, and higher mortality rates compared to the windward side. This is attributed to deteriorating of water quality in more stagnant water on the leeward side. These differences were attributed to the sheltered conditions experienced on the leeward side, which led to a deterioration in water quality. As mentioned earlier, various coral species have distinct preferences for specific water depths. It is recommended to conduct desk research through bathymetry data and natural occurrence of coral reefs to promptly determine these preferences when designing for target species.

With regards to topographic complexity, minimizing shady surfaces and holes favored by non-photosynthetic and/or heterotrophic invasive species is another consideration in the design of the submerged breakwater in a potential nutrient-rich environment Jayanthi et al. [2020]. Furthermore, it is favourable to mimic natural substrate complexity of natural reefs in the design. The results of the study of Foley [2015] suggest that the artificial reef design should emulate the natural spur and groove structure with regards both macro and micro scales for example. They also highlighted the importance of placement of the structure in orientation with wave direction, and water depth. A parameter often used to quantify complexity is roughness [Hearn, 2011].

3.5. Application

The research objective includes the application of the conceptual model as a design tool to promote a more integrated design for the case study. The three primary purposes of the conceptual model are repeated here:

1. Identifying physical-chemical and biological variables that require further examination and analysis to explore coral habitat potential of a design.

2. Identifying physical variables that require further examination and analysis to explore coastal protection services provided by a design.

3. Identifying design variables influencing physical-chemical and biological variables that can be modified within a design to explore potential integral solutions.

The preceding sections have highlighted the significance of considering all physical-chemical, biological, and design variables, emphasizing the absence of universal solutions and the presence of numerous complex interrelations among these variables. Given the time and scope limitations of this research, not all variables and interrelations within the conceptual model were fully analyzed in depth. This section provides an elaboration on the decisions made regarding the application of the conceptual model to this particular case study. For other case studies, different decisions may have been and should be made, taking into consideration unique circumstances of every other project and corresponding constraints of time and resources. Choices need to be made that align with each specific context. As mentioned earlier, the conceptual model developed in this research (see Figure 3.4) serves as a foundation for guiding decision-making processes that can be adapted and applied to any unique situation or new case study.

As previously explained in Section 3.4, numerical modelling is often applied, particularly in the field of coastal engineering, to simulate flow and transport processes and to conduct in-depth analyses of behaviour of specific variables of interest. It is noted that numerical modeling is used as a method to evaluate wave transmission changes of the artificial reef design alternatives in the case study, instead of relying on empirical design formulas such as Equation 3.1 from van Gent et al. [2023]. This is done because investigating the potential benefits of OpenFOAM as a dual-purpose design tool was an important objective of this research. The selection of OpenFOAM as the primary numerical modeling software is based on its significant potential as a dual-purpose design tool, as OpenFOAM enables the simultaneous evaluation of coral habitat potential and coastal protection services in terms of wave transmission. OpenFOAM offers the versatility to modify and analyze **all** design variables within the conceptual model, regardless of scale, within the computational domain. This includes the capability to handle complex geometries and perform three-dimensional (3D) simulations, providing a comprehensive framework for examining desired phenomena.

Coral habitat potential

In this research in Chapter 5, physical-chemical variables and biological variables from the conceptual model (see Figure 3.4) are identified and analyzed to explore coral habitat potential of the case study (the first purpose of the conceptual model). The analysis of **biological**, **water quality**, and **light availability** variables is conducted through desk research, incorporating various sources of information, including a comprehensive environmental impact assessment (EIA) conducted by the Maldivian Ministry of National Planning, Housing Infrastructure for the proposed reclamation project at Addu City, Maldives [EIA, 2022]. Onsite field investigations pertaining to physical-chemical and biological variables were not conducted in this research, as the majority of the required information was readily available within the EIA.

In the context of coral habitat potential, a deeper analysis was carried out for one interrelation between flow velocity and CO_2 chemistry using OpenFOAM. **Water motion** is of great importance to the biological and ecological functioning of coral reefs [Foley, 2015]. Globally, numerous coral species exist, each preferring distinct water motion regimes and is therefore studied in more detail in this case study. In the research of van Gent et al. [2023], it was advised that for applications of artificial reefs to enhance marine life and to improve the biodiversity, it is recommended to study velocities around a structure. The PIANC [2010] report on dredging and port construction near coral reefs that can be used for initial assessments (Appendix A) for example indicates that narrow, branching, and delicate plate-like corals exhibit a low wave energy tolerance. Thus, a specific water motion regime influences the growth potential of corals. OpenFOAM is capable of providing detailed results of various aspects of fluid flow, including flow fields and turbulence, throughout the entire computational domain.

Coral growth can be related to the physical-chemical variable 'CO_2 chemistry'. Corals utilize (in)organic carbon metabolism to build their skeletons. They extract calcium ions (Ca^{2+}) and carbonate ions (CO_3^{2-}) from seawater and undergo a process called calcification, represented by Equation 3.2.

$$\mathrm{Ca}^{2+} + \mathrm{CO}_3^{2-} \rightleftharpoons \mathrm{CaCO}_3 \tag{3.2}$$

This reaction results in the formation of solid calcium carbonate (CaCO_3), which contributes to coral skeleton growth. In unfavourable conditions, such as increased acidity, the reverse reaction, dissolution, can occur, where CaCO_3 dissolves back into Ca^{2+} and CO_3^{2-}. The balance between calcification and dissolution is crucial for coral health and the growth of coral reefs. The coral reef carbon cycle is primarily driven by two processes: the metabolism of organic carbon (photosynthesis and respiration) and the metabolism of inorganic carbon (precipitation and dissolution of CaCO_3). Inorganic carbon metabolism influences coral growth in terms of calcification or skeleton building. In adult symbiotic corals, enhancement of calcification by increased seawater motion is proposed to be mediated by the enhancement of symbiotic algal photosynthesis and respiration, which provide the metabolic energy for calcification [Iwasaki et al., 2018].

The relation between inorganic carbon metabolism and flow velocity for a specific target species is further analyzed in Chapter 5 utilizing the OpenFOAM numerical model. This analysis aided in the preliminary decision-making process, comparing flow regimes around different design configurations. OpenFOAM is also used to obtain insights in turbulence regimes around the structure and initial assessment of coral habitat potential. Iwasaki et al. [2018] measured skeletal growth in stirred and unstirred conditions and concluded that seawater turbulence increased the amount of skeletal carbonate and directly influenced calcification of coral hosts compared.

Coastal protection

Also in this research, physical variables are identified and further analyzed exploring coastal protection services of design alternatives (the second purpose of the conceptual model). Wave climate and water level data for the case study area in Addu City, Maldives were made available by Van Oord and used as input data in OpenFOAM. For the case study in this research, preliminary assessments of coastal protection services were made using OpenFOAM. The analysis focused on examining *changes* in wave transmission and longshore sediment transport estimates for design alternatives *in comparison to the traditional design*. Levels of wave transmission determine the extent of overtopping and shoreline response in the area behind an artificial reef or submerged breakwater, in relation to erosion and sediment transport. Focusing mainly on coastal engineering purposes, to ensure more comprehensive and detailed evaluations of designs, it is recommended to incorporate additional criteria into the assessment. These criteria can include the utilization of empirical formulas for wave transmission and overtopping, as provided by EurOtop [2018]. By considering these additional factors, the performance of coastal protection measures can be more accurately analyzed in terms of wave structure interaction and shoreline response.

Integrated design

In this research, the design variables that influence physical-chemical variables are identified. These variables can be modified within a design to explore potential integrated solutions (the third purpose of the conceptual model). In this research, OpenFOAM is utilized to assess the effects of altering the slope and dimensions of the traditional design. The objective is to evaluate the impacts on coral habitat potential and coastal protection services within the context of the research described earlier.

It is important to emphasize that certain variables and their interrelationships have not been extensively analyzed in this research. Specifically, the **substrate** variables including materials, topographic complexity, and resistance are closely linked, and very important variables in design of artificial reefs. Furthermore, this research has not conducted comprehensive assessments of turbulence, sedimentation around coral canopies, and sediment transport modeling. These variables hold significant importance not only in comprehending coastal dynamics but also in evaluating the health and well-being of coral ecosystems.

4. Numerical model

In this research, OpenFOAM is utilized to examine the impacts of altering design variables from the conceptual model (Chapter 3). In this chapter the OpenFOAM numerical model is set-up (Section 4.2), calibrated (Section 4.3), and validated (Section 4.4), using data from physical model tests for average and design conditions of the case study carried out by DHI Group (Section 4.1). In Section 4.5 some results of the best performing run are presented, and Section 4.6 elaborates on the further application of the model for the rest of the research.

4.1. Physical model

Physical model tests are regularly being used to validate the hydraulic performance of a coastal structure [Jacobsen et al., 2015]. The numerical model in this thesis is set-up, calibrated, and validated using data obtained from physical model experiments carried out at DHI Group in Hørsholm, Denmark, based on the case study. Calibration has been carried out for average conditions and validation for design conditions, ensuring reliability and accurate representation of real-world phenomena that are studied.

Wave generation

The waves in the flume were generated by an electric, piston-type wave generator. The wave generating system includes an online active wave absorption control system, DHI AWACS, which makes it possible for the wave maker to absorb the majority of the wave energy reflected from the tested revetment profile. Hence, the system largely eliminates undesirable re-reflection at the wavemaker and thereby ascertains the accuracy of the incident wave field impacting on the test profile. Standard JONSWAP wave spectra with a peak enhancement factor of $\gamma = 3.3$ were applied for wave generation in the tests. Wave maker control signals were non-repetitive. This was done to achieve a more correct random statistical distribution of the wave spectra. Five wave gauges in front, and five wave gauges behind the structure at the locations shown in Figure 4.1, measure the significant wave height at these locations as four times the standard deviation of the surface elevation: $H_s = 4\sigma_\eta$.

Scaling

The length scale (horizontal and vertical) of the model is 1:20. According to the Froude model law this leads to the following model scales:

Length scale	1:λ	1:20
Time scale	1:$\lambda^{1/2}$	1:4.47
Volume scale	1:λ^3	1:8,000

An on-scale sketch of the physical model wave flume is shown in Figure 4.1. The wave flume is 28 m long and 1.2 m high. Here, h is the water depth in m. A drawing in prototype scale from x = -324 m to x = - 200 m is presented in Appendix B.

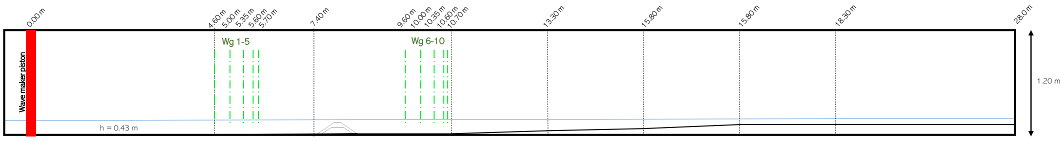


Figure 4.1.: Longitudinal cross-section of the DHI wave flume for physical model experiments

The physical modelling test plan of average (H_s = 0.60 m, T_p = 11.9 s) and design (H_s = 0.90 m, T_p = 19.9 s) conditions are scaled with $\lambda = 20$ and presented in Table 4.1.

Table 4.1.: Model scale ($\lambda = 20$) test plan

Test ID	Wave conditions	Water level (m MSL)	Target Hs (m)	Target Tp (s)	Duration (h)
D-92	Average	+0.00	0.030	2.7	3
D-96	Design	+0.06	0.045	4.4	3

Rock and water densities in prototype scale (subscript p) differ from densities in model scale (subscript m):

Rock: $\rho_{sp} = 2680\,\mathrm{kg/m^3}$
Rock: $\rho_{sm} = 2720\,\mathrm{kg/m^3}$

Seawater: $\rho_{wp} = 1025\,\mathrm{kg/m^3}$
Water: $\rho_{wm} = 1000\,\mathrm{kg/m^3}$

Scaling of the rock properties is performed using Hudson's stability formula:

$$\overline{W} = \frac{H_s^3 \rho_s}{K_D \alpha \left(\frac{\rho_s}{\rho_w} - 1\right)^3} \tag{4.1}$$

where:

$$\overline{W} = \text{mean weight of rock gradation [kg]}$$
$$H_s = \text{significant wave height [m]}$$
$$\rho_s = \text{density of rock [kg/m}^3\text{]}$$
$$\rho_w = \text{density of water [kg/m}^3\text{]}$$
$$K_D = \text{dimensionless stability factor [-]}$$
$$\alpha = \text{slope}$$

The ratio of inertia and gravity forces should be the same in real life and model scale. Therefore the dimensionless stability number ($N_s = K_D \cdot \alpha$) should be the same in prototype and model scale. Combining this with Equation 4.1, the following relation is obtained:

$$\frac{\overline{W_m}}{\overline{W_p}} = \frac{1}{\lambda^3} \frac{\rho_{sm}\left(\frac{\rho_{sp}}{\rho_{wp}} - 1\right)^3}{\rho_{sp}\left(\frac{\rho_{sm}}{\rho_{wm}} - 1\right)^3} \tag{4.2}$$

This leads to a scale factor of rock weight:

$$\overline{W_m} = 0.8396 \frac{\overline{W_p}}{\lambda^3} \tag{4.3}$$

Using the following relation between D_{50} and rock volume [CIRIA et al., 2007]:

$$D_{50} = 1.2 \cdot \sqrt[3]{V} = 1.2 \cdot \sqrt[3]{\frac{M}{\rho}} \tag{4.4}$$

And Equation 4.3, the scaled properties of both the outer and core layer are determined and outlined in Table 4.2.

Table 4.2.: Properties of the outer and core layers

(a) Outer layer

Scale	**Property**	**Value**
Prototype	$W_{50,p}$	1900 kg
Model	$W_{50,m}$	0.20 kg
Prototype	$D_{50,p}$	89.2 cm
Model	$D_{50,m}$	4.2 cm

(b) Core layer

Scale	**Property**	**Value**
Prototype	$W_{50,p}$	800 kg
Model	$W_{50,m}$	0.082 kg
Prototype	$D_{50,p}$	66.8 cm
Model	$D_{50,m}$	3.1 cm

Results physical model tests

The results of the physical model tests carried out by DHI Group, presented as significant wave heights (where $H_s = 4\sigma_\eta$) for every wage gauge, are presented in Table 4.3 for both average and design conditions. The numerical model is optimized in this chapter with the aim to obtain similar results.

Table 4.3.: Physical model test results

(a) D-92 (50%)			(b) D-96 (90%)		
Gauge	$H_{s,p}$ **[m]**	$H_{s,m}$ **[m]**	**Gauge**	$H_{s,p}$ **[m]**	$H_{s,m}$ **[m]**
wg1	0.635	0.0317	wg1	0.770	0.0385
wg2	0.674	0.0337	wg2	0.695	0.0348
wg3	0.664	0.0332	wg3	0.674	0.0337
wg4	0.627	0.0313	wg4	0.687	0.0343
wg5	0.613	0.0306	wg5	0.706	0.0353
wg6	0.396	0.0198	wg6	0.683	0.0341
wg7	0.408	0.0204	wg7	0.667	0.0333
wg8	0.407	0.0204	wg8	0.643	0.0321
wg9	0.405	0.0202	wg9	0.639	0.0319
wg10	0.407	0.0204	wg10	0.646	0.0323

4.2. Numerical model set-up

The 2DV numerical flume, shown in Figure 4.2, is designed to replicate the wave flume used in the physical experiments, depicted in Figure 4.1. In this section, first the wave generation and absorption technique is elaborated on. This is followed by an explanation on temporal and spatial resolutions of the model. Then, motivations for carrying out calibration runs to improve the model are explained. Results of the calibration runs are presented in Section 4.3, resulting in an optimal outcome that closely matches the results obtained from the physical model test for average conditions, as presented in Table 4.4. The results for design conditions are used to validate the model in Section 4.4.

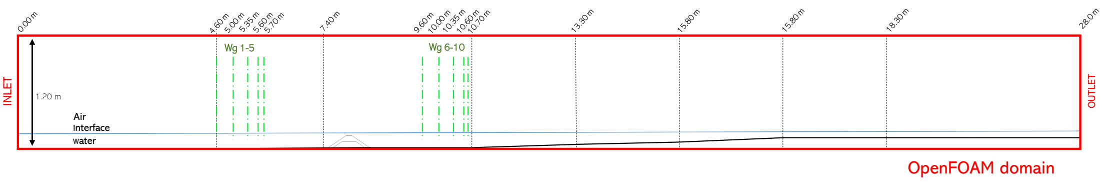


Figure 4.2.: Sketch of numerical wave flume and OpenFOAM domain

Wave generation and absorption

The boundary conditions for wave generation and active wave absorption play a crucial role in the model setup, as they serve as the fundamental basis for obtaining realistic final results. In the real world, waves can propagate beyond the study area. However, in physical or numerical experiments, this is not the case. The case study and the wave propagation area are bounded, leading to potential reflections that may cause inconvenience. These reflections need to be properly addressed in order to achieve realistic results. In the numerical model, this is accounted for via a wave absorption outlet boundary. More details can be found in Appendix C.

In the numerical model via the `waveDict` file, JONSWAP irregular waves matching the wave conditions of the physical model test are fed into the computational domain. A Python code is utilized to simulate a JONSWAP spectrum and 1000 corresponding wave heights, phases, and periods, adhering to the target wave conditions outlined in Table 4.1. The spectrum in Equation 4.5 as proposed by Goda [1988] is dependent on frequencies f, a spreading parameter β, a shape factor σ, peak enhancement factor γ, H_s and T_p:

$$S(f) = \beta_f H_s^2 T_p^{-4} f^{-5} exp[-1.25(T_p \cdot f)^{-4}]\gamma^{exp[-\frac{(T_p \cdot f - 1)^2}{2\sigma^2}]} \tag{4.5}$$

where:

$$\beta_J = \frac{0.06238}{0.230 + 0.0336\gamma - 0.185(1.9+\gamma)^{-1}}(1.094 - 0.01915 ln(\gamma)) \tag{4.6}$$

$$\sigma = \begin{cases} 0.07 & \text{if } \omega < \omega_p \\ 0.09 & \text{if } \omega \geq \omega_p \end{cases} \tag{4.7}$$

The parameter γ modifies the shape and amplitude of the JONSWAP spectrum. A value of 3.3 for this parameter is commonly applied, as is the case for wave generation in the physical model test and in the numerical model set-up for this case study. Furthermore 1000 frequencies range from 0 to 1.2 Hz. σ represents the spreading or width of the wave energy distribution around the peak frequency ω_p.

1000 random phases have been generated in between 0 and 2π and 1000 amplitudes related to the energy present in the wave record are calculated as:

$$a_i = \sqrt{2S(f)\Delta f} \tag{4.8}$$

In this manner the continuous JONSWAP spectrum can be transformed into a discretized amplitude spectrum. From here, wave heights $H_i = 2a_i$ and surface elevations can be calculated:

$$\underline{\eta}(t) = \sum_{i=1}^{N} \underline{a}_i cos(2\pi f_i t + \underline{a}_i) \tag{4.9}$$

When running this wave generation method, each simulation produces random results. Therefore, a calibration process is conducted to seek agreement between the simulated waves and the waves generated in the physical model tests. Further elaboration on this calibration process is provided in Section 4.3.

Temporal resolution

The CFL (Courant-Friedrichs-Lewy) condition is a necessary conditions or requirement for numerical stability of the model. It is defined by the Courant Number C_o:

$$C_o = \frac{u\Delta t}{\Delta x} \tag{4.10}$$

Here, u is flow velocity, Δx is a space step, and Δt is the time step. Δx is elaborated in the next section. The adjustable time step method in OpenFOAM is enabled, where the solver automatically adjusts time steps using the CFL condition. This approach ensures both numerical stability and efficiency. A maximum C_o for the adjustable time stepping method is defined by the user. The default value in OpenFOAM $C_o = 0.35$ was used in this case study.

