Effectiveness of a multipurpose artificial underwater structure as a coral reef canopy

Master Thesis
Hydrodynamic and ecological connectivity in a ground consolidator canopy.

by
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SUMMARY

It can be said that a broader consensus exists worldwide amongst researchers, government institutions, industry and the public that the world’s oceans are changing due to natural and anthropogenic influences. These changes require adaptation and new solutions to mitigate the more severe effects which may be felt by these eco-systems. Primarily there is a global loss of bottom roughness in the near-shore environment which acts to stabilize coastlines whilst providing critical marine habitat. One solution to increase bottom roughness traditionally provided by natural reef systems is to introduce artificial underwater structures. The following research focuses on artificial underwater structures (a.k.a. artificial reefs) in a coral reef environment. The research question is stated as: “Establishing a method to determine if a multipurpose artificial underwater structure (MAUS) can perform the functions of a natural canopy cover on a coral reef flat”. The MAUS selected for this investigation is composed of a canopy of 1000’s of interlocking synthetic hooks known as ground consolidators (GCs). This study is unique in that it incorporates many separate fields of science bridging various gaps of established research in order to deliver more complete and comprehensive design recommendations. Additional outcomes from this study include a more thorough oversight of required changes and additions to current interpretation of porous vegetation canopies.

Literature suggests that the relevant parameters required to assess the research question can be found by obtaining the flow characteristics inside the canopy and wave induced hydrodynamic dampening across the canopy. To address these processes, the study primarily focuses on finding the bulk drag coefficient ($C_d$) across the canopy, and wave-driven flow velocities within the canopy. These results are compared with a database of field observation and laboratory results from previous studies. The results will give an indication whether the GCs can provide a suitable climate for the establishment, and long-term vitality, of a benthic community within the pore structure, in addition to providing design guidance for construction of such a MAUS. The steps which can be taken to design a GC MAUS with the results of this study are as follows:

1. Select desired location for canopy where hydrodynamic conditions are known
2. Determine primary purpose of intended canopy (ecological and hydrodynamic functions)
3. Collect information of local aquatic species / vegetation and their needs
4. Compute wave-driven Reynolds number at locations of interest and compute anticipated GC $C_d$ value from the results of this investigation
5. Use $C_d$ value as input for the numerical canopy model tested in this investigation. This model can be iteratively used to determine the desired canopy dimensions based on total wave height reduction which can be accomplished and the desired hydrodynamic climate in the canopy.

6. Wave height reduction and associated orbital velocities computed at the landward side of the canopy can be used as an indication whether larval settling is possible.

7. Local wave-climate can be compared using a similar approach as employed in section 7.3 to determine if the reef is attractive for larval recruitment.

The steps required to complete the proposed research consists of a detailed literature review linking natural reef ecology and associated flow conditions to the conditions found inside a physical model representation of the reef. Due to the physical nature of a fringing reef, the large bathymetrical features could not be re-produced in a scale model. This bathymetry is however, critical in forming the reef-top wave climate. Therefore, an alternative method had to be developed for this study to model the hydrodynamic conditions in the wave-flume. It was decided to model the wave transformations on the fringing reef in a numerical model, from which the desired time-series could be extracted at the location of interest and scaled to the required flume scale. The scaled and transformed wave conditions were then converted to a time series driving the wave paddle. A number of limitations exist, mainly the physical limits of the flume, and the time required to conduct a wider variety of tests. 2 canopy configurations were tested at a scale of 1:5 consisting of 1400 hooks. Data was recorded for 168 tests consisting of almost 119hrs of testing. The 1st canopy was 0.3m high and 1.1m wide and the 2nd canopy is 0.2m high and just over 2m wide.

The method described by Mendez & Losada (2004) was used to parameterize the wave averaged drag coefficient ($\tilde{C}_d$). This thesis takes a novel approach in applying canopy theory developed for mangroves, sea grasses and other conventional natural canopies, to an artificial reef canopy. The wave averaged drag coefficients were plotted for all of the test cases against the wave-driven Reynolds (RE) number recorded just prior to the canopy and also the Keulegan-Carpenter number ($K_c$). These relationships are used to establish a line of best fit through the data. The following relationship were found, and are applicable to both reef configurations:

$$\tilde{C}_d = 5.8 \left( \frac{\text{RE}\left(\frac{H}{h}\right)}{H} \right)^{-0.6} \quad \tilde{C}_d = 31.9(\text{RE})^{-1.4}$$

The ratio $H:h$ (water depth to reef height) was incorporated to account for the canopy geometry. This is an important factor for design and investigation of a GC canopy. The resulting fit provides an $R^2$ value of 0.5 and is valid for a large range of hydrodynamic conditions typically found at fringing reef sites worldwide. The relationship can also be given with the $H:h$ ratio (on the right) and results in a better fit with an $R^2$ value of 0.7.

The in-canopy wave-driven flow was used to calculate the forces on an individual GC element including drag, lift and shear stresses. These were then compared to the tolerable limits of various marine organisms and aquatic plant species. It was found that the internal wave-driven forces on the wave exposed side of the canopy exceeded most of the tolerable
thresholds required to provide a suitable habitat. The shore side of the canopy provided a more suitable environment in the canopy, accommodating all of the considered species.

Finally, a brief case study is used to illustrate coralline larval recruitment. The chosen study site is Kaneohe Bay which has been extensively studied in literature. This area is home to the species *P. Sibogae*. A study from Koehl & Hadfield (2004) is used as the primary reference for this case where flow velocities were measured within the naturally existing canopies. These are then compared to laboratory experiments aimed at finding peak dislodgment shear stresses of the larvae on a variety of substrates. By using this study as a reference it was found that a longer and lower canopy provides enough wave driven flow-reduction near the shoreline face of the canopy to establish conditions within the tolerance required for *P. Sibogae* larval recruitment.

With regard to wave damping across the structure it was found that:

- A best fit relationship could be established for a GC parameterized bulk $C_d$ value incorporating additional information such as H:h.
- Canopy arrangement 1 performed better for net wave height reduction with a small H:h, and arrangement 2 performed better with a large H:h
- It was found that with higher water levels (H = 2h-1.5h), the wave height reduction generally fell within 10-30%, whereas with lower water levels (H = 1.25h – 1.0h) the wave height reduction fell within 25-50%. These results were similar for both canopies.
- Initial testing with the vegetation canopy in the computational model XBeach using the GC specific $C_d$ values, allows for numerical modelling of the GC concept.
- A local shoaling effect occurs on top of the canopy.

With regard to Hydrodynamics within the structure it was found that:

- The most important geometrical characteristics of the canopy determining the success of larval adhesion is the length of the canopy on the ocean floor within which the wave-driven flow can dissipate, the H:h and L:H (wave length : water depth) ratio which dictates how much wave energy is transferred to the canopy crest.
- It was found that the wave-driven velocities were lower in canopy 2, which generally fell within the acceptable thresholds for *P. Sibogae* recruitment. It was found that larval recruitment of *P. Sibogae* follows a similar process under similar conditions as with coralline larvae.
- Given some of the high energy-wave climates experienced by the canopy, the overall canopy resistance and/or material strength may become a limitation before the actual in-canopy velocities become too large for the recruitment of marine organisms.

Additional findings include:

- The Shaw & Trowbridge method for turbulence decomposition is applicable outside its suggested range of validity due to the micro-structure of turbulence in the canopy.
- Numerical modeling using a non-hydrostatic individually wave-resolving model can produce wave conditions for flume studies within a 95% confidence limit of the condition generated in XBeach and found on a natural fringing reef.
• A comprehensive database of global hydrodynamic fringing reef characteristics was established.
• GC volume ratio to total canopy volume consistently ranged between 30-34%.
• Mechanical limits of the wave-paddle at the TU Delft hydraulics laboratory were explored and presented.

Ultimately, given the above considerations and limitations, it was found that a GC canopy can perform some of the key functions of a natural canopy, if adapted to the local wave climate and aquatic species. In a reef environment coral recruitment is usually higher on vertical or inclined surfaces as compared to horizontal ones, mainly due to lower sedimentation levels and increased water circulation on the former. These types of surfaces are abundant in a GC structure. Furthermore, the structural complexity of a natural reef (like a GC MAUS) greatly affects the species diversity, density and size distribution of both invertebrates and fish, as a more complex and heterogeneous reef structure offers a greater array of niches.

Recommendations for future work includes but is not limited to:
• Deploying the GC canopy in calmer conditions with the primary purpose of providing a marine habitat and the secondary objective of providing wave dampening properties.
• Conduct a small pilot study focusing on coralline larval adhesion
• Explore alternative methods to parameterize the $C_d$ values across the canopy, such as those used for permeable breakwaters and other porous media. These methods employ a Forcheimer’s friction factor. Such investigations may improve the fitted relationship to the $C_d$ values.
• Measure turbulent structures and flows just above the canopy as this is a critical region dictating successful larval recruitment.
• Future work could consist of closer collaboration with ecologists and marine biologists to measure larval recruitment and adhesion thresholds for a variety of species. It would be beneficial to start this analysis at a global reef scale, narrowing it down to a larval scale using CFD (computational fluid dynamics) modelling in programs such as open FOAM. This allows for analysis at a larval-scale on a GC or coral surface using a high resolution canopy mesh.
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<th>Symbol</th>
<th>Description</th>
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<tr>
<td>αh</td>
<td>Mid-canopy height from bottom</td>
</tr>
<tr>
<td>$C_D$</td>
<td>Averaged drag coefficient</td>
</tr>
<tr>
<td>$U_{(1)}$</td>
<td>Wave induced velocity at position (1)</td>
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<tr>
<td>$\bar{u}$</td>
<td>Wave driven component</td>
</tr>
<tr>
<td>$\bar{u}'$</td>
<td>Turbulent component</td>
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<tr>
<td>$\bar{h}_r$</td>
<td>Maximum wave set-up on reef-top</td>
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<td>$H_{rms}$</td>
<td>Root mean square wave height</td>
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<td>$S_{\bar{u}\tilde{w}(f)}$</td>
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<td>Nyquist sampling frequency</td>
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<td>$\bar{\eta}$</td>
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<td>$\tau_o$</td>
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<td>$\omega_g$</td>
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<tr>
<td>A</td>
<td>$\text{MxN windowed}$</td>
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<tr>
<td>A$_{pl}$</td>
<td>Characteristic area</td>
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<tr>
<td>$b_u$</td>
<td>Plant area per unit height of each vegetation stand normal to $u$</td>
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<tr>
<td>C</td>
<td>Celerity</td>
</tr>
<tr>
<td>$C_d$</td>
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<tr>
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<tr>
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<td>Individual wave height</td>
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<tr>
<td>h</td>
<td>Vector of filter weights</td>
</tr>
<tr>
<td>h$_c$</td>
<td>Still water depth at reef-edge</td>
</tr>
<tr>
<td>h$_r$</td>
<td>Still water depth over horizontal reef-top</td>
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<td>J</td>
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</tr>
<tr>
<td>$K_c$</td>
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</tr>
<tr>
<td>L</td>
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</tr>
<tr>
<td>N</td>
<td>Number of vegetation stands per horizontal area</td>
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<tr>
<td>N$_{(2)}$</td>
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<td>$R^2$</td>
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<tr>
<td>RE</td>
<td>Wave-driven Reynolds number</td>
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<tr>
<td>S(z)</td>
<td>Strike of wave paddle can be described</td>
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<tr>
<td>$S_{d,pt}$</td>
<td>Shape coefficient of drag</td>
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<td>$S_{l,pl}$</td>
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<td>Wave period</td>
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<td>$T_p$</td>
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<tr>
<td>u</td>
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<td>$u_z$</td>
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<td>$X_e$</td>
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<td>$\eta$</td>
<td>Water surface elevation</td>
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<td>$\rho$</td>
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INTRODUCTION

Chapter summary: The following chapter introduces the research topic “artificial underwater structures (a.k.a. artificial reefs) in a coral reef environment. The research question is stated as: “Establishing a method to determine if a multipurpose artificial underwater structure (MAUS) can perform the functions of a natural canopy cover on a coral reef flat”. The MAUS selected for this investigation is composed of a canopy of 1000’s of interlocking synthetic hooks known as ground consolidators (GCs).

Literature suggests that all relevant parameters required to assess the research question can be found by obtaining the flow characteristics inside the canopy and wave induced hydrodynamic dampening across the canopy. To address these processes, the study primarily focuses on finding the averaged drag coefficient (Cd) over the canopy and wave-driven flow velocities within the canopy. These results will be compared with a database of field observation and laboratory results from previous studies. The results will give an indication whether the GCs provide a suitable climate for the establishment, and long-term vitality, of a benthic community within the pore structure, in addition to providing design guidance for construction of such a MAUS.

The steps required to complete the proposed research consists of a detailed literature review linking natural reef ecology and associated flow conditions to the conditions found inside a physical model representation of the canopy. A fringing reef environment represents the boundary conditions within which this analysis will take place. Due to the physical nature of a fringing reef, the large bathymetrical features could not be re-produced in a scale model. This bathymetry is however, critical in forming the reef-top wave climate. Therefore, an alternative method had to be developed for this study to model the hydrodynamic conditions in the wave-flume. It was decided to model the wave transformations on the fringing reef bathymetry in a numerical model, in which the transformed wave was extracted from the reef top and scaled to the flume scale. The scaled and transformed wave conditions were then converted to a time series driving the flume paddle motion.

The world’s oceans and reefs systems have historically always undergone change, at times radical, from the moment they were formed. However, it is notable that in recent years this change is happening at an accelerated rate across a diverse spectrum of habitats, individual species, and micro-organisms. Change per se, does not have to carry a negative connotation. However, a greater understanding of these changes and how they will directly impact humanity’s coexistence with the world’s oceans is necessary. This research hopes to contribute to the broader effort in understanding the need for preservation, adaptation and restoration of reef environments, which makes up just a small portion of the world’s largest ecosystem.
Since the 1950’s an increase in the use of artificial man-made structures to restore or stabilize marine habitat has gained popularity. Although often costly, these man-made structures are meant to closely represent the conditions of natural reefs in order to preserve or establish healthy benthic communities and associated aquatic species. Recent scientific findings which more accurately portray the future effects of climate change and increased anthropogenic influence have spurred a renewed effort in finding solution to stabilize marine and coastal ecosystems using these types of solutions.

Coastal ecosystems composed of large bottom canopies regulates processes such as local hydrodynamics, sediment transport, ecology, aquatic species and communities, water quality and provides coastal protection. Aquatic vegetation is known to be food and shelter for many organisms, to control biogeochemical cycles in the coastal zone and to dissipate wave energy and turbulence protecting the shore from erosion (Mendez, Losada, 2004). Understanding the relationship between the structural features of an artificial canopy and its developing benthic communities has great biological and ecological significance for reef rehabilitation and enhancement (Perkol Finkel et al. 2006).

In large public and private engineering works clients increasingly demand new & competitive innovations which provide sustainable solutions to habitat impact or loss. This is in part the result of increased public and corporate awareness and responsibility for oceanic habitat preservation. The increased interest from lawmakers, researchers and industry requires the development of sound knowledge of quantitative and qualitative characteristics of artificial ecosystem restoration. The following research will extensively review ecological literature, where the term “reef” is most commonly associated with living organisms, whereas artificial structures are man-made and not formed by natural processes. Therefore the term “reef” should not in best practice be associated with artificial structures.

**Artificial underwater structures**

The following terminology is proposed:

1. Artificial underwater structure (AUS)
   - Any underwater structure one builds or deploys. These support marine life, either intentionally or incidentally.

2. Artificial underwater barrier (AUB)
   - AUS aimed at altering water (including waves) and/or sediment (including rubble) movements.

3. Artificial underwater habitat (AUH)
   - AUS aimed at providing habitat for underwater organisms beyond that already found at a site.

4. Multipurpose underwater structure (MAUS)
   - AUS which forms a combination of AUB and AUH purposes.

The selected MAUS concept for this study is known as a “ground consolidator” (GC), a synthetic hook shaped object, which when placed in packets of 1000+ units, creates a dense irregularly spaced canopy. This concept will be discussed in more detail in the upcoming
sections. The following research will intimately study the success of this particular MAUS concept and provide a general methodology for determining the success of future MAUS concepts.

1.1 RESEARCH QUESTION

This study of canopy flow works towards understanding how canopies regulate the hydrodynamics, sediment transport and ecological processes (such as larval settlement) within coastal systems. Investigating these questions is not only beneficial to advancing the field of science, but also aids public and private sectors in investing more economical and targeted solutions. Boskali has acquired the ground consolidator (GC) concept from Anome Projects as a tool to introduce green infrastructure components into large civil works such as dredging and coastal developments. This tool may restore or strengthen sensitive marine habitats affected by construction operations and provides soft-engineering solutions aimed at restoring long term ecosystem vitality. Therefore a methodology is required to “study the effect of an artificial GC-canopy on the local hydrodynamics (waves and currents) and aquatic ecosystems.” This includes establishing design parameters to apply the GC concept more effectively whilst gaining a better understanding of the needs of aquatic life and marine ecology within the canopy. The research question is stated as follows:

“Establishing a method to determine if a multipurpose artificial underwater structure can perform the functions of a natural canopy cover on a coral reef flat”

Literature (Reidenbach, Koseff, Koehl, 2009) describing the interaction of hydrodynamic processes with marine species and vegetation suggests this question can be answered with two fundamental principles, which consist of understanding the:

1. Hydrodynamic dampening across the reef structure
   a. Parameterizing the global canopy drag coefficient (C_d) of the GC structure is an important indicator which can be used to compare the properties of natural canopies and that of the GC canopy
   b. Bulk wave height decay
   c. Attaining a global drag coefficient allows for more robust design, implementation and understanding of the expected behavior of a GC canopy in select environments.
2. Hydrodynamics within the reef structure:
a. Understanding the magnitude of the wave driven flows and turbulent fluctuations within an artificial canopy provides many indicators required to determine whether the GC concept or generalized MAUS concept, can successfully be implemented in a given environment.

b. More specifically the success of providing a robust and sustainable habitat within the structure depends on the successful settlement of larval species associated with a wide range of benthic species, which form the basis of the in-canopy eco-system.

A correlation can be established between the wave driven flows within the canopy and the bulk wave reduction above the canopy. Currently the links between these processes are primarily established using field and laboratory results. Linking separate data sets of internal and external canopy velocity measurements is needed to understand which wave conditions above the canopy result in favorable internal canopy conditions. However, as computational canopy modules improve, specifically in terms of describing pore-space velocity fluctuations; a direct links may be more easily described for design purposes. Therefore, this research is an important step forward in describing which factors are most critical in advancing the understanding of current and future requirements for internal canopy computational flow models. The desired results from the above research questions consists of:

1. Wave damping across the structure:
   a. Parameterized global drag coefficients for the GC canopy with a fitted relationship suitable for design purposes.
   b. A recommendation as to which type of canopy configuration can provide the best hydrodynamic dampening.
   c. Implementation of GC canopy characteristics in a numerical modelling package for further canopy testing and optimization.

2. Hydrodynamics within the structure
   a. Compute wave driven lift, drag and shear forces that organisms can expect on a GC surface and compare those to the thresholds for each individual organism. Results can dictate which parameters are most critical in successful MAUS design.
   b. Compare natural wave driven canopy flows within the canopy with those observed in field studies.
   c. Provide recommendation as to which environments would provide the most successful hydrodynamic conditions for the GC concept.

It is important to note that the GC concept is used as a tool to answer the research question. However, in a broader context the methodology and processes used in this investigation are applicable to other MAUS concepts.

“This study is unique in that it incorporates many separate fields of research bridging various gaps of established ocean sciences in order to deliver more complete and comprehensive design recommendations.”
1.2 APPROACH

To answer the research question above the problem is split into 4 successive parts, each consisting of distinct tasks and outcomes. There are as follow:

<table>
<thead>
<tr>
<th>1. Extensive literature review</th>
<th>desired outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tasks</td>
<td></td>
</tr>
<tr>
<td>• Determine typical hydrodynamic conditions found at fringing reef sites worldwide.</td>
<td>Database with a wide range of hydrodynamic reef top conditions.</td>
</tr>
<tr>
<td>• Determine which ecological parameters and specie characteristics are required for in-canopy habitat assessment.</td>
<td>Understanding of natural reef stability and long term development and growth.</td>
</tr>
<tr>
<td>• Describe method required for canopy drag coefficient parameterization.</td>
<td>Database of aquatic species and their associated thresholds to dislodgement from wave-driven flows on various surfaces.</td>
</tr>
<tr>
<td>• Review turbulence decomposition methods and compare their advantages/disadvantages.</td>
<td>Method to parameterize and describe the random canopy structure.</td>
</tr>
<tr>
<td>• Database with a wide range of hydrodynamic reef top conditions.</td>
<td>Concrete methodology to separate wave-driven and turbulent flows in the canopy.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2. Numerical modelling study</th>
<th>desired outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tasks</td>
<td></td>
</tr>
<tr>
<td>• Select a suitable model capable of generating individually resolved waves.</td>
<td>A fringing reef profile constructed with a relatively inexpensive non-hydrostatic computational model.</td>
</tr>
<tr>
<td>• Schematize a typical fringing reef site and force a variety of monochromatic, bichromatic and irregular wave conditions.</td>
<td>A series of desired flume paddle inputs for monochromatic, bichromatic and irregular waves representative of globally observed reef-top conditions.</td>
</tr>
<tr>
<td>• Scale wave conditions to flume scale and make adjustments for wave reflections.</td>
<td>2-3 GC MAUS configuration with varying dimensions and properties targeted at providing insightful contrasts and similarities.</td>
</tr>
<tr>
<td>• Turn wave signal into wave maker time series and clean signal.</td>
<td></td>
</tr>
<tr>
<td>• Determine MAUS set-up in the flume using estimated GC parameters and various iterations of GC configurations with a computational tool.</td>
<td></td>
</tr>
</tbody>
</table>
### 3. Physical modelling study

<table>
<thead>
<tr>
<th>Tasks</th>
<th>desired outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Determine which instrumentation to use and where to place the instruments in the canopy to obtain the desired results.</td>
<td>Effectively placed, well calibrated instruments with relatively clean data records.</td>
</tr>
<tr>
<td>Preparation and calibration of scaled wave conditions.</td>
<td>Acceptable difference in characteristics of wave conditions measured in the flume and those generated by the computational tool for reproduction in the flume.</td>
</tr>
<tr>
<td>Detailed planning of construction, calibration, testing and take-down for all tests.</td>
<td>Timely completion of the modelling campaign.</td>
</tr>
<tr>
<td>Analysis of initial results during testing and completing the required adjustments.</td>
<td>Accurate representation of the planned GC canopy configuration/size.</td>
</tr>
<tr>
<td></td>
<td>Effective adjustments to testing methods based on initial analysis using turbulence decomposition techniques and wave height reduction estimates.</td>
</tr>
</tbody>
</table>

### 4. Data analysis, conclusions and recommendations

<table>
<thead>
<tr>
<th>Tasks</th>
<th>desired outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comparison and selection of most effective post-processing techniques.</td>
<td>Efficient turbulence decomposition and data filtering.</td>
</tr>
<tr>
<td>Corrections and filtering of all output data.</td>
<td>Geometrically well-defined canopy.</td>
</tr>
<tr>
<td>Canopy description and parameterization.</td>
<td>Line of best-fit and associated equation for $C_d$ values using all test conditions/outputs.</td>
</tr>
<tr>
<td>Establish canopy averaged drag coefficient and suggest a best-fit model for use in design.</td>
<td>Comparison of the impact that various GC canopy configurations and water levels has on results.</td>
</tr>
<tr>
<td>Compare in-canopy flows with those found at natural reef sites.</td>
<td>Insight into aquatic species survivorship on GC elements for various wave conditions.</td>
</tr>
<tr>
<td>Estimate drag/lift/shear forces on GC elements within the canopy.</td>
<td>Insight into long term feasibility of GC concept.</td>
</tr>
<tr>
<td>Comment on species survival in GC canopy and associated long term canopy success.</td>
<td>Practical recommendations for GC implementation and design.</td>
</tr>
<tr>
<td>Make recommendations for improvements and future research.</td>
<td>Recommendation for future research and MAUS studies.</td>
</tr>
</tbody>
</table>
The tasks and outcomes listed in the above tables will be addressed in the upcoming sections.

1.3 SCOPE

The study of artificial reefs in a physical model setting and the schematization of artificial canopies in computational modeling packages are both relatively immature research areas. This is primarily due to the complex nature of these processes and the required advances in both physical and numerical modelling techniques to develop these fields further. There is an evident need to improve the understanding of the dynamics of waves and currents in complex porous canopies such as artificial reefs. This research will attempt to contribute some additional physical and numerical modeling insight using a combination of established laboratory techniques and newly developed numerical and physical modelling tools. The outcome aims to add momentum and direction to future developments in MAUS and reef studies.

Prior to describing the study methodology and approach used to answer the research question stated above, it is important to define the global boundaries of the study. These are defined in Figure 1.3-1.