Spatial resolution

The `blockMesh` utility of OpenFOAM is used for matching the dimensions of the flume, and to generate a computational grid. The Joint Industry Project (JIP) CoastalFOAM program, a collaboration between Van Oord, Boskalis, Royal HaskoningDHV and Deltares, recommends 100-150 cells per wave length L_p based on the peak period for the horizontal resolution to obtain accurate results. For a water depth h = 0.425 m and peak period T_p = 2.66 s for this case study, L_p can be calculated using:

$$L_p = \frac{gT_p^2}{2\pi}\tanh(\frac{2\pi h}{L_p}) = \frac{9.81 \cdot 2.66^2}{2\pi}\tanh(\frac{2\pi \cdot 0.425}{L_p}) \tag{4.11}$$

Iteration resulted in $L_p = 5.21$ m (this is an intermediate water regime since $\mathrm{h}/L_p = 0.425/5.21 = 0.08$ and $0.05 < 0.08 < 0.5$). A horizontal resolution of 550 cells in x direction (N_x) was chosen, resulting in a spatial resolution $\Delta x = 550/28 = 0.05$ m and 0.05/5.21 = 102 cells per peak wave length, in line with the suggestion of JIP CoastalFOAM.

In general, square cells are widely applied and recommended for accurate modelling of wave propagation as they give better solutions when modeling non-linear waves [Jacobsen et al., 2012; Jonker, 2020; Irías Mata, 2021]. At the same time 10-20 cells per wave height are recommended by JIP. If square cells would be applied in this case study for $N_x = 550$, $\Delta z = \Delta x = 0.05$ m. H_s for average conditions in this case study is 0.03 m, which would mean that not even one H_s would fit in a cell.

For average conditions where $H_s = 0.03$ m, a 1.2 m high flume and for example also 550 grid cells over the vertical (N_z), $\Delta z = 550/1.2 = 0.002$ m, resulting in $0.002/0.03 = 14$ cells per wave height, in line with the suggestion of JIP. A grid with $\Delta z = 0.002$ m and $\Delta x = 0.05$ m is a flat ($\Delta z < \Delta x$) cell. In their study, Roenby et al. [2017] compared square, flat, and tall ($\Delta z > \Delta x$) cell aspect ratio performances of the MULES solver. Compared to an exact solution of surface elevation, square cells produced wiggles in the solution, tall cells exhibited even greater wiggles, while flat cells eliminated the wiggles entirely, only introducing a small phase error.

Considering all the above, a grid resolution was chosen to encompass a single cell capturing 1.5 H_s, aiming to minimize computational time whilst still being able to make preliminary assessments. This decision resulted in a vertical resolution of $\Delta z = 0.02$ and 60 cells over the vertical direction. The chosen $\Delta z/\Delta x$ ratio is 0.4, which closely aligns with the ratio observed in the study by Roenby et al. [2017] for flat cells (0.5). The primary motivation behind this decision was the significant reduction in computational time. Implementing both the horizontal and vertical resolutions recommended by JIP for this case study ($\Delta x = 0.05$, $\Delta z = 0.002$) resulted in a run time of 78 minutes for 600 time steps. Conversely, adopting the horizontal resolution suggested by JIP alongside a more flattened vertical resolution

($\Delta x = 0.05$, $\Delta z = 0.02$) reduced the computational time to 9 minutes, which is almost nine times faster.

4.3. Calibration

In this section, the numerical model is calibrated. Calibration runs for wave generation and friction coefficients have been carried out with the aim to find the numerical model set-up that matches the results of the physical model tests in a way that the model is usable for analysis in this research. In terms of computational times, all OpenFOAM runs were executed for 100 seconds, with intervals of 0.025, reflecting the physical model test results and yielding a total of 4000 time steps. Consequently, the average duration for a single calibration run amounted to approximately one hour of computational time.

For all runs, the wave transmission coefficient, denoted as K_t, is calculated. The limit of $K_t = 0$ indicates no wave transmission, while $K_t = 1$ implies no reduction in wave height.

$$K_t = \frac{\overline{H_t}}{\overline{H_i}} \tag{4.12a}$$

$$\overline{H_t} = \frac{1}{5}\sum_{i=6}^{10} H_{s,wg_i} \tag{4.12b}$$

$$\overline{H_i} = \frac{1}{5}\sum_{i=1}^{5} H_{s,wg_i} \tag{4.12c}$$

For each run, the average significant wave height is calculated for each wave gauge using the formula $H_s = 4\sigma_\eta$. Errors are presented in terms of a Root Mean Squared Error (RMSE) in m to evaluate the performances of calibration runs. Every RMSE is defined as:

$$\text{RMSE} = \sqrt{\frac{1}{10}\sum_{i=1}^{10} |y_i - \hat{y}_i|^2} \tag{4.13}$$

Here, y_i are the observed values from OpenFOAM results, and $\hat{y}_i$ predicted values from the physical model tests. The RMSE measures the average deviation between these values. Alongside RMSE, the wave transmission coefficient K_t is presented for all runs.

Results from the physical model tests as described in Table 4.1, are repeated here in Table 4.4, where surface elevation data is translated into significant wave height data using $H_s = 4\sigma_\eta$, inluding results for wave transmission.

Table 4.4.: Physical model test results

(a) D-92 (50%)			(b) D-96 (90%)		
Gauge	$H_{s,p}$ **[m]**	$H_{s,m}$ **[m]**	**Gauge**	$H_{s,p}$ **[m]**	$H_{s,m}$ **[m]**
wg1	0.635	0.0317	wg1	0.770	0.0385
wg2	0.674	0.0337	wg2	0.695	0.0348
wg3	0.664	0.0332	wg3	0.674	0.0337
wg4	0.627	0.0313	wg4	0.687	0.0343
wg5	0.613	0.0306	wg5	0.706	0.0353
wg6	0.396	0.0198	wg6	0.683	0.0341
wg7	0.408	0.0204	wg7	0.667	0.0333
wg8	0.407	0.0204	wg8	0.643	0.0321
wg9	0.405	0.0202	wg9	0.639	0.0319
wg10	0.407	0.0204	wg10	0.646	0.0323
$K_t =$	0.63		$K_t =$	0.93	

For average conditions, a wave coefficient of K_t = 0.63 is calculated. For design conditions this value increases to 0.93, which is mainly caused by the increase in water level (+ 1.17 m). The calibration that is carried out aims to generate similar results. In Chapter 5, wave transmission results of different design alternatives are compared to the best performing calibration run and further evaluated.

Wave generation

By generating a random JONSWAP spectrum as described in Section 4.1, a calibration is performed with the aim to minimize the error of the physical model test run D-92 (see Table 4.1), and a random simulation. Results for wave gauge 1 are used for comparison.

The predicted (subscript p) significant wave height of wave gauge 1 for average conditions of the physical model test is $H_{s,p,wg1} = 4 \cdot \sigma_{\eta,p,wg1} = 0.0317$ m. In the same manner, the simulated (subscript s) significant wave height of the simulated surface elevations resulting from Equation 4.9 are calculated as $H_{s,s,wg1} = 4 \cdot \sigma_{\eta,s,wg1}$. The error between these values is defined as e $= H_{s,p,wg1} - H_{s,s,wg1}$. After several iterations at one point e = 1.8 $\times 10^{-6}$ m was found, which was considered a small enough deviation of H_s. 1000 irregular waves with wave heights, random phases, and periods based on H_s and T_p from this simulation were fed into the `waveDict` file in OpenFOAM.

Friction coefficients

The parameters α and β, as explained in Section 2.3.1 are dependent on porous media physical properties but also on the flow regime. These parameters can be (and are often) determined using calibration based on numerical computations [Higuera, 2015]. In general, In the `porosityDict` utility of OpenFOAM, values for α and β are varied. The value of the friction coefficient C = 0.34 (Equation 2.2b) is applied by default, as it is proven to be less significant to variations of α and β [del Jesus, 2011]. Settings for a similar case study as suggested by Phicau [2021] are chosen as a starting point for the calibration and presented in Table 4.5.

Table 4.5.: Base case settings for calibration parameters α and β

Parameter	Value
α	50
β_{outer}	0.6
β_{core}	1.2

Results of this run are presented in Table 4.6.

Table 4.6.: Base case results for calibration parameters α = 50, $\beta_{outer} = 0.6$, $\beta_{core} = 1.2$

	Base case
K_t	0.77
RMSE [m]	0.0033

The base case run resulted in a RMSE of 0.33 cm in model scale and a K_t value of 0.77, meaning that more waves are transmitted when comparing the result to the physical model test where K_t = 0.63. Higher values for parameters α and β increases resistance of the structure, thus it is expected that increasing the values for these parameters result in less waves being transmitted over and through the structure. For turbulent flow regimes, which is most common for coastal engineering applications and wave-structure interaction, variations in β will dominate the total resistance over variations in α [Losada et al., 2016]. In this research, one run was performed keeping the β parameter constant, doubling the α parameter.

Table 4.7.: Results α parameter = 100

	Base case	$\alpha = 100$
K_t	0.77	0.76
RMSE [m]	0.0033	0.0028

As doubling of this parameter indeed resulted in a minor difference in between results, it was decided to not calibrate this parameter and to keep α at 50 as suggested by Phicau [2023], and to focus on a calibration of the parameter β, representing the nonlinear drag term.

To increase resistance targeting a lower wave transmission value, higher values have been chosen for the β resistance coefficients in the calibration runs. Losada et al. [2016] presented a table of several applied porous media drag coefficients varying in between 0.5 and 3.6. First, resistance of both the core and outer layer are increased to 3.5 and 3 to see what the consequences are. This run is called $C\beta_0$ (calibration of β, run 0) Results were immediately promising as demonstrated in Table 4.8.

Table 4.8.: Results calibration run $C\beta_0$

	Physical model test	**Base case**	$\beta_{outer} = 3.5$, $\beta_{core} = 3$
K_t	0.63	0.77	0.59
RMSE [m]	0	0.0033	0.0012

In line with expectations, resistance is increased and the wave transmission coefficient is reduced compared to the base case, it approaches the target solution of 0.63. From this point it was decided to perform another calibration run, slightly decreasing resistance of the outer layer. This run is called $C\beta_1$, and results are presented in Table 4.9.

Table 4.9.: Results calibration run $C\beta_1$

	Physical model test	**Base case**	$\beta_{outer} = \beta_{core} = 3$
K_t	0.63	0.77	0.61
RMSE [m]	0	0.0033	0.00053

As resistance of the outer layer was slightly decreased, the wave transmission parameter slightly increased, which resulted gave a desirable result. A more detailed comparison of this run comparing physical and numerical model results is presented in Table 4.10. More detailed results for every calibration run and all wave gauges are presented in Appendix D.

Table 4.10.: Performance evaluation of calibration run $C\beta_1$ Table 4.9

(a) Physical model test D-92

Gauge	$H_{s,m}$ **[m]**
wg1	0.0317
wg2	0.0337
wg3	0.0332
wg4	0.0313
wg5	0.0306
wg6	0.0198
wg7	0.0204
wg8	0.0204
wg9	0.0202
wg10	0.0204
$K_t =$	0.63

(b) OpenFOAM $C\beta_1$

Gauge	H_s [m]	ΔH_s [m]
wg1	0.0321	0.0003
wg2	0.0346	0.0009
wg3	0.0333	0.0001
wg4	0.0314	0.0000
wg5	0.0301	0.0006
wg6	0.0199	0.0001
wg7	0.0197	0.0007
wg8	0.0198	0.0006
wg9	0.0198	0.0004
wg10	0.0196	0.0008
$K_t =$	0.61	
RMSE [m]	0.00053	

K_t from the physical model test and from this run both round of to a value of 0.6, and an average error of 0.0005 m or 0.05 cm is considered a small enough error. In prototype or real life scale, this error of 1 cm is considered to not significantly affect the purposes of preliminary assessments of coral growth potential or to greatly affect the amount of coastal protection delivered by the breakwater.

4.4. Validation

To validate the OpenFOAM model, the results obtained from physical model tests conducted under extreme conditions are incorporated, as illustrated in 4.11.

Table 4.11.: Evaluation of validation run

(a) D-96 (90%)

Gauge	$H_{s,m}[m]$ [m]
wg1	0.0385
wg2	0.0348
wg3	0.0337
wg4	0.0343
wg5	0.0353
wg6	0.0341
wg7	0.0333
wg8	0.0321
wg9	0.0319
wg10	0.0323
$K_t =$	0.93

(b) OpenFOAM

Gauge	$H_{s,m}$ [m]	ΔH_s
wg1	0.0402	0.0017
wg2	0.0367	0.0019
wg3	0.0360	0.0023
wg4	0.0374	0.0030
wg5	0.0382	0.0029
wg6	0.0336	0.0006
wg7	0.0336	0.0002
wg8	0.0335	0.0014
wg9	0.0336	0.0016
wg10	0.0336	0.0013
$K_t =$	0.89	
RMSE [m]	0.002	

The model once again demonstrates a slight underestimation of the wave transmission coefficient, with a greater deviation compared to the best performing calibration run. This larger difference can be attributed to the random nature of the generated waves (which were generated again according to extreme conditions following the method explained in Section 4.2). However, even with this difference, the RMSE is still only 0.002 m or 0.2 cm. Considering the preliminary nature of the design explorations for coral habitat restoration potential and coastal protection function, this level of error was anticipated and deemed acceptable. Therefore, it was determined that run C-β_1 would be continued for the remainder of the study. The outcomes of this run will be further presented and analyzed in the subsequent section.

4.5. Results

In this section, the final results of the calibration procedure outlined in Table 4.10 are presented through several plots. These plots are presented to provide an initial sense of the hydrodynamic conditions within the flume. The visual representation of the flume includes a segment up to x = 20 meters, encompassing wave propagation up to the horizontal part of the platform. Figure 4.3 shows the magnitude of the velocity vector u_{mag} at t = 1 s. It illustrates the first wave that enters the domain through the inlet boundary with a maximum velocity of u_{mag} at 12 cm/s.

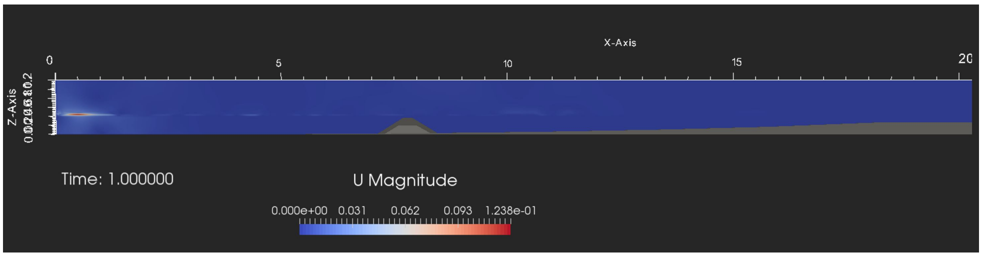


Figure 4.3.: OpenFOAM result for u_{mag} in m/s for t = 1 s

For the plots that follow, the data range from 0 to 12 cm/s was intentionally kept constant to facilitate result interpretation with the colorbar. In Figure 4.4, it is illustrated that the initial waves propagate over the structure. The irregular patterns near the free surface and motion beneath wave troughs indicate the randomness of the waves. The wave climate in the lagoon appears relatively calm, characterized by longer wave periods and the absence of severe wave breaking. Above the structure, the velocity increases due to mass continuity reasons; the reduced cross-sectional area results in an increased flow rate. In Figure 4.5, the first waves reach the shore. The wave climate behind the breakwater is noticeably calmer, aligning with the wave transmission result and the energy reduction caused by the breakwater.

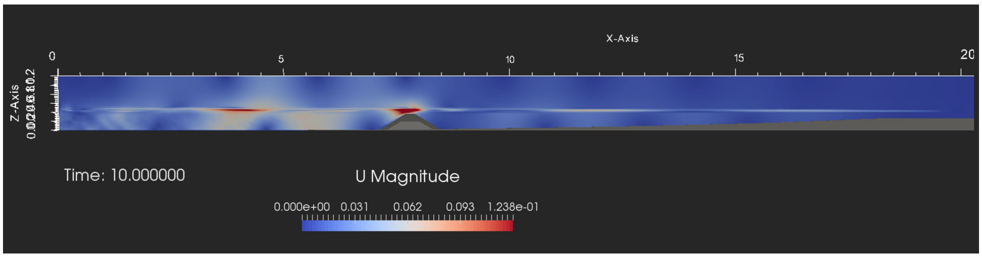


Figure 4.4.: OpenFOAM result for u_{mag} in m/s for t = 10 s

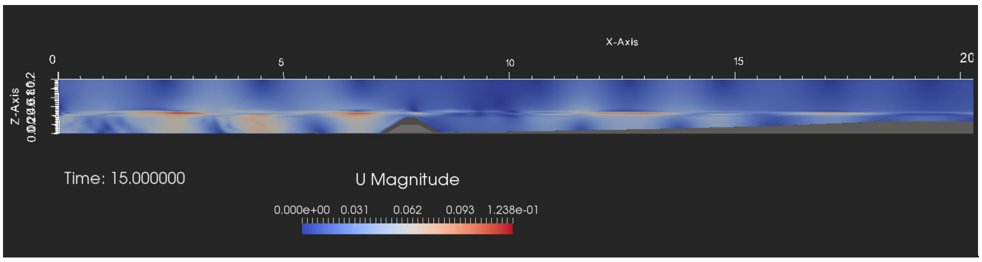


Figure 4.5.: OpenFOAM result for u_{mag} in m/s for t = 15 s

4.6. Application

The OpenFOAM numerical model developed in this chapter is used as a tool for the initial assessment and decision-making process of alternative designs in Chapter 5. It is used to examine the impacts of altering the slope and dimensions of the structure for evaluating the potential for coral habitat restoration through assessment of 1) the interrelation between flow velocity and inorganic carbon metabolism and 2) turbulence regimes, and for coastal protection assessing the (long-term) wave transmission levels of various design alternatives in light of climate change. By employing this model, informed decisions can be made regarding the suitability and effectiveness of different designs.

5. Case study - Design Alternatives

5.1. The Building with Nature approach

The Building with Nature (BwN) approach as pioneered by EcoShape [2023], aims to achieve a paradigm shift from building in nature to building with nature, an important step for achieving sustainable development and ensuring the long-term coexistence of humans and nature. It goes beyond nature development or nature compensation to integrate natural processes as an essential part of the design, looking for an optimal combination of green and gray infrastructure. The approach responds to the urgent challenges of rising sea levels, heat stress, drought, and biodiversity loss and continues to broaden its applicability for sustainable development [van Eekelen and Bouw, 2020]. A Building with Nature design process typically involves following five cyclical steps, as shown in Figure 5.1. These five steps describe a creative process that can be applied at any stage of project implementation.

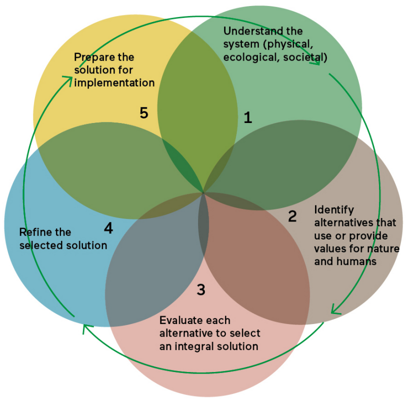


Figure 5.1.: The five Building with Nature design steps [van Eekelen and Bouw, 2020]

The BwN philosophy demands a mindset change from engineers, managers, policymakers, and other stakeholders involved in developing solutions and designs for clients. Frequently, a tendency exists to place more emphasis on limitations, obstacles, and issues, rather than exploring and engaging possibilities. The prevailing outlook towards climate change, for instance, tends to be pessimistic, with problem-solving strategies fixated on achieving rigid targets. However, the BwN approach adopts a more dynamic change of view with regards to solutions and calls for a different mindset — one that encourages tackling societal challenges as opportunities. It challenges one to identify opportunities through system understanding, that is, starting from the functioning of the natural and societal systems in which (the) infrastructure is to be realized [De Vriend et al., 2015]. System understanding lies at the core of climate-positive marine developments.

5.2. Application

The conceptual model developed in Chapter 3, the numerical model developed in Chapter 4, and the five Building with Nature design steps are applied on the case study here and used as tools to reach the research objective.

The first three steps of the Building with Nature design process are applied to the case study in this section. However, the fourth and fifth steps of refining the solution and preparing for implementation are not directly applicable or necessary for the purposes of this research. The focus of this study is to analyze and evaluate the feasibility and effectiveness of different design alternatives, allowing assessment of potential benefits and challenges associated with these. Step four and five involve practical considerations such as funding, budgeting, governance, and stakeholder engagement. Due to limitations in time and access to implementation opportunities, these aspects fall outside the scope of this research. The primary objective is to contribute knowledge and insights to the field of building with nature design through analysis, evaluation, and the assessment of potential benefits and challenges associated with the design alternatives.