There are various interfaces between land and sea where a MAUS may be applied, such as mangrove strands and salt marshes. However, it was determined that an ideal trial location for the MAUS concept is a relatively horizontal and shallow fringing reef flat. The selection of this type of habitat is also driven by the increased desire for understanding of not only artificial coral canopies but also the natural coral reef communities inhabiting these regions. The methodology described in this research could similarly, be applied to coastal mangrove, sea grass meadows and salt marsh regions.

Limitations and Boundary Conditions

To complete the following investigation, some assumptions, limitations and adjustments had to be made. These are:

- **Unidirectional flow** - will not be incorporated. The study will focus on wave-driven flows in order to reduce the complexity of the physical modelling campaign.
• **Breaking waves** - will not be reproduced in the wave flume as it is assumed that waves have already broken on the reef edge. Comparing the characteristics of a wave which is breaking at or just in front of the flume paddle with the outcome of a numerical modelling tool which does not resolve wave spilling and/or plunging may be unreliable. Instead all waves will be transformed to their skewed and asymmetric state.

• **Material properties** – Varying GC materials may impact ability of larval adhesion and/or aquatic growth. The effect of these materials will not be considered in this study.

• **Model scale** – model GC’s are scaled to size but not to mass. As it is intended to secure the canopy to the flume bottom, the threshold of canopy dislodgement will not be tested.

• **Installation** – GC’s will be placed in the flume without water to increase the precision of installation required for proper instrument placement and orientation within and above the reef.

• **Specie origin & diversity** – A broad range of coralline species and/or aquatic species found on intertidal and shallow reef top environments will be used in the analysis. These species are not native to one specific area and were primarily chosen due to available literature and the volume of data required to complete an initial review. Localized and more complementary specie data sets were not easily acquired.

• **Sedimentation** - may affect larval settlement and adhesion. Testing with sediment requires an intimate understanding of hydrodynamics, which is the focus of this study.

• **Generic fringing reef profile** – numerical modelling will be completed using one generic fringing reef bathymetric profile which has been tested and calibrated for certain conditions. The tests derived from other locations will be forced onto this profile until the desired conditions observed in literature are obtained.

• **Wave paddle** - The wave paddle cannot reproduce the most severe conditions modelled in the numerical modelling tool. Instead the paddle will be calibrated up to the maximum tolerable threshold of mechanical motion.

• **Limited model runs** – A limited number of physical model conditions had to be selected due to the time required to prepare each test and the limited testing time available for this investigation.

• **In canopy velocity profiles** – can only be conducted at a limited number of locations in the reef at select heights throughout the canopy. Acquiring a complete velocity profile in the canopy from the flume bottom to the canopy crest is not feasible given time and instrumentation limitations. Instead select areas and locations within the canopy will be strategically chosen.

• **Data post processing** – the abundance of available data may result in redundant data sets which do not require post processing for use. These data sets will only be used if it is found that corresponding data sets are of low quality or require comparison and verification. Furthermore, data will be selectively analyzed with the sole purpose of answering the research question. This illustrates the value of the data which has the potential for many more applications and uses.
BACKGROUND

Chapter summary: The following section provides the necessary background required to frame the research question. Three fundamental topics are covered, consisting of a general description of fringing reef systems, relevant ecological parameters, and reef top hydrodynamics.

The key features of a fringing reef are the water levels above the reef, local offshore and reef top wave heights, wave period, set-up and bathymetry. Furthermore, some of the pressures faced by natural reef systems, such as anthropogenic influences are listed. The benefits and disadvantages of MAUS structures to mitigate these pressures are discussed and the GC MAUS concept is introduced. Features which are discussed include the concept’s random/dense pore spacing which mimics natural canopy structures such as those found in mangrove strands.

The general structure of a reef-top eco-system is presented as a hierarchal food-chain or pyramid. The foundation or base of this pyramid is the benthic community consisting of larvae and slightly larger predators/species. The study focuses on this segment as it is the foundation from which all other species/ecology evolves and develops (Roberts, 2012). The parameters required to analyze larvae at a feasible scale are discussed. This can be done using the local Re number in combination with estimates of hydrodynamic forces on the larvae or aquatic organism. Finally, a methodology suggested by Mendez & Losada (2004) required to parameterize the canopy as a whole is introduced.

This thesis also introduces the relatively novel concept of using a numerical model to generate a tailored wave time-series for a physical modelling campaign. Due to the extreme depths at the edge of a fringing reef profile, it is not feasible to reproduce the bathymetry of a fringing reef in a wave flume. The reef edge is a critical feature in transforming the waves before they dissipate across the reef flat. Therefore, a computational model is used to provide the basis needed to incorporate shoaling, skewness, asymmetry and higher harmonic elements of the wave. Once produced, these transformed wave time series undergo Froude scaling from which a wave paddle time series is produced. Velocities induced by these wave drive flows measured within the canopy of the physical model require decomposition into turbulent and wave-driven components. A number of methods are discussed including, ensemble averaging, collated velocity measurements - Shaw & Trowbridge (2001), spectral wave-turbulence decomposition – Bricker & Monismith et al (2007), and a moving average method using a Quintic Savitsky-Golay fit.
2.1 REEF SYSTEMS

To determine the critical boundary conditions required for the study various coral reef structures were identified and categorized. The description used by Gourlay, (1996a) introduces 4 basic reef configurations which are identified in Figure 2.1-1 and classified as:

**Fringing reef** - a reef which fronts a continental land mass or island  
**Platform (or island) reef** - a reef surrounded by the sea, similar to a fringing reef geometry  
**Lagoon / barrier** - a body of water enclosed by a reef or by a reef and a continental or island  
**Cay / atoll** - a reef-top island formed from reef-derived sediments

The most prominent reef type in Figure 2.1-1 is the fringing reef, which has been widely studied worldwide and will be the focus of this study. Each reef configuration shares universal features which are the reef face, top and edge. These can be described by:

**Reef-face** - the seaward facing underwater slope of the reef  
**Reef-top** - the skyward facing surface of the reef, usually submerged except at low tides  
**Reef-edge** - the intersection of the reef-face and reef-top

Figure 2.1-2 more closely describes a fringing reef. The features in Figure 2.1-2 will be frequently referenced in this body of work, as they form the fundamental inputs for analyzing the reef top hydrodynamics. In the figure, \( H_i \) is the incident offshore wave height, \( h_e \) is the still water depth at reef-edge, \( Z_r \) is the height of reef face relative to reef edge, \( X_s \) is the distance from reef edge to the maximum mwl, \( h_r \) is the still...
water depth over horizontal reef-top, $\bar{\eta}$ is the mean water level relative to still water level and $\eta_r$ is the maximum wave set-up on reef-top. The form and slope of a reef profile depends very much upon the local reef building processes. Present day coral reefs have been formed by Holocene coral growth during which sea level has risen since the last ice age 18 000 before present (BP) and then stabilized about 6000 BP in places such as eastern Australia (Gourlay, 1996b).

**Changing reef systems**

The systems described above are highly dynamic and undergo continuous change. It is however becoming apparent that these systems are changing more rapidly than the time required for them to remain in a stable equilibrium. This has introduced the need for such solutions as a MAUS system to stabilize and decelerate eco-system loss. Some of the primary drivers of change in coral reef eco-systems are presented and adapted from a comprehensive review presented by Smithers et al. (2007):

1. **Rising sea level**
   Rising sea levels may affect the inundation of coral reef systems, which could lower irradiance for deeper corals and lead to slower growth or even ‘drowning’ of some species. This is because projected rates of sea level rise are well below published rates of coral growth (Smithers et al. 2007). Sea level rise could however increase accommodation space into which depth-constrained reef communities may extend in addition to shoreline retreat presenting additional habitable substrate.

2. **Rising sea surface temperature**
   Sea surface temperatures affect the coral community structure due to the effect on photosynthetic and autotrophic activities. Calcification rates and contributing calcifiers may intensify which threatens the primary production of benthic communities, resulting in erosion (including bioerosion) and disease which decreases the overall reef strength. Increased carbon absorption by the ocean makes the oceans more acidic, this decreases calcification.

3. **Increased tropical cyclone activity and storm surge**
   Recent trends suggest that coastlines are experiencing an increase in severe storm events due to climatic changes. This may increase wave severity and exposure of coral reef systems. The exposure to larger waves from severe storm events can result in the physical destruction of corals and other living benthos whilst changing local bathymetry near a coral reef system. A side effect of this is a reduced structural complexity, strength and long-term wave resistance of the entire system.

4. **Changing rainfall patterns**
   Global climate change can result in both increasing and decreasing rainfall. An increase in rainfall can result in an increase of fluvial and groundwater inputs into coral reef systems, of which the effects are highly dependent on the runoff quality, source water salinity and content of anthropogenic inputs such as fertilizers and industrial wastes. This increased delivery of sediments, nutrients and contaminants by flood plumes may increase benthic algae and reduced coral cover and increase bioerosion. In those areas with decreased rainfall,
a reduction in the duration and extent of flood plumes may be expected, this reduces the delivery of sediments, nutrients and contaminants and could lead to an increased coral cover.

5. Anthropogenic effects

A relatively recent concern associated with anthropogenic influence is the increased acidification of oceans worldwide. This may reduce coral and other biotic calcification because acidification poses a critical threat to calcifying organisms that form delicate skeletons (Smithers et al. 2007). Invasive plant/aquatic species which have accidentally been introduced pose an additional threat to non-competitive native species. Furthermore, coastal development, especially in areas with less stringent environmental regulation may be responsible for the destruction of large areas of coral reef habitat. Finally, destructive fishing and tourism activities account for a significant loss in healthy coral reef systems and highlight the need for protected marine reserves.

The above pressures describe the processes which have aided in the degradation and loss of coral reef communities worldwide and therefore demonstrate some of the functions which a MAUS may try to mitigate or restore. It is important to identify that although the above processes are important considerations for the placement and design of a MAUS, not all will be the primary focus of this study.

Artificial canopy concepts

There have been many attempts at developing successful MAUS concepts worldwide. This study will not focus on historical MAUS concepts as it is the aim to establish a generalized methodology for analyzing all types of MAUS concepts using the GC’s as a product. However, some of the general limitations and benefits of a MAUS will be introduced in this section. Table 2.1-1 displays some of the common limitations and benefits of a MAUS. The features highlighted in Table 2.1-1 will be repeatedly referenced throughout the study as a reminder of which processes may be regarded as a potential strength or weakness to the GC concept.

<table>
<thead>
<tr>
<th>Potential benefits</th>
<th>Potential disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Increase in available substrate for reef organisms</td>
<td>• Slow development</td>
</tr>
<tr>
<td>• Structural complexity</td>
<td>• Poor control of community development</td>
</tr>
<tr>
<td>• Increase in settlement and recruitment</td>
<td>• Limited knowledge and prediction ability</td>
</tr>
<tr>
<td>• Increase in species diversity</td>
<td>• Reduction of larval supply from natural reefs</td>
</tr>
<tr>
<td>• Improving connectivity between habitats</td>
<td>• Attraction of organisms from natural reefs rather than production</td>
</tr>
<tr>
<td>• Relatively easy removal in case of failure</td>
<td>• Possible adverse effects on neighbouring natural reefs</td>
</tr>
<tr>
<td>• Immigration of diverse reef-dwelling species</td>
<td>• Promotion of common/dominant species</td>
</tr>
<tr>
<td>• Promotes public awareness</td>
<td></td>
</tr>
</tbody>
</table>
It is intended to outweigh the benefits from the disadvantages with a GC MAUS system, although the true extent of successfully achieving this can only be known once a fully operational pilot study is placed in a fringing reef environment.

2.1.1 **Ground Consolidators**

Many coral species, as well as other invertebrates, will preferably settle on a complex substratum rather than on a simple one. Similarly, there is a correlation between the structural complexity of the reef and its species diversity and abundance of the inhabiting fishes (Perkol, Finkel et al. 2006). The concept used in this study is known as the Ground Consolidator (GC), which was conceived by Anome Projects in 2004 by L. Boskma & J. Hoebe. This structure is composed of 1000’s of individual hook shaped elements which form a complex canopy with random pore spacing ideally simulating the complex substratum on which coral species and their inhabitants can thrive.

From 2005 to 2008 the concept was further developed with a series of feasibility studies and flume tests at TU Delft to determine whether the GCs were capable of damping wave propagation. In August 2009 an embankment pilot project (Maasvlakte, Rotterdam) was conducted and monitored by a consortium of Anome, Rijkswaterstaat, TNO, Witteveen+Bos, the Port of Rotterdam, Boskalis, Rotterdam Engineering Consultancy and TU Delft. Further testing of stability and installation techniques of the GC concept continued throughout 2011-2013 in addition to various materials testing (biodegradable and composite plastics) by Anome and Pezy. Applications of the GC product range from embankments in harbor areas, and rivers, deep sea application around pipelines, shoreline stabilization, sand accretion applications and MAUS structures for both mangrove and coral reef applications.

The largest GC project to date is a MAUS pilot study in the Markermeer (The Netherlands) which is depicted in Figure 2.1-3. This canopy has been built up with ~60,000 GCs and was installed by Boskalis in March, 2013. The canopy measures about 2.4m high, 11m wide and 80m long and is monitored by Rijkswaterstaat, TU Delft, ATKB and Witteveen+Bos.

A site-visit was conducted to the pilot study in October 2013. Considerable settling of the canopy was observed in addition to algae and growth of various aquatic species on the GC surface. A large collection of data is available from the pilot study and is expected to become
public in 2015. Installation techniques of the pilot study were also discussed and identified. Due to the large variations in the pilot study and intended flume study, installation techniques for this investigation will not mimic those techniques used to construct the pilot study. Instead installation of the GC MAUS in the physical model study will done in the most practical and feasible approach given the laboratory constraints. Improved installation techniques will not be the focus of this study.

The GCs allocated for the physical model can be mass produced using an injection mold process requiring a steel mold. This mold limits the scale of the model in the flume. Available GC dimensions are listed below:

<table>
<thead>
<tr>
<th>Scale</th>
<th>Dimensions (m)</th>
<th>Mass (g)</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilot</td>
<td>0.40x0.40x0.40</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1:5</td>
<td>0.08x0.08x0.08</td>
<td>10.56</td>
<td>1.52</td>
</tr>
<tr>
<td>1:8</td>
<td>0.05x0.05x0.05</td>
<td>9.432</td>
<td>-</td>
</tr>
</tbody>
</table>

The average packing density based on previous pilot and laboratory testing was found to be ~29GCs/m³. The 1:5 scale GC hooks represents the latest design iteration based on two different rib orientations that are supported by extra brackets to guarantee forming a truss structure of Ubrackets and Ibrackets (depicted in Figure 2.1-4). It was decided to use this scale and hook model for the current study to incorporate the most recent design iteration. Further reasons for choosing the larger scale include reducing the model scale effects when measuring turbulent flows within the canopy. This point will be elaborated further in the upcoming sections.

![Figure 2.1-4: GC 1:5 scale design](Source: Pezy, 2013)

GCs are a well suited candidate for the study of a MAUS. In a reef environment coral recruitment is usually higher on vertical or inclined surfaces as compared to horizontal ones, mainly due to lower sedimentation levels and increased water circulation on the former.
These types of surfaces are abundant in a GC structure. Furthermore, the structural complexity of a natural reef (like a GC MAUS) greatly affects the species diversity, density and size distribution of both invertebrates and fish, as a more complex and heterogeneous reef structure offers a greater array of niches (Perkol, Finkel et al. 2006).

### 2.2 ECOLOGY

Natural reef ecology forms the basis of the theory required to conduct this investigation. The following section provides the background required to determine whether the GC MAUS can develop a long term stable coral reef habitat. Canopies of attached organisms (e.g., coral, kelp, sea grass) provide a complex three-dimensional habitat in which many species live, affect ambient flow and the dispersal of dissolved materials. Organisms in canopy habitats are supplied with dissolved gases, nutrients, and particulate food, from which their wastes, gametes, larvae, or spores can be dispersed (Reidenbach et al. 2009). Many of organisms in benthic communities reproduce, via sexual reproduction utilizing planktonic larvae that are transported by ambient currents to colonize new surfaces (Koehl, 2007). The recruitment of larvae and subsequent retention to benthic sites is a critical process affecting population dynamics and community structure. Therefore this study will focus on larval reproduction, retention and growth in benthic communities to benchmark the sustainability of a MAUS structure.

#### System analysis

To establish a focus area within the aquatic ecosystem, the food web is examined more closely. Figure 2.1-1 is generated to illustrate the hierarchal nature of the food chain, ordered from the largest primary producers to anthropogenic consumers which dominate the food web. The categories in Figure 2.1-1 may be described by:

- **Primary producers:** photosynthetic autotrophs-phytoplankton, coralline algae, filamentous turf algae, zooxanthellae (photosynthetic algae) in coral, and many species of seaweed.
- **Primary consumers:** herbivores, zooplankton, invertebrate larvae, benthic grazers, some corals, sea urchins, crabs, green sea turtles, and herbivorous fish
- **Secondary consumer:** plankton feeders, corallivores, benthic invertebrate feeders, and piscivores.
- **Tertiary consumers:** carnivores such as sharks and barracuda.

Figure 2.2-1: Food pyramid in a coral reef environment
As a pyramid model, the base of the food web is essential in sustaining all of the levels higher up in the structure. The large community of primary producers creates the bio-mass needed to provide habitat and nourishment for ensuing organisms and species. This study will therefore be limited to benthic primary producers in order to focus the research scope.

“The assumption is made that demonstrating the feasibility of primary production on a GC MAUS can lead to the development and growth of secondary and primary consumers.”

The critical process for coral community recovery and resilience is the addition of individual corals to a reef by larval recruitment. Successful coral recruitment is the result of survival through three sequential life history stages: larval availability, larval settlement and metamorphosis, and post settlement growth and survival (Ritson-Williams et al. 2010). Whether the hydrodynamic conditions required for coral growth by larval recruitment are attainable is of primary interest in this study.

Some processes which will not be included in this investigation are sedimentation and GC material textures/properties which may affect larval settlement and adhesion. Additionally, important bio-chemical processes often needed for larval recruitment will not be incorporated in this study. To consider sedimentation, a thorough understanding of hydrodynamics is required, which is the focus of this study. Subsequent investigations with sediment may follow this investigation in the future. With regards to surface texture, Abelson (2006) demonstrated that larval recruitment was greater on rough textured surfaces. However, the current GC material properties will not be adjusted due to production constraints. Relationships between GC materials and adhesions strengths may be determined in a later study pending the recommendations from this investigation.

2.2.1 Reef system reproduction

Along many reefs, spawning occurs as a synchronized event, when many reef species in an area release their eggs and sperm at about the same time (NOAA, 2011). The release of sperm and eggs must be precisely timed, and usually occurs in response to multiple environmental cues. There are both long-term and short-term controls that affect the timing of spawning events. The long-term control of spawning may be related to temperature, day length, or rate of temperature change. The short-term control is usually based on lunar cues. The final release, or spawn, is usually based on the time of sunset. Corals use mass spawning to facilitate successful reproduction. By spawning at the same time when water movement is minimal (i.e. neap tides), corals maximize the concentration of eggs and sperm thereby increasing the chances of fertilization. The simultaneous spawning of many different species at night ensure enough coral larvae, survive by inundating predators with an excess of food over a short period, minimizing the impact of predation by fishes on the survivorship of larvae (Exmouth 2011).
Water motion on large spatial scales plays an important role in determining spatial and temporal patterns in recruitment by transporting marine larvae between sites and from offshore waters to the coast (Koehl 2007). This study will focus on the local or yearly-self seeding in addition to some effect of archipelago wide recruitment. Natural dispersal of larvae forms a large plume which circulates along the natural coral canopy. Water motion near the substratum not only affects the transport of larvae from the water column to a benthic habitat but also determines whether larvae that have landed on the substratum are swept away (Reidenbach et. al. 2009). Larvae actively choose a suitable area to settle and if no appropriate substrate is available, larvae can delay settlement until a desirable environment is located (Abelson 2006).

Offshore transport of larvae or lack of suitable substrate for recruitment can result in loss of recruitment and ultimately coral habitat. As noted in section 2.1 the increased pressures on reef systems worldwide from larger storm events and anthropogenic influence has resulted in a weakened benthic community on many of the world’s reef flats. Furthermore, the interconnectivity of reef systems and the exchange of larval plumes between these systems play an additional role. The pressures exerted on one systems may result in a decrease of available coral larvae for recruitment in an adjacent systems. This demonstrates the interconnectivity of these systems.

The reduced structural complexity, strength and possibly long-term wave resistance of the system means that coral recruitment becomes more difficult with larvae running the risk of being swept away or eventually dying off before connecting to a substrate. The hypothesis is therefore:

“A GC MAUS structure can be placed on a reef flat to capture and retain circulating larvae and spores from a large variety of local organisms and aquatic vegetation.”

The selection of suitable settlement habitat is critical to post-settlement survival and thus is a potential demographic bottleneck for most species (Ritson-Williams et al. 2010). With a high density network of pores, the GC MAUS structure has the potential to provide sufficient sheltered adhesive surfaces for coral recruitment. Ideally, natural coral recruitment can be utilized to populate a GC MAUS structure, however if this is no longer feasible at the location of interest, some specialized techniques exist to introduce larvae and eggs artificially. This approach will not be the focus of this study as it is a costly and relatively inefficient technique for coral recruitment. Recruitment of most species can be described in 3 phases, these are:

**Larval Transport**

Larvae of benthic marine invertebrates are dispersed from their birth sites and utilize vicissitudes of tides and currents to deliver them to suitable locations for recruitment (Hadfield, Koehl 2004). Once a larva has spawned it is triggered to settle when confronted with a chemical inducer by a predator or when the larvae finds a suitable environment for settlement. When a larva arrives at or below the top surface of the reef, it is considered as transported to the reef.
Settlement
Settlement occurs when a coral larvae stops its dispersal phase and chooses a surface to colonize (Ritson-Williams et al. 2010). Some types of larvae actively explore surfaces after they land and choose a specific spot on which to settle. Larvae that have landed can reject surfaces and resume swimming. Both the strength and speed of attachment to a surface affect where a larvae can settle. To settle, a larvae must anchor itself during the brief stress lulls between burst-sweeps (Crimaldi et al., 2002). Larvae that stick to surfaces upon contact (e.g. larvae of barnacles, bryozoans, some cnidarians) can settle on surfaces exposed to high water velocities, whereas larvae that develop their adhesion to surfaces more slowly are able to settle only in spots where peak local shear stresses during burst-sweeps are too low to dislodge them (Koehl, Hadfield 2004).

Metamorphosis
Also known as recruitment, this stage is the metamorphosis of a settled larvae into a juvenile that survives (Koehl 2007). Once the larvae has settled it exchanges dissolved metabolites (e.g., CO$_2$, O$_2$, NH$_4^+$, NO$_3^-$, and PO$_4^{3-}$) between benthic organisms and ambient water to sustain critical biological processes such as growth, photosynthesis, and respiration (Lowe et. Al 2005). A physiological and morphological transition takes place from a settled larvae to a spat.

Successful larval settlement is critical to the long-term stability of benthic populations and communities (Hadfield, Koehl 2004). Therefore, the ability of larvae to adhere to a GC MAUS structure will directly determine whether a natural benthic community can be preserved or introduced on a MAUS. The next section describes the adhesive process and requirements of individual larvae.

2.2.2 Larval adhesion
Hydrodynamic forces challenge individual larval adhesion to benthic substrate. Benthic communities as a whole can also be at risk from colony dislodgement caused by severe hydrodynamic forces. However, this investigation will only consider thresholds of flows on individual larvae. It is assumed that a GC MAUS will be installed with sufficient capacity to sustain site-specific hydrodynamic forces. Large hydrodynamic forces experienced by larvae force them to attach to surfaces quickly and firmly. Conversely, larvae with low adhesive strengths and larvae that attach themselves to surfaces slowly are more likely to settle on surfaces within a reef that are shielded from rapid water movement (Koehl & Hadfield 2004).

Hydrodynamic Forcing
Hydrodynamics play a major role in controlling the dynamics of the underwater vegetation fields by dispersing spores, as well as influencing the structure of underwater plant communities by setting distribution limits related to wave and current exposure (Mendez, Losada, 2004). Relevant physical mechanisms through which waves interact with benthic organisms are complex. A species’ distribution can be controlled by the hydrodynamics on larvae after they’ve settled due to various magnitudes of hydrodynamic forces, the time between these forces, and the number of repetitions (or pulses) of these forces (Denny, 1995). A settling larvae in a turbulent flow experiences numerous hydrodynamic forces.
associated with the fluid motion. These forces fluctuate in time, and the character of the fluctuation is governed by the structure of the turbulence (Crimaldi, 2002). These hydrodynamic forces include:

- Lift,
- Form drag,
- Skin friction,
- Fluid acceleration, and
- Forces due to viscous and turbulent shear stresses.