The three primary purposes of the conceptual model emphasizing both coral habitat restoration and coastal protection aims are repeated here:

1. Identifying physical-chemical and biological variables that require further examination and analysis to explore coral habitat potential of a design.

2. Identifying physical variables that require further examination and analysis to explore coastal protection services provided by a design.

3. Identifying design variables influencing physical-chemical and biological variables that can be modified within a design to explore potential integrated solutions.

Physical-chemical and biological variables are analyzed to understand the system (step 1) in Section 5.2.1. Design variables are regulated and alternative designs are identified (step 2) in Section 5.2.2 using the OpenFOAM numerical model developed in Chapter 4. It is utilized to evaluate (step 3) the impacts of altering the slope and dimensions of the structure on coral habitat restoration and coastal protection services. Five criteria are chosen to assess these effects in Section 5.2.3, of which 2 criteria are assessed uzing the OpenFOAM model. Eventually, a design is pre-selected as a (preliminary) integral solution for the case study in Section 5.2.4, and finally recommendations on coral habitat restoration for the pre-selected solution utilizing the OpenFOAM model are formulated.

5.2.1. Understand the system

Understanding the natural, physical, and societal system and how they function together should be a key starting point of an intended implementation of a project.

Area of interest

The case study area of interest is located within Addu City, see Figure 5.2, located in Addu (Seenu) Atoll. This is the most southern atoll[1] of the Maldives, located in the Indian Ocean.

Figure 5.2.: Case study area

The city consists of six districts, namely Hithadhoo, Maradhoo, Maradhoo-Feydhoo, Feydhoo, meedhoo and Hulhudhoo. Addu city is the second largest urban city in the Maldives with a population of approximately 35,000 people, which will keep growing in the near future. The atoll is known for its diverse marine life, being most famous for its coral reefs. Addu atoll is composed of multiple low-lying islands encircling a deep lagoon, granting the region its distinctiveness, but also its vulnerability to sea level rise and flooding.

Physical-chemical-biological system

The conceptual model is employed here and repeated in Figure 5.3 alongside additional research in the area of interest, in order to understand the system. UNESCO [2020] declared Addu Atoll as a UNESCO Biosphere Reserve. Within the biosphere reserve there are a large variety of ecosystems present such as reef passes, seagrass beds, coral islands, tropical vegetation, wetlands, brackish lakes locally known as kilhis, agricultural land and residential areas [UNESCO, 2020]. Many protected species live on the atoll such as turtles, sharks, and rays. The majority of fish are herbivorous fish such as surgeonfishes, wrasses, and parrotfishes that play an important role in coral reef resilience by controlling the growth of algae. Algae can outcompete corals for space and light, inhibiting coral growth and survival. By consuming algae, herbivorous fish help keep its population in check, allowing corals to thrive.

The key sensitive receivers of the project are protected areas, resorts, breeding turtles and juvenile rays, fishing grounds, and coral and seagrass habitats. Due to reclamation of new

[1] An atoll island forms a ring-shaped or circular coral reef structure enclosing a lagoon.

land, some of these key sensitive receivers need to be relocated, which include seagrass and coral relocation. As a potential part of the project scope, the submerged breakwater that is studied in this thesis is chosen to optimize the efficiency of protecting key sensitive areas, having the highest effect on reduction of beach losses at the most commonly used beach area of Hithadhoo that is shown in Figure 1.4.

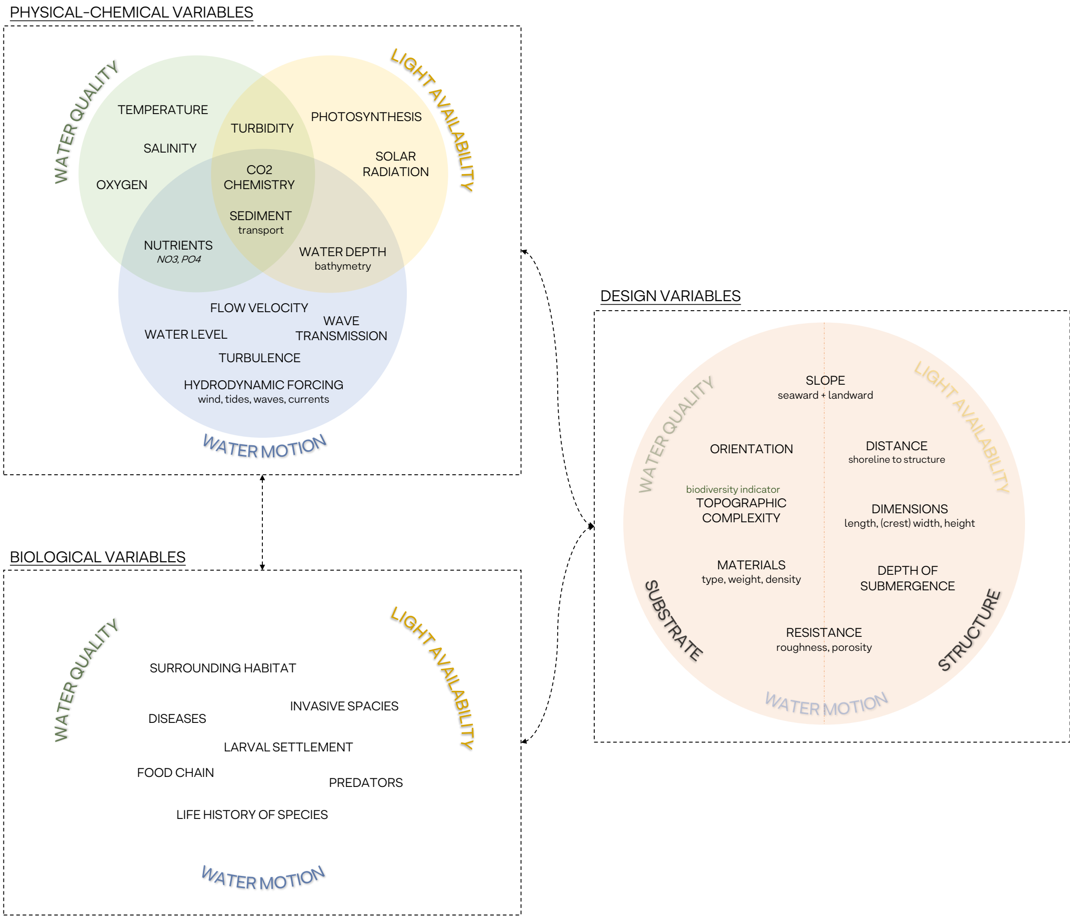


Figure 5.3.: A conceptual model that can be used as a tool for analysis and design of a submerged breakwater delivering coral habitat restoration and coastal protection services.

The conceptual model is used to identify important physical-chemical and biological variables, stuyding the area of interest in more detail exploring coral growth potential. The atoll is divided into four channels and shaped by the peripheral reef. As a result of this geographical characteristic, the sea current typically circulates within the atoll during both NE and SW monsoons. Outside the reef flats waves can reach heights of 3 meters, but inside the lagoon waves vary from 0.6 to 1.2 m maximum and the tidal regime is semi-diurnal with diurnal inequalities. A tropical climate is present with average temperatures around 28 degrees. An EIA was carried out by the Maldivian Ministry of National Planning, Housing and Infrastructure for the proposed reclamation project at Addu City, Maldives [EIA, 2022]. They presented the marine water quality guideline issued from the Environmental

Protection Agency as in Table 5.1:

Table 5.1.: Optimal ranges for marine water quality [EIA, 2022]

Parameter	Optimal Range
Temperature	18 °C and 32 °C
Salinity	3.2% - 4.2%
pH	8.0-8.3 (levels below 7.4 pH causes stress)
Turbidity	3-5 NTU (levels over 5 NTU causes stress)
Sedimentation	Max mean annual rate 3 $mg/cm^2/day$
Nitrates	< 5 mg $1^{-}1$ NO_3 ^{-}N
Phosphate	0.005 – 0.020 mg $1^{-}1$ PO_4 ^{-}P

According to the EIA, all values within the area of interest have fallen within the optimal range. Marine benthic surveys done at Addu atoll displayed that some of the reefs in Addu Atoll were very healthy with high coral cover, with 10 sites exhibiting over 40% hard coral cover, with more abundance in shallower depths within the lagoon. Furthermore the reef consits of rocks, rubble, and sand.

A high diversity of corals are present, some of the species being *Pocilliopora meandrina, Acopora microphthalma, Acopora digitifera, Acopora muricata, Acopora nobilis, Favia favus, Fungia concinna, Cycloseris sinensis, Goniopora lobata, Pocillopora meandrina, Halomitra pileus, Ctenactis crassa, Herpolitha weberi, Lobophyllia hemprichii, Porites lutea* and species belonging to Dendrophylliidae, Mussidae, Fungiidae, *Gonipora Sp.*. Non-living reef cover at this site was dominated by recently killed coral (22 %) and living reef cover was dominated by hard coral (56 %). Often, recently killed corals are found due to bleaching events combined with sedimentation effects from dredging and harbor activities. This is also the case for the case study area.

In an old report on the stony corals from the Maldive Archipelago from Scheer and Pillai [1976] that reported 161 coral species in Addu, it was found that Acropora species are the most abundant species. This genus of branching or tabular coral belongs to the family *Acroporidae* of the order *Scleractinia*. The sheltered lagoon case study area is associated with a relatively calm wave energy environment. When designing for target coral species, it is advantageous to consider this and identify the coral species that are already thriving in the area. The biological variable *surrounding habitat* in the conceptual model takes this into account. This approach enhances the likelihood of achieving greater success in coral conservation and restoration efforts. Considering the inclusion of long-term coastal protection in the design, it has been determined that a branching type of coral would be appropriate. This choice is based on the fast growth rate of these species, that also offers the potential to adapt to sea level rise effectively Beck et al. [2016]. The *Acropora Formosa* species has been identified as the fastest growing branching type of coral [Khasanah et al., 2020] amongst the present Acropora species in the area of interest. Taking this into consideration, *A. Formosa* is selected as the target species for this particular case study. Also from the Marine Ecology Baseline Survey Report for Addu City carried out by Van Oord [VO, 2023], it was evident that in the area of interest the branching coral *A. Muricata*, which is a synonym for *A. Formosa*, is present.

Socio-economic system

With a population of around 35,000 inhabitants and the presence of an imposing biodiversity, the Addu Atoll Biosphere Reserve serves as a hub for tourism in the form of underwater sports, fisheries, and tropical vacations. The region greatly relies on (the growth of) tourism in Addu City, as it serves as a crucial driver for maintaining a robust economy and encouragement of sustainable development. Preserving the health and integrity of the coral reefs present on the atoll, which function as protection of foundation and protection of the atoll, indicators of biodiversity, and facilitators of tourism, stands out as a significant challenge in the region. Also regarding the growing population, housing supply is one of the main socio-economic issues in Addu City. One thing can already be said about Hithadhoo, the second largest island of Addu City, where the case study area is located in. Hithadoo consists of habitable land, wetlands, and reef areas that are scheduled for reclamation in order to provide space for new land development. The actions of land reclamation in Hithadoo have the potential to drive economic growth, provide employment opportunities, and enhance infrastructure. However, it is crucial to closely manage and mitigate the environmental and social impacts associated with these actions.

5.2.2. Identify alternatives

The second of the five BwN design steps is to identify realistic alternatives that make use of the potential that the system has to offer. Ideally, these alternatives should incorporate the opportunities the system offers and align with a sustainable long-term vision in accordance with the building with nature approach. 28 BwN concepts are suggested by van Eekelen and Bouw [2020] that can be applied when a concept matches a specific system. Considering the case study, Addu City is located on a sandy coast in a tropical region characterized by an abundant biodiversity. This biodiversity on the atoll plays a crucial role both environmentally and socio-economically. It could be stated that coral reefs represent one of the most valuable assets of Addu City since they deliver many services. They contribute to biodiversity, fisheries, food security, tourism and recreation, coastal protection, and climate regulation. In light of these considerations the building with nature Concept: *facilitating coral development* has been applied in this case study (Figure 5.4). That is: to protect a section of the reclamation area by implementing a submerged breakwater that serves the dual purpose of coastal protection and coral habitat restoration.

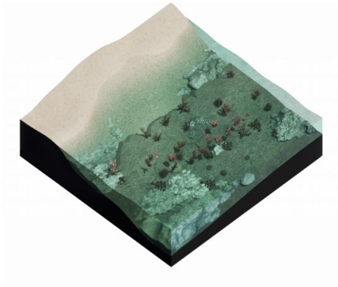


Figure 5.4.: Building with Nature concept: facilitating coral development [van Eekelen and Bouw, 2020]

As a result of the extensive reclamation project, numerous corals face the need for relocation or the risk of being affected by sedimentation and turbidity caused by the ongoing dredging activities, on top of the bleaching events that are already happening. However, this situation presents a valuable opportunity to embrace a collaborative approach with nature instead of working in opposition to it. Coral reefs not only function as carbon sinks but also serve as natural wave attenuators, which enhances their long-term coastal protection abilities. This dynamic nature of coral reefs and thus the solution holds potential to increase value in terms of sustainability, particularly over the long term.

Long term benefit

First, the numerical model is used as a tool to illustrate and explore long-term and sustainable advantages of a nature-based building approach versus a traditional one in light of climate change. Sea level rise projections based on the assessment presented in the IPCC Sixth Assessment Report according to the Sea Level Projection Tool developed by the Intergovernmental Panel on Climate Change [IPCC, 2023] for GAN II near Addu City in the median/likely range are as follows:

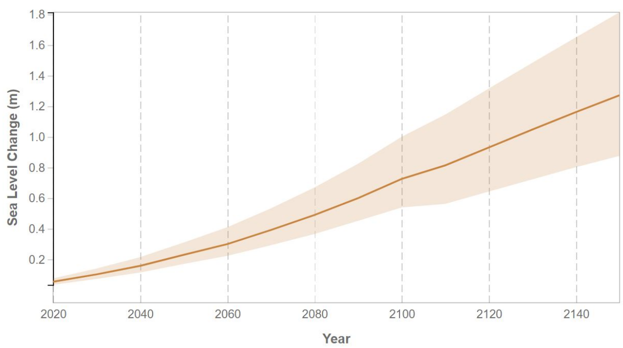


Figure 5.5.: Median or likely range of sea level rise near Addu City [IPCC, 2023]

In addition to serving as natural wave attenuators, it is increasingly acknowledged that coral reefs have the capacity to accrete and potentially keep pace with sea level rise [Beck et al., 2016]. Whether or not corals continue to accrete towards sea level, the incorporation of an additional dynamic and biodiverse layer atop the conventional submerged breakwater is anticipated to improve resistance and minimize wave transmission in comparison to the structure alone. To illustrate this, some runs of potential future scenarios have been performed. It is essential to recognize upfront that these scenarios involve rough estimates and are highly speculative.

First an estimation of average growth behaviour of *A. Formosa* is explored. It is common for *A. Formosa* to grow to a height of about 0.50 m and to thrive in between 0 and 25 m [SeaLifeBase, 2023] water depth. Scheer and Pillai [1976] reported that *A. Formosa* was present in Addu City at depths of 1.5, 2, and also 20 m, confirming this. Several growth rates of *A. Formosa* reported in Xin et al. [2016] and shown in Figure 5.6 are used to assume an average growth rate of the species per month.

Location	***Species***	***Growth rates (cm mth^{-1})***	***Source***
Tekek, Tioman, Malaysia	***Acropora formosa***	0.68±0.13 to 1.45±0.09	Present study
Renggis, Tioman, Malaysia	***Acropora formosa***	0.55±0.13 to 0.72±0.11	Present study
Salmon Bay, Australia	***Acropora yongei***	0.43±0.04	Ross et al (2015)
Virgin Island, USA	***Acropora cervicornis***	0.59±0.05	Gladfelter et al (1978)
	Acropora prolifera	0.68±0.03	
Phuket, Thailand	***Acropora formosa***	0.51±0.15	Charuchinda & Hylleberg (1984)
Western Australia	***Acropora formosa***	0.44±0.16 to 0.66±0.13	Harriot (1998)
Sulawesi, Indonesia	***Acropora valenciennesi***	0.55±0.13 to 1.00±0.17	Crabbe & Smith (2002)
Okinawa, Japan	***Acropora formosa***	0.39±0.13 to 0.69±0.20	Okubo et al (2005)
Florida, USA	***Acropora cervicornis***	0.63±0.29	Lirman et al (2010)

Figure 5.6.: Growth rates of different Acropora species from Xin et al. [2016]

Taking the average of average *A. Formosa* growth rate values, a growth rate of 0.58 cm/month is calculated and assumed as an average growth rate. This results in a fully grown coral of about 49 cm, h_c being the height of the coral, over a time span of 7 years starting in 2023:

$$h_c = (2030 - 2023) * 12 * 0.58 = 49 \text{ cm} \tag{5.1}$$

It is thus assumed that the layer of corals stops growing after 7 years. Wave transmission results have been examined using the OpenFOAM model under various sea level rise scenarios and are compared to a base case scenario (B101 and B102) where no corals are restored. It is assumed that a layer of *A. Formosa* corals is thriving over the entire span of the submerged breakwater (excluding the crest as they should remain below the surface). Since these type of corals exist in very shallow waters, this could be an optimistic, yet realistic scenario. The numerical model developed in Chapter 4 is used to model future scenarios. A D_{50} of 2 mm [Scheer and Pillai, 1976] and a porosity of 80 % [Roche et al., 2010] are assumed for the coral layer of *A. Formosa* and used as input in the `porosityDict` file of OpenFOAM. Wave transmission is again calculated with Equation 4.12a.

The runs for future scenarios are indicated with the letter F. F1 indicates average conditions, F2 indicates design conditions. The consequences of future sea level rise scenarios with and without coral habitat restoration efforts on wave transmission are explored. Results are presented in Table 5.2.

Table 5.2.: Exploring long term consequences of coral habitat restoration in sea level rise scenarios for the base case scenario

Run	Waves	Year	SLR [cm]	Corals [cm]	Kt	Kt change (%)
B101	50%	2023	0	0	0.61	0%
F1a	50%	2030	10	49	0.75	+23%
F1b	50%	2030	10	0	0.82	+35%
F1c	50%	2050	22	49	0.93	+52%
F1d	50%	2050	22	0	0.95	+55%
B201	90%	2023	0	0	0.89	0%
F2a	90%	2030	10	49	0.95	+6%
F2b	90%	2030	10	0	0.95	+7%
F2c	90%	2050	22	49	0.95	+7%
F2d	90%	2050	22	0	0.95	+7%

The results in Table 5.2 show that after seven years time from 2023 to 2030, in the median/likely range SLR scenario for Addu City, comparing coral growth and no coral growth scenarios, around $35\% - 23\% = 12\%$ wave energy reduction is achieved in the year 2030 in a scenario with corals thriving on the breakwater, as the corals act as additional wave attenuators. In the year 2050 this benefit of additional wave energy reduction is still present, but lowered to $55\% - 53\% = 3\%$ as the water level increased with 0.22 m. Under design conditions, the presence of corals on the breakwater has limited to no impact as the water level in design conditions (MSL + 1.17 m) plus additional sea level rise scenarios (+ 0.10 and + 0.22 m) is too high for corals to have any wave attenuation service.

This analysis shows that a BwN alternative with a growing layer of corals on top of the artificial reef, along with potentially other thriving species in a sea level rise scenario, could offer additional benefits to a traditional solution in terms of additional wave energy reduction in potential SLR scenarios, delivering additional coastal resilience, as the corals act as additional wave attenuators.