The relative strength of the forces listed above depends on the larval morphology, the character of the bed, and the flow state. In the surf zone (on top of the reef flat), where benthic organisms are by definition submerged, the presence of a water column above the substratum protects benthic organisms from the rapid water velocities found at the wave crest or the leading edge of a swash (Denny, 1995). Structures protruding above the substratum can enhance turbulent mixing, thereby increasing the flux of larvae to the substratum, but also reducing their settlement by raising the frequency of burst-sweeps along the bottom (Koehl, Hadfield 2004). It is anticipated that a GC MAUS structure will introduce turbulence near the surface (on top of the reef flat), while providing some protection for larval recruitment within the canopy.

The magnitude of the hydrodynamic forces experienced by larvae within the canopy will be investigated. It has been suggested that larvae with weak adhesive strength settle in areas of low hydrodynamic stress where they are less likely to be washed away (Reidenbach et. al. 2009). Therefore, to ensure that the highest possible levels of growth are accomplished on the GC MAUS it is important to:

*Measure the hydrodynamic forces within the GC MAUS to demonstrate if weaker larvae can accomplish firm attachment and retention.*

Small-scale flow through a reef canopy on larval settlement has not been extensively studied in the past (Koehl, Hadfield 2004). This is due to the challenges associated with representing a complex natural canopy by a simple set of geometric parameters (Lowe et. al 2008). Therefore the flow within the GC MAUS will be recorded in a physical model study which does not require the parameterization of complex geometries using computational methods.

**Role of Turbulence**

Oscillatory wave driven flow can create separation along benthic roughness elements, which disrupts the boundary layer by reducing the thickness of the viscous sublayer and increases turbulence near the bed (Reidenbach et. al. 2009). Crimaldi (2002) noted that predicting all of the instantaneous constituent forces acting on a larvae is complex. However, at the scale of a larvae, the temporal variation of all of the hydrodynamic forces depends only on the
temporal variation of the local velocity field, i.e., the turbulence structure. Therefore a study of the turbulence structure yields information about the temporal fluctuations of the forces acting on a larva. It can now be reasoned that the temporal character of the Reynolds stress should indicate the temporal character of all of the hydrodynamic forces that potentially influence larval settling. Therefore this study will focus on finding the Reynolds stresses at the site of larval adhesion to determine if recruitment is possible.

The study of Reynolds stresses is easily accomplished in a laboratory and will indicate the character of all hydrodynamic forces influencing larval settling

In its simplest form the Reynolds number (Re) may be calculated near the surface of a GC element, where $D_v$ is the width of a GC member, $U$ is the velocity recorded in the canopy and $v$ the kinematic viscosity.

$$Re = \frac{UD_v}{v}$$  \hspace{1cm} [2-1]

A common way of measuring the adhesive strength of larvae, spores, and other microorganisms on surfaces has been to measure the bed shear stress at which these microscopic bodies wash away (Koehl and Hadfield 2004). Reidenbach et. al. (2009) also employs this method by comparing the hydrodynamic stresses on larvae at different positions within a coral reef canopy using measures of particle or larval dislodgement. However, these studies use the instantaneous measurements of water velocities 200 μm above the surfaces of corals to calculate the instantaneous bed shear stresses along those surfaces. Given the available laboratory equipment, and dense canopy structure, it will not be possible to measure turbulence at this scale.

Therefore, the analysis will require a time averaged approach which compares available field and laboratory data with the velocities found inside the canopy during the experiment. The maximum expected drag, lift and shear forces expected on the surface of an individual GC can be calculated from the wave-driven flow in the canopy, once the local turbulent component is removed. This will give a good indication whether larvae and other micro-organisms find a favorable environment in the GC canopy.

“Given the dense canopy structure and difficulty of measuring instantaneous velocities on the GC surface boundary layer, peak velocities measured in the canopy will be used to approximate time-averaged maximum drag, lift, and shear forces.”

For each test performed in the physical model, lift, shear and drag forces are calculated at various locations in the canopy on the project surface of a GC element. For many organisms it is useful to incorporate the Reynolds-number dependence of drag into the velocity term in
the drag equation, thereby leaving the index of object shape as a constant that is independent of velocity (Denny, 1995). The drag force on a GC is estimated as:

\[ F_d = 0.5 \rho u^{\beta_d} S_{d, pr} A_{pr} \] \hspace{1cm} [2-2]

Where the coefficient \( \beta_d \) is the velocity exponent of the drag and \( S_{d, pr} \) is the shape coefficient of drag, defined using the object’s profile area. Because the velocity-dependent character of shape has been incorporated in the exponent \( \beta_d \) and \( S_{d, pr} \) are constant for each organism. The traditional drag coefficient \( C_{d, larva} \) experienced by the organism can be calculated for a given \( \beta_d \) and \( S_{d, pr} \) using:

\[ C_{d, larva} = u^{(\beta_d - 2)} S_{d, pr} \] \hspace{1cm} [2-3]

Additionally lift (L) acts at right angles to the flow direction past the larvae and may be described by:

\[ F_l = 0.5 \rho u^{\beta_l} S_{l, pl} A_{pl} \] \hspace{1cm} [2-4]

Where \( A_{pl} \) is the velocity exponent of lift and \( S_{l, pl} \) is the shape coefficient of lift, defined using the object’s planform. Similarly to \( C_{d, larva} \) the lift coefficient \( C_{l, larva} \) may be calculated with the following expression:

\[ C_{l, larva} = u^{(\beta_l - 2)} S_{l, pl} \] \hspace{1cm} [2-5]

In addition to drag and lift force, a third acceleration force acts along the direction of flow (Denny, 1995). Unlike drag (which is proportional to the area exposed to flow), the acceleration force is proportional to the volume of water displaced by an organism. As a result, the magnitude of the acceleration force increases faster than that of drag as an organism grows. Despite its importance in size limitation, under all but the most severe wave conditions and for all but the largest organisms the acceleration force is small relative to drag, and its effects do not have to be treated. Therefore the total force on a larvae may be taken as the \( F_l \) and \( F_d \) together, which results in:

\[ F = \left( F_d^2 + F_l^2 \right)^{1/2} \] \hspace{1cm} [2-6]

The variable required to complete equations 2-2 to 2-6 are presented in Table 2.2-1 and will be used in the analysis in section 7.2.
In addition to the force exerted on GC surface, the maximum time-averaged shear stress experienced by larvae can also be computed. It is defined by:

$$\tau_0 = 0.5C_{d,GC}\rho U_m^2$$  \[2-7\]

In this expression $C_{d,GC}$ is 1.0 as it is the drag expected on a GC element in flow. The forces calculated on the individual GC element within the canopy will be compared with thresholds recorded for a large variety of aquatic species. Coral larvae will be compared with the shear stress expected on the surface of one GC element, as this is a better indication of the likelihood that a larvae can recruit on a GC element.

### 2.2.3 Vegetation parameterization

Various theories regarding the dissipation of wave energy in canopy covers were explored by the likes of Mendez & Losada (2004), and Suzuki, (2011). Suzuki (2011) schematized mangroves trees into layers with various canopy densities. It can be argued that mangrove roots form the same random porous structures found in a GC MAUS. This is clearly illustrated in Figure 2.2-2. This thesis extends the use of established canopy theory used to describe mangroves and sea grasses to artificial coral reef canopies. The hypothesis is that such irregular canopy structures resemble the irregular canopy structures found in coral reef systems.

**Figure 2.2-2: Canopy structure of mangroves (L) and GCs (R)**
It was therefore decided to apply the theory used to schematize mangroves and other porous plant media for the GC MAUS. This allows the GC MAUS to be implemented into a computational modeling tool.

“A GC specific $C_D$ value parameterized from a physical model can be implemented into a computational canopy module to optimize MAUS configurations.”

Variability of wave damping is very large, therefore finding a generalized behavior of the ‘plant-induced dissipation’ can be difficult. Nonetheless adequate modelling of wave transformation along vegetation fields is highly desirable. Mendez & Losada (2004) describes initial plant-induced dissipation models based on neglecting plant motion and expressed in terms of a wave shear stress friction coefficients, or the drag force acting on vegetation. In its simplest form as a non-breaking unidirectional wave modelled on a flat bottom, dissipation can be found with a method described by Mendez & Losada (2004) which assumes that linear wave theory is valid and regular waves are normally incident on a coastline with straight and parallel contours. The relationship from Mendez & Losada (2004) is valid for emergent and submerged canopies.

The nonlinear drag force may be written as:

$$\frac{\partial H^2}{\partial x} = -A_o H^3$$  \[2-8\]

Where $H$ is the individual wave height and $A_o$ is described as:

$$A_o = \frac{8}{9\pi} C_D b_v N k \frac{\sinh^3 k \omega h + 3 \sinh k \omega h}{(\sinh 2k h + 2k h) \sinh k h}$$  \[2-9\]

Where $b_v$ is the plant area per unit height of each vegetation stand normal to $u$ (the horizontal velocity in the vegetation region due to the wave motion), $N$ is the number of vegetation stands per unit horizontal area and $C_D$ is a depth-averaged drag coefficient. Detailed descriptions of the derivation of $N$ and $b_v$ are provided in section 6.1. Solving the linear differential equation and assuming that the wave height at the seaward limit of the vegetation field is $H(x=0) = H_o$ the wave height evolution is equal to:

$$H = \frac{H_o}{1 + \beta_x} = K_v H_o$$  \[2-10\]

Where $K_v$ is the damping coefficient:

$$K_v = \frac{1}{1 + \beta_x}$$  \[2-11\]
and $\beta$ is:

$$\beta = \frac{A_oH_o}{2} = \frac{4}{9} C_D b_v N H_o k \frac{\sinh^3 k \omega h + 3 \sinh k \omega h}{(\sinh 2kh + 2kh) \sinh kh}$$ \[2-12\]

Using this relationship the $C_D$ value can be found at each location above the reef where a wave height measurement is taken. The $\beta$ can be fit to the data in order to parameterize a $C_D$ for the entire canopy.

In the event of irregular waves the $C_D$ value is not valid and an averaged drag coefficient ($\tilde{C}_D$) must be implemented which is valid for a random wave transformation model. For a flat bottom an expression similar to the expression used for a regular wave may be implemented:

$$\frac{\partial H_{rms}^2}{\partial x} = -B_o H_{rms}^3$$ \[2-13\]

where:

$$B_o = \frac{2}{3\sqrt{\pi}} C_D b_v N k \frac{\sinh^3 k \omega h + 3 \sinh k \omega h}{(\sinh 2kh + 2kh) \sinh kh}$$ \[2-14\]

When applying the boundary condition $H_{rms}(x=0) = H_{rms,o}$ the root-mean-square wave height evolution is equal to:

$$H_{rms} = \frac{H_{rms,o}}{1 + \tilde{\beta} x}$$ \[2-15\]

Where:

$$\tilde{\beta} = \frac{B_o H_{rms,o}}{2} = \frac{1}{3\sqrt{\pi}} C_D b_v N H_{rms,o} k \frac{\sinh^3 k \omega h + 3 \sinh k \omega h}{(\sinh 2kh + 2kh) \sinh kh}$$ \[2-16\]

Again, the $\tilde{C}_D$ value can be found at each location above the canopy where a wave height measurement is taken. The $\tilde{\beta}$ can be fit to the data in order to parameterize a $C_D$ for the entire canopy. The above theory has recently been implemented into XBeach and will be used to schematize a GC MAUS concept. The $C_D$ value extracted from the physical model can then be used to aid in the design and understanding of GC structures at various locations.

### 2.3 REEF HYDRODYNAMICS

This thesis introduces the relatively novel idea of using a numerical model to generate tailored wave time-series for a physical modelling campaign. This method was developed after it was deemed unpractical to replicate the steep fringing reef edge in a physical model due to the large model scale of 1:5. Wave breaking on a fringing reef edge is a critical process that must be incorporated. One cannot propagate regular or irregular waves from the laboratory wave paddle without including the effects of the wave transformation.
occurring at the reef edge. These effects have been extensively studied in literature and will be briefly discussed.

The shape of the reef profile, particularly the slope of the reef-rim and the relative elevations of the reef-edge and the reef-crest, affect the amount of energy dissipated by the waves breaking on the reef-rim and hence the magnitude of the wave set-up on the reef-top (Gourlay, 1996b). After the breaking of waves on the reef's seaward edge, regeneration of waves may occur over the reef, creating waves of lower height and shorter period (Gerritsen, 1980). These waves will experience continued energy dissipation, leading to a reduction in wave height as they propagate over the reef top. This is primarily due to bottom friction and breaking. For waves approaching a beach or a shallow reef, breaking occurs when the wave height over depth ratio assumes a critical value. Wave set-up does not occur if the water depth, over the reef is large enough to allow waves to pass over the reef without breaking (Gourlay, 1996a).

The following general characteristics have been documented:

1. Periodic waves propagating into shallow water are likely to demonstrate cnoidal characteristics (Gerritsen, 1980).
2. A solitary wave progressing over a sloping bottom onto a shelf or reef, where no breaking occurs, disintegrates into a train of solitary waves of decreasing amplitude, these are called solitons.
3. Incident waves usually have a narrow-band spectrum, often showing distinct wave group behavior. As the waves shoal and break, secondary waves are typically formed and are indicative of a nonlinear wave process. The wave attenuation is primarily at the expense of the energy near the peak frequency of the spectrum (Gourlay, 1996a). This is where nonlinear energy transfer takes place from the peak frequencies to higher and lower frequencies (Gerritsen, 1980).
4. The surf beat variation increases with reducing reef width and may amplify if the surf beat period corresponds with the natural period of the reef-top (Gourlay, 1996b).
5. The mean value of the wave set-up is unaffected by reef width when wave breaking is confined to the reef-rim, provided there is no escape of water either laterally or leeward (Gourlay, 1996a).

In the following analysis it will be assumed that conditions are reasonably two dimensional and that no significant escape of water either laterally along the reef or over the leeward reef-edge occurs. This establishes that wave induced set-up will become an important factor in producing an accurate wave climate on the modeled reef top. To incorporate these complex wave conditions, a series of transformations must be incorporated into the incoming wave signal on the reef flat.

2.3.1 Wave breaking

Wave breaking is a difficult phenomenon to capture accurately, however, these processes must be incorporated on the fringing reef. Lower frequency energy components are found in surf beat which are induced by the height modulation of the breaking waves and the corresponding variation in shoreward mass transport. The higher frequency waves are
generated in the breaking process in the form of secondary waves riding on the crests of the primary waves. As a result of these transformations, the mean period of the waves inside the reef is considerably lower than the period of the incident waves outside the reef (Gerritsen, 1980). These relationships must be well represented by the computational model used in this investigation to generate reef top-waves.

Due the mixing between air and water in breaking waves the interface is hard to define. Computational methods that can handle these types of problems are numerically intensive and too detailed for the current application. In the upcoming section the selected model (XBeach) will be described in detail. This model will be used in the non-hydrostatic mode. XBeach resolves the problem of resolving the breaking wave interface by modeling the free surface as a single valued function of the horizontal plane. Although this approach is more efficient it does mean that breaking waves can no longer be captured in detail. Instead, wave breaking is regarded as a sub-grid process. Thus the waves are allowed to steepen until the front face is almost vertical, but then the detailed process of breaking (spilling / overturning) is not modelled. (Smit, et al. 2014). For example, in Figure 2.3-1 XBeach would model a spilling breaker up to a point between step 2 and 3, and for a plunging breaker up to a point between 4 and 5.

In the region just before the surf-zone the wave is still steepening and both frequency dispersion and non-linear effects are important. Non-hydrostatic models include frequency dispersion and are therefore applicable in the region prior to breaking. Furthermore, because they reduce to the NSW equations for shallow water they can also be used after breaking has been initiated (Smit, et al. 2014). Zijlema and Stelling (2011) showed that their non-hydrostatic model is capable of predicting the breakpoint accurately using a conservative scheme for mass and momentum. No external parameters (such as a maximum steepness) which tell the model when breaking should be initiated are required.

XBeach uses an adapted version of the depth averaged non-hydrostatic model presented in Zijlema and Stelling (2008). Momentum and mass conservation are guaranteed using a conservative numerical method based on Stelling and Duinmeijer (2003). The model behaviour for wave breaking is therefore similar to their model. The largest differences are
due to the assumption of depth averaged flow. Due to this assumption linear dispersion is modelled less accurately and this can lead to overestimation of wave energies in the high frequency range. The position of the breaking point is unaffected but the amount of energy dissipation is underestimated and may therefore result in an overestimation of wave heights in the surf zone (Smit, et al. 2014). Execution of the model is discussed in more detail in section 4.2.1.

2.3.2  **Turbulence decomposition**

Apart from generating a representative wave signal in the flume and measuring the wave height reduction at various locations, the turbulence decomposition of the wave driven flow represents the most intensive analytical step in the analysis. The flow velocities recorded in the canopy due to the wave driven flow must be decomposed into turbulence attributed fluctuations and wave flow velocity, which can then be used to calculate the forces a larvae may experience on a GC element. The averaged velocity component found in the GC canopy is decomposed into the u,v,w directions with a turbulent component ($u'$) and a wave driven component ($\bar{u}$). These can be presented as follows:

\[
\begin{align*}
\bar{u} &= u' + \bar{u} \\
\bar{v} &= v' + \bar{v} \\
\bar{w} &= w' + \bar{w}
\end{align*}
\]

A number of methods were considered to accomplish decomposition into turbulent and wave driven flows. The methods identified and investigated are:

1. Ensemble averaging (for regular or bichromatic waves only).
2. Collated velocity measurements - Shaw & Trowbridge (2001)
4. Moving average method - Quintic Savitsky–Golay Fit
5. Correlation of the displacement of the free surface and high-frequency velocity measurement - Benilov and Filyushkin (1970)
6. Wavelet analysis

The first four methods mentioned were employed for this investigation. Proper documentation of the method from Benilov and Filyushkin (1970) was lacking and therefore this method could not be applied. Additionally it was found that wavelet analysis did not provide enough quantitative information to produce the required decomposed time series. This method was therefore abandoned at an early stage in the investigation. The remaining methods will be described in brief detail:

**Ensemble averaging**

Ensemble averaging is a method suitable for the decomposition of regular waves and longer bichromatic wave time-series. The ensemble average of a repetitive signal is defined by defining a fiducial time for each wave, creating the ensemble of time varying signals.
referenced to that time and then averaging across this ensemble at every time throughout the duration of the individual waves. The method requires a large number of time steps to accurately capture the average over all of the wave components. It is the easiest and least computationally intensive method for turbulence decomposition. However, the method cannot be applied for irregular waves as these time-series have no repetition and vary from wave to wave. An example is illustrated in section 6.2.1.

**Collated velocity measurements - Shaw & Trowbridge (2001)**

For irregular waves the method applied by Shaw & Trowbridge (2001) was analysed and applied. This method uses two velocity measurements spaced farther apart than the largest turbulence scale (approximately one quarter the water depth, but well within one wavelength of each other). Motions that correlate between the sensors are waves, while motions that do not correlate are turbulence. This method requires the use of two high frequency velocimeters, synchronized with each other. The set-up required to conduct this analysis is depicted in Figure 2.3-2 where the orientation and vertical position of the velocimeter are highlighted.

The underlying principle of the method introduced by Shaw & Trowbridge is that if \( \tilde{U}_1 \) and \( \tilde{U}_2 \) are perfectly coherent, then \( \tilde{U}_1 \) is completely predictable from \( \tilde{U}_2 \). To accomplish this a filter is applied \( h(t) \) which represents the relationship between the wave-induced fluctuations at the 2 locations. This is incorporated in the following relationship:

\[
\tilde{U}_1(t) = \int_{-\infty}^{\infty} h(t')\tilde{U}_2(t - t')dt'
\]  

[2-18]

The estimated wave velocity \( \tilde{U}_1 \) contains a turbulence component, but it is of no consequence if the assumption that the turbulence is spatially incoherent is valid. If the estimates \( \text{cov}[\Delta U, W_1] \) and \( \text{cov}[\Delta W, U_1] \) are replaced by \( \text{cov}[\Delta \tilde{U}, W_1] \) and \( \text{cov}[\Delta \tilde{W}, U_1] \), respectively. The filter weights \( h(t') \) are estimated by finding the ordinary least squares solution of a transversal filter model that has been modified to non-causal form for post processing purposes (Shaw & Trowbridge, 2001):

\[
Ah = U_1
\]  

[2-19]
Where \( A \) is an \( M \times N \) windowed data matrix of velocity at position (2), where \( M \) is the number of data points and \( N \) is the number of filter weights (\( N \) must be odd for the filter to be symmetric). In the current study \( N \) was taken as the peak period multiplied by the recording interval of the vectrino profiler (100Hz) to be used in the flume studies. Therefore, \( h \) is a vector of filter weights, and \( U_1 \) is a vector of position (1) velocity. The solution is then:

\[
\hat{h} = (A^T A)^{-1} A^T U_1
\]  

[2-20]

And the estimates of \( \tilde{U}_1 \) of the wave induced velocity at the position (1) are found by convolving the measured velocity records with the estimated filter weights:

\[
\tilde{U}_1 = A \hat{h}
\]  

[2-21]

The vectrino profiler measures 3 velocity components, and therefore the filtered estimate must be expanded to a \( M \times 3N \) data matrix \( A \) with the form:

\[
\begin{bmatrix}
u \left(m - \frac{N-1}{2}\right), ..., u(m), ..., u \left(m + \frac{N-1}{2}\right), \\
\nu \left(m - \frac{N-1}{2}\right), ..., v(m), ..., v \left(m + \frac{N-1}{2}\right), \\
w \left(m - \frac{N-1}{2}\right), ..., w(m), ..., w \left(m + \frac{N-1}{2}\right)
\end{bmatrix}
\]  

[2-22]

For this technique to work in practice, the sensor separation must be large relative to the correlation length scale of the turbulence so that the turbulence cross-correlation terms are small. Sensor separation length is taken as \( r > 5z \) as determined by empirical relationships established by Trowbridge and Shaw. However the need to impose the limitations is tested and challenged later on in the investigation in section 5.2. Further considerations include instrumentation bias which may be attributed to inconsistent instrumentation placement and changes in the bed level and slope. However, with a flat flume bottom and constant instrument placement, these limitations should not significantly affect the data.

**Spectral wave-turbulence decomposition – Bricker & Monismith (2007)**

The following method uses the phase lag between the \( u \) and \( w \) components of the surface waves to interpolate the magnitude of turbulence under the wave peak. The wave stress is calculated through the spectral sum:

\[
\overline{u\bar{w}} = \int_{-f_{Nyquist}}^{f_{Nyquist}} S_{\bar{u}\bar{w}}(f)df
\]  

[2-23]

where \( S_{\bar{u}\bar{w}}(f) \) is the 2-sided cross-spectral density (CSD) of the wave-induced orbital velocities, \( f \) is frequency and \( f_{Nyquist} \) is the Nyquist sampling frequency, which is half the
sampling frequency of the discrete signal. The turbulence spectrum can be expressed as the difference between the spectrum of raw velocities and that of wave-induced orbital velocities such that:

\[ S_{u'w'}(f) = S_{uw}(f) - S_{\overline{uw}}(f) \]  \hspace{1cm} [2-24]

The CSD of the spectra in eq. 2-24 are then integrated to obtain the turbulent Reynolds stress:

\[ \overline{u'w'} = \overline{uw} - \overline{\overline{uw}} \]  \hspace{1cm} [2-25]

The velocities, \( u(t) \) and \( w(t) \) become \( U_j = U(f_j) \) and \( W_j = W(f_j) \) which are the Fourier transforms at a certain frequency in the Fourier transform. The integral of a wave stress then becomes:

\[ \overline{\overline{uw}} = \sum_{j=N/2}^{j=-N/2} \overline{U_j} \overline{W_j} \]  \hspace{1cm} [2-26]

Where \( N \) is the number of data points used in the Fourier transform and the magnitude of \( \overline{W_j} \) is the difference between the raw \( W_j \) and the turbulence \( W'_j \) interpolated below the wave peak, via a least-squared fit straight line. \( \overline{W_j} \) is solved for by expressing the wave stresses in terms of power spectral density (PSD):

\[ S_{wwj} = \frac{1}{d_f} |W_j|^2 \]  \hspace{1cm} [2-27]

The same method is used to solve for \( \overline{U_j} \). The Fourier coefficients can be written in phasor notation as:

\[ \overline{\overline{uw}} = \sum_{j=\text{wave peak}} \overline{U_j} \overline{W_j} = \sum_{j=\text{wave peak}} |\overline{U_j}||\overline{W_j}||\cos(<W_j- <U_j) \]  \hspace{1cm} [2-28]

Where \( <W_j \) and \( <U_j \) are the phases of the Fourier coefficients. The wave stress is then found by integrating the wave components over the width of the wave peak and subtracting it from the integral of the total stress, over the full frequency spectrum in order to obtain the Reynolds stress. The resulting averaged wave driven flow can be used to find turbulent kinetic energy and turbulent shear stress profiles. However, this method does not allow for decomposition of time series and is therefore not suitable to analyze wave driven forces on a GC member over time. An example is illustrated in section 6.2.1.
Moving average method - Quintic Savitsky–Golay Fit

Although not often cited in literature as a preferred method, a moving average turbulence decomposition scheme was applied as a way to compare the results obtained from the various schemes mentioned above. A number of moving average techniques exist, of which the Quintic Savitzky–Golay filter provided the most agreeable results. It is a filter that smooths the data to increase the signal-to-noise ratio without greatly distorting the signal. This is achieved, in a process known as convolution, by fitting successive sub-sets of adjacent data points with a low-degree polynomial by the method of linear least squares. The resulting fit to the wave signal provides a good estimate of the wave driven flow, with the original signal scatter providing information on the turbulent components of the signal. An example is illustrated in section 6.2.1.
Chapter summary: The following chapter presents the results of a number of extensive data collection efforts in order to provide the required boundary conditions for testing and the data sets needed to compare the test results with observations from laboratory and field work.

A comprehensive literature review was conducted of approximately 50 fringing reef studies, collecting data of 30 reefs worldwide. This consisted of typical offshore conditions and reef top observed water levels, wave heights, periods, and bathymetry profiles. The range of inputs will be used to generate the wave conditions in the flume using a numerical modelling approach.

A database of well documented aquatic species studied on the pacific west-coast of North America is introduced. The thresholds for lift, shear and drag forces for a variety of species is listed in preparation for the final analysis of the expected in-canopy flow conditions. It should be noted that most of these species are found in the Pacific Northwest down to the Mexican pacific coast. This is primarily due to the fact that this region is very well studied with a lot of valuable data readily available for this study. Although not applicable on a global level, these thresholds should give a good indication of survivorship in the GC MAUS in high energy wave environments typical to the North American Pacific coast.

Coraline larvae are also introduced, such as the well-studied Phestilla Sibogae native to the tropical portions of the Indian and western Pacific Oceans ranging from Panama to western Africa. The collected data from these species will be extensively used in section 7.0.

Afringing reef bathymetry will likely be too large to construct in the flume at a 1:5 scale. Therefore, a hybrid of a computational and numerical model is needed. To construct both of these models an extensive understanding of the expected hydrodynamic conditions on the reef top is required. This includes:

- Offshore wave period, and recorded water levels
- Reef flat water levels and wave conditions
- Tidal variations
- Fringing reef bathymetric profiles
- Canopy heights above the ocean floor
- Reef width and length
3.1 GLOBAL HYDRODYNAMIC REEF SURVEY

Typical hydrodynamic conditions offshore from a fringing reef and on top of the reef flat must be better understood. A comprehensive literature review was conducted of approximately 50 studies, collecting data of various fringing reefs around the world. The review considers the locations illustrated in Figure 3.1-1. A large database of global fringing reef characteristics was not readily available. For the purpose of this study, this newly developed data set was assembled. Such a collection of information can prove to be useful in future studies.

![Figure 3.1-1: Study sites - hydrodynamic conditions on fringing reefs](image)

1. Kaneohe Bay – Hawaii – USA
2. Sandy Bay – Kaneohe Reef – Australia
3. Coral Bay – Kaneohe Reef – Australia
4. Paapa Bay - Moorea – French Polynesia
5. Bora Bay – Miyako Island – Japan
6. Heron Island – Queensland – Australia
7. John Brewer Reef – Queensland – Australia
8. Rib Reef – Queensland – Australia
9. Yonge Reef – Queensland – Australia
10. Abore Reef – New Caledonia
11. Hanalei Bay – Hawaii - USA
12. Pelekane Bay – Hawaii – USA
13. Kahana Reef – Hawaii – USA
15. Asan Bay – Guam – USA
17. Glover Reef – Belize
18. Great Pond Bay – St. Croix
19. Mokuleia Beach – Hawaii – USA
20. Lady Elliot Island – Queensland – Australia
22. Kwajalein Atoll – Marshall Islands – USA
23. Ipan – Guam – USA
24. Bamburi Lagoon – Kenya
25. Male Island – Maldives
26. Lifuka Island - Tonga

Each of the locations presented in Figure 3.1-1 was reviewed from previous research which provided information such as, offshore/reef top water level time series, reef bathymetry, tide and set-up, canopy height, wave spectra and results from numerical modelling. The aim was to analyze fringing reefs on a global scale with representative sites across the tropics and subtropics.

All available fringing reef profiles were extracted and plotted in order to generate a generic reef profile which could be used for the analysis. This profile is presented in Appendix 1, section 1.0. Figure 3.1-2 summarizes all of the data collected from the various studies. The maximum, minimum and average of each data set, or point is displayed. All of the data presented represent in-situ measurements and field observations, but does not necessarily capture extreme events in all cases. The data may be considered as a good representation of typical conditions. Of the reefs studied in Figure 3.1-2 the most important characteristics for the current flume study are the wave period, height and water level observed on the reef.

Figure 3.1-2: Summary of literature review (fringing reefs)

01-14: Kaneohe Bay – Hawaii - USA
15-18: Sandy Bay – Kaneohe Reef – Australia
19 : Coral Bay – Kaneohe Reef – Australia
20 : Paopao Bay - Moorea – French Polynesia
21 : Bora Bay – Miyako Island – Japan
22 : Heron Island – Queensland – Australia
23-26: John Brewer Reef – Queensland – Australia
27 : Rib Reef – Queensland – Australia
28 : Yonge Reef – Queensland – Australia
29-32: Abore Reef – New Caledonia
33 : Hanalei Bay – Hawaii – USA
34-36: Pelekane Bay – Hawaii – USA
37 : Shiraho Reef – Ishigaki-shima – Japan
38 : Great Pond Bay – St. Croix
39 : Asan Bay – Guam – USA
40 : Sheikh Said Island – Eritrea
41 : Glover Reef – Belize
42 : Mokuleia Beach – Hawaii – USA
43-45: Lady Elliot Island – Queensland – Australia
46-47: Pelekane Bay – Hawaii – USA
48-51: Majuro Atoll – Marshall Islands – USA
52-54: Kwajalein Atoll – Marshall Islands – USA
55-58: Ipan – Guam – USA
59 : Bamburi Lagoon – Kenya
60-61: Male Island – Maldives
62 : Lifuka Island - Tonga
Although Figure 3.1-2 is a good overview of the conditions which can be found on the reef flat, complete time series provide more valuable long-term data. This can be analyzed statistically to find the distribution of available data. The various studies which provided more information are presented in Appendix 1, section 2.0 and will be summarized in this report. Offshore conditions were particularly important for the input in the XBeach model to generate the reef top conditions. These are displayed in Figure 3.1-3, where the offshore measured wave period (Tp) and wave height (Hs) for various locations are observed.

The data in Figure 3.1-3 is summarized in Table 3.1-1, where the distributions will be used as input for the XBeach offshore locations.

<table>
<thead>
<tr>
<th>Percentile</th>
<th>Peak period (s)</th>
<th>Hrms (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5th</td>
<td>3.63</td>
<td>0.22</td>
</tr>
<tr>
<td>15th</td>
<td>4.78</td>
<td>0.34</td>
</tr>
<tr>
<td>50th</td>
<td>8.01</td>
<td>0.68</td>
</tr>
<tr>
<td>75th</td>
<td>10.83</td>
<td>1.28</td>
</tr>
<tr>
<td>95th</td>
<td>14.16</td>
<td>1.97</td>
</tr>
<tr>
<td>99th</td>
<td>16.36</td>
<td>2.64</td>
</tr>
</tbody>
</table>

The transformation from offshore conditions to reef top conditions will be calibrated using various time-series recorded on the reef top. The time series are displayed in Figure 3.1-4 and illustrate the thresholds of wave height versus reef top water levels recorded on various fringing reefs worldwide.
As with the offshore conditions the distribution of the data was analyzed in Table 3.1-2 and used to determine the boundary conditions in which the tests would take place. In Figure 3.1-4 it can be seen that clear families of data exist. This is due to the specific fringing reef characteristics. Although all the reef edge bathymetries of the reefs in Figure 3.1-4 are quite different, there is a clear trend of increasing wave height as water depth increases. A larger data set would provide a better indication of the types of conditions on fringing reef flats worldwide. However, these were not readily available. The data sets from Ningaloo reef is an outlier, with relatively low wave heights for deeper water levels. This may be explained by the local wave climate which is composed of longer low-amplitude infragravity waves unique to this geographical location. This is therefore an important wave climate to incorporate and is not removed from the analysis in Table 3.2-2 where the distribution of the data is analyzed.

Table 3.1-2: Reef top wave hydrodynamic parameters collected from field campaigns

<table>
<thead>
<tr>
<th>Percentile</th>
<th>Depth (m)</th>
<th>$H_{rms}$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5th</td>
<td>0.28</td>
<td>0.03</td>
</tr>
<tr>
<td>15th</td>
<td>0.54</td>
<td>0.06</td>
</tr>
<tr>
<td>50th</td>
<td>1.24</td>
<td>0.15</td>
</tr>
<tr>
<td>75th</td>
<td>1.70</td>
<td>0.28</td>
</tr>
<tr>
<td>95th</td>
<td>2.15</td>
<td>0.46</td>
</tr>
<tr>
<td>99th</td>
<td>2.41</td>
<td>0.57</td>
</tr>
</tbody>
</table>

With the desired hydrodynamic boundary conditions, the time series required for the numerical model can be prepared for the numerical modelling analysis presented in chapter 4.0.
3.2 ECOLOGICAL PARAMETERS

The following section provides the adhesive strengths and settling thresholds for various aquatic species, including limpets, muscles, urchins, and a number of algae species. These species are not necessarily found in all coral reef environments, however they provide a good indication of recruitment and survivorship of species in high energy environments. Coral larvae found in coral reef habitats will also be considered in this study. The data collected in this section will be used to determine whether the in-canopy hydrodynamic conditions exceed the thresholds needed for these species to successfully establish themselves. Larvae that stick to surfaces upon contact (e.g. larvae of barnacles, bryozoans, some cnidarians) can settle on surfaces exposed to high water velocities, whereas larvae that develop their adhesion to surfaces more slowly are able to settle only in spots where peak local shear stresses during burst-sweeps are too low to dislodge them (Koehl, Hadfield 2004).

Adhesive strengths of larvae have only been measured for a few species and dictates where a larval species is able to settle in complex habitats exposed to turbulent flow (e.g. Abelson et al. 1994; Abelson & Denny, 1997; Crimaldi et al. 2002) (M. A. R. Koehl 2007). Adhesive strengths have been measured for species such as the Semibalanus balanoides (Yule and Walker 1984), Balanus amphitrite (Eckman et al. 1990), and the nudibranch Phestilla siboga (Koehl and Hadfield 2004). From these sources it was determined that the Phestilla siboga is a good candidate for this study as it is currently one of the most well documented larval species worldwide. Information regarding the adhesive strength of this species is essential in determining if recruitment can occur within the GC MAUS similar to that in a natural coral reef canopy.

3.2.1 Marine species & organisms

Limited studies have been performed on the dislodgement thresholds of marine species in wave driven flow. However, studies from Denny, (1995), Gaylord, Blanchette, Denny (1994), Denny (1993), and Reidenbach et. al. (2009) provide a good basis to determine the feasibility of larval adhesion and retention once settlement has occurred. The threshold of allowable drag and lift forces for various plant species and canopy organisms is collected and presented in the following section. The species used for this analysis are presented in Table 3.2-1 and displayed in Figure 3.2-1.

- **Lottia pelta**
- **Balanus glandula**
A brief description of each species is given below:

- **The *Mytilus californianus*** (California mussel), is a large a marine bivalve mollusk in the family *Mytilidae*. This species is native to the west coast of North America, occurring from northern Mexico to the Aleutian Islands of Alaska. California mussels are found clustered together, often in very large aggregations, in the upper intertidal zone on the open coast (Schmidt, 1999).

- **Balanus Glandula** is one of the most common barnacle species on the Pacific coast of North America, distributed from the U.S. state of Alaska to Bahía de San Quintín near San Quintín, Baja California. It has been intensely studied in recent years as a model species for linking physical oceanography and population genetics surveys (Morris et al 1980).

- **Lottia Pelta**, common named the shield limpet, is a species of sea snail in the family Lottiidae. The shield limpet is found in the intertidal zone on rocks and kelp holdfast from Alaska to Baja California. The largest specimens occur in the northern part of the range (Sorensen & Lindberg 1991).

- **Strongylocentrotus Purpuratus** (The purple sea urchin) lives along the eastern edge of the Pacific Ocean extending from Ensenada, Mexico to British Columbia, Canada. This sea urchin species is deep purple in color and lives in lower intertidal and nearshore subtidal communities (Ricketts & Calvin 1939).

It should be noted that most of these species are found in the Pacific Northwest down to the southern Mexican pacific coast. This is primarily due to the fact that this region is very well studied with a lot of valuable data readily available for this study. Although not applicable on a global level, these thresholds should give a good indication of survivorship in the GC MAUS in high energy wave environments typical to the North American Pacific coast. The next section covers the well-studied specie *Phestilla Sibogae* which may be more applicable in a coral environment. However, more indicators are require to understand the thresholds of the GC MAUS structure. In forthcoming research more data should be made available of various aquatic organisms and their environmental thresholds.
For each species the following relationship can be used to determine the maximum predicted breaking force which is required to dislodge the organism from the surface it has decided to settle.

\[ F_p = j + mA^q \]  

[3-1]

The predicted breaking force, \( F_p \), varies with the size of organisms. For present purposes, size is quantified by a characteristic area \( A \) and \( j \), \( m \), and \( q \) are empirical coefficients determined from laboratory experiments conducted with various aquatic species. The results of these experiments are depicted in Table 3.2-1 for each individual species.

**Table 3.2-1: Various aquatic species and their adhesive strengths**

<table>
<thead>
<tr>
<th>Species</th>
<th>Family</th>
<th>A (m²)</th>
<th>J (N)</th>
<th>( m ) (dimensionless)</th>
<th>( q ) (dimensionless)</th>
<th>FL (N)</th>
<th>FD (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M. californianus*</td>
<td>Mussel</td>
<td>0.001</td>
<td>7.2676</td>
<td>486300</td>
<td>1.1903</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B. glandula*</td>
<td>Barnacle</td>
<td>0.0176</td>
<td>10.0138</td>
<td>96540000</td>
<td>1.5130</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lottia pelta***</td>
<td>Limpet</td>
<td>5.77.\times10^{-4}</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>23</td>
<td>35</td>
</tr>
<tr>
<td>Strongylocentrotus purpuratus***</td>
<td>Urchin</td>
<td>3.9.\times10^{-3}</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>148</td>
<td></td>
</tr>
</tbody>
</table>


Besides analyzing various living organisms it is also beneficial to study prominent plant species, such as algae which may settle on the GC surfaces. This will give an indication of the types of organic matter which may settle on the GC surfaces which could improve and in some cases hinder the establishment of other aquatic species and coral larvae. The selected vegetation types are depicted in Figure 3.2-2.

![Mastocarpus papillatus](image1)

![Mazzaella flaccida](image2)
A brief description of each plant type is given below:

- **Mastocarpus Papillatus** has flattened dark to brownish red blades that are thin yet tough. Range extends from Alaska to Pta. Baja, Baja California (Carrington, 1990).

- **Pelvetiopsis Limitata** are infrequent, on tops of rocks, rarely on sides; upper intertidal, frequents more wave-exposed sites and are found from Vancouver Island, British Columbia, to Cambria (San Luis Obispo County), CA (Abott & Hollenberg 1976).

- **Mazzaella Flaccida** is light tan to olive; densely branched, cylindrical at the base becoming flattened to cylindrical in the upper fronds; dichotomous; branches tend to arch inward. Mazzaella flaccida is abundant in the mid to low intertidal zones. The two subspecies of *M. splendens* have a combined range that extends from southeast Alaska to Punta Baja, Baja California (Abott & Hollenberg 1976).

- **Gigartina Leptorhynchos** is bushy, irregularly branched, and appears woolly with many elongate papillae on margins & faces of branches; dark brown to blackish. Common in Northern California to northern Baja growing in patches in the lower mid-intertidal zone, in the protected outer coast.

As with the aquatic species, the vegetation can also be parameterized using a series of empirical coefficients derived from laboratory testing to determine the maximum predicted breaking force which is required to dislodge the vegetation from the surface it inhabits.

\[ F_b = z_1 + z_2A^{z_3} \]  \[ \text{[3-2]} \]

The breaking force may be estimated using the coefficients $z_1$, $z_2$, $z_3$ determined from laboratory experiments. The results for each plant species is depicted below in Table 3.2-2.
### Table 3.2-2: Various plant species and their adhesive strengths

<table>
<thead>
<tr>
<th>Species</th>
<th>Family</th>
<th>$A$ (m$^2$)</th>
<th>j</th>
<th>m</th>
<th>q</th>
<th>$F_{av}$ (N)</th>
<th>Z1</th>
<th>Z2</th>
<th>Z3</th>
</tr>
</thead>
<tbody>
<tr>
<td>M. papillatus*</td>
<td>Algae</td>
<td>0.0007</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.63</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>G. leptorhynchos*</td>
<td>Algae</td>
<td>0.004</td>
<td>2.23</td>
<td>31.93</td>
<td>0.35</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>P. limitat*</td>
<td>Algae</td>
<td>0.003</td>
<td>8.66</td>
<td>260.73</td>
<td>0.49</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>I. flaccida*</td>
<td>Algae</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>12.09</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>I. flaccida**</td>
<td>Algae</td>
<td>0.0083</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>44.8</td>
<td>0.353</td>
<td>0.260</td>
</tr>
<tr>
<td>G. leptorhynchos**</td>
<td>Algae</td>
<td>0.0039</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.23</td>
<td>31.9</td>
<td>0.353</td>
<td></td>
</tr>
<tr>
<td>P. limitata**</td>
<td>Algae</td>
<td>0.0034</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>8.66</td>
<td>260.7</td>
<td>0.494</td>
<td></td>
</tr>
</tbody>
</table>

Note: $z_1$, $z_2$, $z_3$, m, j and q are dimensionless

#### 3.2.2 Phestilla Sibogae

Limited data is available for field-sampled coral larval settling and its associated adhesive strengths. However, one the most well studied larval species is the *Phestilla Sibogae*, which will be used in this study due to the abundance of available scientific data. Reidenbach et. al. (2009) suggested that the nudibranch *Phestilla Sibogae* (depicted right of Figure 3.2-4) is currently the most ideal species to study due to the fact that it has for many years been a model organism in studies of larval settlement and metamorphosis, and thus there is a wealth of background information available.

The recruitment process of a larva (*Fungia scutaria* - a species of plate or mushroom coral in the family Fungiidae) is depicted in Figure 3.2-3, this process is similar for most coralline species (Schwarz et. Al, 1999) and larval inhabitants such as the *Phestilla Sibogae*. The *Fungia scutaria* depicted to the right of Figure 3.2-3 is also found in Kaneohe Bay, Hawaii as is the *Phestilla Sibogae*, however very little information exists regarding its behavior during recruitment from a hydrodynamic perspective. The recruitment process of the *Fungia scutaria* can however, be compared to that of a *Phestilla Sibogae* due to similar settlement rates, swimming speeds, and environmental conditions at Kaneohe Bay (Schwarz et. Al, 1999). It is recognized that in future research a much larger data set of larval species is required to obtain a more comprehensive and encompassing study of larval adhesion and retention with a MAUS canopy.

![Figure 3.2-3: Larval recruitment process](source: Schwarz J.A. et. al (1999) – (L), B.W. Hoeksema – (R)
The *Phestilla Sibogae* is representative of a large geographic area. The species is found in the tropical portions of the Indian and western Pacific Oceans and ranges from Panama to western Africa. This makes it an important indicator as it applies to most of the case studies presented in the fringing reef hydrodynamics review presented earlier. The nudibranch *Phestilla Sibogae* feeds only on corals of the genus *Porites Compressa* (depicted left of Figure 3.2-4) and generally requires the host to be present for successful spawning and settlement. This means that these “hosts” must be present in an area where a GC MAUS is installed. This limitation can be overcome by introducing the chemical inducers or “cues” which the *Porites Compressa* releases naturally to instigate the settlement of *P. Sibogae*. Such seeding techniques of chemical cues and larvae have been successfully applied in the Florida Keys.

![Figure 3.2-4: (L) Phestilla Sibogae, (R) coral Porites Compressa](source: (Gov. Australia, 2013))

Many *P. sibogae* larvae fail to attach within the 2hr time-span required for settling and are washed off surfaces at the top of a reef. These larvae sink into the spaces within the reef where they are likely to land on surfaces exposed to lower, less frequent events that could dislodge them (Hadfield et al. 2007). Larval adhesion strengths must be known to understand the successful recruitment of *P. sibogae*.

If adhesion is successful, metamorphosis can take place, which takes 12 to 24h and requires larval exposure to inducer of at least 6h. However, once larvae of *P. sibogae* enter the slow-moving water within the structure of a coral reef, they are likely to remain in contact with *P. compressa* inducer and surfaces for many hours, such that settlement and recruitment can occur (Koehl & Hadfield 2004). The hydrodynamic forces which *P. sibogae* can withstand will be implemented in section 7 to analyze the success of coral larvae recruitment in the GC canopy.
NUMERICAL MODELLING

Chapter summary: The following chapter considers the various methods available to construct the time series required to drive the wave paddle flume which generates the desired reef top conditions. The use of a computational model was found to be the most economical method to produce the required time series. This could be done by resolving individual wave conditions (both long and short) using a non-hydrostatic module in the open-source model XBeach. The process required to generate the wave paddle time series is discussed in detail.

The wave transformation from offshore to reef top conditions is simulated in XBeach for monochromatic, bichromatic and irregular waves. The reef top signal is then split into incoming and reflecting components using a method proposed by Guza, (1984) which assumes the shallow water relationships where all waves move at the same speed. The incoming signal is then despiked to ensure that the wave paddle can produce the required paddle accelerations to generate the higher harmonic signals in the time series. This despiked incoming signal is then scaled down to a 1:5 scale using Froude scaling. Using the program DELFT-AUKE the signal is transformed to the mechanical wave paddle time series using the principals of a Biesel transfer function. This time series requires some adjustments and calibration before it is ready to be used in the flume.

A newly implemented vegetation canopy module in XBeach using the principles of Mendez & Losada (2004) is also used. Estimates of the canopy characteristics are implemented in the module to observe the effects of varying the reef geometry for a constant set of wave conditions. Output from these simulations is used to determine the 2 reef set-ups required for flume tests.

Using a numerical model the offshore wave conditions can be transformed onto the reef flat after they have broken on the reef edge. The reef flat is uniform enough to be schematized by the smooth flume bottom without any major adjustments to the flume itself. This hybrid approach allows for a more efficient modeling campaign. A series of steps required to generate the physical model wave inputs are illustrated in Figure 3.2-1.

Figure 3.2-1: Process required to generate physical model wave input
Each of these steps will be discussed in detail in the upcoming section. The methods which were considered to determine the wave signal on the reef flat are described in detail in Table 3.2-1. The table was used to determine the optimum method for the current investigation.