Exploring alternatives

Design variables (Figure 5.7) from the conceptual model influence physical-chemical variables, among which water motion variables. There is no single optimal design or one-size-fits all solution that can be applied universally and for every case study, every system is unique and all variables should be carefully considered. The numerical model is used to analyze how changes in design variables are of influence on water motion and wave transmission, balancing coral habitat restoration and coastal protection values. Water motion, as explained, is an important variable concerning the grown potential and survival of corals. Within the scope of this research, it has been determined to maintain constant values for topographic complexity, materials, distance from shoreline to structure, depth of submergence (d′), structure width (B), and resistance design variables. The depth of submergence has been identified by many authors as the governing parameter for wave attenuation [Van der Meer et al., 2005; Bleck, 2006; Srineash et al., 2020], keeping this parameter constant is therefore

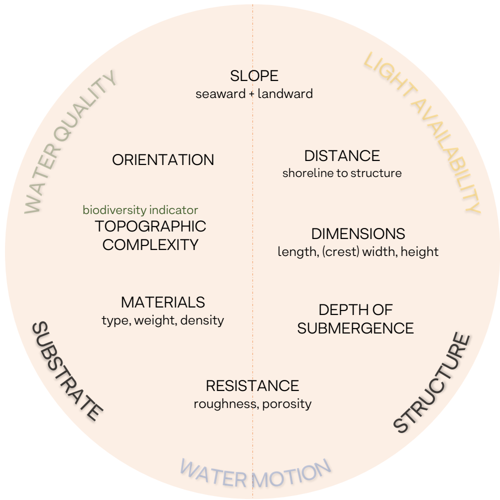


Figure 5.7.: Conceptual model - design variables

useful since wave transmission values will not be influenced. The slope and length of the structure are adjusted aiming to analyze growth rates of *A. Formosa* as explained in Section 3.5 in relation to flow regimes around the structure successful growth of *A. Formosa*. In order to fully comprehend and analyze the implications of flow regime changes on coral growth in the vicinity of the structure, significant variations in slopes are defined.

The traditional alternative or base case scenario, has been tested in a wave flume for coastal protection, and has been calibrated and validated with an OpenFOAM numerical model as explained in Chapter 4. The performed runs are presented in Table 5.3. Simulations B101 and B201 represent 1, the average 50% wave conditions scenario and 2, the design 90% wave conditions scenario for the traditional design with a slope of 2:3, serving as the **B**ase case scenario. A sketch of the base case layout is presented in Figure 5.8 showing average (+ 0.00 m MSL) and design (+ 1.17 m MSL) conditions. **G**eometry is altered for simulations G102 and G202 that depict runs with a milder slope of 3:2, while simulations G301 and G302 involve a steeper slope of 1:3. Sketches of both layouts are shown in Figure 5.9 and Figure 5.10. The traditional, milder slope, and steeper slope structure, each have their (dis)advantages considering coral habitat potential and coastal protection services. An evaluation of 5 criteria is carried out in the next section using a MCA to pre-select an integral solution.

Table 5.3.: Properties of evaluated design alternatives

Run ID	Waves	a	L [m]
B101 - Base case	50%	2:3	26.4
G102 - Mild slope	50%	3:2	13.7
G103 - Steep slope	50%	1:3	48.0
B201 - Base Case	90%	2:3	26.4
G202 - Mild slope	90%	3:2	13.7
G203 - Gentle slope	90%	1:3	48.0

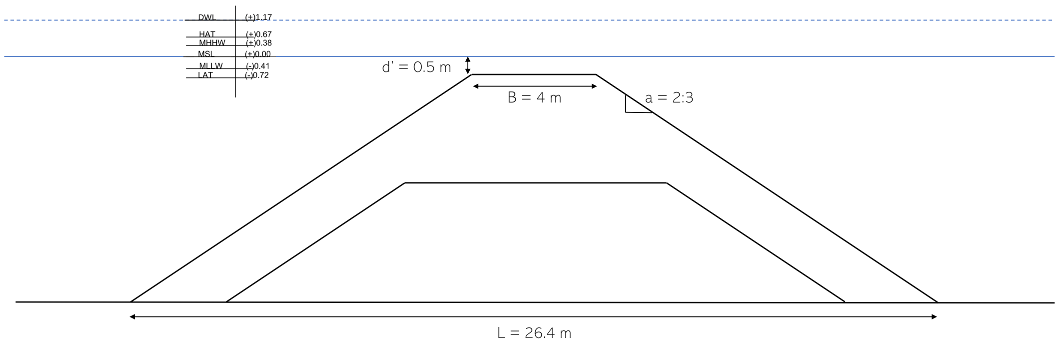


Figure 5.8.: Sketch of base case design

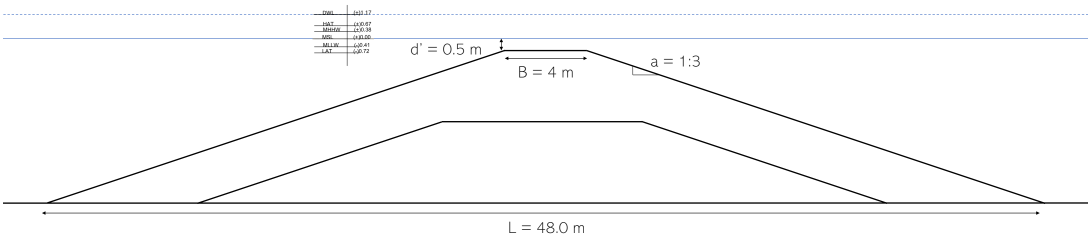


Figure 5.9.: Sketch of mild slope design

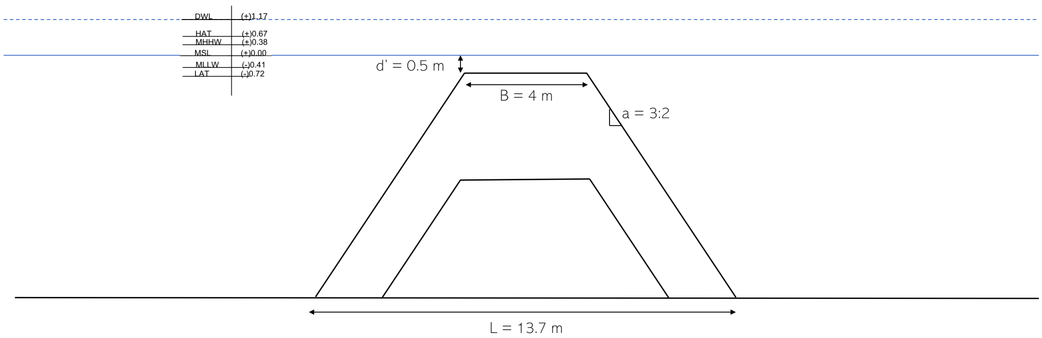


Figure 5.10.: Sketch of steep slope design

5.2.3. Evaluate alternatives and pre-select integral solution

In this research, five criteria are used to evaluate the alternatives with the objective of finding an integral emphasizing both coral habitat restoration and coastal protection services. In this section, each criterion is explained, and analyses are conducted, followed by a discussion of results. Subsequently, a multi-criteria analysis (MCA) is performed to compare the outcomes of the three design alternatives, to aid in deciding on a preliminary integral solution in Section 5.2.4.

An assessment of changes in wave energy and longshore transport for the year 2023 (so prior to any coral growth) due to changes in structure configuration has been conducted. Longshore transport is a key driver of coastal erosion as it moves sediment along the shore. By reducing longshore transport, the submerged breakwater helps mitigate erosion and protects the beach from the loss of sand and sediment. Compared to the base case scenario for both average and design conditions, changes in the amounts of wave transmission in terms of wave energy reduction (-) or wave energy increase (+) are presented. Also, changes in the amounts of longshore transport in terms of longshore transport reduction (-) or increase (+) are presented. According to Van Rijn [2014], a simple general equation for longshore transport of sand, gravel and shingle can be expressed as:

$$Q_{t,mass} = \alpha M \tag{5.2}$$

Where $Q_{t,mass}$ is a longshore mass transport rate in kg/s, α a calibration coefficient, and M a mobility parameter in kg/s. This parameter is dependent on sediment density, grain size, wave angle, and wave height. An important conclusion of the work of Van Rijn [2014] is that $Q_{t,mass}$ is proportional to wave height to the power 3.1:

$$Q_{t,mass} \propto H^{3.1} \tag{5.3}$$

The average transmitted significant wave heights $\overline{H}_{s,T}$ for each run in prototype scale are presented. Using Equation 5.3, these are compared to the base case scenario for average and design conditions, providing preliminary insights into consequences on longshore transport for changes in configuration. Generally, a decrease in the wave transmission coefficient indicates greater reduction in wave energy and decreased longshore transport. Conversely, an increase in the wave transmission coefficient suggests less reduction in wave energy and increased longshore transport. Results are presented in Table 5.4.

Table 5.4.: Evaluating alternatives - wave transmission

Run ID	Waves	K_t	Change in K_t	$\overline{H}_{s,T}$	Longshore transport
B101 - Base case	50%	0.61	0%	0.40	0%
G102 - Mild slope	50%	0.57	-7%	0.35	-32%
G103 - Steep slope	50%	0.63	+2%	0.42	+17%
B201 - Base case	90%	0.89	0%	0.67	0%
G202 - Mild slope	90%	0.86	-3%	0.62	-21 %
G203 - Steep slope	90%	0.90	+1%	0.69	+9%

It can be observed from the results in Table 5.4 that the mild slope structure, specifically run G102 and run G202, results in a 7% reduction in wave energy for average and a 3% reduction under design conditions. The larger structure with a milder slope compared to the other designs, creates more resistance against incoming waves compared to the base case, primarily due to its increased surface area. Conversely, the steep slope structure exhibits the opposite effect, with a 2% reduction in wave energy on average and a 1% reduction under design conditions. Considering the estimates for impacts on longshore transport rates as mentioned in Equation 5.3, the alterations in wave energy, whether decreased or increased, have a significant influence on longshore transport.

2. Flow regime preference

As explained in Section 3.5, one interrelation between physical-chemical variables displayed by the conceptual model in terms of inorganic carbon metabolism and flow velocity is studied and analyzed in more depth in this research. Hossain [2013] studied the effect of water flow on growth of the hard coral *A. Formosa*. He designed experiments to observe the growth of the coral under different water flow conditions in a laboratory. These results have been used to test different geometries of the structure and growth performance of *A. Formosa*. Useful results from Hossain [2013] have been presented in Table 5.5. Oscillatory flow here is defined as the average of lowest and highest flow speed. A linear regression analysis was conducted and shown in Figure 5.11 to determine the relationship between growth of *A. Formosa* and water flow.

Table 5.5.: Growth of *A. Formosa* in different flow speeds from Hossain [2013]

Oscillatory flow	**u = 16 cm/s**	**u = 30 cm/s**	**u = 40 cm/s**
Growth (μmol/kg/hr)	8.37	9.84	10.22

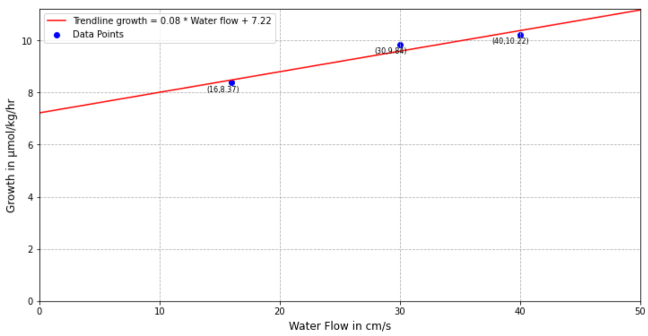


Figure 5.11.: Growth parameter of A. Formosa vs water flow

Shown on the y-axis is growth in μmol/kg/hr. The resulting extrapolated trendline resulted in the following linear relation:

$$\bar{g} = 0.08 \cdot \bar{u}_x + 7.22 \tag{5.4}$$

Where $\bar{g}$ represents a growth parameter in μmol/kg/hr related to inorganic carbon metabolism and $\bar{u}$ represents average flow velocity in cm/s. Hossain [2013] used a method of Hata et al. [2004] to define $\bar{g}$ in terms of inorganic carbon metabolism as equal to half the change in total alkalinity, which can be directly measured in a water column. The extrapolation method assumes that the observed linear relationship between growth and water flow continues beyond the measured range. Based on the trendline and conclusions of Hossain [2013], it can be observed that at higher water flow rates, skeletal growth of A. Formosa increases.

In a similar manner to the illustration shown in Figure 5.12, each alternative configuration of the structure has been divided into six areas of similar size: three seaward (S) transects and three landward (L) transects. The objective of testing these setups and transects was to see where water flow around the structure changes in favour of coral growth.

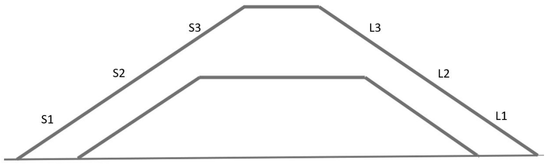


Figure 5.12.: Seaward and landward transects of the breakwater

The analysis carried out by Hossain [2013], uses the average of the highest and the lowest occurring horizontal flow speeds. Similarly, the OpenFOAM model is employed to calculate the average horizontal velocity along each transect, both seaward and landward, for every configuration. This approach allows for a comparison of the growth performance across different transects. For the method that is used to perform this analysis using OpenFOAM the reader is referred to Appendix E. Results for flow velocities for each transect are presented first in Table 5.6.

Table 5.6.: Average velocities in x-direction from t = 0 s to t = 100 s over seaward and landward transects

Results	**B101** - base case	**G102** - mild slope	**G103** - steep slope
Flow velocity $\bar{u}_{x,S1}$ [cm/s]	6.5	5.3	9.4
Flow velocity $\bar{u}_{x,S2}$ [cm/s]	8.4	9.7	10
Flow velocity $\bar{u}_{x,S3}$ [cm/s]	11	12	16
Average $\bar{u}_x$ over S [cm/s]	8.8	9.1	11.7
Flow velocity $\bar{u}_{x,L1}$ [cm/s]	5.2	4.0	3.2
Flow velocity $\bar{u}_{x,L2}$ [cm/s]	5.5	6.1	4.9
Flow velocity $\bar{u}_{x,L3}$ [cm/s]	10	9.3	9.7
Average $\bar{u}_x$ over L [cm/s]	6.3	6.4	5.9

In general for all transects, the seaward side experiences greater velocities compared to the leeward side, as the latter is sheltered. Also, all transects experience greater velocities for transects S3 and L3 that are closest to the free surface and the faster travelling wave crests. The highest velocities for all transects occur at transect S3, the highest of all being transect S3 of the steeper structure as the waves experience less resistance from the structure's surface area. As explained in Section 4.5, velocities on top of the structure, and therefore also for transect L3 as it is close to this region, increase due to mass continuity regions. the reduced cross-sectional area results in an increased flow rate. Three plots of u_x are shown for a section of the wave flume of the steep structure as illustrated in Figure 5.13. These plots represent the time interval from t = 12 s to t = 12.9 s, demonstrating the propagation of a wave over the structure. In line with the results, velocities on the seaward side of the structure are overall higher and increasing for transects 1-3, and the increase in velocity on top of the structure is visible. Results for growth rates $\bar{g}$ in μmol/kg/hr that are calculated using Equation 5.4 are presented in Table 5.7.

Based on the findings presented in Table 5.7, it can be observed that $\bar{g}$ increases along each transect compared to the base case, with the exception of the deepest transect (S1) in run G102. Equation 5.4 is a linear relation, meaning that an increase in flow velocity implies more growth potential in that area. Following this reasoning, on the seaward side, growth performance exhibits a more significant increase compared to the leeward side, therefore this transect has the highest chance of succession for corals to grow. Run G103 performs best with the highest overall growth rate for the seaward side. For the leeward side, it is not necessarily true that G103, which has a steeper slope, performs better, but the average differences in growth rates between the three runs are minor.

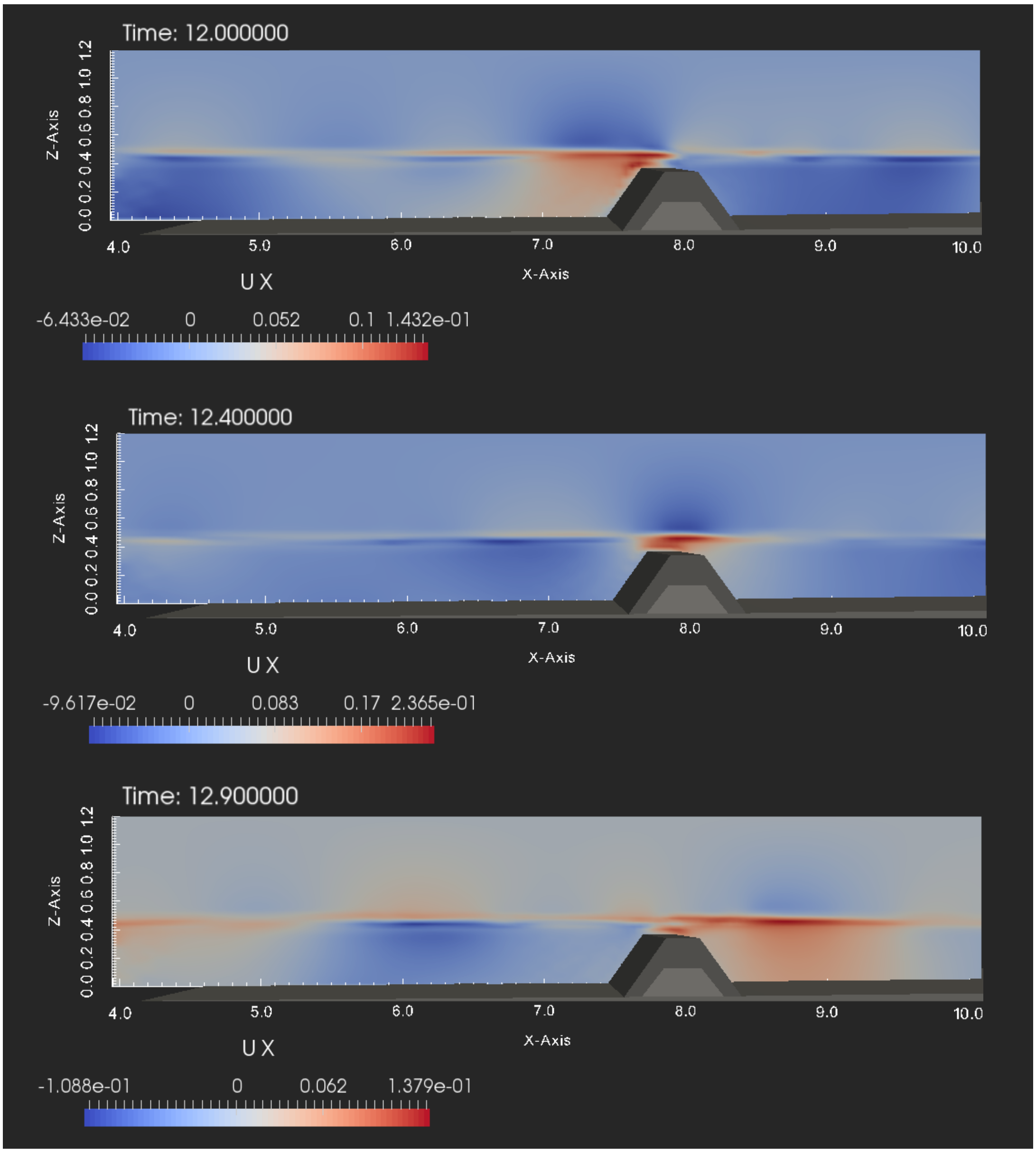


Figure 5.13.: OpenFOAM results of u_x in m/s for the steep structure showing a wave travelling over the breakwater from t = 12 s to t = 12.9 s

Table 5.7.: Average growth rates over seaward and landward transects

Results	**B101** - base case	**G102** - mild slope	**G103** - steep slope
Growth rate $\bar{g}_{S1}$ [μmol/kg/hr]	7.73	7.63	7.96
Growth rate $\bar{g}_{S2}$ [μmol/kg/hr]	7.87	7.98	8.02
Growth rate $\bar{g}_{S3}$ [μmol/kg/hr]	8.12	8.18	8.45
Average $\bar{g}$ over S [μmol/kg/hr]	7.91	7.93	8.14
Growth rate $\bar{g}_{L1}$ [μmol/kg/hr]	7.47	7.53	7.47
Growth rate $\bar{g}_{L2}$ [μmol/kg/hr]	7.65	7.69	7.60
Growth rate $\bar{g}_{L3}$ [μmol/kg/hr]	8.01	7.95	7.98
Average $\bar{g}$ over L [μmol/kg/hr]	7.71	7.72	7.68

3. Slope

When considering once again the design variables from the conceptual model (Figure 5.7), the slope and orientation of the structure are important since they impact the successful attachment and expansion of corals onto the substrate. The report on stony corals from the Maldive Archipelago by Scheer and Pillai [1976] includes information of the abundance of *A. Formosa*, as previously mentioned. Through observing the historical abundance patterns of the *A. Formosa* species and comparing them to bathymetry data of the area of interest (via the software VOSS.NET developed by Van Oord), it was possible to identify the slopes that *A. Formosa* naturally occur on. It was apparent that these corals have a preference for settling on shallow slopes, often even shallower than the mild slope structure in this case study. This behavior can be attributed to the species' need to compete for space and expand horizontally to survive and thrive.

Moreover, when a wave interacts with the breakwater, this leads to an increase of wave energy in the vicinity of the structure. This, in turn, results in higher flow velocities and an increased growth rate, as discussed in the previous section. When comparing the mild slope structure to the steep slope structure, when subjected to the same wave, the mild slope structure exhibits higher wave energy over an extended duration, surpassing that of the steep slope structure. Based on this, the mild slope structure retains a greater amount of wave energy within the same time interval, in comparison to the steep slope structure.

For these reasons, the mild slope structure performs best in terms of slope preference, followed by the base case and steep slope structure, since following the above reasoning shallower designs have a greater likelihood of achieving successful settlement of *A. Formosa*.

4. Potential habitat area

A comparison is made of Table 5.8 coral habitat potential, simply related to the surface area of the structure. Additionally, it can be observed from Table 5.8 that the potential habitat area increases significantly for the mild slope structure, up to 74% compared to the base case, in favour of coral settlement. The opposite is true for the steep slope structure, where a 43% decline in potential habitat area is observed.

Table 5.8.: Coral habitat potential area - comparison of design alternatives

Scenario	**Total area per 50 m breakwater [m3]**	**Potential habitat area comparison**
B1 - Base case	1342.4	100 %
G2 - Mild slope	2340.1	+ 74 %
G3 - Steep slope	889.4	- 43 %

5. Initial costs

Van Oord's initial project proposal includes the implementation of a submerged breakwater with a length of 50 meters in the longshore direction. Estimated costs per 50 meter breakwater are 250 € per m3 breakwater. Costs of every configuration of the structure are compared to each other and shown in Table 5.9.

Table 5.9.: Cost - comparison of design alternatives

Cost per 50 m breakwater	**Volume [m_3]**	**Costs**
B1 - Base case	5624	€ 1,406,000.00
G2 - Mild slope	9694	€ 2,423,500.00
G3 - Steep slope	3305	€ 826,333.33

5.2.4. Pre-select integral solution

Belton and Stewart [2002] described the Multi Criteria Decision Analysis (MCDA) method, also commonly known as Multi-Criteria Analysis (MCA), to aid in decision-making. This method is designed to support humans in making decisions, rather than making decisions on their behalf. A MCA is carried out in this research to aid in pre-selecting a preliminary integral solution for the case study, focussing on both coral habitat potential and coastal protection services. Table 5.10 outlines five criteria, their descriptions, and an explanation of their scoring in the MCA. In this particular scenario, both coastal protection and coral habitat potential services are assigned equal weights of 40% in the analysis in the search for integral solutions. The coral habitat potential service comprises three criteria, each of which carries an equal weight. Costs are assigned a weight of 20 %. While in this research costs may not be the most critical criterion, they are still considered important. It is important to note that for every case study and purpose of a project weights and priorities are most likely different. In Table 5.11 results of the MCA are shown.

Table 5.10.: Definitions and scoring of criteria used in the MCA

	Criterion	Weight (/ 100)	Score = 1	Score = 5
Coastal protection service	1. Coastal protection value	40	Structure does not function as a coastal defense measure	Structure functions as an effective coastal defense measure
Coral habitat potential service	2. Flow regime preference	13.3	Very limited to no coral growth potential around structure	Favourable coral growth potential around structure
	3. Slope	13.3	Structure with a very steep slope	Structure with a very mild slope
	4. Potential habitat area	13.3	Limited to no potential coral habitat area	Extensive potential coral habitat area
Costs	5. Initial costs	20	Costly investment	Cheaper investment

Table 5.11.: MCA Analysis of design alternatives (for definitions see Table 5.10)

		Base case		Mild slope		Steep slope	
Criterion	**Weight**	**Score**	**Total score**	**Score**	**Total score**	**Score**	**Total score**
1. Coastal protection value	40.0	3	160	4	200	2	120
2. Flow regime preference	13.3	4	40	4	40	4	40
3. Slope	13.3	2	27	4	53	1	13
4. Potential habitat area	13.3	3	40	5	67	2	27
5. Initial costs	20.0	3	60	1	20	4	80
Total	100.0		300		**353**		253

1. When considering **coastal protection value**, the design conditions become relevant. Table 5.4 presented a 21% decrease in longshore transport for the mild slope structure, and a 9% increase in longshore transport for the steep slope structure compared to the base case. for this case study to determine the "sufficient" level of coastal protection necessary to safeguard the beach stretch. Nevertheless, it is argued that a 9% increase in longshore transport for the steep slope structure leads to additional coastal erosion near the beach, while a 21% decrease for the mild slope structure reduces coastal erosion in comparison with the base case. These effects are even more pronounced under average conditions. Referring back to the analysis of long-term consequences in terms of potential sea level rise scenarios and the presence of coral habitats mentioned in Section 5.2.2, it is expected that even in the base case scenario where a layer of corals has developed on the sides of the structure, a wave energy increase of at least 23% for average conditions and 6% for extreme conditions may exist by the year 2030 (see Table 5.2). These consequences on wave transmission also have a significant impact on longshore transport rates. A 43% increase in longshore transport rate in design

conditions was estimated already in the year 2030, when comparing run F2a (10 cm SLR) to the base case scenario using Equation 5.3 and $\overline{H}_{s,T,B201} = 0.67$ m and $\overline{H}_{s,T,F2a} = 0.75$ m. The 21% decrease in longshore transport caused by the mild slope structure (Table 5.4) is argued to reduce and mitigate this increase in longshore transport rate and contribute to the prevention of coastal erosion compared to the base case scenario. Consequently, it is argued that the mild slope structure performs best in terms of coastal protection criteria, followed by the base case, and steep slope structures.

2. Referring to the analysis of **flow regime preference** in terms of growth potential and -rates in Table 5.7, changes in design alternatives have led to alterations in the flow regime around the structure. Consequently, it is argued that an increase of growth rates on specific transects compared to the base case scenario is preferable for coral settlement. Taking the averages of all transects, both the milder and steeper slope structures are associated with an increase in flow regime around the structure compared to the base case. However, the overall growth rate for the shallow structure only shows a marginal increase of 0.2%, while the steeper structure demonstrates a growth rate increase of 1.3%. Therefore it is still argued that none of the structures significantly outperforms the others, and scores are assigned equally. Initially, there was not much growth potential as this particular stretch of beach did not contain any corals prior to construction. It is known that *A. Formosa* branching species, are in general not tolerant of high wave energy as they are prone to dislodgement [PIANC, 2010] (see Appendix A). Since the lagoon in this area exhibits calmer wave conditions, as indicated by the results of the OpenFOAM model, it is deemed to be a suitable environment for coral growth and is assigned a score of 4 for each alternative. It can be observed in Figure 5.11 that a slightly more energetic area in terms of higher water flow velocities would have lead to a higher growth parameter. After pre-selecting the integral solution, a final advice is given concerning coral habitat potential in terms of growth rates for each transect.

3. Regarding the **slope** or orientation of the structure, it was argued before that there is a preference for *A. Formosa* corals to settle on shallow slopes, most often even shallower than the mild slope structure in this particular case study. Based on this reasoning, the mild slope structure receives the highest score due to its closer alignment with the preferred settlement conditions, followed by the base case structure and the steep slope structure, which deviates the most from the preferred slope conditions for coral settlement. Enough space to compete for and for horizontal expansion of the branching coral is not expected for the steep slope structure.

4. Regarding the **potential habitat area** of different designs (Table 5.8), the expansion in habitat area for the mild slope structure could facilitate the thriving of a greater population of *A. Formosa*. Scores for the alternative designs are assigned based on a comparison to the base case design for an increase of 74% of the mild slope, and decrease of 43% for the steep slope structure, the mild slope structure receiving the highest score, followed by the base case and steep slope structure.

5. With regards to **costs**, it is evident from Table 5.9 that the steep slope structure requires fewer materials, resulting in lower initial costs. Initial costs are highest for the mild slope structure, which is considered as its primary drawback. Scores are assigned based on a comparison to the base case design for an increase of 72% in costs for the mild slope, and a decrease of 41% in costs for the steep slope structure, the steep slope structure receiving the highest score, followed by the base case and mild slope structure.

In conclusion, the mild slope structure receives the highest score and is pre-selected as an integral solution, providing benefits in coral habitat potential and coastal protection services over the traditional design. In general, as concluded in Chapter 5, water motion is a crucial factor in facilitating coral growth. It plays a vital role in delivering nutrients, supplying oxygenated water, removing sediment and waste products, and aiding in the formation of coral skeletons. Increased water motion is proposed to enhance calcification, which is the process through which corals build their skeletons. This enhancement is attributed to the influence of inorganic carbon metabolism utilized by corals for skeletal development. Intensified flow regimes are associated with higher rates of inorganic carbon metabolism, thus increasing the likelihood of successful coral growth. The preferred flow regime is where most energetic areas are present, that is the seaward side of the structure and closest to the water surface. Based on the data presented in Table 5.12, the transect S3 (illustrated in Figure 5.14) is expected to exhibit the greatest success in coral growth, followed by L3, S2, L2, S1, and L1, in terms of the interrelation between flow velocity and inorganic carbon metabolism.

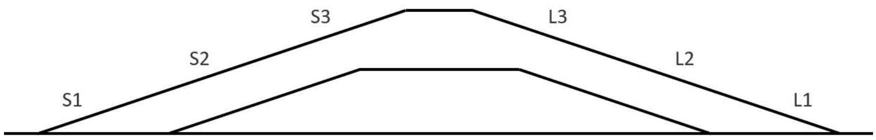


Figure 5.14.: Seaward and landward transects of shallow breakwater

Table 5.12.: Average growth rates of *A. Formosa* over seaward and landward transects

Growth rate $\bar{g}$ in μmol/kg/hr	**G102**
$\bar{g}_{S1}$	7.63
$\bar{g}_{S2}$	7.98
$\bar{g}_{S3}$	8.18
$\bar{g}_{L1}$	7.53
$\bar{g}_{L2}$	7.69
$\bar{g}_{L3}$	7.95

The plot in Figure 5.15 illustrates the distribution of turbulent kinetic energy (represented by the parameter k in m^2/s^2) in the wave flume for one wave traveling over the structure. Turbulence occurs when velocity differences between two layers cause friction and flow instabilities that amplify small disturbances and lead to the breakdown of smooth, laminar flow into a complex, turbulent flow pattern. Figure 5.15 reveals that turbulence is induced when faster-traveling wave crests travel through the water column that contains significantly lower flow velocities. Also, turbulence levels are notably higher in immediately behind the breakwater. This can be attributed to the velocity differences between the water flowing over the breakwater and the water located in the sheltered part behind the breakwater. Over the entire time frame, similar results were observed, with no excessive turbulence present on the breakwater as the wave climate in the lagoon is relatively calm. Iwasaki et al. [2018] studied how seawater turbulence affected the physical characteristics of the polyp skeleton of a similar Acropora species in stirred (turbulent) and unstirred (zero turbulence) conditions. They concluded that seawater turbulence increased the amount of skeletal carbonate and directly influenced calcification of coral hosts and thus promoted coral growth. Based on this reasoning, it is not necessarily true that specific transects of the structure have more coral growth potential in relation to higher turbulent kinetic levels, as these are very small around the structure. In relation to water motion, hydrodynamic energy around the structure is highest for transects S3 and L3, and thus coral settlement preference for these transects. Finally, when revisiting the design variables in the conceptual model, it is crucial to emphasize the inclusion of a substrate top layer that facilitates the attachment of the target coral species, despite not being explicitly addressed in this context.

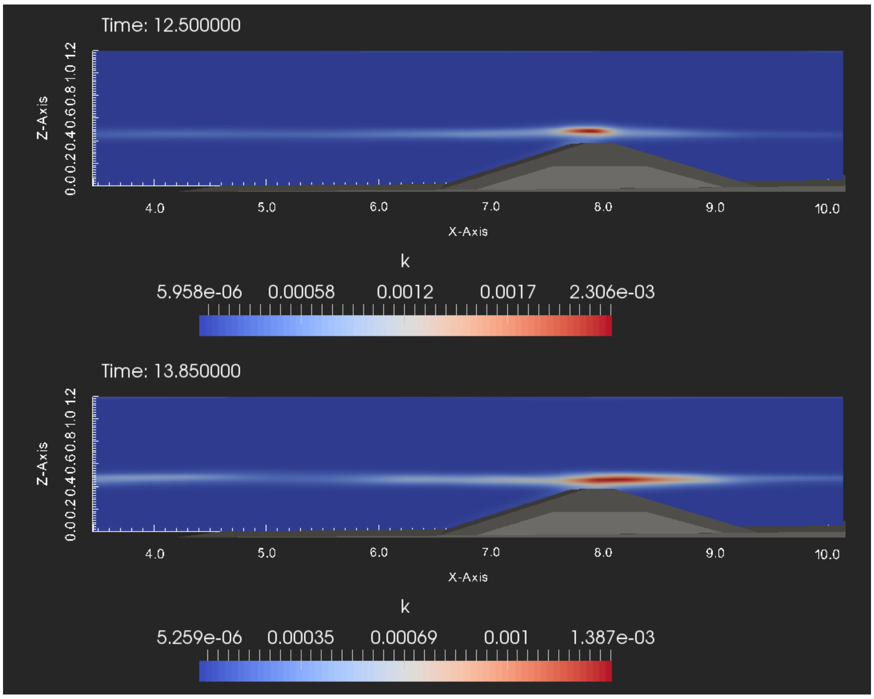


Figure 5.15.: Turbulent kinetic energy k in m^2/s^2 for t = 12.5 s to t = 13.65 s

6. Discussion

The research aimed to explore environmental preferences and design tools for coral development emphasizing both coral habitat restoration and coastal protection services, and to use this knowledge to optimize artificial reef design for a case study in Addu City, Maldives. This chapter provides a discussion on methods, findings, and some limitations of the research. The concluding chapter follows this discussion and presents the main conclusions derived from the research.

6.1. Conceptual model

At the beginning of this research, critical engineering and ecological variables were explored based on an extensive literature research, that are important in the design of an artificial reef with the dual objective of coral habitat restoration and coastal protection. These variables were presented by means of a conceptual model representing a visualization of important and interrelated physical-chemical, biological, and design variables. It is important to recognize that interrelations between variables are complex, as the combined story of coral habitat restoration is interdisciplinary crossing engineering and ecological disciplines. In turn the dynamics and interactions of these systems are very case-specific. Careful consideration of all relevant variables is necessary to address the specific goals and challenges of each unique project or case.

This research focused on studying the interrelation between flow velocity and CO_2 chemistry, as it is a crucial factor affecting coral growth, particularly for the target species *A. Formosa*. The decision to investigate this specific interrelation was based on the findings of literature research, which highlighted the significant impact of water motion variables on coral growth, including their influence on CO_2 chemistry. It is highlighted that defining and quantifying the relationship between flow velocity and CO_2 chemistry through literature research was challenging. The quantification and identification of these relations in future studies and application can be a time-consuming and complex process, requiring careful investigation and analysis.

The development of the conceptual model in this study is based on diverse views encountered during the cross disciplinary literature review in the fields of ecology and engineering. Because of this, to mitigate potential biases, and to also recognize the complexity of interrelations, it is recommended for researchers to actively participate in a collaborative and transparent process, while users should practice thorough assessment and consider contextual factors. Due to limitations in scope and practical considerations, a comprehensive investigation of all physical-chemical, biological, and design variables was not carried out. In Chapter 5, design alternatives were explored based on five identified criteria, which were informed, in part, by the conceptual model. Exploring additional or other variables in-depth could have led to different criteria and design outcomes.

6.2. Numerical model

For the purposes of this research, OpenFOAM was chosen as a tool to replicate the results of physical models. OpenFOAM is a valuable numerical modeling software that offers a diverse selection of solvers to address a wide range of fluid dynamics problems. It supports various meshing techniques and parallel computing. OpenFOAM's user-friendly visualization tool, ParaView, enables the user to intuitively visualize and analyze simulation results generated by OpenFOAM. With ParaView, it was possible to extract flow velocity data from any selected grid cell(s) in an easy manner. Given the substantial amount of data typically produced by OpenFOAM, Paraview's advanced data processing techniques readily provide insights and understanding.

In this study, a the decision was made to adopt a grid of Δx = 0.05 and Δz = 0.02 m as explained in Section 4.2, prioritizing computational efficiency over accuracy. Squared cells, often recommended, did not even capture one significant wave height for average conditions. Implementing both the horizontal and vertical resolutions recommended by JIP for this case study (Δx = 0.05, Δz = 0.002) would have resulted in very long computational times. This fine grid (Figure 6.2) was compared to the coarse grid (Figure 6.1) for t = 13.75 s used in the case study to discuss the consequences of this decision. For a run of 600 time steps, the finer grid resulted in a run time of 78 minutes for 600 time steps. Conversely, the coarser grid, adopting the horizontal resolution suggested by JIP alongside a more flattened vertical resolution reduced the computational time to 9 minutes, which is almost 9 times faster. The same flow velocity range is set in the two plots. It becomes obvious from the plots that detailed accuracy of flow reduced using the coarser grid.

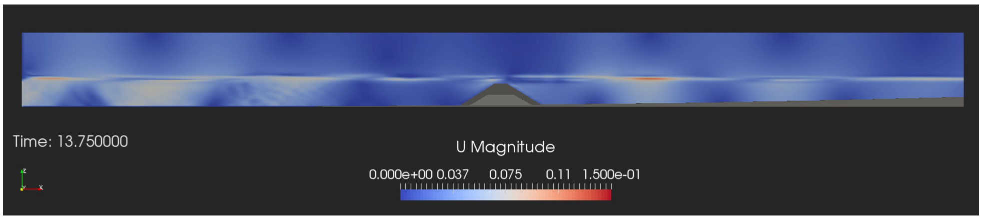


Figure 6.1.: OpenFOAM result for u_{mag} in m/s for t = 13.75 using a coarse grid

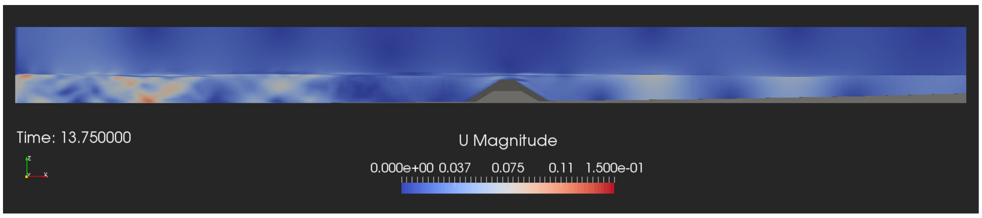


Figure 6.2.: OpenFOAM result for u_{mag} in m/s for t = 13.75 using a fine grid

The primary objective of the numerical model was to obtain initial insights in flow regimes around the structure, and to provide preliminary estimates of wave transmission with and without sea level rise and coral growth scenarios. Unlike coastal engineering applications, this research does not aim to dive into detailed aspects of wave-structure interaction and submerged breakwater stability. Furthermore, the conditions in the lagoon are quite mild, energetic movement or severe wave breaking around or behind the structure is not expected. It is recommended to refine the grid and conduct further studies on grid resolution when more detailed analysis of (flow) fields and/or wave structure interaction is required.