<table>
<thead>
<tr>
<th>METHOD</th>
<th>ADVANTAGES</th>
<th>DISADVANTAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ONE: 2 STAGE PHYSICAL MODEL</strong></td>
<td>• No numerical modelling required. • Conditions reproduced well. • High resolution time series • Easy to generate signals for a variety of wave types / tests</td>
<td>• Costly in terms of funding and time • Only allows modelling of one specific scenario • Reduces time available for testing of study focus (MAUS structure) • Limited by flume size and scaling</td>
</tr>
<tr>
<td>This method requires 2 physical models. First a physical model at a scale of &gt;1:20 is constructed of the fringing reef. The incoming waves are extracted as a time series at the desired location. A second physical model is then constructed at a scale of &lt;1:5 of the reef top where the time series extracted from the previous model can be used as an input.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TWO: NUMERICAL MODEL</strong></td>
<td>• Allows for the schematization of many types of reefs • Allows for multiple iterations of tests / waves • Generates more information • Less expensive • Prepares numerical framework for analysis of physical model results.</td>
<td>• Computationally expensive • Some processes are simplified • Requires more time to prepare physical model testing</td>
</tr>
<tr>
<td>The fringing reef is schematized numerically and an offshore wave signal is transformed to a signal on the reef top. The signal is extracted, scaled according to Froude and transformed to a wave paddle signal which can be used as input for 1 physical model of the reef flat alone.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>THREE: FILTERED FIELD DATA</strong></td>
<td>• Wave signal a true representation of reality • Requires less preparation time prior to physical model testing • Easiest method</td>
<td>• Only portrays conditions of the sites where data is available • Unable to portray monochromatic or bichromatic waves</td>
</tr>
<tr>
<td>Existing field data of time series on a reef flat is scaled according to Froude and transformed to a wave paddle signal which can be used as input for 1 physical model of the reef flat alone.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>FOUR: EMPIRICAL RELATIONSHIPS</strong></td>
<td>• Requires no numerical or physical model set-up • Quick computation once computational framework has been established</td>
<td>• Not very accurate • Requires extensive algebraic manipulations • Applies to idealized scenarios</td>
</tr>
<tr>
<td>Using theoretical relationships for wave set-up and breaking waves at the reef edge, wave characteristics can be estimated to produce a theoretical time series of wave conditions on the reef edge.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Upon careful consideration it was determined to select method 2 for the current investigation. The flexibility obtained by using this method outweighs the advantages of the other methods suggested in Table 3.2-1. The main disadvantages of method 1 is that it requires too much time and material costs, method 3 is too limiting in terms of available field data, and method 4 only provides an idealized time series devoid of smaller perturbations associated with reef top wave breaking, such as wave skewness and asymmetry. Therefore, the preferred choice is selecting a numerical model to execute the steps described in Figure 3.2-1.
4.1 SELECTION OF A COMPUTATIONAL MODEL

To successfully complete the numerical modeling of the wave climate on the fringing reef, a numerical model must be selected. Numerical wave models can be considered in two categories: stochastic (phase-averaged) and deterministic (phase-resolving). Stochastic models simulate wave processes in a probabilistic manner whereas deterministic models simulate wave processes based on the conservation laws (mass and momentum) (Buckley M., Lowe, 2013). Phase averaged models such as XBeach solve the depth averaged non-linear shallow water (NLSW) equations in a Generalized Lagrangian Mean (GLM) formulation (Andrews and McIntyre, 1978). These equations are forced by a time-dependent wave action balance similar to the 2nd generation spectral HISWA model Holthuijsen et al. (1989). Examples of phase resolving models are the Boussinesq (e.g. Chen et al., 2000) and non-hydrostatic models (e.g. Casulli and Stelling, 1998) such as SWASH (Zijlema et al., 2011). These models resolve the wave field on the timescale of individual waves and are as such capable of modelling the non-linear evolution of the wave field accurately (Smit, et al. 2014).

Three models were considered in this study, these were SWASH (Zijlema et al., 2011), XBeach (Roelvink et al., 2009), and SWAN (Booij et al., 1999). SWAN was disregarded early on in the process because the model does not incorporate low frequency waves which, as noted by Demirbilek et al. (2007), account for ~1/2 the total energy on fringing reefs. Therefore only SWASH and XBeach will be considered further.

The SWASH model (Zijlema et al., 2011) is a shock-capturing hydrodynamic model for simulating non-hydrostatic free-surface flows. The model is based on the non-linear shallow water equations, including non-hydrostatic pressure, which are derived from the incompressible Reynolds Averaged Navier Stokes equations that describe conservation of mass and momentum. In principal, shock-capturing non-hydrostatic models inherently account for the energy dissipation in the surf-zone due to breaking waves. This however requires high vertical resolutions and is subsequent computationally expensive (Van Vledder, Ruessink, Rijnsdorp, 2013). Modelling of a fringing reef using SWASH has recently been completed by Zijlema, (2011) and Buckley & Lowe (2013).

The XBeach model by Roelvink et al. (2009) is a numerical model of near shore processes intended as a tool to assess the natural coastal response during time-varying storm and hurricane conditions, including dune erosion, overwash and breaching. The model consists of formulations for short wave envelope propagation, non-stationary shallow water equations, sediment transport and bed update. XBeach has been used to model fringing reefs by Bodde (2013), Buckley & Lowe (2013), Van Dongeren et al. (2013), and Pomeroy et al. (2012). More recently (Smit, et al. 2014), the capability to model the wave field using a phase resolving model, has been added as an extension to XBeach.

Upon comparison of SWASH and XBeach it was decided to use XBeach for the following reasons:

1. The generated wave input for the physical model can be used at a later stage when reproducing the physical model tests in a numerical wave flume. These tests can make
use of the XBeach vegetation canopy module which can be calibrated to schematize the MAUS in a computational model. Calibrating such a module is one of the goals outlined in this study.

2. The implementation of the non-hydrostatic model as described by Zijlema and Stelling (2008) and the second order scheme based on a flux limited version of the McCormack scheme implemented into XBeach by Smit, et al. (2014) allows for reasonably comparable performance of modelling of short waves as in SWASH.

3. Replication of field measurements taken on a fringing reef have successfully been reproduced with previous XBeach models (Van Dongeren et al. 2013).

4. A calibrated model of Ningaloo Reef (Australia) was made available for initial testing of the non-hydrostatic phase resolving model in XBeach.

5. Extensive documentation and model support is readily available. The results presented in this thesis must be easily applicable for those intending to use XBeach as a design tool to implement a MAUS structure. XBeach provides a more established support community than SWASH for those using the model for the first time.

6. Traditionally, deterministic models such as SWASH resolve individual waveforms, requiring a grid resolution fine enough to capture the shortest wave length (highest frequency) waves of interest in a study. This requires more computation power than stochastic models. A stochastic models such as XBeach does not have the same restriction on grid resolution or time steps allowing much larger scale and longer term studies to be conducted (Buckley, Lowe, 2013). Although XBeach will likely be used in non-hydrostatic mode, a combination of hydrostatic and non-hydrostatic simulation can be considered to reduce computational time.

### 4.2 XBEACH

XBeach can function in 3 distinct modes. These are surf-beat, Hydrostatic, and non-hydrostatic. A brief overview of the 3 model modes is given in Table 4.2-1 with advantages and disadvantages. For the current investigation XBeach will be run exclusively in non-hydrostatic mode using the non-linear shallow water equations (NSWE). Although computationally more expensive, and not much used, it is the most reliable way to resolve individual short waves breaking on the reef edge.

<table>
<thead>
<tr>
<th>Table 4.2-1: XBeach run options</th>
</tr>
</thead>
<tbody>
<tr>
<td>SURF BEAT</td>
</tr>
<tr>
<td>HYDROSTATIC</td>
</tr>
<tr>
<td>NON-HYDROSTATIC</td>
</tr>
<tr>
<td><strong>Hydrodynamics</strong></td>
</tr>
<tr>
<td>• Action balance</td>
</tr>
<tr>
<td>• NSWE</td>
</tr>
<tr>
<td>• Extended NSWE</td>
</tr>
<tr>
<td><strong>Advantages</strong></td>
</tr>
<tr>
<td>• Computationally cheap</td>
</tr>
<tr>
<td>• Model boundary on deep water</td>
</tr>
<tr>
<td>• Commonly used</td>
</tr>
<tr>
<td>• Information on individual wave scale</td>
</tr>
<tr>
<td>• Accurate</td>
</tr>
<tr>
<td>• Commonly used</td>
</tr>
<tr>
<td>• Information on individual wave scale</td>
</tr>
<tr>
<td>• Accurate</td>
</tr>
<tr>
<td>• Model scale on deeper water</td>
</tr>
<tr>
<td><strong>Disadvantages</strong></td>
</tr>
<tr>
<td>• No information on individual wave scale</td>
</tr>
<tr>
<td>• Less accurate</td>
</tr>
<tr>
<td>• Computationally very expensive</td>
</tr>
<tr>
<td>• Not much used yet</td>
</tr>
</tbody>
</table>
Initially, only the single layer version of the non-hydrostatic model was implemented. However, experience has shown that first order schemes generally introduced too much damping to accurately model short wave propagation. Therefore, more recently a second order accurate scheme was incorporated into XBeach using the MacCormack (1969) scheme. Non-hydrostatic models need a high resolution in the vertical (~20 layers) to obtain similar results to the depth averaged formulated Boussinesq models. Recently Stelling and Zijlema (2003) showed that by using an edge based finite difference scheme in the vertical, it is possible to construct a non-hydrostatic model that is competitive to the Boussinesq models. (Smit, et al. 2014).

The non-hydrostatic and the McCormack scheme are formulated as corrections to the first order hydrostatic calculations in XBeach and are implemented as subroutine calls enabled by the user. In Zijlema and Stelling (2008) the authors also showed that, when using momentum conservative numerical schemes as described in Stelling and Duinmeijer (2003), the effect of wave breaking can be captured accurately without the use of a breaking model. Wave breaking is a very important process in the current study. Therefore, its schematization will be discussed in more detail in the upcoming section. For additional background regarding the theory used in XBeach, the XBeach manual can be consulted.

### 4.2.1 Generating wave conditions in XBeach

To generate the desired wave input conditions using XBeach non-hydrostatic mode a number of adjustments had to be made to the model. These adjustments were performed after a series of tests were conducted to indicate the optimum model set-up needed to provide the most reliable results. It was found that:

- \( k_h = 3 \rightarrow \) the non-hydrostatic XBeach mode becomes unstable.
- \( k_h = 1 \rightarrow \) the non-hydrostatic XBeach mode provides the most favourable results.
- \( n > 0.9 \rightarrow \) offshore boundary conditions become unstable in XBeach.
- \( n \leq 0.8 \rightarrow \) offshore boundary conditions presented favourably.

where:

\[
k = \frac{2\pi}{L} \quad \text{and} \quad n = \frac{C_g}{C}
\]

with:

\[
C = \frac{g}{k} \tanh(kh) \quad \text{and} \quad C_g = \frac{1}{2} C_p \left( 1 + kh \frac{1 - \tanh^2(kh)}{\tanh(kh)} \right)
\]

- Monochromatic and bichromatic waves require considerable spin-up time to incorporate reef top set-up (~30 minutes in Xbeach model time).
- Set-up best is best represented when right boundary is schematized as a wall instead of an absorbing-generating (weakly-reflective) boundary.
- Input for wave conditions (Bound_U.bcf file) requires consideration of deep / intermediate / shallow wave input conditions at the left boundary.
- Iterative testing to determine which number of grid would produce a smooth time series whilst optimizing computational time was conducted. This occurred at about
30~32 grid cells per wavelength using the short wavelength anticipated on the reef flat.  
- Time steps (d_t) of 1.0~0.1 seconds provide favourable results.  
- Reduce and optimize bathymetry to save computational time.

The model was run numerous times to verify that the observations noted above would provide the reliability required by the model to generate the wave input conditions.

**Monochromatic**

The hydrodynamic conditions specified previously occur over a wide variety of reef flats. It is not feasible to model each of these reef flats individually. Therefore, one representative reef flat bathymetry will be chosen on which the desired wave conditions will be forced. To accomplish this a large variety of offshore wave conditions in combination with specific reef top water levels will be generated to force the desired hydrodynamic conditions on the standardized reef top bathymetry.

The non-hydrodynamic module performs best when a water level time series or Boun_U.bcf file is introduced at the boundary. This file consists of a time series which specifies the horizontal U-velocity and water level for each time step. First, monochromatic waves were tested. Monochromatic waves are significantly easier to write and analyze using linear wave theory. In addition no statistical methods are required to analyze the time series. Therefore, monochromatic conditions are ideal for initial testing, validation and calibration of both the physical and numerical model. For monochromatic wave generation, the wave period was chosen for each run and the conditions described in the previous section were applied (n ≤ 0.8 & kh = 1). With a chosen water depth and period, the corresponding wave length could be determined using the following expression;

\[ L = \frac{g}{2\pi} \frac{T^2 \tan h}{L} \]

With the wave length, the corresponding wave number (k) can be found to determine the water surface time series needed for the Boun_U.bcf file. This expression is:

\[ \eta = \frac{H}{2} \cos(kx - \sigma t) \]

where;

\[ k = \frac{2\pi}{L} \quad \text{and} \quad \sigma = \frac{2\pi}{T} \]

The velocity at each time step is also required. This can be found using the following expression:

\[ u = \frac{gHk \cosh kh (h + z)}{2\sigma \cosh kh} \]
The above wave input was used to set up a number of XBeach non-hydrostatic simulations. The process was repeated for a number of iterations until the desired wave conditions required on the reef flat had been generated.

Figure 4.2-1: Example of wave input at XBeach offshore location and resulting wave on reef top

An example of a long and short incoming wave at the boundary and its transformation to a point on the reef flat is presented in Figure 4.2-1. It can be seen that the wave on the reef flat has undergone significant wave height reduction and that significant set-up takes place on the reef flat. It should be noted that this signal has not yet been split into incoming and reflected waves. This process will be described near the end of section 4.2.1.

**Bichromatic waves**

The next phase of the physical model testing involves increasing the wave input complexity to bichromatic waves. This is the simplest form of a progressive wave group and can be obtained by the superposition of two primary waves with slightly different frequencies. In the simple case of two linear waves being superimposed with each other, the pattern formed has two wave-type features. First, the superimposed primary waves result in a spatial and temporal variance of the surface elevation (a resultant wave) which itself propagates with a velocity equivalent to the mean of the two primary waves. Secondly, there is an envelope of the resultant wave representing its group structure. The properties of these waves are given as:

\[
\omega_m = \frac{\omega_1 + \omega_2}{2} \quad [4-7]
\]

\[
\omega_g = \frac{\omega_1 - \omega_2}{2} \quad [4-8]
\]
where the subscripts ‘m’ and ‘g’ denote the representative mean individual wave and the envelope of the wave group respectively.

\[ k_m = \frac{k_1 + k_2}{2} \quad [4-9] \]
\[ k_g = \frac{k_1 - k_2}{2} \quad [4-10] \]

The mean individual wave and the envelope of the wave group velocity can now be represented by:

\[ c_m = \frac{\omega_m}{k_m} = \frac{\omega_1 + \omega_2}{k_1 + k_2} \quad [4-11] \]
\[ c_g = \frac{\omega_g}{k_g} = \frac{\omega_1 - \omega_2}{k_1 - k_2} \quad [4-12] \]

The relationships presented were applied for a broad range of bichromatic wave conditions. An example of this process is illustrated in Figure 4.2-2. The upper left hand panel displays the two individual wave signals with varying periods and equal wave height. Once combined with the relationships presented above, these two signals result in the signal displayed in the lower left hand panel. This signal is used to generate the Boun_U.bcf file needed for the non-hydrostatic model input. The horizontal U-velocity is also computed for each time step.

---

![Figure 4.2-2: Bichromatic wave signal in XBeach](image)

Note: left figure display the 2 separate monochromatic wave with varying periods. The right figure is the resulting bichromatic signal of the two individual waves.

**Irregular waves**

The irregular non-hydrostatic model is treated differently from the monochromatic and bichromatic waves described earlier. Instead of providing a Bound_U.bcf file with a horizontal velocity and water level time series, a JONSWAP-spectrum is specified by the user. The input file from the use requires \( H_{m0} \), \( f_p \), main angle of incidence, gamma, \( s \), and the Nyquist frequency. Once the JONSWAP input file has been specified, XBeach uses the following relationship to create a JONSWAP spectrum, which it applies at the left hand model boundary:

\[ E(f) = \alpha g^2 (2\pi)^{-4} f^{-5} \exp \left( -\frac{5}{4} \left( \frac{f}{f_p} \right)^{-4} \right) \exp \left( \frac{-(f-f_p)^2}{2\sigma_f^2} \right) \quad [4-13] \]
Where
\[ \sigma = 0.07 \text{ for } f \leq f_p \quad \text{and} \quad \sigma = 0.09 \text{ for } f > f_p \] \hspace{1cm} \text{[4-14]}

With a peak frequency:
\[ \alpha = \frac{H^2 \sigma^4}{16g^2(0.065\gamma^{0.803} + 0.135)} \text{ for } 1 < \gamma < 10 \] \hspace{1cm} \text{[4-15]}

A series of wave spectra signals recorded on various reef flats were extracted from the literature review presented in section. These spectra represent typical wave conditions on a reef flat and were used as a guideline for generating an irregular wave signal for the flume tests.

To generate the laboratory wave paddle input, the XBeach output has to be split into incoming and reflecting waves. The incoming wave signal will then be scaled according to Froude scaling laws. This scaled signal can be interpreted by the program DELFT-AUKE/GENERATE which generates a wave paddle signal in the format of a time series.

**Signal decomposition**

The total signal can be separated into its incoming and reflected component using co-located measurements of the surface elevation and the cross-shore velocity. On the reef flat the water is shallow, and therefore it can be assumed that all waves propagate with the same velocity. It is therefore not necessary to analyze the incoming and reflecting waves using the frequency domain. Instead a method suggested by Guza et al. (1984) may be used. For each times series the kh values were plotted to verify that the waves fell within the long-wave boundary. This check is a necessity in order to apply the following method valid for shallow water waves;

\[ \eta = \eta_i + \eta_r \quad \text{and} \quad u = u_i + u_r \] \hspace{1cm} \text{[4-16]}

therefore;

\[ u_i = \frac{c}{h} \eta_i \] \hspace{1cm} \text{[4-17]}
\[ u_r = \frac{c}{h} \eta_r \]

and;

\[ \eta_i = \frac{\eta + \frac{h}{c} u}{2} \] \hspace{1cm} \text{[4-18]}
The resulting total incoming water level elevation over time can be scaled for the physical model. For each of the outputs from XBeach a check is conducted to ensure that the reef top conditions can be described by shallow water waves. This allows for the application of Guza (1984). An example of a monochromatic and irregular wave signal decomposition from an XBeach output is displayed in Figure 4.2-3.

![Image](image.png)

**Figure 4.2-3: Example of regular and irregular wave signal decomposition using Guza (1984)**

To the left of Figure 4.2-3 the spectra of the total signal is indicated in red, with the dashed black signal representing the filtered reflected signal. A time step of this decomposition is shown on the right of Figure 4.2-3 where the reflected signal can clearly be seen in red. Although this only makes up a small component of the total signal, it is significant enough to be removed to ensure that only the incoming signal is generated in the flume.

**Scaling**

When a measurement is made at another location (e.g. in the field or another laboratory facility) it must be scaled down in order to generate it in a flume or a basin. In most instances Reynolds and Froude scaling laws are sufficient for hydrodynamic physical modeling. The wave signal generated by XBeach will be scaled using Froude scaling.

The following similitude ratios for Froude and Reynolds similarities are used to convert basic dimensions as described by Hughes (1993):

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Dimension</th>
<th>Froude</th>
<th>Reynolds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>[L]</td>
<td>(N_L)</td>
<td>(N_L)</td>
</tr>
<tr>
<td>Area</td>
<td>[L^2]</td>
<td>(N_L^2)</td>
<td>(N_L^2)</td>
</tr>
<tr>
<td>Time</td>
<td>[T]</td>
<td>(N_L^{1/2} N_D^{1/2} N_P^{1/2} N_V^{1/2})</td>
<td>(N_L^{1/2} N_D^{-1/2} N_P^{1/2} N_V^{1/2})</td>
</tr>
<tr>
<td>Velocity</td>
<td>[LT^{-1}]</td>
<td>(N_L^{1/2} N_D^{-1/2} N_P^{-1/2} N_V^{-1})</td>
<td>(N_L^{1/2} N_D^{-1/2} N_P^{-1/2} N_V^{-1})</td>
</tr>
</tbody>
</table>

The Froude criterion is a parameter that expresses the relative influence of inertial and gravity forces in a hydraulic flow and is given by the square root of the ratio of inertial gravity forces, i.e.,
\[
\sqrt{\frac{\text{inertial force}}{\text{gravity force}}} = \sqrt{\frac{\rho L^2 V^2}{\rho L^3 g}} = \frac{V}{\sqrt{gL}} \tag{4-19}
\]

This relationship gives the relative importance of the inertial forces acting on a fluid particle to the weight of the particle. The Froude number must be the same in the model as in the prototype, therefore:

\[
\left(\frac{V}{\sqrt{gL}}\right)_p = \left(\frac{V}{\sqrt{gL}}\right)_m \tag{4-20}
\]

In terms of scale ratios:

\[
\frac{N_v}{\sqrt{N_g N_L}} = 1 \tag{4-21}
\]

\[
N_t = \sqrt{\frac{N_L}{N_g}} \tag{4-22}
\]

Equation [5-7] is the Froude model criterion for modeling flow in which the inertial forces are balanced primarily by gravitational forces. Both the time and length must be scaled properly using the scale ratio of 1:5.

**Signal despike**

It was found that a number of the signals could not be generated by the wave paddle. These signals were generally irregular wave signals composed of a 45 minute JONSWAP spectra which contained a number of peaks or “spikes”. These spikes required such a rapid acceleration from the paddle that the mechanics of the system could not tolerate the motion. These spikes had to be removed from the signal. It was decided to employ a method used by Goring & Nikora (2002) to despike the signals.

Single point spikes that protrude above or below the surrounding data are easily detected and replaced. However, multipoint spikes and spikes that blend with the background are much more difficult to detect. Goring & Nikora (2002) found that of the methods various available despike methods, the phase-space thresholding method is the most suitable for detecting spikes in these types of data sets. This method requires the use a polynomial of best fit through the data on either side of the spike, then interpolating across the spike with the obtained polynomials. Trials have shown that for ADV data the best options is to use a third-order polynomial through 12 points on either side of the spike. This method was applied and can be observed in Figure 4.2-4 where the raw signal is plotted in red and the despiked signal is plotted on top in black. The difference can be clearly observed in the right hand panel where the spectra has been slightly reduced.
Signal generation

With an incoming, scaled and despiked signal, the wave maker signal can be generated using the available surface elevation time-series. As demonstrated by Biesel (1951), the surface elevation $\eta(x,t)$ in the generated wave field is calculated by:

$$
\eta(x,t) = c \sinh(kh) \cos(\omega t - kx) + \sum_{n=1}^{\infty} C_n \sin(k_n h) e^{-k_n x} \sin(\omega t)
$$

The first term in the function expresses the velocity potential at infinity, which Biesel called the far-field solution, and the second term is the near-field solution. The first term describes the generated progressive wave, while the second describes the standing waves which decreases with the distance from the wave maker (Frigaard, Hogedal, Christensen, 1993). In general only the far-field solution is considered. The displacement, $e$, of the wave generator can be defined by:

$$
e(z,t) = \frac{S(z)}{2} \sin(\omega t)
$$

The far-field surface elevation is seen to be phase shifted $\pi/2$ relative to the displacement of the wave generator. The “disturbance” from the near-field solution will in a distance of 1-2 wave lengths from the wavemaker be less than 1% of the far-field solution (Frigaard, Hogedal, Christensen, 1993). Therefore the Biesel Transfer Function can be calculated for any wave maker as long as the strike, $S(z)$, of the paddle can be described. The far field Biesel transfer function for piston-type wave maker is:

$$
S(z) = S_o \quad \text{where} \quad \frac{H}{S_o} = \frac{2\sinh^2(kh)}{\sinh(kh) \cosh(kh) + kh}
$$

The theory described by Biesel (1951) is applied to the wave signals generated in XBeach. This process is conducted using the wave generation program DELFT-AUKE/GENERATE which was designed and developed by WL|Delft Hydraulics for use in flume and directional basin facilities. The program computes time series for the wave board motion in order to generate a desired wave field. The Measurement setting will be used in DELFT-AUKE/GENERATE to
construct a time series representing a measured wave field. A typical input for DELFT-AUKE/GENERATE in the measurement setting is provided in Appendix 1, section 3.0.

Some of the wave paddle signals generated in DELFT-AUKE/GENERATE had inexplicable spikes or “errors” in the time series which made it difficult for the wave paddle to execute the signal. This can be clearly observed in the left hand panel of Figure 4.2-5, indicated by the red panel.

These errors exclusively consisted of one outlier or spike which could be removed from the time-series. At this stage the signal was converted to a binary file and therefore the spike had to be removed in a binary text editor. The spike was interpolated and smoothed. The acceptable steer file is shown on the left hand side of the figure. This process was performed for half of the irregular input files.

A summary of all of the conditions selected from the XBeach results for the final physical model is presented for monochromatic, bichromatic and irregular waves in Figure 4.2-6. The $k_h$ and $H_{rms}$ values provide the key indicators required to understand the conditions on top of the reef flat. The $k_h$ value is the water depth of the test times the wave number, which incorporates the peak period-$T_p$ (s) of that test. The $H_{rms}$ (m) of the time series is applicable for monochromatic, bichromatic and irregular time series. The selected time-series span most of the range of conditions previously collected in from fringing reef sites worldwide and presented in Table 3.1-2. The monochromatic waves are resembled by red circles, bichromatic waves by blue squares, and irregular waves by black triangles. These conditions are presented more thoroughly in section 5.2 where they are calibrated in the wave flume.
4.2.2 Numerical calibration of reef configuration for physical modeling

In preparation for the physical model a number of tests were conducted with the new XBeach vegetation module to optimize the canopy layout. The module requires the canopy area per unit height ($b_v$), drag coefficient ($C_d$), number of canopy elements per m$^2$ (N), canopy height ($a_h$), and the canopy location. The theory in the module is that of Mendez & Losada (2004) where the drag coefficient is found at a location on the canopy using the depth averaged velocity at that point in the canopy. All of the parameters required in the Mendez & Losada (2004) relationships were tested in a sensitivity analysis. It was found that the most important factors for design in the canopy is the drag coefficient ($C_d$), canopy dimensions and the water levels. Canopy $C_d$ values for the GCs are not yet known at this point, therefore a constant was assumed typical of dense canopy covers. The canopy geometry and water levels were then varied to observe the effect of wave dissipation across the canopy.