The lack of precise agreement in surface elevation between the physical and OpenFOAM model can be also be attributed to this, and to the random nature of the wave generation method (as explained in Section 4.2) performed in this research. This dissimilarity, in turn, led to differences in significant wave heights. As a result, accuracy errors were observed during the calibration and validation procedures. An alternative approach to this method potentially increasing accuracy would be to utilize another feature in the olaflow toolbox, which incorporates a dynamic (moving) boundary condition to replicate wave paddle makers.

In relation to the preliminary nature of this research and in order to balance computational efficiency and model precision, the duration of calibration, validation, and all runs was limited to 100 seconds. This decision was made to conserve computational time, since OpenFOAM tends to deliver accurate results but requires longer computational times. Furthermore, this allowed for more calibration and application runs to explore alternative scenarios. For the purposes of coral growth potential in relation to flow regimes, an accurate velocity range was captured within this timeframe. However, the limited duration of these runs introduces a level of uncertainty and may account for calibration and validation errors. Particularly for assessing coastal protection, longer simulation runs are preferred as they enable the capturing of more extreme events and yield statistically more accurate results.

With regards to the calibration of the friction coefficients and β, the calibration run C_{β_1} yielded a plausible outcome and was considered acceptable; however, there is again room for improvement in terms of accuracy here. The numerical model for average conditions underestimates K_t with 0.02, and results in a RMSE of 0.00053. The numerical model for design conditions underestimates K_t with 0.04, and results in a RMSE of 0.002. This lack of accuracy in the model may be attributed to several factors, such as inaccuracies in grid resolution, the random nature of wave generation, calibration decisions, or the limited time frames utilized for the assessment. To improve the model's accuracy, it is advisable to employ wave paddle replication as a wave generation method in Olaflow, utilize a finer grid, conduct a comprehensive grid calibration study, and further calibrate resistance parameters.

It is important to acknowledge that OpenFOAM still presents a significant learning curve and is often perceived as non-user-friendly, with the exception of its Paraview feature. It lacks a graphical user interface (GUI) for all boundary conditions and input data for example. Attaining proficiency in comprehending the underlying physics, numerical methods, and software usage demands both time and effort. Less computationally demanding numerical modeling methods, such as SWASH, could have been applied in this research to obtain similar outcomes for flow velocities around the reef. It could be argued that it is not the most efficient method for the application in this research. In other case studies involving more energetic areas and involved wave breaking and wave-structure interaction, OpenFOAM is more accurate in solving turbulence and flow regimes that are crucial for assessing coral growth potential. This is because OpenFOAM solves the entire VARANS equations, allowing for precise results on flow regimes and their relation to coral growth. Simultaneously, it enables the assessment of coastal protection services.

Additionally, OpenFOAM's advantage over other numerical modelling software within the broader context of this research functioning on its role as a design tool, is its ability to manipulate **all** the design variables provided by the conceptual model. This includes the ability to observe and analyze the impact of altering these variables on desired physical, chemical, or biological interdisciplinary interrelations, even in 3D if desired. OpenFOAM's flexibility in accommodating diverse geometries, including complex 3D designs, enhances its applicability, particularly in representing intricate structures like corals and simulating water motion regimes around them. This capability opens up opportunities for conducting more detailed modeling and analysis in scenarios involving coral growth, allowing for a deeper exploration of interrelations.

6.3. Case study

In the context of exploring design alternatives, it was previously emphasized that considering all variables from the conceptual model, as outlined in Figure 3.4, is crucial for a comprehensive assessment. However, in the scope of this study, not all variables were fully assessed and considered. Critical aspects that were not accounted for and highlighted here were topographic complexity, substrate type or base material, curcial variables in the design targeted for coral habitat restoration as explained in Section 3.3. The substrate type plays a vital role as it directly influences coral settlement and growth. Neglecting to consider the suitable substrate type may have implications for the success and sustainability of coral colonization on the designed structures.

During the exploration of design alternatives to enhance water motion around the structure, the decision was made to solely focus on *A. Formosa* as the target species. The study area is known to host a diverse range of coral species that have the potential to thrive on the breakwater. By expanding the scope to include additional target species, a wider range of design alternatives could be explored, leading to a more comprehensive assessment of the potential ecological benefits and impacts.

The findings of Hossain [2013] demonstrate that higher flow velocities have a positive effect on the growth and thriving of *A. Formosa*. This understanding formed the basis for comparing the performance of flow regimes that favor *A. Formosa* for each structure configuration, allowing for the evaluation of each design's growth performance relative to the others in the MCA performed in section Section 5.2.3. The parameter g, used to express coral growth, is defined by Hossain [2013] and furhter analyzed in this thesis as inorganic carbon metabolism in μmol/kg/hr and solely depends on flow velocity. It is important to note that this parameter alone does not encompass all aspects of coral growth. Relating the parameter to a growth rate in cm/month is difficult as it is dependent on many other variables such as light intensity and nutrient availability. Additional growth indicators, such as skeletal accretion or colony size increase, should be considered to obtain a comprehensive understanding of *A. Formosa*'s growth. Furthermore, extending a trendline beyond the range of observed data through extrapolation and linearity of the trendline introduce uncertainty.

The estimation of growth rates for *A. Formosa* and the projection of sea level rise scenarios utilized in this study are subject to certain uncertainties. It is important to acknowledge that the growth rates assumed for *A. Formosa* were based on rough estimates and may not accurately reflect the actual growth patterns of this species. Furthermore, the assumption that *A. Formosa* would grow 49 cm over a period of 7 years represents a crude estimate and does not account for potential variations in growth rates due to environmental factors or other ecological dynamics. Also, the layer of corals was represented by a layer of small rocks with high porosity for illustrative purposes. However, for more detailed modeling of a coral layer on top of artificial reefs, it is recommended to add more complex geometries of corals. Furthermore, sea level rise scenarios are are subject to uncertainty, as is widely acknowledged. The analysis solely served to illustrate the potential (longer term) benefits of incorporating coral habitat restoration in coastal protection strategies in terms wave transmission reduction.

While the comparative approach used in the MCA is considered as reasonable given the preliminary stage of the research, there is room for improvement by incorporating more advanced quantitative techniques and adopting a more systematic and transparent approach. This would strengthen the evaluation process, increase the reliability of the results, and facilitate more informed decision-making regarding the selection of the design configurations.

For the selected design, the numerical model estimated that the structure reduces wave energy by 3% resulting in a reduction of longshore transport by 21% based on a simple general equation for longshore transport of sand, gravel and shingle [Van Rijn, 2014] where longshore transport rates are proportional to wave heights to the power 3.1 ($Q_{t,mass} \propto H^{3.1}$). The longshore transport rate is dependent on other factors as well, such as the wave angle of incidence and properties of the sand, that are not taken into consideration here, and results are estimates for preliminary assessments. It is difficult to draw conclusions regarding the effectiveness of this erosion reduction estimate for the case study due to the absence of criteria specifying the required wave transmission coefficient thresholds for the structure in terms of sufficient coastal protection delivery. Yet, it is argued that a this amount of reduction is quite substantial for the case study. For a calm lagoon setting, the sediment transport rates are generally lower compared to more energetic coastal environments. Therefore, even a modest reduction in the longshore transport rate can have a significant impact on sediment deposition and erosion patterns within the lagoon.

6.3.1. Building with nature

Building with nature approaches, such as incorporating coral growth potential into the design as was done in this research, present both challenges and opportunities in comparison to traditional solutions. On one hand, integrating coral habitat restoration and considering coral growth potential may introduce additional costs and require ongoing monitoring and maintenance efforts. The establishment and maintenance of coral colonies can be a complex and resource-intensive process. Moreover, the long-term success of coral habitat restoration efforts necessitates continued monitoring and management to ensure the sustained growth and survival of the coral colonies. Also, the overall design process of the structure, including incorporating coral growth potential with for example conceptual and numerical modelling tools as was done in this research, may require higher energy inputs and resource expenditures compared to traditional approaches. Despite these challenges, embracing nature-based solutions offers significant environmental, socio-economic benefits, and longer term coastal protection benefits, also with regards to sea level rise. By incorporating coral growth potential, artificial reef structures have the potential to enhance biodiversity, promote ecological resilience, and provide habitats for various marine organisms beyond corals.

7. Conclusions and recommendations

In this concluding chapter, the research questions are answered and the research objective is met. First, the research questions are addressed, leading to the accomplishment of the research objective, which is then elaborated upon. The research objective is repeated here:

To explore environmental preferences and design tools for coral development emphasizing both coral habitat potential and coastal protection services, and to use this knowledge to optimize artificial reef design for a case study in Addu City, Maldives.

7.1. Conclusions

> **RQ1:** What are the critical engineering and ecological variables important in the design of an artificial reef, in terms of a conceptual model that can be used as a dual-purpose design tool for coral development?

A conceptual model that can be used as a dual-purpose design tool and represents the critical engineering and ecological variables important in artificial reef design is presented in Figure 7.1. The conceptual model encompasses physical-chemical, biological variables, and design variables.

The set of physical-chemical variables consists of light penetration, water quality, and water motion variables, and are **necessary** factors for coral habitat potential. Light penetration is crucial for the growth and survival of corals as it enables photosynthesis necessary for their growth, health, and maintenance of symbiotic relationships with zooxanthellae. Coral species thrive in areas where water quality variables meet their preferred conditions. Water motion, generated by hydrodynamic energy, performs a multitude of functions for coral reefs, including the delivery of nutrients, provision of oxygenated water, removal of sediment from the water column, enhancement of coral tissue respiration rates, and improved elimination of waste products like carbon dioxide. Also, it is an important group of variables for coastal protection or engineering purposes, as hydrodynamic energy affects the stability of structures, and coastal defenses are constructed to dissipate wave energy and manage sediment transport rates. Biological variables should be taken into consideration for initial assessment of coral habitat potential in case studies.

The design variables are suggested and categorized into substrate and structure variables. Substrate variables are primarily important for facilitating coral attachment. Modifying structure variables, affects coastal protection services via wave-structure interaction, wave energy alterations, and shoreline response. Additionally, these modifications also influence physical-chemical and biological variables, important for creating potential coral habitats. By adjusting design variables, it is possible to explore potential integral solutions.

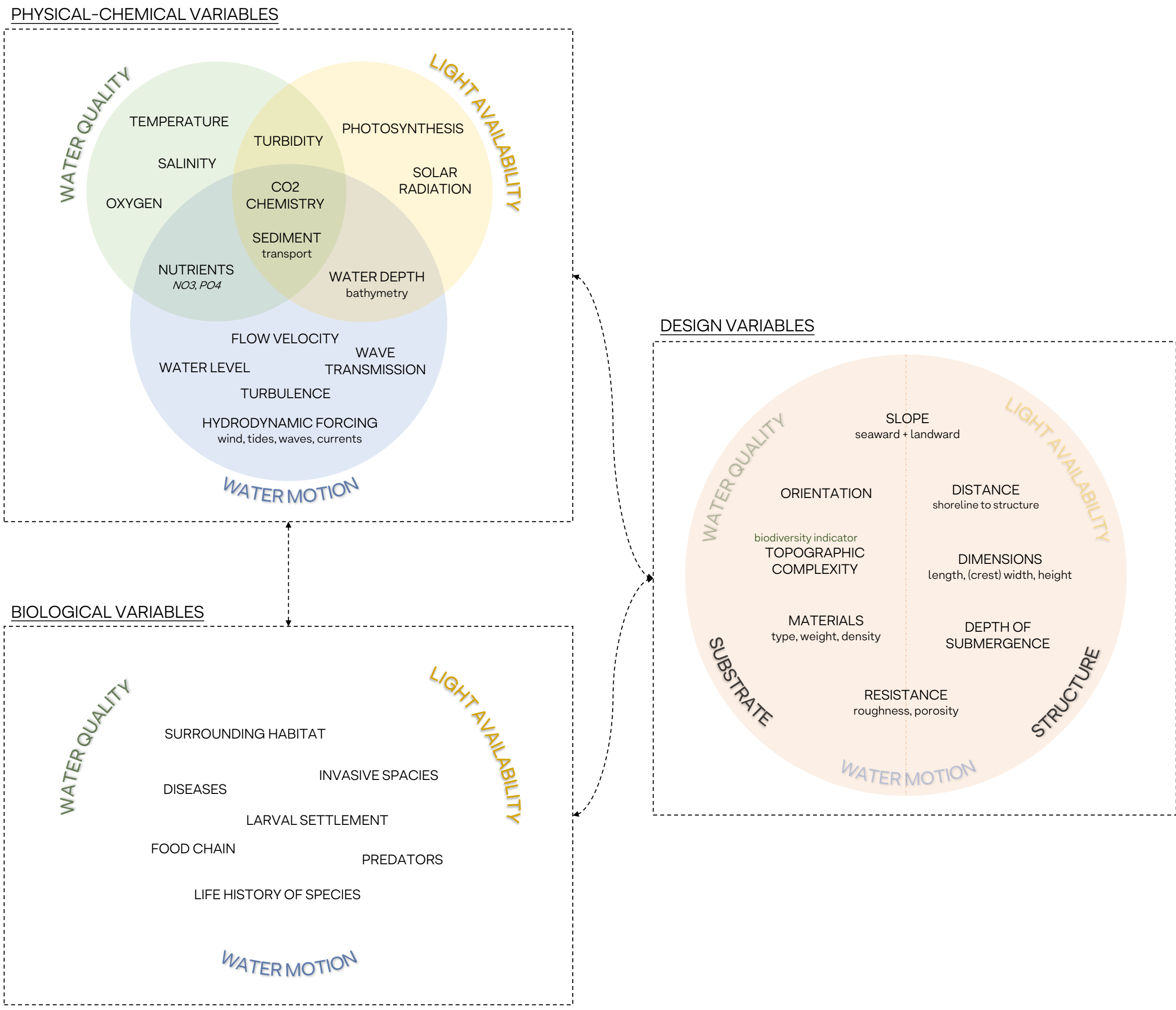


Figure 7.1.: A conceptual model that can be used as a tool for analysis and design of an artificial reef delivering both coral habitat potential and coastal protection services.

The conceptual model provides a valuable starting point for initial assessments in artificial reef design and serves as a broad guide rather than a prescriptive blueprint. It visually represents the core elements of physical-chemical, biological, and design variables and serves as a design tool for practical applications, fulfilling three primary purposes:

1. Identifying physical-chemical and biological variables that require further examination and analysis to explore coral habitat potential of a design.
2. Identifying physical variables that require further examination and analysis to explore coastal protection services provided by a design.
3. Identifying design variables influencing physical-chemical and biological variables that can be modified within a design to explore potential integral solutions.

It is highlighted that the combined story of coral habitat potential and coastal protection is interdisciplinary, and highly site- or case-specific, resulting in a complex interplay between all variables. The physical-chemical variables are visible in the boxes displaying biological and design variables, illustrating this interplay. There is no single optimal design or one-size-fits all solution that can be applied universally and for every case. Many researchers expressed diverse perspectives, and the absence of definitive design rules further emphasizes the complexity of the subject.

In terms of the model's practicability, various methods are commonly used to conduct deeper and in detail analyses of variables. These methods mainly include desk research, in-situ measurements, laboratory works, analytical techniques, empirical design guidelines, physical modeling, and numerical (hydrodynamic) modeling, ranging from extensive and time-consuming approaches to quicker methods suitable for initial assessments. When a new case study or project starts, each with its own distinct timeframe and scope, decisions must be made regarding practicality and objectives that align with the specific context and purpose of the project. The conceptual model developed in this research serves as a fundamental framework for guiding decision-making processes, and can be interpreted, customized and applied to any unique situation or new case study.

> **RQ2:** Is it possible to use an OpenFOAM numerical model as a dual-purpose design tool for coral development?

It is demonstrated in this research that an OpenFOAM numerical model can effectively be used as a dual-purpose design tool for coral development. Currently, OpenFOAM has gained popularity, has shown promise, and primarily finds application as a coastal engineering tool within the field of hydraulic engineering. This study aimed to explore the potential of OpenFOAM as a dual-purpose tool for broader applications. Specifically, the objective was to explore how OpenFOAM can be used as a design tool to address both coastal protection and coral habitat potential services in the context of artificial reef design.

To be able to explore OpenFOAM's potential as a dual-purpose design tool, an OpenFOAM numerical model using the olaFlow [Higuera, 2018] package was set-up, calibrated, and validated for the case study using data from physical model tests carried out by DHI Group. Users have the option to select their preferred wave theories, including regular or irregular waves, or even use wave paddle data to simulate waves in the domain. The model provided accurate modeling of two-phase flow through porous media, using state-of-the-art active wave generation and absorption techniques working at the boundaries (i.e. without increasing the computational cost). The numerical model for average conditions underestimates the wave transmission coefficient K_t by 0.02 and yields an average RMSE of 0.00053 m for average significant wave heights H_s across 10 wave gauges. The numerical model for design conditions underestimates K_t by 0.04 and produces a RMSE of 0.002 m for average H_s across 10 wave gauges. These errors were chosen acceptable for the purposes of this research, where only preliminary assessments and initial design decisions were made. For the case study, the numerical model presented a relatively calm wave climate appearing wave climate, characterized by longer wave periods and the absence of severe wave breaking.

OpenFOAM has the capability to analyze various hydrodynamic variables effectively for both coastal protection and coral habitat restoration purposes. These variables include flow fields, wave heights, turbulence, pressures, within the desired spatial and temporal scales. It is possible to retrieve surface elevation data at desired locations in the domain for the analysis of wave heights. In this research the model has successfully provided insights into wave parameters and wave transmission results that can be utilized in the analysis of coastal protection measures. Also, the tool allows for an assessment of long-term performance of design alternatives and it's advantages over conventional design. This capability was demonstrated in this thesis through examining sea level rise and potential coral growth scenarios. Additionally, OpenFOAM is able to accurately model turbulence regimes, important in areas with energetic wave conditions where extensive wave breaking occurs around the structure, as it plays a crucial role in wave-structure interaction. Furthermore, OpenFOAM offers potential for sediment transport modeling, further enhancing its capabilities for comprehensive coastal engineering analyses.

With regards to coral habitat potential, in this research OpenFOAM has proved to be a valuable tool for assessment of flow and turbulence regimes around artificial reefs. It was evident from the conceptual model that these are important aspects to consider for coral habitat potential, which was also highlighted by many authors that stress the importance of water motion or flow regimes to the ecological and biological functioning of coral reefs [Jokiel, 1978; Dennison and Barnes, 1988; Foley, 2015; Davis et al., 2021; van Gent et al., 2023].

For the case study of this research in Addu City, the wave climate was relatively calm. Yet, for other scenarios with more energetic areas larger differences in flow and turbulence regimes around artificial reefs and different transects can be expected and OpenFOAM proved to be a valuable tool to simulate and assess these phenomena in ecological design. Insights gained from assessing the entire flow regime around a structure aided in the decision-making process for an integral solution of the case study.

Although not all of the design variables from the conceptual model were taken into consideration in this research, OpenFOAM offers the versatility to modify and analyze **all** design variables from the conceptual model, regardless of scale, within the computational domain. This includes the capability to handle complex geometries and perform three-dimensional (3D) simulations, providing possibilities in altering design variables for accurate examinations of desired phenomena. For instance, incorporating detailed 3D coral reef geometries into the domain allows for an assessment of flow and turbulence regimes around them, as well as the implications of their presence on wave energy behind the reef.

In summary, OpenFOAM functions as a flexible and dual-purpose design tool, providing the opportunity to explore design alternatives that specifically target coral habitat potential, at the same time enabling the evaluation of the effectiveness of these designs in functioning as coastal defense structures.

> **RQ3:** Utilizing 1) the conceptual model and the OpenFOAM numerical model as design tools and 2) a Building with Nature design approach, what is a preliminary integral design for the case study?

By applying the first three of the five Building with Nature design steps, as developed by van Eekelen and Bouw [2020], to the case study, three design alternatives were identified and evaluated. These alternatives include a traditional alternative (base case) with a slope of 2:3, a mild slope design alternative with a slope of 1:3, and a steep slope design alternative with a slope of 3:2. The identification and evaluation process involved utilizing the conceptual model and the OpenFOAM numerical model as design tools. Following this, five criteria were used to evaluate each design alternative. Finally, a preliminary integral solution that best balances coral habitat potential and coastal protection was pre-selected for the case study using a multi-criteria analysis (MCA).