The simulations were run for a variety of canopy shapes and sizes which could accommodate the available number of GC units which had been ordered for the flume experiments. The water levels were also varied and target the observed values in the literature presented earlier. The remaining parameters including wave conditions were estimated and kept constant. These variables will require updates once the modeling has been completed and therefore do not provide a truly representative result. However, the indication of canopy performance obtained with this investigation should provide a good starting point for designing the canopy configurations for testing in the flume. The canopy area per unit height was taken as 0.25, with N = 40, and $C_d$ estimated at 0.8. The results are depicted in Figure 4.2-7.
The varying canopy profiles depicted on the bottom left of Figure 4.2-7 are all feasibly options. However, only two arrangements can be considered for the physical model testing due to time constraints. It was decided to analyze one wide and low crested canopy and one narrow and high crested canopy. It was determined to test a 1.25 and 2.00 meter long canopy based on the wave dissipation estimated to occur at those canopies. Furthermore, it was also decided to test all of the water levels up to the canopy crest to observe the variance in wave height reduction which can be observed on the right of Figure 4.2-7. The water levels will not be lowered below the canopy crest because it is the intention of the MAUS structure to be submerged permanently. Furthermore, wave height reduction is more difficult to observe once the water levels extend below the canopy crest.
Chapter summary: The following chapter describes in detail the physical modelling campaign completed at the TU Delft hydraulics laboratory. The tests were performed in a flume with dimensions of 32x0.8x0.8m. In total 119hrs of testing was completed which includes calibration of the wave conditions and data collection for 2 canopy configurations consisting of about 1400 1:5 scale hooks each. Tests took 45 minutes, with data recorded 5 minutes prior to testing, 30 minutes during testing and 15 minutes post testing to observe any perturbations in the wave flume which required filtering.

The flume was fitted with a vectrino I and vectrino II profiler, in addition to 9-11 GHM gauges, 4 EMS gauges and video recordings for each test. The vectrino profilers were installed at the front and rear of the canopies to observe the in-canopy wave driven and turbulent flows.

The canopies were constructed in six steps. The hooks had to be assembled by hand and were stored and installed using similar techniques to the 2013 Markemeer pilot study. GC’s were woven through a geo-textile and fastened to the flume bottom. Temporary pipes were placed in the locations where cavities were required for the vectrino to be inserted into the canopy. A frame with the instrumentation was placed above the canopy and the GC’s were placed at random with red GC’s placed on the crest to observe and GC migration which may take place. Placement densities of the hooks was found to be about 33% to total volume.

The instruments were calibrated using reputable calibration techniques. Results from the EMS flow meters were compared with those of the Vectrino profilers to ensure that the recorded data from these instruments agreed. Vectrino output data required filtering based on the number of particulates present in the water column required for accurate acoustic readings of the instrument. During initial turbulence decomposition trials using the method proposed by Shaw & Trowbridge (2001), it was found that the limitation of instrument spacing was not applicable. This was due to the smaller than expected scale of turbulent flows in the canopy. This observation allowed for more closely spaced and regular turbulence measurements throughout the canopy.

Finally, the wave conditions were calibrated in the flume. Reflection compensation was required due to the porous nature of the canopy and a stone berm with slope 1:10 was constructed at the back of the flume. It was found that the wave-paddle was unable to reproduce the mechanical motions of some of the more extreme cases modelled in XBeach. However, the conditions suitable for testing represented up to 99% of the conditions found in the literature. The final conditions generated in the flume matched those produced in XBeach within a 95% confidence interval.
The following section describes the physical modelling campaign including the design, set-up and testing campaign.

TU Delft hydraulics laboratory

The experiments were carried out in the largest flume at the Environmental Fluid Mechanics Laboratory at the Technical University of Delft. The length of the flume is roughly 38m, with an effective length of 32m. The depth of the flume is 0.85m with a width of 0.80m. The wave paddle is mechanically driven using a computer guided system capable of producing a large range of wave conditions. The flume is depicted in Figure 4.2-1.

The testing was conducted over a period of 7 weeks which includes initial laboratory clean-up, set-up, installation and calibration of all instruments, wave calibration, initial analysis of instrumentation output, construction of 2 canopy configurations, the testing campaign itself, and subsequent take-down of the experiments.

All of the tests conducted in the flume are presented in Table 4.2-1. These conditions were generated in the previous chapter using XBeach and input conditions from the fringing reef data base constructed earlier. It was decided to increase the complexity of the wave conditions progressively, starting with simple monochromatic waves, followed by bichromatic waves and ending with the analysis of more complex irregular waves.

<table>
<thead>
<tr>
<th>Hrms (m) on reef flat</th>
<th>Tp (s)</th>
<th>WL to reef flume bottom (m)</th>
<th>Test #</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MONOCHROMATIC WAVES</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.03 / 0.06</td>
<td>3</td>
<td>0.52</td>
<td>1-2</td>
</tr>
<tr>
<td>0.03 / 0.04 / 0.08</td>
<td>3 / 7</td>
<td>0.48</td>
<td>3-5</td>
</tr>
<tr>
<td>0.04</td>
<td>3 / 5</td>
<td>0.42</td>
<td>6-7</td>
</tr>
<tr>
<td>0.03</td>
<td>3</td>
<td>0.38</td>
<td>8</td>
</tr>
<tr>
<td>0.07</td>
<td>5</td>
<td>0.36</td>
<td>9</td>
</tr>
<tr>
<td>0.03 / 0.04</td>
<td>3 / 7</td>
<td>0.32</td>
<td>10-12</td>
</tr>
<tr>
<td>0.06</td>
<td>7</td>
<td>0.30</td>
<td>13</td>
</tr>
<tr>
<td><strong>BICHROMATIC WAVES</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.07 / 0.08 / 0.09</td>
<td>3 / 5 / 7</td>
<td>0.52</td>
<td>14-16</td>
</tr>
<tr>
<td>0.06 / 0.07</td>
<td>3</td>
<td>0.42</td>
<td>17-18</td>
</tr>
</tbody>
</table>
The tests highlighted in Table 4.2-1 resulted in a total of 119hrs of recorded data from the various instruments placed in the flume. This data collection process can be broken down into 3 general categories:

1. Wave calibration consisting of 28 calibration tests, each lasting 30 minutes for a total of 14hrs of data collections.
2. Testing of the 1st canopy configuration consisting of 84 tests, each lasting 45 minutes for a total of 63hrs of data collections.
3. Testing of the 2nd canopy configuration consisting of 56 tests, each lasting 45 minutes for a total of 42hrs of data collections.

For each test, data was recorded for 5 minutes prior to the test with no wave generation, followed by 30 minutes of wave generation and another 10 minutes of data recording without wave generation. The data 5 minutes prior to wave generation could be used for zeroing the instruments, whereas the data collected 10 minutes after the wave testing could be used to observe any standing wave patterns in the basin. The layout design, instrumentation placement, construction and calibration will be discussed in the forthcoming sections.

5.1 LAYOUT & INSTRUMENTATION

Based on the initial layout analysis presented in section 5.1.1 two canopy configurations were designed. These are presented in Figure 5.1-7 & Figure 5.1-8. The canopy in Figure 5.1-7 known as Canopy One is 30cm high, consisting of approximately 1400 GC hooks and is 1.25m wide. The canopy in Figure 5.1-8 known as Canopy Two is only 20cm high, consisting of approximately 1400 GC hooks and is approximately 2m wide. Both canopy configurations will have comparable instrument set-up.

The instruments displayed in Figure 5.1-1 will be discussed in more detail in the upcoming section. Both configurations have three GHM wave height meters installed upstream of the MAUS intended to split the incoming and reflected waves. GHM wave height meters have also been installed along the top of the canopy to measure the drag coefficient along the top of the canopy. It is also intended to use these GHM units to observe any local wave motions such as shoaling, on top of the canopy. In addition to the GHM units, visual observations and water levels will be measured in front, and after the MAUS structure in the flume. Due to the additional canopy width, canopy two incorporates extra GHM wave height meters.

Two vectrino instruments will be inserted inside the canopy structure. One Nortek Vectrino I and one Nortek Vectrino II. It is expected that the highest velocities will be measured in the
front of the canopy before much of the energy is dissipated. It was therefore decided to install the Vectrino profiler at this location to acquire more data for the analysis at this location. The Vectrino II is capable of recording a small profile of in-situ water velocities whereas the Vectrino I only records point measurements of the velocity.

Finally, 4 electromagnetic flow meter (EMS) units are installed in the flume. These are installed at the bottom of the canopy to observe the wave induced flow in the MAUS which indicates the transport of nutrients. The EMS units will primarily be used to indicate whether the vectrino profilers are providing accurate readings.
Canopy configuration one

Figure 5.1-1: Physical model layout 1
Canopy configuration two

Figure 5.1-2: Physical model layout 2
5.1.1 **Instrumentation**

The instrumentation introduced in the previous section is discussed in more detail. A series of instruments are required to collect the desired data. It is intended to use:

1. 11 GHM wave probes,
2. 2 Vectrinos
   a. Nortek Vectrino I
   b. Nortek Vectrino II
3. 3 Electromagnetic Flow Meter (EMS)
4. Measuring tape

**GHM WAVE HEIGHT METER**
The GHM probes are constructed of two parallel stainless steel rods, mounted underneath a small box. This box contains electronics for sensor excitation, signal detection, amplification and galvanic isolation. The rods act as the electrodes of an electric conduction meter. A platinum reference electrode is included to compensate the surface elevation measurement for the effect of varying electrical conductivity of the fluid. The analogue output signal is linearly proportional to the liquid level between the sensor rods (Deltares, 2012) and represents the instantaneous water level. The probe can sample with a frequency of 0-10 Hz.

**VECTRINO PROFILER**
The vectrino profiler (Figure 5.1-3) allows for multiple instantaneous observations over the wave boundary layer for each wave passing. It produces velocity profiles which help to characterize flow around or behind a structure such an individual GC or collections of GCs. The ADV emits sound waves which are scattered by fine particles in the flow and detected by three receivers oriented such that they register the signal from a well-defined volume. The water motion causes a Doppler shift in the ultrasound frequency proportional to the velocity. With three receivers the full three-dimensional velocity vector is measured in a volume of typically 0.25 cm$^3$ located 5 cm from the probe (Nortek As. 2012). A typical probe and its basic functions is illustrated in Figure 5.1-3.
The laboratory possess a Nortek Vectrino I and the newer Nortek Vectrino II. Both of these instruments will be used. Their characteristics are displayed in Table 5.1.1 where the main difference between the Vectrino I and the Vectrino II us that the later can record a small velocity profile whereas the Vectrino I only records a point measurement.

<table>
<thead>
<tr>
<th>Table 5.1.1: Vectrino I &amp; II characteristics</th>
<th>Source: Nortek As. (2012)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water velocity measurements</strong></td>
<td></td>
</tr>
<tr>
<td>Velocity range</td>
<td>0.1, 0.3, 1, 2, 4 m/s</td>
</tr>
<tr>
<td>Adaptive ping interval</td>
<td>-</td>
</tr>
<tr>
<td>Accuracy</td>
<td>+/- 0.5% of measured value</td>
</tr>
<tr>
<td>Sampling rate</td>
<td>1 – 25 Hz</td>
</tr>
<tr>
<td><strong>Distance measurement</strong></td>
<td></td>
</tr>
<tr>
<td>Minimum range</td>
<td>-</td>
</tr>
<tr>
<td>Maximum range</td>
<td>-</td>
</tr>
<tr>
<td>Cell size</td>
<td>3 – 15 mm</td>
</tr>
<tr>
<td>Accuracy</td>
<td>-</td>
</tr>
<tr>
<td>Sampling rate</td>
<td>-</td>
</tr>
<tr>
<td><strong>Sampling Volume</strong></td>
<td></td>
</tr>
<tr>
<td>Profile range</td>
<td>-</td>
</tr>
<tr>
<td>Location</td>
<td>50 mm</td>
</tr>
<tr>
<td>Diameter</td>
<td>6 mm</td>
</tr>
<tr>
<td>Cell Size</td>
<td>-</td>
</tr>
</tbody>
</table>

**ELECTROMAGNETIC FLOW METER**

The principle of the (EMS) as depicted in Figure 5.1-4 is that the measured voltage between two electrodes is proportional to the instantaneous velocity. After proper calibration the EMS allows for maximum frequency observations of 10 Hz. The signal is obtained from the volume directly underneath the probe where the electrodes are mounted. A flow \( u \) in the \( x \)-direction through a magnetic field \( B \) in the \( z \)-direction creates a potential \( V \) in the \( y \) direction. This relationship is presented below:

\[
\vec{V} = \vec{u} \vec{B} \quad \text{and therefore} \quad V_y = u_x B_z
\]  

With a typical coil diameter of 3cm the probing volume is a few cubic centimeters. For laboratory applications this resolution is sufficient to measure mean velocities and the fluctuations of large scale turbulence.
The advantage of this type of flow meter is that it is easy to use and that it can measure two velocity components simultaneously. A disadvantage is that it requires a careful calibration, the combination of electrodes and electronics makes this device susceptible for electronic noise and zero-offset drift.

5.1.2 Construction

The steps taken in the construction of each canopy are displayed in Figure 5.1-5.
Approximately 1400 GC hooks were ordered and delivered (depicted in image 1. - Figure 5.1-5) in 3 separate components that had to be assembled by hand to form a completed GC. Each GC measured 8x8x8cm. These GC’s were stored in a similar manner as that of the pilot study conducted at the Markermeer (depicted in image 2. - Figure 5.1-5), this allowed for easy installation once the flume was prepared. The bottom layer of GC’s was woven through a geotextile to ensure total canopy stability (depicted in image 3. - Figure 5.1-5). This layer was then fastened to the flume bottom (depicted in image 4. - Figure 5.1-5). Pipes were installed at the locations where the vectrino profilers would be placed in the canopy to create a cavity. Each of these locations was kept clear of GC hooks by stretching a transparent wire from the flume bottom to the top of the Vectrino with enough tension to keep the mass of the hooks away from the Vectrino probes. This prevented any interference of the vectrino probes with the GC elements but also minimized any turbulence that could be caused by the wires themselves.

Step 5 (depicted in image 5. - Figure 5.1-5) shows the installation of the remaining GC hooks. Instillation methods were replicated from previous studies, where it was ensured that GC distribution remained irregular and that no regular interlocking occurred. In step 6 additional red GC’s were added to the top of the canopy to indicate whether any significant GC migration would occur. The final set-up which features all of the instrumentation, canopy, and dissipative rocky slope are displayed in Figure 5.1-5.

During construction of each of the canopies, a tally was kept at random of GC’s placed in pre-allocated bins. Placement occurred in intervals of 10-30 hooks. At the end of construction the number of GC’s in each bin was tallied and totaled. This allowed for an unbiased approach to find the average distribution of GC’s across the canopy. It was found that in all of the bins the volume ratio of GC to total canopy volume consistently ranged between 30-34%. This had originally been indicated as a typical GC distribution and therefore, as indicated in Figure 5.1-7 and Figure 5.1-8 the estimated required amount of GC’s for each configuration very closely matched that actual number of GC’s placed.
5.1.3 Instrument calibration

The following section outlines the steps required to calibrate each instrument. Calibration had to be performed for the GHM gauges, EMS flow meters, Vectrino’s and the wave paddle.

GHM gauges

All wave GHM sensors need to be calibrated individually. This is done by creating series of fixed water level differences and measuring the corresponding response in volts. The sensors
possess a linear relation between pressure/water level and voltage. This relationship can then be used to calculate the water surface elevation at each individual time step. When the water levels vary between tests, it is crucial to tare the voltage on each receiver used to convert the incoming signal for data processing. Not performing this action can result in large discrepancies which make the data set unreliable.

**EMS gauges**

EMS gauges had been previously calibrated by laboratory technician and required very little calibration. It was however found, that many of the instruments provided inconsistent results when compared with the vectrino velocities measured at similar locations in the canopy. This may be attributed to some of the errors observed with the receivers which transform the incoming signal. The equipment had recurring errors where the recorded voltage would jump up or down by 1-2 volts, which required periodic readjustments. Furthermore, it was noticed that replacing some of the cables improved reliability of the EMS data, this indicated that some of the connections may have suffered from wear-and-tear. Additional, local velocity fluctuations may contribute to some differences in the average velocity, although given the long time-series and similar locations in the canopy, it is expected that the Vectrinos and the EMS should have similar velocity distributions. All of these factors combined resulted in somewhat unreliable EMS data. Therefore, this data was only used to indicate whether the Vectrino data was within the correct order of magnitude to be considered valid. An example of this type of time-series velocity distribution analysis is provided in Figure 5.1-9 (box-plot) for the monochromatic wave tests. A similar analysis was performed for all other tests.

![Compare EMS & Vectrino Output - Monochromatic waves](image)

**Figure 5.1-9: In-situ Vectrino profiler measurements compared with EMS flow readings**

It can be observed that for tests 2, 5, 7, and 12 the vectrino and EMS data match nicely. This indicates the reliability of both the vectrino and EMS measurements in the canopy. However, for tests 1 and 8 the EMS data is offset considerably. However, in each of these cases it appears that only 1 of the 2 EMS meters is offset from the other two data samples which indicates that the fault lies with the data record from the EMS. This is an important distinction to make, especially when using the Vectrino profiler data for the turbulence decomposition analysis at a later stage in the experiment.
Vectrino I

The Vectrino I is a relatively user friendly instrument to install and calibrate. The most important considerations are instrument orientation in the flume with respect to flow direction and the flume bottom. These must be kept consistent throughout the testing campaign in order to compare results between the various tests. Furthermore, the water must be sufficiently turbid for the vectrino to record accurate/high-resolution results. This can accuracy can be observed using the correlation coefficient between the 3 vectrino probes. It was determined that this must remain above 85%. To accomplish this the flume was periodically seeded with silica clay.

Vectrino II (profiler)

The vectrino profiler records a large quantity of data every mm over a 3cm interval at 100Hz. This results in a large amount of data with the potential for errors and scatter. Results from the profiler are displayed in Figure 5.1-10 where the top row representing a measurement taken in the middle of the canopy, the middle row in the middle of the canopy and the bottom row subsequently recorded near the flume bottom. The results are displayed for a short 3 second interval recorded for a monochromatic wave.

Figure 5.1-10: Vectrino profiler data reliability

Figure 5.1-10 already incorporates the turbulence decomposition using ensemble averaging as discussed in section 2.3.2. Each of the time-series above displays important features that had to be considered when calibrating the Vectrino profiler and when post-processing the results. For each row in Figure 5.1-10 comments are:

- The top row of panels indicates a perturbation at about 22.5 cm from the bottom. This is due to signal interference, which corresponds with an increase or “spike” in the correlation coefficient. It is expected that with a reduction in data quality the correlation coefficient would decrease. This interference may be explained by either
an interfering GC element or other feature which was present at that height during the tests. Such data was removed from the time-series for the data analysis.

- The second row indicates a series of data near the bottom of the profile which lies below a correlation of 85%. This data included a lot of spikes and gaps and was therefore removed from the data set. This is most likely due to a lack of silica clay in the flume. It was found that this type of error could be removed for all remaining tests by drastically increasing the turbidity of the water column.
- The bottom row of Figure 5.1-10 displays a time record with very high quality data. The correlations is consistently above 95% or higher. This can be seen in the resulting decomposition as well, where the wave driven flow is depicted as a smooth oscillatory regular wave flow pattern.

**Vectrino II profiler positioning for Shaw & Trowbridge (2001)**

As mentioned previously, one of the major limitations to applying the method from Shaw & Trowbridge for turbulence decomposition is that the sensor separation length is typically taken as $r > 5z$. This requires the sensors to be spaced at large intervals allowing for only 2 locations (top and bottom of canopy) where turbulence decomposition may be applied. To contest the sensor separation recommended by Shaw & Trowbridge a sensitivity analysis was completed in Figure 5.1-11. The Vectrino profiler was moved in the vertical to location A,B,C and each test condition was repeated for this location.

On the far right of Figure 5.1-11 the 3 locations where the vectrino II recorded a profile in the canopy is displayed. Typically location B can be used to decompose the signal at location C and vise-versa. However, according to the restrictions applied to this turbulence decomposition method, turbulence decomposition at location A cannot be derived from both
locations B and C. To test the validity of this relationship the Shaw & Trowbridge was applied for all possible combinations using the time-series at locations A, B, C. The results indicate very similar results at all locations, using all of the possible combinations. The turbulence spectrum (containing higher frequencies), is plotted with dots, whereas the wave driven flow is indicated with a solid line. The red and the blue indicate the 2 locations used to decompose the signal. Ideally both decomposed signals generate an exact match. However, due to the synchronization required of both signals, a slight irregularity is introduced which makes it difficult to get an exact match between all 3 signals. However, for this monochromatic wave, the results suggest that all combinations provide similar results. It can therefore be concluded that:

“Turbulence in the canopy is at such a fine scale that within a 5cm instrument spacing little to no turbulence correlation occurs”

This finding greatly improves the flexibility of the Shaw & Trowbridge method for this investigation. When one of the 3 time-series was contaminated a different combination of instruments could be used to still separate turbulent from wave driven flows.

5.2 WAVE CALIBRATION

Calibrating the wave conditions in the flume required the following steps:

1. Testing the initial time-series generated in section 4.0
2. Calculating and reducing the wave reflection
3. Finding the threshold of the wave paddle
4. Performing multiple iterations of adjusted to the time-series to determine the final input signal used for testing.

WAVE REFLECTION

For the wave decomposition of incoming and reflecting waves in the flume a method described by Funke & Mansard (1980) was employed. This method uses a least squares method to separate the incident and reflected spectra from the measured co-existing spectra. The method requires a simultaneous measurement of the waves at three positions in the flume which are in reasonable proximity to each other and are on a line parallel to the direction of wave propagation. The distances between these gauges can be calculated using a method described by Lin & Huang (2004).

The steps required to perform the method described by Mansard & Funke are as follows:

1. Calculate phase shift at positions of the wave gauges, and if needed, calculate the change of the amplitude caused by changes in water depth.
2. For each wave gauge, calculate FFT $A$, variance spectrum $E$, and averaged spectrum $Es$, averaged over frequency bands of length specified by input.
3. Calculate amplitude spectra of incident and reflected wave from FFT-values $A$ for each spectral component.
4. Variance spectrum and spectrum averaged over frequency bands of incident and reflected wave in specified frequency range.
5. Spectral parameters from "raw" variance spectra of incident and reflected wave: moment $m_0$, significant wave height, and mean factor of reflection.
6. Reconstruction of the incident and reflected wave as a time series by inverse FFT. Only the "valid" part of the spectrum will be used for this computation.

The results from applying this method was initially used to investigate the reflection experienced in the flume with the various wave conditions before the canopy was installed.

Reflection compensation
Initially a curved panel with slats perpendicular to the wave direction was installed at the back of the flume to dissipate incoming waves. However, it was found that this solution created too much reflection, especially due to the porous nature of the canopy which allowed significant transmission. It was decided to remove the panel and replace it with a sloping rubble mound berm. The berm had a slope of 1:10 and is depicted in Figure 5.2-1.

![Figure 5.2-1: Wave absorbing rubble mound structure](image)

It was the aim to reduce the reflection to as low as possible, this process can be observed in Table 5.2-1 where the initial wave height reduction from using the absorbing wave panel to the rubble mound berm is almost 20%. The berm was readjusted numerous times until the reflection was reduced to just 15%. The same wave conditions were also tested just after placing the canopy and it was found that the reflection was only 11% which was deemed acceptable.

<table>
<thead>
<tr>
<th></th>
<th>Stone dike</th>
<th>Stone dike extended</th>
<th>Stone dike + installed canopy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original ribbed absorbing wave board</td>
<td>39%</td>
<td>20%</td>
<td>15%</td>
</tr>
<tr>
<td>Stone dike extended</td>
<td>15%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stone dike + installed canopy</td>
<td>11%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Tested with a monochromatic wave, WL 0.4m, Hrms 0.04m, Tp 6.7s.
Wave paddle calibration

The process to generate the waves in the flume has been extensively explained in section 4.0. Regardless of the rigorous preparation for each signal, the results obtained in the flume were limited to the mechanical threshold of the paddle. This is the limit of acceleration which the paddle can achieve to produce the higher harmonic at the tail of the waves propagating over the canopy flat. No clear documentation existed of the limit at which the paddle could function. This limit had to be established using an iterative process which used the outlying extreme wave conditions generated in XBeach. At a threshold the paddle turns off and a reset is required. This procedure was carried out for a large number of XBeach simulations to determine in which region the paddle can operate properly. This is depicted in Figure 5.2-2.

Figure 5.2-2 shows the calibration process for all of the monochromatic waves generated in XBeach. Each of these conditions is represented by a point where the period, water depth and Hrms values are all plotted at pilot scale. From Figure 5.2-2 it can be seen that 4 sets of waves with varying periods are plotted, ranging from 7 seconds to 22 seconds. Each of these points represents a time series generated in XBeach which can be used to produce a wave paddle input signal for the flume. The distribution of data from the literature review of hydrodynamic conditions at various canopy locations presented in section 3.0 is plotted on top of these points for reference. The yellow area represents the region of time-series which are of interest to test in the flume.

After testing the limit of the wave paddle it was found that only the green region could be reproduced in the flume. One can observe that most of the points in the green region lie
within the 50th to 95th percentile of the data collected in the literature review. This indicates that only the most extreme events cannot be replicated. This is an obvious limitation of the study. However, the appropriate data falls within the majority of the distribution of observed events and therefore the data set is still well represented in the flume. This process was also conducted for bichromatic and irregular waves and is presented in Appendix 1, section 2.0.

The selected conditions for the investigation were tested in the flume prior to installing the canopy. This allowed for calibration of each wave to ensure that it matched the output from XBeach. This was primarily accomplished by slightly adjusting the Gain-factor on the wave paddle.

The Gain-factor is initially set at 0.8 which means the paddle reproduces the input file as given. However, for a variety of reasons which include flume effects and the process used to generate the signal, there are opportunities for this signal to become contaminated. The signal is therefore not a true representation of what is observed in the XBeach model. The gain factor can therefore be adjusted (+/- 0.15) to alter the signal. This is a simple linear relationship which increases the amplitude while keeping the signal period constant. The Gain-factor should not be increased too much, as this may change fundamental components, such as the period, of the wave.

The calibrated waves produced by XBeach and the wave flume for all wave conditions are plotted in Figure 5.2-3 where the spectral zeroth moment (m0) and peak periods are compared. Three wave gauges were installed in front of the canopy at the same location where the wave signal was extracted on the reef flat in XBeach. These gauges were then used to split the wave signal into incoming and reflecting components, as described by Funke E.R. & Mansard E.P.D (1980). It was found that the flume results of purely incoming waves agreed within a 95% confidence level with the XBeach results. This result is satisfactory for creating the wave conditions desired on the reef flat.

![Figure 5.2-3: XBeach vs. flume generated wave conditions](image-url)
RESULTS & DATA PROCESSING

Chapter summary: In the following chapter the initial results from the flume experiments are processed and prepared for the analysis. The two main tasks include processing the data required to describe the wave dissipation across the canopy and decomposing internal canopy velocities to wave-drive flows.

The method described by Mendez & Losada (2004) was used to parameterize the wave averaged drag coefficient ($\tilde{C}_D$), to describe the vegetation plant height, plant area per unit height of each vegetation stand normal to $u$, and the number of vegetation stands per unit horizontal. Due to the random nature of the canopy this was done using a statistical method after digitizing various cross sections within the canopy. For each of the water levels used in the flume all of the averaged wave height profiles were plotted across canopy 1 & 2. It was found that a slight dissipation occurred in the flume due to wall-effects and frictional losses. The tests were adjusted with observations made in the flume prior to placing the canopy. The drag coefficients for each test were then computed using the best of 3 available identical data sets from the various tests for each condition.

From wave-dissipation profiles it was found that the longer and lower canopy (canopy 2), provides greater wave dissipation (for most cases), when the water level is significantly higher than the canopy crest level. As the water level drops closer to the crest level, the reverse effect occurs and the higher crested canopy (canopy 1), has a larger dissipative effect. Furthermore, the in-canopy flows for the Vectrino I and Vectrino II at the back of the canopy and the front of the canopy were decomposed into wave-driven and turbulent signals using the afore mentioned turbulence decomposition schemes. It was found that the Shaw & Trowbridge (2001) turbulence decomposition method provides the most satisfying result. It is however far more computationally expensive than ensemble averaging.
6.1 CANOPY DRAG & DISSIPATION

To implement the theory by Mendez & Losada (2004) discussed in section 2.4.4 in order to parameterize the wave averaged drag coefficient ($\tilde{C}_D$), the vegetation must be properly described. This requires the following parameters to be well understood:

- $d_v =$ plant height (m)
- $b_v =$ the plant area per unit height of each vegetation stand normal to $u$ (m)
- $N =$ number of vegetation stands per unit horizontal area

It was previously found during construction of the canopies that they inhabit about 30% volume of the reef space occupied. However, this does not provide enough information for the analysis. Therefore a more rigorous approach is required to parameterize the random canopy. Four cross sections were marked at random, 2 in canopy 1 and 2 in canopy 2, this is indicated in Figure 6.1-1. These areas were chosen within the canopy and measured at the end of testing to accurately portray a settled canopy profile.

The critical parameters to identify is the area of hooks perpendicular to flow proportional to $1m^2$ of surface area, and the length of each vegetation strand exposed to flow. To accomplish this each strand exposed to the surface was painted green. A high resolution photograph was then digitized and the green surface area was calculated. This allowed for an estimate of the total coverage of vegetation. These coverage estimates are displayed in Figure 6.1-1.

This method is not entirely correct, as it does not take the three-dimensional nature of the hooks into account. Such a consideration would require stereo-photography using multiple cameras. This option was neither feasible in terms of time nor available equipment. Therefore, the results obtained with this method give only a good indication of the surface
area exposed to waves. Additionally the Mendez and Losada (2004) method uses an Re number averaged over the water column, and as a result the water velocities are too high, which means the $C_d$ values become too low. It is better to use a method which derives local $C_d$ values on the surface of the canopy. Therefore, additional testing and/or adjustment of the analytical procedure used to parameterize the vegetation could lead to more satisfactory results in the future.

When using the Mendez & Losada (2004) relationship a critical parameter is the average stem length. For each green stem in Figure 6.1-1 the stem length was measured and plotted in Figure 6.1-2. This figure gives a good indication of the stem length distribution and indicates that the average stem perpendicular to the flow, when protruding from the canopy has a length of about 2cm. Using this data for each of the four samples depicted in Figure 6.1-1 the number of strands anticipated per m$^2$ are estimated and averaged in Table 6.1-1.

![Vegetation length perpendicular to flow](image)

**Figure 6.1-2: Distribution of vegetation member length observed in the canopy**

The remaining parameters required for the drag coefficient parameterization are listed in Table 6.1-2. In addition to the vegetation strand count per m$^2$ described earlier, the vegetation length perpendicular to the flow $d_v$ was found to be 0.0192m using the method described earlier. The stem width or GC width can be directly measured and was found to be 0.006m.

![Table 6.1-2: Vegetation input parameters](image)
6.1.1 **Required corrections and adjustments**

When completing the preliminary calculations of the drag coefficients a discrepancy existed which could not be corrected. It was decided to analyze if any flume effects may account for this discrepancy. The same experiments that were run with the canopy were also run without the canopy. The results of the control experiments were used to identify some of the other sources of uncertainty. The most important ones are:

- Transient (evanescent) waves created during wave generation,
- Resonance with the longitudinal and lateral seiche period of the wave tank,
- Friction losses.

At the location where the future canopy crest is located the wave height was recorded, in addition to the wave height at the back of the canopy. The difference in wave height recorded at these locations was divided over the length between the locations. This dimensionless factor could be used to calculate the proportion of the total wave height at any given location above the canopy compromised of canopy dissipation and flume induced dissipation.

All of the tests in the empty flume were analyzed for flume generated wave attenuation and plotted in Figure 6.1-3 vs. the ratio of water level to wave height. Although small, it was found that the difference obtained using this factor had a noticeable impact on the $C_D$ calculations and resulted in $C_D$ values within the same order of magnitude cited in literature for coral canopies (presented in section 7.1). Without the correction the $C_D$ values obtained were an order of magnitude outside of the acceptable range. Similar findings in the same flume were also made by Hu et al (2014) whom used the results from empty flume tests to correct for the dissipative influence of the flume. The results from this analysis are discussed and presented in section 7.0.

6.1.2 **Initial results**

For each test, 3 runs were completed to acquire all of the necessary data in the canopy with the vectrino profilers. For each of these runs the GHM wave meters also recorded data which could be used for computing the $C_D$ value and the wave height reduction. However, only one wave records was needed to analyze the wave height reduction. Therefore, for each test condition the most reliable GHM data set was chosen to perform the analysis. This was
determined based on a number of factors such as, observed instrument error, improper calibration prior to the test and overall quality of the time series.

The $H_{rms}$ wave height was computed at each gauge for canopy 1 and canopy 2 and is plotted for the various water levels used during testing. One such example is illustrated in Figure 6.1-4 where the water level was 0.32m in the flume and therefore close to the canopy crest. The results are plotted for all monochromatic, bichromatic and irregular tests at this water level. The entire set of results for all of the water levels is presented in Appendix 1, section 4.0. From Figure 6.1-4 it can be seen that canopy 1 has more of a dissipative effect than canopy 2. This can be attributed to the canopy height and water level ration $h:H$ which is significantly smaller for canopy 2 because the canopy crest is 10cm lower than for canopy 1.

It can also be seen that at the crest of both canopies, the wave height initially increases before it decreases. From the observations and video footage this was found to be a shoaling effect on top of the canopy. The incident wave breaks on the canopy top and then shoals over the structure. It is was found that the wave dissipates more gradually for canopy 2 than canopy 1.

**Wave height transformation across reef profiles – WL 0.32m**

![Wave height transformation across reef profiles – WL 0.32m](image)

Additionally, it was observed that the wave height reduction when comparing canopy 2 to canopy 1 is less for low-amplitude long period waves than short period waves, because these waves have a smaller elevation and “travel” over the 2nd canopy less disturbed than the choppier, shorter waves. However, higher amplitude long-period waves experience greater wave height reduction because the canopy length is comparable to a wave length, which allows the whole wave to “feel” the canopy top and dissipate. These types of wave characteristics can also be observed on natural reefs. To acquire a more encompassing view of the variation between wave height reduction for each canopy type and water level, Figure 6.1-5 and Figure 6.1-6 are introduced.
The left of Figure 6.1-5 illustrates the wave-height reduction as a function of the initial wave height per test condition in addition to the water level during that test on the secondary y-axis. To compute the wave height reduction the wave height prior to the canopy was compared to the wave height observed behind the canopy.

From wave-dissipation profiles it was found that the longer and lower canopy (canopy 2), provides greater wave dissipation (for most cases), when the water level is significantly higher than the canopy crest level. As the water level drops closer to the crest level, the reverse effect occurs and the higher crested canopy (canopy 1), has a larger dissipative effect. At higher water levels, the wave-trough is farther from the canopy crest and therefore the distance the wave travels over the dissipative canopy is the dominant reducing effects of the wave height. As the water level reduces, the canopy interferes with the wave crest and trough, therefore reducing wave-energy, providing greater wave height reduction for the canopy with the higher crest (canopy 1).

Another approach which can be used to illustrate this effect is displayed on the right of Figure 6.1-5 where all of the monochromatic test results from both canopy tests 1 & 2 are categorized by the water level to canopy crest height ratio (H:h) and where each point resembles a different test. The higher the ratio, the higher the water column above the canopy. This data is plotted against the recorded wave-driven flow inside the canopy (Re number). As expected, It can be observed that wave height reduction is larger with a smaller H:h ratio. In addition the plot indicates that the internal Re number increases as the wave height reduction increases. This is expected as more of the wave energy is transmitted to the canopy resulting in higher internal flows.
Figure 6.1-6: Wave height reduction for bichromatic and irregular waves

Figure 6.1-6 displays the wave height reductions for the bichromatic and irregular tests. The previous analysis using the H:h ratios and Re numbers were not possible for these tests due to a lack of total tests completed. Again, similar patterns can be observed as with the monochromatic tests, where wave dissipation with a lower H:h ratio is significantly larger. In this study it was found that with higher water levels (H = 2h-1.5h), the wave height reduction generally fell within 10-30%, whereas with lower water levels (H = 1.25h – 1.0h) the wave height reduction fell within 25-50%. These results were similar for both canopies.

6.2 IN-CANOPY FLOW

The following section briefly outlines the initial results of the Vetrino Profiler measurements taken inside the canopy.

6.2.1 Turbulence decomposition

As noted in section 2.3.2 a number of methods were selected to decompose the velocity signal inside the canopy into wave-driven flow and turbulent flow. The methods which will be covered here are:

a. Ensemble averaging
b. Shaw & Trowbridge (2001)
d. Moving average
Ensemble averaging method

Most of the monochromatic tests could be decomposed into turbulent and wave-averaged flow using the relatively quick technique of ensemble averaging. The vectrino profiler provided flow readings in the U-V-W directions as illustrated in Figure 6.2-1. For each signal the monochromatic wave period was identified from the GHM readings in the flume. This period was then used to split the vectrino velocity components into individual wave segments.

![Figure 6.2-1: Ensemble averaging Vectrino profiler signal](image)

Figure 6.2-1 illustrates this process for a wave with a period of about 4 seconds where each line represents an individual wave with a total of 100 waves “stacked” on top of each other. The black lines indicate the average of all 100 waves at each point and resemble the wave-driven flow, where the scatter around each line indicates the turbulent flows in the canopy. To ensure that each average was a good fit to the data, the wave-driven velocity components were plotted in red against the raw signal in Figure 6.2-2 for each velocity component in U-V-W directions. It can be seen that considerable scatter exists and that the ensemble averaged velocity signal provides a good fit to the data.

![Figure 6.2-2: Ensemble averaged fit to Vectrino profiler data](image)
The same method can be applied to the bichromatic wave sets, however with only a limited number of wave groups. In Figure 6.2-3 the average wave-drive flow is depicted by the black time series, and is only taken of 7 wave-groups which is far less than the 100 wave groups used in the monochromatic tests. Given this limitation, the method used by Shaw & Trowbridge (2001) is more reliable as it does not require a limited amount of wave-packets.

Although the ensemble averaging method, and the Shaw & Trowbridge methods were primarily used in this investigation due to their ease of use and accepted theoretical background in turbulence decomposition studies, other methods such as using a moving average and phase-method were also applied to determine whether alternative methods provided similar results.

Figure 6.2-3: Ensemble averaged bichromatic wave

**Moving average and phase-methods**

Various FFT spectra of moving average methods are depicted to the left of Figure 6.2-4 where the methods employed are the Quintic Savitzky-Golay filter, Gaussian expansion, Exponential moving average and moving average. It can be seen that the Quintic Savitzky-Golay filter used to identify the wave-driven spectra (in red) has the best fit, because this spectrum incorporates the various higher harmonics present in the monochromatic wave signal generated in XBeach. Although this method is not often used in laboratory signal decomposition, it can be used as a check to ensure that the ensemble averaged signal has the correct characteristics & features.

Figure 6.2-4: Moving average (L) and phase-averaged (R) methods
On the right of Figure 6.2-4 an example is presented of the set-up required to perform the Phase-averaged method suggested by Bricker and Monismith (2007). The signal is plotted as a power-density spectrum, where the portion in red represents the wave-driven component and the portion in black the turbulent driven flow. The distance between each red-point and the line of best fit is summed to perform the operation required to find the averaged wave-driven flow as described in section 2.3.2. The main disadvantage of this method is that it can only be used to find the averaged wave-driven flow required to find the turbulent kinetic energy and Reynolds Shear stress, and is therefore less practical for analyzing the time series as a whole.

6.2.2 **Comparison of turbulence decomposition methods**

To summarize the methods described above the spectra of each turbulent and wave-driven signal is plotted for the same test. In Figure 6.2-5 the blue signal represents the wave-driven spectra and the red signal the turbulent driven spectra. It can be seen that all 3 methods presented provide comparable results where the secondary higher harmonic is well represented. The ensemble averaged signal produces a considerable amount of noise in the FFT at higher frequencies, however the turbulence is well represented. The method from Shaw & Trowbridge (2001) produce the most satisfactory result with a clear distinction between turbulent and wave-driven spectra. The moving average-method produces a distinct transition from turbulent to wave-driven flows where the Quintic Savitzky-Golay filter produces a less sophisticated cut-off point from turbulent to wave driven flows.

![Figure 6.2-5: Comparison decomposition techniques which produce a time series](image-url)
Although preferred the Shaw & Trowbridge (2001) method is computationally expensive and is not practical for all cases. Therefore, the ensemble averaging method is also used for all monochromatic tests.

The Shaw & Trowbridge (2001) turbulence decomposition method provides the most satisfying result but is computationally far more expensive than ensemble averaging.

An alternative way to compare the various turbulence decomposition schemes is to analyze the turbulent kinetic energy and shear stress profiles produced by each method. This is presented in Appendix 1.0, section 6.0, and is not critical to the current discussion. The separated wave-driven and turbulent velocities are primarily required to estimate the wave-driven drag/lift and shear forces on an individual GC which an organism could be subjected to.
**ANALYSIS**

**Chapter summary:** The drag across the canopy and the internal wave-driven flow velocities are analyzed in the following chapter. The results of the wave averaged drag coefficient $\tilde{C}_d$ and the normal drag coefficient $C_d$ are plotted for all of the test cases against the Re number recorded just prior to the canopy and also the Keuligan-Carpenter number ($K_c$). These relationships are used to establish a line of best fit through the data. The following relationship were found:

$$\tilde{C}_d = 5.8 \left( RE \left( \frac{H}{h} \right)^2 \right)^{-0.6}$$

$$C_d = 31.9 (RE)^{-1.4}$$

The ratio $H:h$ was incorporated to account for the canopy geometry. This is an important factor for design and investigation of a GC canopy. The resulting fit is valid for a large range of hydrodynamic conditions typically found at fringing reef sites worldwide.

The in-canopy wave-driven flow was used to calculate the forces on an individual GC element including drag, lift and shear stresses. These were then compared to the tolerable limits of various marine organisms and aquatic plant species introduced earlier. It was found that the internal wave-driven forces on the wave exposed side of the canopy exceeded most of the tolerable thresholds required to provide a suitable habitat. The shore side of the canopy provided a more suitable environment in the canopy, accommodating all of the considered species.

Finally, a brief case study is used to illustrate coralline larval recruitment. The chosen study site is Kaneohe Bay which has been extensively studied in literature. This area is home to the species P. Sibogae. A study from Koehl M.A.R. & Hadfield M.G. (2004) is used as the primary reference for this case where flow velocities are measured within the naturally existing canopies. These are then compared to laboratory experiments aimed at finding peak dislodgment shear stresses of the larvae on a variety of substrates. By using this study as a reference it was found that a longer and lower canopy provides enough wave driven flow-reduction near the shoreline face of the canopy to establish conditions within the tolerance required for P. Sibogae larval recruitment.
7.1 DRAG COEFFICIENT PARAMETERIZATION

To analyze the drag across the canopy the drag coefficient ($C_d$) is computed for each test according to the theory presented in section 2.2.3. The required process to obtain the $C_d$ value for each test consists of:

1. Computing the $H_{rms}$ for each test at all wave gauges across the canopy,
2. Using the $H_{rms}$ values across the canopy to calculate the damping parameter ($\beta$) as described in equation 2-11 (for regular waves) and 2-15 (for irregular waves),
3. Using the damping parameter to find the $C_d$ canopy drag coefficient from the relationship presented in equation 2-16.

By comparing the drag coefficients to the observed wave-driven Reynolds number (RE) just prior to the canopy, one can estimate the local $C_d$ coefficient in a range of environments if the local in-situ conditions for a particular site are known. Another frequently used parameter to compare the $C_d$ value with is the Keulegan-Carpenter number or ($K$) value (Mendez & Losada, 2004).

$$K = \frac{u_c T_p}{b_v} \quad [7-1]$$

Where $u_c$ is the characteristic velocity acting on the plant and defined as the maximum horizontal velocity at the middle of the vegetation field $x = b/2$ and $z = -h+\alpha h$, where $\alpha h$ is the height in the middle of the canopy from the flume bottom. The velocity $u_c$ is defined using $H_{rms}$ and $T_p$ as the wave height and the wave period corresponding to the monochromatic wave train. For irregular waves the following relationship can be used from Mendez & Losada, (2004):

$$Q = \frac{K}{\alpha^{0.76}} \quad [7-2]$$

Where $Q$ can be found using a relationship derived by Mendez & Losada (2004) from his experimental results:

$$\tilde{C}_d = \exp(-0.0138 Q) \quad Q^{0.3} \quad 7 \leq Q \leq 172 \quad [7-3]$$

This is called the modified Keulegan-Carpenter number. Similarly, the $C_d$ is compared to the wave driven Reynold number (RE). This value is derived from the orbital velocity recorded just prior to the canopy in the flume. The velocity can be found using:

$$U_{rms} = \frac{H}{2} \sqrt{gk \tanh(kh)} \times \frac{\cosh(k(h+z))}{\sinh(kh)} \quad [7-4]$$
Where the wave driven Reynolds number (RE) is:

\[
RE = \frac{U_{rms} b_v}{v}
\]  

[7-5]

**Regular waves**

The monochromatic wave testing conditions are plotted vs. the Keulegan-Carpenter (Kc) number and the Re number in Figure 7.1-1. It can be seen that the Kc number does not provide a very good fit for the data, with a power fit obtaining an R^2 value of only 0.5. When plotted against the Re number a better fit is obtained. This can also be observed from the data points, where the experimental results more closely match the power fit.

![Monochromatic Waves (H): C_d vs K](image1)

![Monochromatic Waves (H): C_d vs RE](image2)

**Figure 7.1-1: C_d vs. K and RE for regular waves**

**All wave conditions**

To obtain a more complete representation of the canopy drag characteristics, all of the tests conducted may be plotted using the averaged drag coefficient (\(\bar{C}_d\)) which uses Hrms from irregular wave testing. The \(\bar{C}_d\) values obtained are plotted vs. the Re number in Figure 7.1-2. An important characteristic in analyzing the canopy drag is the ratio of the water depth to the canopy height (H:h). This ratio is very beneficial when determining the optimal canopy dimensions and will therefore be incorporated. On the right of Figure 7.1-2 the (H:h) ratio has been incorporated resulting in a slightly less favorable fit. However, the information gained using this approach may outweigh some of the loss of confidence to the fitted data. For a more robust fit additional experiments would have to be performed to create a larger data set resulting in higher confidence.
The resulting lines of best from Figure 7.1-2 can be summarized in Table 7.1-1. The relationships for the power fit can be used as a guideline for designing the canopy.

**Figure 7.1-2: Cd vs. Re for all cases**

<table>
<thead>
<tr>
<th>Lines of best-fit for canopy drag</th>
<th>a</th>
<th>b</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tilde{C}_d = a(RE)^b )</td>
<td>31.9</td>
<td>-1.4</td>
<td>0.7</td>
</tr>
<tr>
<td>( \tilde{C}_d = a \left( RE \left( \frac{H}{h} \right)^2 \right)^b )</td>
<td>5.8</td>
<td>-0.6</td>
<td>0.5</td>
</tr>
<tr>
<td>( \tilde{C}_d = a(K)^b )</td>
<td>3.7</td>
<td>-0.6</td>
<td>0.3</td>
</tr>
<tr>
<td>( \tilde{C}_d = a \left( K \left( \frac{H}{h} \right)^2 \right)^b )</td>
<td>1.15</td>
<td>-0.4</td>
<td>0.4</td>
</tr>
</tbody>
</table>

The \( \tilde{C}_d \) value was also plotted against the Kc number in Figure 7.1-3. The Kc number does not provide a favorable fit compared to the RE number. When the (H:h) ratio is incorporated the fit improves slightly. However, the confidence is still too low compared to the fit provided by the RE number prior to the canopy.
Collectively the results displayed in Figure 7.1-1 - Figure 7.1-3 can be used to provide a basis for design or analysis of a GC canopy. The $R^2$ values do not indicate a very high level of confidence when the $(H:h)$ ratio is incorporated. This can be improved by conducting additional experiments with varying water levels / canopy elevations. Further difficulty arises in the theory used to parameterization the vegetation. The widely used Mendez and Losada (2004) method uses an $Re$ number averaged over the water column, and as a result the water velocities are too high, which means the $C_d$ values become too low. It is better to use a method which derives local $C_d$ values on the surface of the canopy.