In the case study, the conceptual model was utilized to understand the system and analyze important physical-chemical variables and a biological variable variables from the conceptual model necessary for coral growth potential. The case study area of interest offered coral habitat potential, and the species *Acropora Formosa* was chosen as a target species for the design, as they are abundant in the area of interest and fast growing branching coral species.

The OpenFOAM numerical model was used to evaluate the impacts of altering the design variables 'slope' and 'dimensions' for evaluating the potential for coral habitat potential through assessment of 1) the interrelation between flow velocity and inorganic carbon metabolism and 2) the turbulence regime for the selected integral solution, and for coastal protection assessing the (long-term) wave transmission levels of various design alternatives in light of climate change. Using the MCA, the decision was made to pre-select the mild slope structure with a 1:3 slope as an integral solution for the case study as it proved to be most effective as a dual purpose artificial reef design. It demonstrated enhanced coral habitat potential and coastal protection values compared to the base case scenario.

An important criterion regarding coral habitat potential considered in the MCA was the preferred flow regime of the target species *A. Formosa*, in terms of a growth rate parameter. This criterion was evaluated by conducting a detailed analysis of the relationship between flow velocity and inorganic carbon metabolism for *A. Formosa*. The linear relation, based on the work of Hossain [2013]:

$$\bar{g} = 0.08 \cdot \bar{u}_x + 7.22 \tag{7.1}$$

where g represents a growth parameter in μmol/kg/hr and $\bar{u}$ represents average flow velocity in cm/s, was defined and employed to assess the growth rate potential using the OpenFOAM numerical model for flow regime analysis around the breakwater structure. The mild slope structure resulted in increased average velocities and thus growth rate around the breakwater, consequently enhancing the growth potential of *A. Formosa*. A range for $\bar{g}$ between = 7.53 - 8.18 μmol/kg/hr around the breakwater was observed. It is expected that growth of corals is beneficial on the seaward side of artificial reefs, and higher up in the water column. Furthermore, the structure offered a well-suited slope for the settlement of A. Formosa and the largest potential habitat area compared to the other designs.

In comparison to the base case under extreme conditions, the numerical model estimated that the structure reduces wave energy by 3% and minimizes longshore transport by 21%, thereby reducing coastal erosion. An analysis of potential sea level rise scenarios and coral habitat growth scenarios was conducted to assess the long-term consequences of a coral-inclusive solution under climate change stress. The findings indicate that already by the year 2030, under extreme conditions and based on the median/likely sea level rise scenario projected by the IPCC [2023], the traditional structure with a slope of 2:3 could experience a 6% increase in wave energy and a 43% increase in longshore transport rate. The 21% decrease in longshore transport caused by the mild slope structure is argued to mitigate this factor and contribute to the prevention of coastal erosion.

The research objective:

To explore environmental preferences and design tools for coral development emphasizing both coral habitat potential and coastal protection services, and to use this knowledge to optimize artificial reef design for a case study in Addu City, Maldives.

Is now met. The conceptual model and OpenFOAM numerical model developed in this chapter have demonstrated their value as design tools for the initial assessment and optimization of artificial reef design in the case study, based on an initial exploration of environmental preferences. In summary:

7.2. Recommendations

The conceptual model as a design tool

For similar aims as this research objective, the conceptual model fulfills three primary purposes:

1. Identifying physical-chemical and biological variables that require further examination and analysis to explore coral habitat potential of a design.
2. Identifying physical variables that require further examination and analysis to explore coastal protection services provided by a design.
3. Identifying design variables influencing physical-chemical and biological variables that can be modified within a design to explore potential integral solutions.

To mitigate potential biases in and to recognize the complexity of interrelations, it is recommended for researchers to actively participate in a collaborative and transparent process, while users should practice thorough assessment and consider contextual factors.

Assessments and analyses can be conducted quickly as was done for the case study in this research regarding for example water quality variables, or in greater detail through field studies, extensive research, and more comprehensive research and analysis of interrelations, as was done in this research for an interrelation between flow velocity and CO_2 chemistry.

The OpenFOAM numerical model as a design tool

By utilizing OpenFOAM as a design tool, it becomes feasible to design coastal protection measures while simultaneously enhancing the potential for coral habitat. The tool allows users to explore different design alternatives that are specifically customized to enhance the growth potential of target coral species, as was demonstrated in this thesis through analysis of flow regimes around artificial reef design alternatives. Simultaneously, the impacts on coastal protection services in terms of changes in wave transmission can be assessed. The insights gained from assessing the entire flow regime around a structure specifically aided in the dual-purpose decision-making process. By utilizing this approach, it becomes possible to proactively design structures that cater to the preferred settlement of certain species while discouraging others.

OpenFOAM allows for accurate modeling of two-phase flow through porous media, using state-of-the-art active wave generation and absorption techniques working at the boundaries (i.e. without increasing the computational cost) in the olaFlow package. The comprehensive assessment of coral growth potential is facilitated by the model's ability to adjust **all** the design variables presented by the conceptual model. This includes the capability to handle complex geometries and perform three-dimensional (3D) simulations, providing possibilities in altering design variables for accurate examinations of desired phenomena. The flexibility of OpenFOAM allows users to assess specific parameters on any desired scale within the domain.

Additionally the main recommendations with regards to ecological design and coral growth potential for any new case study or project, are given here:

- Verify if there are adequate light availability, water quality, and biological variables in the area of interest for target species;
- Assess and analyze the water motion regimes surrounding artificial reefs (as was demonstrated in this research), including flow velocities and turbulence levels. OpenFOAM possesses the capability to accurately simulate these phenomena, including the option to model flow regimes on the scale of the corals themselves, also in 3D if desired.
- Pay close attention substrate variables, specifically topographic complexity, to ensure proper coral attachment.

Recommendations for future research

About detailed (3D) modelling of corals using OpenFOAM:

In this research, the representation of the coral layer was highly simplified, and only preliminary assessments of long-term wave transmission due to the presence of a coral layer were conducted. To gain a more comprehensive understanding of wave dynamics and their impacts on and around artificial reefs, it would be valuable to incorporate more detailed and intricate geometries of corals (in 2D, or even in 3D) into the OpenFOAM model. Specifically, when implementing 3D modeling of coral structures on the artificial reef, it becomes feasible to study hydrodynamic interactions at the scale of individual corals. As highlighted by the conceptual model in this research and by Davis et al. [2021] in their work, understanding the complex physical-chemical-biological feedbacks will become important if we are to effectively manage the climate-driven changes occurring in coastal ecosystems globally. An example of the potential value of studying hydrodynamic impacts at the coral scale pertains to the physical-biological relationship described by Hearn et al. [2001], that defined a relation between nutrient uptake by corals and turbulent dissipation rate.

About modelling on the scale of naturally occuring coral reefs:

Significant ongoing efforts are currently being made to better understand the wave attenuation function of naturally occurring coral reefs and acknowledging the crucial role of restoration in maintaining this function. For instance, Roelvink et al. (2021) conducted research utilizing the numerical modeling tool XBeach to explore wave attenuation in naturally occurring coral reefs. To further advance research in this area and achieve more accurate results, future studies can consider utilizing OpenFOAM as it allows for precise replication of reef geometries, for coastal protection purposes as in the work of Roelvink et al. [2021], but also for coral habitat restoration purposes. The research conducted by Norris et al. [2023] demonstrated the effect of coral reef roughness on turbulence using OpenFOAM, highlighting its implications for reef restoration design. For example in that research, adding wave gauges in the numerical domain would have additionally provided valuable insights in implications on wave transmission by the presence of the reef.

About target species in design:

In the current study, the research focused exclusively on one target species. However, to achieve a more comprehensive understanding of coral habitat potential, it is recommended that future research expands its scope to incorporate multiple target species. By adopting a broader perspective, researchers can promote biodiversity and enhance the overall resilience of the coral ecosystem.

About accuracy of the OpenFOAM model:

It is recommended to explore the replication of wave paddle data from the physical model test within the olaFlow package using the `waveDict` utility. This will ensure precise replication of surface elevation data. Moreover, especially if modelling on the scale of corals is desired, it is advisable to incorporate grid refinements in regions of interest, particularly the surface surrounding the artificial reef. In the preliminary stage of this research, grid refinements were not implemented.

Bibliography

Adams, J. (2006). Water flow is more important for corals than light. part ii: The science of corals and water flow.

Beck, M., Lange, G., Accounting, W., et al. (2016). Managing coasts with natural solutions: Guidelines for measuring and valuing the coastal protection services of mangroves and coral reefs. Technical report, The World Bank.

Belton, V. and Stewart, T. (2002). *Multiple criteria decision analysis: an integrated approach*. Springer Science & Business Media.

Bleck, M. (2006). Wave attenuation by artificial reefs. *PIANC magazine" on course" nr 125*.

Bosboom, J. and Stive, M. J. (2023). *Coastal dynamics*. TU Delft Open, 1.2 edition.

Boström-Einarsson, L., Babcock, R. C., Bayraktarov, E., Ceccarelli, D., Cook, N., Ferse, S. C., Hancock, B., Harrison, P., Hein, M., Shaver, E., et al. (2020). Coral restoration–a systematic review of current methods, successes, failures and future directions. *PloS one*, 15(1):e0226631.

Bouwmeester, J., Daly, J., Zuchowicz, N., Lager, C., Henley, E. M., Quinn, M., and Hagedorn, M. (2023). Solar radiation, temperature and the reproductive biology of the coral lobactis scutaria in a changing climate. *Scientific Reports*, 13(1):246.

Brathwaite, A., Clua, E., Roach, R., and Pascal, N. (2022). Coral reef restoration for coastal protection: Crafting technical and financial solutions. *Journal of Environmental Management*, 310:114718.

Brathwaite, A., Pascal, N., and Clua, E. (2021). When are payment for ecosystems services suitable for coral reef derived coastal protection?: A review of scientific requirements. *Ecosystem Services*, 49:101261.

Burcharth, H. and Andersen, O. (1995). On the one-dimensional steady and unsteady porous flow equations. *Coastal engineering*, 24(3-4):233–257.

Burke, L. and Spalding, M. (2022). Shoreline protection by the world's coral reefs: Mapping the benefits to people, assets, and infrastructure. *Marine Policy*, 146:105311.

Burt, J. A. and Bartholomew, A. (2019). Towards more sustainable coastal development in the arabian gulf: Opportunities for ecological engineering in an urbanized seascape. *Marine pollution bulletin*, 142:93–102.

Burt, J. A., Bartholomew, A., and Feary, D. A. (2012). Man-made structures as artificial reefs in the gulf. In *Coral Reefs of the Gulf*, pages 171–186. Springer.

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

Coles, S. L. and Jokiel, P. L. (1992). *Effects of Salinity on Coral Reefs*. CRC Press, 1st edition.

Cornwall, C. E., Comeau, S., Kornder, N. A., Perry, C. T., van Hooidonk, R., DeCarlo, T. M., Pratchett, M. S., Anderson, K. D., Browne, N., Carpenter, R., et al. (2021). Global declines in coral reef calcium carbonate production under ocean acidification and warming. *Proceedings of the National Academy of Sciences*, 118(21):e2015265118.

d'Angremond, K., Van Der Meer, J. W., and De Jong, R. J. (1996). Wave transmission at low-crested structures. In *Coastal Engineering 1996*, pages 2418–2427.

Davis, K. A., Pawlak, G., and Monismith, S. G. (2021). Turbulence and coral reefs. *Annual review of marine science*, 13:343–373.

De Vriend, H. J., van Koningsveld, M., Aarninkhof, S. G., de Vries, M. B., and Baptist, M. J. (2015). Sustainable hydraulic engineering through building with nature. *Journal of Hydro-environment research*, 9(2):159–171.

del Jesus, M. (2011). Three-dimensional interaction of water waves with maritime structures. *University of Cantabria (Ph. D. thesis)*.

Deltares (2023). White paper - Climate-positive marine developments. Technical report.

Dennison, W. C. and Barnes, D. J. (1988). Effect of water motion on coral photosynthesis and calcification. *Journal of Experimental Marine Biology and Ecology*, 115(1):67–77.

EcoShape (2023). Building with nature. https://www.ecoshape.org/en/what-we-do/building-with-nature/.

EIA (2022). Environmental impact assessment report for the proposed reclamation project at addu city, maldives. Technical report, Maldives Ministry of National Planning, Housing, and Infrastructure.

Engelund, F. (1953). *On the laminar and turbulent flows of ground water through homogeneous sand*. Akad. for de Tekniske Videnskaber.

EurOtop, I. (2018). Manual on wave overtopping of sea defences and related structures: An overtopping manual largely based on european research, but for worldwide application. *Eur. Overtopping Man.*

Fabi, G., Scarcella, G., Spagnolo, A., Bortone, S. A., Charbonnel, E., Goutayer, J. J., Haddad, N., Lök, A., and Trommelen, M. (2015). Practical guidelines for the use of artificial reefs in the mediterranean and the black sea. *General Fisheries Commission for the Mediterranean. Studies and Reviews*, (96):I.

Fabian, R., Beck, M., and Potts, D. (2013). Reef restoration for coastal defense: a review. *Santa Cruz, CA: University of California, Santa Cruz.*

Fellowes, T. E., Anggadi, F., Byrne, M., Vila-Concejo, A., Bruce, E., and Baker, E. (2022). Stability of coral reef islands and associated legal maritime zones in a changing ocean. *Environmental Research Letters*.

Ferrario, F., Beck, M. W., Storlazzi, C. D., Micheli, F., Shepard, C. C., and Airoldi, L. (2014). The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. *Nature communications*, 5(1):1–9.

Foley, M. J. (2015). *Submerged breakwater modeling and coral reef ecological analyses for harbor protection*. University of Hawai'i at Manoa.

Forchheimer, P. (1901). Wasserbewegung durch boden. *Zeitschrift des Vereines Deutscher Ingenieure*, 45(50):1781–1788.

Goda, Y. (1988). *Random seas and design of maritime structures*. World Scientific.

Hassanpour, N., Vicinanza, D., and Contestabile, P. (2023). Determining wave transmission over rubble-mound breakwaters: Assessment of existing formulae through benchmark testing. *Water*, 15(6):1111.

Hata, H., Kudo, S., Muramoto, A., Nozaki, K., Kato, K., Negishi, A., Saito, H., Yamano, H., Watanabe, A., and Kayanne, H. (2004). The application of ph and pco2 monitoring to estimating the rates of coral reef community metabolism. *Journal of the Japanese Coral Reef Society*, 2004(6):21–42.

Haywood, M. (2007). *Improved knowledge of Torres Strait seabed biota and reef habitats/authors, MDE Haywood [et al.].* Citeseer.

Hearn, C., Atkinson, M., and Falter, J. (2001). A physical derivation of nutrient-uptake rates in coral reefs: effects of roughness and waves. *Coral Reefs*, 20:347–356.

Hearn, C. J. (2011). Perspectives in coral reef hydrodynamics. *Coral Reefs*, 30(Suppl 1):1.

Higuera, P. (2015). Application of computational fluid dynamics to wave action on structures. *PhD. Universidade de Cantabria*.

Higuera, P. (2018). phicau/olaflow: Cfd for waves.

Hirt, C. and Nichols, B. (1981). Volume of fluid (vof) method for the dynamics of free boundaries. *Journal of Computational Physics*, 39(1):201 – 225.

Hossain, A. (2013). *Effect of Light and Water flow on growth of the hard Coral Acropora formosa*. PhD thesis, Graduate School of Frontier Sciences, The University of Tokyo.

Huang, Z., Brooke, B. P., and Harris, P. T. (2011). A new approach to mapping marine benthic habitats using physical environmental data. *Continental Shelf Research*, 31(2):S4–S16.

Huang, Z.-C. (2015). Vertical structure of turbulence within a depression surrounded by coral reef colonies. *Coral Reefs*, 34(3):849–862.

IPCC (2023). Ipcc, 2023: Summary for policymakers. *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*.

IPCC (2023). Sea Level Projection Tool.

Irías Mata, M. (2021). Numerical estimation of wave loads on crest walls on top of rubble mound breakwaters using openfoam.

Iwasaki, S., Suzuki, A., Iguchi, A., Sasaki, O., Kano, H., Ohno, Y., and Enomoto, K. (2018). Effect of seawater turbulence on formation of coral primary polyp skeletons. *Coral Reefs*, 37:939–944.

Jackson-Bue, T., Williams, G. J., Whitton, T. A., Roberts, M. J., Brown, A. G., Amir, H., King, J., Powell, B., Rowlands, S. J., Jones, G. L., et al. (2022). Seabed morphology and bed shear stress predict temperate reef habitats in a high energy marine region. *Estuarine, Coastal and Shelf Science*, 274:107934.

Jacobsen, N. G., Fuhrman, D. R., and Fredsøe, J. (2012). A wave generation toolbox for the open-source cfd library: Openfoam®. *International Journal for numerical methods in fluids*, 70(9):1073–1088.

Jacobsen, N. G., van Gent, M. R., and Wolters, G. (2015). Numerical analysis of the interaction of irregular waves with two dimensional permeable coastal structures. *Coastal Engineering*, 102:13–29.

Jayanthi, M., Patterson Edward, J., Malleshappa, H., Gladwin Gnana Asir, N., Mathews, G., Diraviya Raj, K., Bilgi, D. S., Ashok Kumar, T., and Sannasiraj, S. (2020). Perforated trapezoidal artificial reefs can augment the benefits of restoration of an island and its marine ecosystem. *Restoration Ecology*, 28(1):233–243.

Jokiel, P. L. (1978). Effects of water motion on reef corals. *Journal of Experimental Marine Biology and Ecology*, 35(1):87–97.

Jokiel, P. L. (2008). Biology and ecological functioning of coral reefs in the main hawaiian islands. *Coral Reefs of the USA*, pages 489–517.

Jonker, R. (2020). Homogeneous detached composite breakwater: Cfd study of the design sensitivities in the 2d geometrical layout using a detached homogeneous low-crested structure to reduce sea wall overtopping.

Jordan, P. and Fröhle, P. (2022). Bridging the gap between coastal engineering and nature conservation? a review of coastal ecosystems as nature-based solutions for coastal protection. *Journal of Coastal Conservation*, 26(2):4.

Khasanah, R., Herawati, E., Hariati, A., Mahmudi, M., Sartimbul, A., Wiadnya, D., Asrial, E., Nabil, E., et al. (2020). Growth rate and survivorship of acropora sp. fragments that transplanted on the artificial substrate made from fly ash and bottom ash. In *IOP Conference Series: Earth and Environmental Science*, volume 441, page 012126. IOP Publishing.

Kim, T., Kwon, Y., Hong, S., Kim, J., Kwon, S., and Lee, J. (2021). Wave attenuation analysis for artificial coral reefs using a physical modelling approach. *Journal of Coastal Research*, 114(SI):529–533.

Koch, E. W., Barbier, E. B., Silliman, B. R., Reed, D. J., Perillo, G. M., Hacker, S. D., Granek, E. F., Primavera, J. H., Muthiga, N., Polasky, S., et al. (2009). Non-linearity in ecosystem services: temporal and spatial variability in coastal protection. *Frontiers in Ecology and the Environment*, 7(1):29–37.

Kuffner, I. B. (2002). Effects of ultraviolet radiation and water motion on the reef coral, porites compressa dana: a transplantation experiment. *Journal of Experimental Marine Biology and Ecology*, 270(2):147–169.

Kurdistani, S. M., Tomasicchio, G. R., Felice, D., Francone, A., et al. (2022). Formula for wave transmission at submerged homogeneous porous breakwaters. *Ocean Engineering*, 266:113053.

Lima, J. S., Zalmon, I. R., and Love, M. (2019). Overview and trends of ecological and socioeconomic research on artificial reefs. *Marine environmental research*, 145:81–96.

Losada, I. J., Lara, J. L., and del Jesus, M. (2016). Modeling the interaction of water waves with porous coastal structures. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 142(6):03116003.

Lowe, R. J., Falter, J. L., Bandet, M. D., Pawlak, G., Atkinson, M. J., Monismith, S. G., and Koseff, J. R. (2005). Spectral wave dissipation over a barrier reef. *Journal of Geophysical Research: Oceans*, 110(C4).

Lowe, R. J., Falter, J. L., Koseff, J. R., Monismith, S. G., and Atkinson, M. J. (2007). Spectral wave flow attenuation within submerged canopies: Implications for wave energy dissipation. *Journal of Geophysical Research: Oceans*, 112(C5).

MA, M. E. S. (2005). *Ecosystems and human well-being: wetlands and water*. World Resources Institute.

Margheritini, L., Møldrup, P., Jensen, R. L., Frandsen, K. M., Antonov, Y. I., Kawamoto, K., de Jonge, L. W., Vaccarella, R., Bjørgård, T. L., and Simonsen, M. E. (2021). Innovative material can mimic coral and boulder reefs properties. *Frontiers in Marine Science*, page 750.

Martin, D., Bertasi, F., Colangelo, M. A., de Vries, M., Frost, M., Hawkins, S. J., Macpherson, E., Moschella, P. S., Satta, M. P., Thompson, R. C., et al. (2005). Ecological impact of coastal defence structures on sediment and mobile fauna: evaluating and forecasting consequences of unavoidable modifications of native habitats. *Coastal engineering*, 52(10-11):1027–1051.

Nakamura, T. (2010). Importance of water-flow on the physiological responses of reef-building corals. *Galaxea, Journal of Coral Reef Studies*, 12(1):1–14.

Norris, B. K., Storlazzi, C. D., Pomeroy, A. W., Rosenberger, K. J., Logan, J. B., and Cheriton, O. M. (2023). Combining field observations and high-resolution numerical modeling to demonstrate the effect of coral reef roughness on turbulence and its implications for reef restoration design. *Coastal Engineering*, 184:104331.

Phicau (2016). OlaFOAM Referance Manual. `https://github.com/phicau/olaFlow/tree/master/reference`.

Phicau (2021). olaFlow breakwater tutorial. `https://github.com/phicau/olaFlow/tree/master/tutorials/breakwater`.

Phicau (2023). Phicau/olaFlow. `https://github.com/phicau/olaFlow`.

PIANC (2010). Overview of pianc report 108-dredging and port construction around coral reefs. In *Coasts and Ports 2011: Diverse and Developing: Proceedings of the 20th Australasian Coastal and Ocean Engineering Conference and the 13th Australasian Port and Harbour Conference*, page 370. Engineers Australia.

Pomeroy, A. W., Lowe, R. J., Ghisalberti, M., Storlazzi, C., Symonds, G., and Roelvink, D. (2017). Sediment transport in the presence of large reef bottom roughness. *Journal of Geophysical Research: Oceans*, 122(2):1347–1368.

Ranasinghe, R., Larson, M., and Savioli, J. (2010). Shoreline response to a single shore-parallel submerged breakwater. *Coastal Engineering*, 57(11-12):1006–1017.

Ranasinghe, R. and Turner, I. L. (2006). Shoreline response to submerged structures: A review. *Coastal Engineering*, 53(1):65–79.

Reguero, B. G., Beck, M. W., Agostini, V. N., Kramer, P., and Hancock, B. (2018). Coral reefs for coastal protection: A new methodological approach and engineering case study in grenada. *Journal of environmental management*, 210:146–161.

Roche, R., Abel, R., Johnson, K., and Perry, C. (2010). Spatial variation in porosity and skeletal element characteristics in apical tips of the branching coral acropora pulchra (brook 1891). *Coral reefs*, 30:195–201.

Roelvink, F. E., Storlazzi, C. D., Van Dongeren, A. R., and Pearson, S. G. (2021). Coral reef restorations can be optimized to reduce coastal flooding hazards. *Frontiers in Marine Science*, 8:653945.

Roenby, J., Larsen, B. E., Bredmose, H., and Jasak, H. (2017). A new volume-of-fluid method in openfoam. In *MARINE VI: Proceedings of the VI International Conference on Computational Methods in Marine Engineering*, pages 266–277. CIMNE.

Rusche, H. (2003). *Computational fluid dynamics of dispersed two-phase flows at high phase fractions*. PhD thesis, Imperial College London (University of London).

Saengsupavanich, C., Ariffin, E. H., Yun, L. S., and Pereira, D. A. (2022). Environmental impact of submerged and emerged breakwaters. *Heliyon*, page e12626.

Saleh, F. and Weinstein, M. P. (2016). The role of nature-based infrastructure (nbi) in coastal resiliency planning: A literature review. *Journal of Environmental Management*, 183:1088–1098.

Scheer, G. and Pillai, C. (1976). Report on the stony corals from the maldive archipelago. *Zoologica*, 43(3):1–83.

SeaLifeBase (2023). Acropora formosa. SeaLifeBase.

Shaheed, R., Mohammadian, A., and Kheirkhah Gildeh, H. (2018). A comparison of standard k–ε and realizable k–ε turbulence models in curved and confluent channels. *Environmental Fluid Mechanics*, 19:543–568.

Spalding, M. D., McIvor, A. L., Beck, M. W., Koch, E. W., Möller, I., Reed, D. J., Rubinoff, P., Spencer, T., Tolhurst, T. J., Wamsley, T. V., et al. (2014). Coastal ecosystems: a critical element of risk reduction. *Conservation Letters*, 7(3):293–301.

Srineash, V., Kamath, A., Murali, K., and Bihs, H. (2020). Numerical simulation of wave interaction with submerged porous structures and application for coastal resilience. *Journal of Coastal Research*, 36(4):752–770.

Stender, Y., Foley, M., Rodgers, K., Jokiel, P., and Singh, A. (2021). Evaluating the feasibility and advantage of a multi-purpose submerged breakwater for harbor protection and benthic habitat enhancement at kahului commercial harbor, hawai 'i: case study. *SN Applied Sciences*, 3(2):1–19.

Stocking, J. B., Laforsch, C., Sigl, R., and Reidenbach, M. A. (2018). The role of turbulent hydrodynamics and surface morphology on heat and mass transfer in corals. *Journal of the Royal Society Interface*, 15(149):20180448.

Strain, E. M., Olabarria, C., Mayer-Pinto, M., Cumbo, V., Morris, R. L., Bugnot, A. B., Dafforn, K. A., Heery, E., Firth, L. B., Brooks, P. R., et al. (2018). Eco-engineering urban infrastructure for marine and coastal biodiversity: which interventions have the greatest ecological benefit? *Journal of Applied Ecology*, 55(1):426–441.

Tinto, R. (2015). A practical guide to the construction and management of artificial reefs in northwestern australia.

Turner, B., Devisscher, T., Chabaneix, N., Woroniecki, S., Messier, C., and Seddon, N. (2022). The role of nature-based solutions in supporting social-ecological resilience for climate change adaptation. *Annual Review of Environment and Resources*, 47.

UN (2022). About small island developing states. Assessed 11-October-2022.

UNEP-WCMC, WorldFish Centre, W. and WRI, T. (2021). Global distribution of coral reefs, compiled from multiple sources including the millennium coral reef mapping project. version 4.1, updated by unep-wcmc.

UNESCO (2020). Addu Atoll Biosphere Reserve, Maldives . https://en.unesco.org/biosphere/aspac/addu-atoll.

Van der Meer, J. W., Briganti, R., Zanuttigh, B., and Wang, B. (2005). Wave transmission and reflection at low-crested structures: Design formulae, oblique wave attack and spectral change. *Coastal Engineering*, 52(10-11):915–929.

van Eekelen, E. and Bouw, M. (2020). *Building with Nature: Creating, implementing and upscaling Nature-based Solutions*. nai010 publishers.

Van Gent, M. (1995). Porous flow through rubble-mound material. *Journal of waterway, port, coastal, and ocean engineering*, 121(3):176–181.

van Gent, M. R., Buis, L., van den Bos, J. P., and Wüthrich, D. (2023). Wave transmission at submerged coastal structures and artificial reefs. *Coastal Engineering*, page 104344.

Van Oord (2022). Van Oord Awarded Land Reclamation Project in the Maldives. https://www.vanoord.com/en/updates/van-oord-awarded-land-reclamation-project-maldives/.

Van Rijn, L. C. (2014). A simple general expression for longshore transport of sand, gravel and shingle. *Coastal Engineering*, 90:23–39.

VO (2023). Marine ecology baseline survey report for addu city. Technical report, Van Oord.

Whalan, S., Abdul Wahab, M. A., Sprungala, S., Poole, A. J., and de Nys, R. (2015). Larval settlement: the role of surface topography for sessile coral reef invertebrates. *PloS one*, 10(2):e0117675.

Xin, L. H., Cob, Z. C., Adzis, K. A. A., and Hyde, J. (2016). Growth performance of acropora formosa in natural reefs and coral nurseries for reef restoration. *AACL Bioflux*, 9(5).

Yoris-Nobile, A. I., Slebi-Acevedo, C. J., Lizasoain-Arteaga, E., Indacoechea-Vega, I., Blanco-Fernandez, E., Castro-Fresno, D., Alonso-Estebanez, A., Alonso-Cañon, S., Real-Gutierrez, C., Boukhelf, F., et al. (2023). Artificial reefs built by 3d printing: Systematisation in the design, material selection and fabrication. *Construction and Building Materials*, 362:129766.

A. Growth and environmental preferences of scleractinian corals

Figure A.1 shows allows for quick assessment of growth and environmental tolerances and preferences of scleractinian corals in terms of wave energy, sedimentation, and location preference for different growth forms of corals according to the World Association for Waterborne Transport Infrastructure [PIANC, 2010].

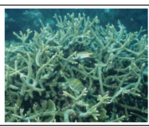
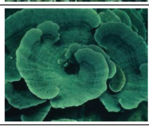
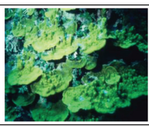
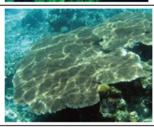
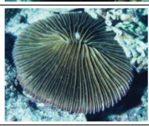
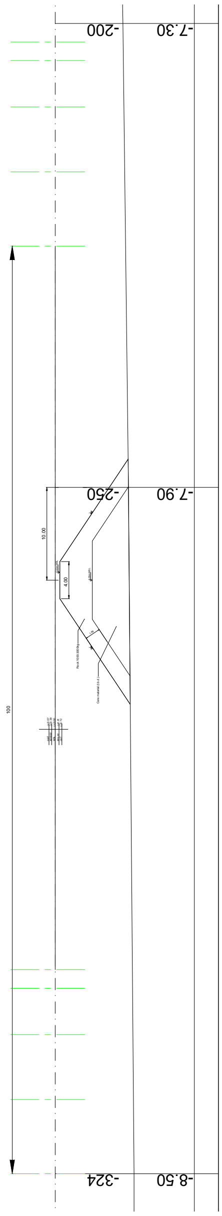
Growth form		Growth rate	Characteristics	Wave Energy Tolerance	Sedimentation Tolerance	Typical location	Examples
Branching		F	Narrow, branching projections. Pioneer species. Fragile skeleton rapidly weathered to rubble after death.	L	H	Reef slopes and lagoons, Shallow turbid reef environments, deeper water soft substrates.	*Anacropora spp* *Acropora formosa* *Porites porites*
Thin, delicate, plate like, foliose, laminar		F	Leaf-like plates. Pioneer species, Highly susceptible to sedimentation. Fragile skeleton rapidly weathered to rubble after death.	L	L	Protected upper reef slope; Shallow turbid environments	*Montipora foliosa* *Montipora florida* *Agricia fragilis*
Globular, bulbous, columnar, digitate		M	Finger-like projections. Relatively robust, become progressively more fragile as length increases with maturity.	M	H	Most reef environments	*Psammocora digitata* *Dendrogyra cylindrus*
Hemispherical, domal irregular, massive and sub-massive		S	Roughly spherical; can reach > 5 m across. Solid, robust, and stable. Resists weathering. High ability to reject sediments.	M H or L	L	Shallow reef environments; Exposed and protected reefs	Brain corals *Favia favus* *Galaexa fascicularis* *Micromussa diminuata* *Diploria strigosa*
Encrusting		M	Broad, low lying. Negligible impact on geological reef structure. Highly susceptible to sedimentation.	I	L	Steeply sloping slopes protected from wave action; Shallow reef environment	*Leptoseris mycetoseroides* *Porites aranetai* *Meandrina meandrites*
Tabular		M-F	Large, robust, laminar formations. Broad table-like canopy with narrow stem and attachment to substrate. Stem susceptible to mechanical damage.	M	L	Shallow reef environments	*Acropora jacquelinae* *Montipora spp*
Solitary			Flat or dome-shaped, circular or elongated with a central mouth.	L	H	Reef slopes and lagoons; Restricted to Indo Pacific	*Fungia spp.*

Figure A.1.: Growth and environmental tolerances of scleractinian corals from PIANC [2010]. Key L = Low; M = Medium; H = High; I = Intense; S = Slow (≈ 0.5 cm/100 years); F = Fast (≈ 10 cm/year)

B. Technical drawing prototype scale

A technical drawing of the submerged breakwater in prototype scale is presented here. The horizontal domain encompasses 124 m.



C. OpenFOAM technical details

The numerical model a boundary condition called `waveAbsorption2DVelocity` is employed at the outlet boundary of the velocity boundary field. This boundary condition enables the absorption of waves by the boundary, effectively preventing them from reflecting back into the computational domain. Moreover, OlaFlow provides a user-friendly interface that enables users to input boundary conditions for wave generation in the velocity and α boundary fields. Different wave theories and either regular or irregular waves be chosen from through the `waveDict` file in the `constant` folder. In this research, random JONSWAP Python simulated irregular waves based on H_s and T_p are fed at the inlet boundary via this file using. For further details on how to use the `waveDict` file, the reader is referred to the reference manual of olaFOAM [Phicau, 2016].

Wave gauges are included in a `sampleDict` file matching the locations of the physical model test. The platform and structure are added within the domain using `stlDefinitions`, where geometries of the platform, and outer and core layers in model scale are applied. Water levels and porosity indexes for the core and outer layer are controlled with `setFieldsDict`. Furthermore, resistance properties of the core and outer layer are controlled in a `porosityDict` file. Here, values of D_{50}, porosity, and friction coefficients α, β, and C from Equation 2.2b, and Equation 2.3 are controlled. The friction coefficients are varied to calibrate the model, as further elaborated on in Section 4.3. To ensure dimensional consistency, the `blockMeshDict` utility is used.

D. Numerical model calibration

Here, calibration runs for the nonlinear parameter β are presented in detail (see Section 2.3.1 and Section 4.3). Significant wave height results for every wave gauge are presented for the physical model test D-92 for average wave conditions, the base case scenario (where $\beta_{outer} = 0.6$, and $\beta_{core} = 1.2$), run $C\beta_0$ (where $\beta_{outer} = 3.5$, and $\beta_{core} = 3$), and run $C\beta_1$ (where $\beta_{outer} = 3$, and $\beta_{core} = 3$).

Table D.1.: Results of calibration runs varying β

(a) Physical model D-92

Gauge	$H_{s,m}$ **[m]**	ΔH_s **[m]**
wg1	0.0317	
wg2	0.0337	
wg3	0.0332	
wg4	0.0313	
wg5	0.0306	
wg6	0.0198	
wg7	0.0204	
wg8	0.0204	
wg9	0.0202	
wg10	0.0204	
$K_t =$	0.61	
RMSE [m]	0	

(b) Base case

Gauge	$H_{s,m}$ **[m]**	ΔH_s **[m]**
wg1	0.0274	0.0044
wg2	0.0279	0.0058
wg3	0.0271	0.0062
wg4	0.0254	0.0060
wg5	0.0247	0.0060
wg6	0.0208	-0.0010
wg7	0.0207	-0.0003
wg8	0.0207	-0.0003
wg9	0.0207	-0.0005
wg10	0.0208	-0.0004
$K_t =$	0.78	
RMSE [m]	0.0033	

(c) $C\beta_0$

Gauge	$H_{s,m}$ **[m]**	ΔH_s **[m]**
wg1	0.0337	0.0020
wg2	0.0357	0.0020
wg3	0.0343	0.0011
wg4	0.0312	0.0002
wg5	0.0298	0.0008
wg6	0.0198	0.0000
wg7	0.0194	0.0010
wg8	0.0193	0.0011
wg9	0.0194	0.0008
wg10	0.0195	0.0009
$K_t =$	0.59	
RMSE [m]	0.0012	

(d) $C\beta_1$

Gauge	$H_{s,m}$ **[m]**	ΔH_s **[m]**
wg1	0.0321	0.0003
wg2	0.0346	0.0009
wg3	0.0333	0.0001
wg4	0.0314	0.0000
wg5	0.0301	0.0006
wg6	0.0199	0.0001
wg7	0.0197	0.0007
wg8	0.0198	0.0006
wg9	0.0198	0.0004
wg10	0.0196	0.0008
$K_t =$	0.61	
RMSE [m]	0.00053	

E. Flow regime analysis method

In a similar manner to the illustration shown in Figure E.1, each alternative configuration of the structure has been divided into six areas of similar size: three seaward (S) transects and three landward (L) transects. Here it is exemplified how data is extract for every transect, using transect S3 as an example.

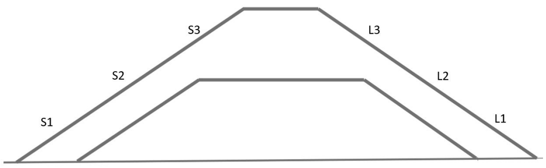


Figure E.1.: Seaward and landward transects of the breakwater

Figure E.2 illustrates a screenshot from ParaView in 3D where data filtering tools are used to extract data for transect S3. Cell size Δz = 0.02 m in model scale corresponds to 0.4 m in prototype scale, which is why 2 cells over the vertical have been selected to make sure that flow around a potential layer of corals is captured (assuming that an average layer of adult *A. Formosa* is approximately 0.5 m [SeaLifeBase, 2023].

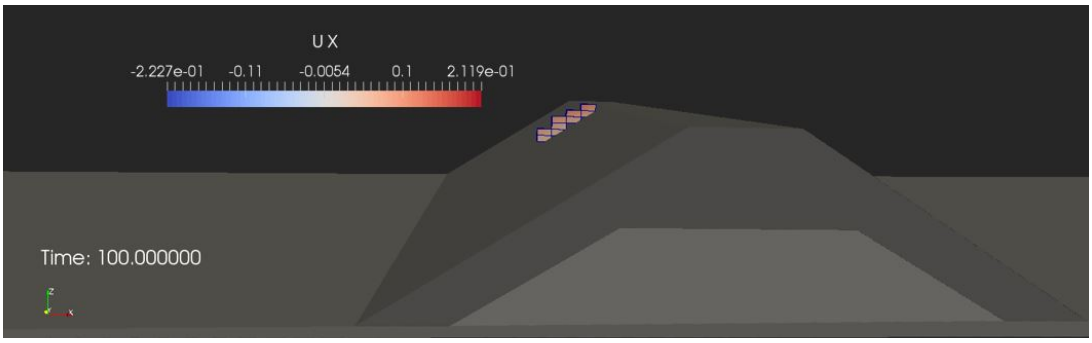


Figure E.2.: ParaView screenshot for transect S3

The highest occuring $u_{x,max}$ over the entire simulation for every transect is determined. The analysis carried out by Hossain [2013], uses the average of the highest and the lowest occurring horizontal flow speeds. Similarly in this application, the average horizontal velocity along each transect, both seaward and landward is calculated and used for the analysis in Section 5.2.3, for every configuration. Results of the average velocities in x-direction $\overline{u}_x$ in cm/s for every transect and every configuration are presented in Table E.1.

Table E.1.: Average velocities in x-direction over seaward and landward transects

Results	**B101**	**G102**	**G103**
Flow velocity $\bar{u}_{x,S1}$ [cm/s]	6.5	5.3	9.4
Flow velocity $\bar{u}_{x,S2}$ [cm/s]	8.4	9.7	10
Flow velocity $\bar{u}_{x,S3}$ [cm/s]	11	12	16
Average $\bar{u}_x$ over transect S [cm/s]	8.8	9.1	11.7
Flow velocity $\bar{u}_{x,L1}$ [cm/s]	5.2	4.0	3.2
Flow velocity $\bar{u}_{x,L2}$ [cm/s]	5.5	6.1	4.9
Flow velocity $\bar{u}_{x,L3}$ [cm/s]	10	9.3	9.7
Average $\bar{u}_x$ over transect L [cm/s]	6.3	6.4	5.9