The $C_d$ values from a selection of natural reef sites and coral types was compared to the results obtained from the GC canopy. It was found that the $C_d$ value of natural canopies was generally lower than that of the GC canopy. However, the GC canopy does not cover as an extensive area as a natural reef and therefore a higher $C_d$ value is required to provide similar wave dissipative qualities. Furthermore, GC canopy coverage is generally denser (although individual interlocking GC units are small in relation to more substantial coral branches / features) than a natural canopy, and therefore higher $C_d$ values may be expected. The $C_d$ values found in the flume experiments lie within the range of $C_d$ values found in natural reefs.
Table 7.1-2: Drag coefficients recorded at natural coral reefs
Adapted from: Rosman J.H., Hench J.J. (2011),

<table>
<thead>
<tr>
<th>Species</th>
<th>Source</th>
<th>$C_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porites compressa</td>
<td>[Baird and Atkinson, 1997]</td>
<td>0.04 - 0.06</td>
</tr>
<tr>
<td>Porites compressa</td>
<td>[Thomas and Atkinson, 1997]</td>
<td>0.06 - 0.1</td>
</tr>
<tr>
<td>Acropora palmate</td>
<td>[Lugo-Fernandez et al., 1998]</td>
<td>0.06 - 0.2</td>
</tr>
<tr>
<td>Sand with coral outcrops</td>
<td>[Baird et al., 2004]</td>
<td>0.036</td>
</tr>
<tr>
<td>Porites compressa</td>
<td>[McDonald et al., 2006]</td>
<td>0.06 - 0.8</td>
</tr>
<tr>
<td>Porites compressac</td>
<td>[McDonald et al., 2006]</td>
<td>0.016 - 0.05</td>
</tr>
<tr>
<td>Corals, seagrass, sand</td>
<td>[Coronado et al., 2007]</td>
<td>0.015</td>
</tr>
</tbody>
</table>

“The expressions for the drag coefficient fit to the laboratory data can be used to provide a basis for design and analysis of a GC canopy.”

7.2 IN-CANOPY FLOW AND IMPLICATIONS FOR LARVAL SETTLEMENT

To determine the in-canopy environment for the various marine plants and organisms identified in section 3.2 the in-canopy wave driven flow is examined. The primary data sets required for this analysis are the Vectrino II profiler and Vectrino I data sets. The Vectrino II is positioned at the leading edge of the canopy and the Vectrino I is positioned at the very rear of the canopy. As a result it is expected that the velocities recorded by the Vectrino II profiler are significantly larger than those at the Vectrino I profiler where the wave driven flows have likely been reduced by canopy interference. To illustrate this, the maximum and minimum wave driven velocities ($\bar{U}$) are plotted for each test and instrument. In Figure 7.2-1 all of the bichromatic and irregular wave tests are plotted. As expected, the in-canopy wave-driven flow velocities at the front of the canopy are significantly higher than at the rear.

It should be noted that the Vectrino I profiler has a significantly lower sampling frequency (25 Hz) than the Vectrino II profiler (100 Hz). Furthermore, far less data is available for the Vectrino I profiler as it only provides a single point measurement as opposed to the Vectrino II profiler which provides 31 data points over a single cross section. Therefore, the data being compared is not of the same quality. However, given the fact that the peak minimum and maximum velocities are being compared for wave-driven flow of each instrument, the lower resolution turbulence measurements of the Vectrino I profiler do not play a significant role in comparing the larger-period wave-driven flows.
The observed wave-driven flows in the canopy at the front of the canopy were used to calculate the total force (drag and lift) on an individual GC member. These forces can be compared to the maximum drag and lift thresholds for a variety of aquatic organisms and plant species. These are plotted against the in-canopy observed Re number for each data point and adjusted to the required scale using Froude scaling. The steps taken to calculate the lift and drag forces are as follow:

1. Separate the internal canopy flow into wave-driven flow and find the maximum and absolute minimum wave-driven velocities for each time series.
2. Compute the maximum allowable breaking force for aquatic species (equation 3-1) and vegetation (equation 3-2), which can be withstood upon settlement and adhesion.
3. Compute the maximum lift and drag forces experienced on an organism (equations 2-2, 2-4) using the species specific drag coefficient (equation 2-3) and find the final total force (equation 2-6) during maximum wave-driven flows.
4. Compare forces experienced by the marine organisms and vegetation to internal wave-driven Reynolds numbers (equation 2-1).

The velocities for all of the monochromatic tests are plotted at pilot scale in Figure 7.2-2 where the black points indicate living organisms and the red points indicate the algae species. The wave-driven force experienced on a GC is divided by the threshold of release for each organism to produce a non-dimensional value where 1.0 represents the dislodgment threshold.

It can be seen that for the lower energy waves with a period of 7 seconds the total force estimated on the various species and plant types is within the tolerable range for settlement and growth. However, as the flow velocities ($\bar{U}$) and subsequent Re number increases in the
canopy for higher energy waves (11-15s Tp) the dislodgment threshold is exceeded. The dislodgement threshold is first exceeded by the various plant species and eventually also by the more resistant limpet and urchin species. The only species able to withstand all of the wave conditions is the larger, Mytilus californianus, a muscle known to exist in high-energy intertidal regions. Traditionally, larvae of barnacles, limpets and muscles can settle on surfaces exposed to high water velocities, however initial results indicate the in-canopy flows are too high at the front of the canopy.

![Dislodgement due to wave-driven forces in the canopy](image)

Figure 7.2-2: Observed forces - monochromatic wave conditions in canopy 1

The same exercise for determining the in-canopy resistance of species settled on a GC surface in the monochromatic tests is also applied to the bichromatic and irregular test cases. These results are observed in Figure 7.2-3.
The bichromatic tests incorporated the largest wave heights of the testing campaign. The result of which can be seen on the left of Figure 7.2-3, where the high in-canopy Re numbers produce forces on the GC members which far exceed the dislodgement threshold of all organisms. Although the irregular test conditions were slightly less severe, the results indicate that under irregular conditions, the majority of plant species would not find a suitable environment in the front of the canopy. Similar patterns and dislodgement thresholds were found for the second canopy configuration presented in Appendix 1.0, section 5.

Although significantly less data was recorded at the location in the back of the canopy by the Vectrino I, the results provide an important indication of the magnitude of wave-driven velocity reduction by the canopy. As noted earlier in Figure 7.2-1 the velocities at the location in the back of the canopy are significantly reduced. All of the results from the monochromatic, bichromatic, and irregular tests are plotted at pilot scale for canopies 1 & 2 in Figure 7.2-4.
From Figure 7.2-4 it can be seen that all vegetation and marine species fall within the dislodgment threshold for both canopy configurations. This demonstrates that enough wave energy reduction has occurred at the back of the canopy to provide a favorable environment for marine life. It should be noted that the forces on an individual GC in the back of the canopy are significantly lower than those experienced on a GC at the front of the canopy.

The $H_{rms}$ profiles observed in Figure 6.1-4 may offer one possible explanation as to why wave driven-flows are much more significant at front of the canopy. The Vectrino II was placed almost exactly in the position where most of the shoaling on top of the canopy occurred. As a result the wave-driven flows are very high at this location, penetrating into the canopy and creating the large flow velocities observed. As this shoaling effect decreases the wave-driven flow is quickly reduced as it travels through the canopy. This explains why the velocities recorded in the rear of the canopy are significantly lower. The threshold required to support a range of larval settling plays a large role in determining the length of the GC canopy required to generate these types of conditions.

“Wave-driven velocities inside the front of canopy 1 & 2 suggest an exceedance of tolerable limits set for the chosen aquatic plants and organisms. The dissipated wave-driven flows in the rear of the canopy suggest a favorable environment for all species.”

### 7.3 CASE STUDY – P. SIBOGAE

To illustrate recruitment of larvae in the GC canopy a brief case study examining the species *P. Sibogae* described in section 3.2.2 will be used. The case study site is Kāneʻohe Bay, a 45 km² reef located on the island of Oʻahu. The Bay is approximately 12.8 km long and 4.3 km broad, with a mouth opening of about 7.4 km. It is one of the most well studied reef sites in the world and has been incorporated in hydrodynamic analysis presented in sections 3.0 & 4.0.

A schematic illustrating the use of GC’s is presented in Figure 7.3-1. A scenario is proposed where the natural coralline structures of Kaneohe are under stress from natural and anthropogenic factors such as those listed in section 2.1. The natural coralline canopies are in decline resulting in reduced settlement surface areas for the larvae circulating the bay. The movement of larvae during spawning is illustrated by the purple arrows, where it is anticipated that they circulate with localized current patterns in the bay.
A section of the reef top is illustrated in red on which the GC canopies are installed. These canopies would be positioned on the reef top as a series of porous arrays through which the larvae seeded in the water column passes freely. A study from Koehl & Hadfield (2004) is used as the primary reference for this case study. The study asks whether dissolved cues released into turbulent, wave-dominated reef environments can affect the adhesion of settling larvae to benthic surfaces. Field measurements of water velocities were taken of wave driven flow above and within the local reef canopy. Laboratory flume studies were used to measure the wall shear stresses required to dislodge larvae of *P. Sibogae* from various surfaces. It was found that a cue from *P. Compressa* is necessary for the larvae to attach to surfaces and, if the cue is dissolved in water bathing the larvae, they can adhere to surfaces other than living *P. Compressa*. It was noted that *P. Sibogae* develop their full attachment strength slowly, however the magnitude and frequency of peak shear stresses due to turbulent sweeps that might wash larvae off surfaces are much lower within than at the top of the reef. Therefore only the wave-driven flow recorded in the GC canopy will be used in this analysis. The information and observations made by Koehl & Hadfield (2004) can be used to establish an indication of larval adhesion success to GC elements.

One of the limitations of the study by Koehl & Hadfield (2004) is that the range of wave periods and wave-driven velocities observed in the reef are the only hydrodynamic conditions mentioned in the research. Information regarding the wave heights at the location of interest were not recorded. To estimate and understand the range of hydrodynamic conditions to which the GC canopies would be subjected at the time of Koehl & Hadfield’s study, previous hydrodynamic studies from Kaneohe Bay are consulted. The water depth at the location of Koehl & Hadfield’s study is known, in addition to the range of wave periods observed during testing. Therefore the range of kh values for this study may be approximated as indicated by the dashed blue lines to the left of Figure 7.3-2.
A selection of hydrodynamic field studies of Kaneohe Bay for which $H_{rms}$ values were known were collected. The corresponding $kh$ values are computed and plotted. The assumption is made that similar wave heights would occur at the site studied by Koehl & Hadfield (2004) if the water depth and wave periods correspond. The field data is scaled using Froude and plotted against the laboratory results for comparison. The flume tests which lie within this region are considered as relevant for comparison to the data collected by Koehl & Hadfield (2004).

The laboratory test cases which fall within the dashed lines (illustrating the boundary conditions of the data collected by Koehl & Hadfield, 2004) are plotted in red and labelled with their respective test #. These tests are then plotted for the top and bottom of the canopy in both the flume and the field study on the right of Figure 7.3-2. The red dashed lines in the histograms indicate the peak velocities recorded at the top and within the natural canopies found at Kaneohe Bay. It is clear that the velocities found in the GC canopy far exceed those found in the natural canopy given similar hydrodynamic conditions just prior to the canopies. However, when the irregular and bichromatic flume tests at the back of the canopy recorded by the vectrino I are plotted the velocities inside the GC canopy lie within or close to the range observed at Kaneohe Bay. This is illustrated in Figure 7.3-3 where the wave-driven velocities in the front and back for both canopy configurations are plotted.
The wave-driven velocities that lie within the range found at Kaneohe bay at the back of the canopy will be analyzed further using the nominal wall shear stresses recorded on *P. Sibogae* larvae by Koehl & Hadfield (2004). The nominal wall shear stresses on an individual GC are estimated using the theory presented in section 2.2.2 and compared to the findings from Koehl & Hadfield (2004). The maximum and minimum nominal wall shear stresses for all bichromatic and irregular tests are plotted in Figure 7.3-4. It can be seen that in the 2nd canopy arrangement most of the estimated nominal wall shear stresses induced by the wave driven flow lie below the maximum allowable thresholds observed by Koehl & Hadfield (2004). The first canopy arrangement exceeds the maximum shear threshold for a number of tests.

One possible explanation for the difference between the maximum and minimum shear stresses found in canopy 1 & 2 is the length of the canopy cover. As noted in Figure 6.1-4 the incident wave breaks on the canopy top and then dissipates over the structure more gradually for canopy 2 in comparison to canopy 1. Canopy 2 is considerably longer than canopy 1 and therefore provides more travel distance for the wave to energy to dissipate within the canopy. In addition, the higher water column above reef 2 means less wave energy reaches the canopy crest when lower amplitude waves pass over the reef. Although total wave height (*H*<sub>rms</sub>) reduction of canopy 1 and 2 seem to be relatively similar, the reduction in internal velocities is noticeably higher for the longer and lower canopy.
It should be noted that the nominal wall shear stresses used to measure the threshold of dislodgement for *P. Sibogae* larvae was conducted on relatively uniform, smooth surfaces. The ribbed structure of the GC's may provide additional protection from high velocity bursts and therefore decrease the shear stresses experienced on those surfaces. Further testing would be required to verify this at a pilot level scale.

“A longer lower canopy provides enough wave driven flow-reduction near the shoreline face of the canopy to establish conditions within the tolerance required for *P. Sibogae* larval recruitment”
CONCLUSIONS & RECOMMENDATIONS

Chapter summary: The conclusions and findings address the initial research questions and provide additional comments on limitations of the testing campaign in addition to recommendations for future work. This study is unique in that it incorporates many separate fields of research bridging various gaps of established ocean sciences in order to deliver more complete and comprehensive design recommendations. This thesis introduces the use of canopy theory for established trials with mangroves and sea grasses to artificial coral reef canopies.

With regard to wave damping across the structure it was found that:

- A best fit relationship could be established for a GC parameterized $C_d$ value incorporating additional information such as $H:h$
- In this study it was found that with higher water levels ($H = 2h - 1.5h$), the wave height reduction generally fell within 10-30%, whereas with lower water levels ($H = 1.25h - 1.0h$) the wave height reduction fell within 25-50%. These results were similar for both canopies.
- Initial testing with the vegetation canopy in XBeach in conjunction with deriving the GC specific $C_d$ values allow for numerical modelling of the GC concept

With regard to Hydrodynamics within the structure it was found that:

- The most important geometrical characteristics of the canopy in determining the success of larval adhesion is the length of the canopy within which the wave-driven flow can dissipate and the $H:h$ ratio which dictates how much wave energy is transferred to the canopy crest
- It was found that the wave-driven velocities at the back of the canopy were lower in canopy 2 and generally fell within the acceptable thresholds for P. Sibogae recruitment.
- Given some of the high energy-wave climates experienced by the canopy, the overall canopy resistance and/or material strength may become a limitation before the actual in-canopy velocities become too large for the recruitment of marine organisms

Additional findings include:

- The Shaw & Trowbridge method for turbulence decomposition is applicable outside its suggested range of validity due to the micro-structure of turbulence in the canopy.
- Numerical modeling using a non-hydrostatic individually wave-resolving model can produce wave conditions in a flume within a 95% confidence.
• A comprehensive database of global hydrodynamic fringing reef characteristics was established
• Placing the canopy as a low-lying structure close to the ocean surface provides more substrate for larval settlement.
• GC volume ratio to total canopy volume consistently ranged between 30-34%.
• A local shoaling effect occurs on top of the reef.

Some additional constraints to those mentioned previously in section 1.3 are mentioned. The section concludes by listing some recommendations for future work:
• It is recommended to deploy the GC canopy in calmer conditions with the primary purpose of providing a marine habitat and the secondary objective of providing wave dampening properties.
• Conduct a small pilot study focusing on coralline larval adhesion
• Explore alternative methods to find the $C_d$ values for the canopy, such as methods used for permeable breakwaters or dams. These methods employ a Forcheimer’s friction factor. Such investigations may improve the fitted relationship to the $C_d$ values.
• Measure turbulent structures and flows just above the canopy as this is a critical region dictating successful larval recruitment.
• Future work could consist of closer collaboration with ecologists and marine biologists to measure larval recruitment and adhesions thresholds for a variety of species. It would be beneficial to start this analysis at a global reef scale and narrow it down to a larval scale using CFD (computational fluid dynamics) modelling in programs such as open FOAM where very high-resolution, small scale details can be investigated.

8.1 FINDINGS AND CONCLUSIONS

The initial research questions raised in section 1.1 are re-visited and assessed using the results gained in this investigation. The initial research question states that the primary purpose of this investigation is to: “Establish a method to determine if a multipurpose artificial underwater structure can perform the functions of a natural canopy cover on a coral reef flat”. It was found that this could be answered by investigating 2 fundamental principles, these are the:

1. Hydrodynamic dampening across the canopy structure
2. Hydrodynamics within the canopy structure

Both of these research questions are important as they are related. The links between describing the wave damping above the canopy and the internal wave-driven flows within the canopy are primarily compared with field and laboratory results. However, as computational canopy modules improve, including more detailed pore-space velocity fluctuations, direct links may be established more easily during the design. Therefore, this research is important in indicating which factors are most critical in advancing the process of establishing in-canopy computational flow models using global wave climates and canopy $C_d$ findings. Each of these principles was broken down into sub-questions in section 1.3 and will be addressed below.
Wave damping across the structure:

a. Parameterized global drag coefficients for the GC canopy with a fitted relationship suitable for design purposes.

The wave height reduction was measured across both canopies and fitted to a canopy average drag coefficient $C_D$. These results were plotted against the RE number prior to the canopy and the observed Keulegan-Carpenter number ($K_c$). For design purposes the $H:h$ ratio of water level and canopy height is very beneficial. This factor was therefore also incorporated. The best fit to the data was found using the wave-driven RE number resulting in the following expressions:

$$\tilde{C}_d = 5.8 \left(RE \left(\frac{H}{h}\right)^2\right)^{-0.6} \quad \tilde{C}_d = 31.9 (RE)^{-1.4}$$

These expressions based on a power-fit have a $R^2$ value of 0.5 and 0.7 respectively and represent a relatively good fit to the data. Although the $R^2$ values do not indicate a very high level of confidence when the $H:h$ ratio is incorporated, the data does indicate a clear trend to which the power fit is aligned. One consideration is that the method employed to find the drag coefficient (Mendez & Losada, 2004) as depicted in Figure 7.1-2 relies heavily on proper geometrical canopy schematization. This was difficult to accomplish given the random canopy pore structure. Additionally the Mendez and Losada (2004) method uses an Re number averaged over the water column, and as a result the water velocities are too high, which means the $C_d$ values become too low. It is better to use a method which derives local $C_d$ values on the surface of the canopy.

Although best efforts were made, an alternative method to find the $C_d$ value for each test may consist of more traditional random porous canopy methods, such as those used for permeable breakwaters or dams. These methods employ a Forcheimer’s friction factor. Such investigations in addition to conducting additional experiments with varying water levels / canopy elevations may go a long way in improving the fitted relationship to the data. Improve parameterization of vegetation. Finally, it should be noted that $C_d$ value of natural canopies was generally lower than that of the GC reef. However, the GC reef does not cover as an extensive area as a natural reef and therefore a higher $C_d$ value is required to provide similar wave dissipative qualities.

b. Recommendations as to which type of reef configuration provides the best hydrodynamic dampening

A number of findings throughout the study provide the required evidence to suggest which type of canopy configuration has the best combination of functionality, footprint and
economic value. By using the same number of hooks in both canopy configuration, direct performance indicators can be compared without varying the cost of the canopy. The alternatives consist of a canopy with a small footprint and a high canopy crest (canopy 1), and a canopy with a large footprint and a low canopy crest (canopy 2).

Ultimately it was found that canopy 2 performed slightly better than canopy 1 for the following reasons:

- It can be seen that the longer and lower canopy (canopy 2), has greater wave dissipation (for most cases), when the water level is significantly higher than the canopy crest level. As the water level drops closer to the crest level, the reverse effect occurs and the higher crested canopy (canopy 1), has more of a dissipative effect. This can be described by the reduction of orbital motion near the GC surface as the water level increases. Additionally, at lower water levels, the wave heights are already depth limited and likely smaller than at higher water levels. These waves transmit less energy to the canopy and therefore provide less disturbance within the canopy.
- In this study it was found that with higher water levels (H = 2h-1.5h), the wave height reduction generally fell within 10-30%, whereas with lower water levels (H = 1.25h – 1.0h) the wave height reduction fell within 25-50%. These results were similar for both canopies.
- More vertical and horizontal (migration of the red GC’s placed on the canopy crest) movement was observed during testing of canopy 1. The movement of GC’s has the potential to significantly alter the canopy structure and may cause irreparable damage in the long term. The lower and larger canopy had considerably less vertical movement and was more stable throughout testing.
- The net wave height ($H_{rms}$) dissipation across canopy 1 and canopy 2 were relatively similar with dissipation occurring at a slower rate across canopy 2. This illustrates that there is limited advantage of having the crest at the water line.
- A submerged canopy is aesthetically more pleasing in a pristine coral reef environment and provides more bottom roughness for the establishment of marine life.
- Canopy 2 may provide a more ideal habitat for larval settling. The canopy is considerably longer than canopy 1 and therefore provides more distance for the wave energy to dissipate within the canopy. Although total wave height ($H_{rms}$) reduction of canopy 1 and 2 seem to be relatively similar, the reduction in internal velocities is noticeably higher for the longer and lower canopy.

### c. Implementation of GC canopy characteristics in numerical modelling package for further canopy testing and optimization.

The XBeach vegetation canopy was used to develop the canopy geometries used in testing. This was illustrated in section 4.2.2 in Figure 4.2-7. The vegetation canopy can be validated using the results from the experiment. XBeach uses the same theory from Mendez & Losada (2004) to schematize the vegetation which makes a direct comparison a relevant exercise.

Due to constraints in the research scope and timing, no such analysis is planned for the current investigation. For future implementation of the results in the XBeach vegetation
module it is recommended to find methods which more accurately schematize the vegetation used in the physical model testing, as this may produce some uncertainty in the simulations. Once the XBeach module has been calibrated and validated, it may be used as a tool to design MAUS structures such as the GC canopy at various locations around the world. The parameterized $C_d$ values will then become a key element in this design process.

The steps which can be taken to design a GC MAUS with the results of this study are as follows:

1. Select desired location for canopy where hydrodynamic conditions are known
2. Determine primary purpose of intended canopy (ecological and hydrodynamic functions)
3. Collect information of local aquatic species / vegetation and their needs
4. Compute wave-driven Reynolds number at locations of interest and find anticipated canopy $C_d$ value from the results of this investigation
5. Use $C_d$ value as input for the numerical canopy model tested in this investigation. Iteratively determine the desired canopy dimensions based on total wave height reduction which can be accomplished and the desired hydrodynamic climate in the canopy.
6. Wave height reduction and associated orbital velocities computed at the landward side of the canopy can be used as an indication whether larval settling is possible.
7. Local wave-climate can be compared using a similar approach as employed in section 7.3 to determine if the reef is attractive for recruitment.

It should be noted that for step 6 there is currently no readily available computational model which can resolve wave-driven velocities within the canopy. Such developments are required for a more reliable understanding of the forces and velocities experienced on larvae in the canopy. Until adequately developed, this connection must be made using approximations, physical model testing and field-observations.

**Hydrodynamics within the structure:**

A collection of marine species was used for the in-canopy analysis of lift and drag forces on an individual GC member subjected to wave-driven flows. One of the primary limitations of this data set was its limited geographical range from Alaska to southern Mexico. This is not truly representative of the global fringing reef study area. However, as noted such data is limited and relatively difficult to access. Although not applicable on a global level, these thresholds should give a good indication of survivorship in the GC MAUS in high energy wave environments typical to the North American Pacific coast.
From these results it was found that typical wave-driven flows at the offshore side of the canopy exceeded tolerable thresholds for most species of algae once the wave period exceeded a pilot scale peak period of 7 seconds. Higher energy waves ranging from 10-15 seconds exceeded thresholds of all algae species and other aquatic life forms such as urchins, limpets, and some barnacles. The larger *Mytilus Californianus*, a muscle known to exist in high-energy inter-tidal regions performed well in the more exposed areas of the canopy. The results in this region of the canopy were similar for both canopy 1 and canopy 2.

The wave-driven velocities observed in the shoreward side of the canopy for both canopy 1 and 2 indicate a suitable environment for all algae and marine species considered. There is a significant reduction of wave-driven velocities throughout the canopy structure indicating the importance of the structural width. Canopy 2 performed better than canopy 1 due to its larger footprint. This was also the case when the maximum acceptable shear stress on a GC was calculated for the larvae *P. Sibogae*. Recruitment processes and speed for the *P. Sibogae* was found to be similar to the coral species *Fungia scutaria* also found at Kaneohe Bay. The hydrodynamic conditions in canopy 2 were more favorable than those in canopy 1.

Ultimately the most critical factors in determining the success of larval adhesion in the canopies are:

- Length of the canopy within which the wave-driven flow can dissipate.
- $H : h$ (water depth : canopy height) and $L : (H-h)$, (wave length : water column above the canopy) dictates how much wave energy is transferred to the canopy crest.

b. *Compare natural wave driven canopy flows within the canopy with those observed in field studies.*

A case study was used to compare the magnitude of wave driven flows in a natural canopy to those found in the flume study. Comparable wave driven flows to those found at a field site (Kaneohe Bay, Hawaii) could be observed in the shoreward side of the GC canopy. These velocities were then used to estimate the shear stresses on a GC surface and compared to laboratory observations of shear stress thresholds for well-studied larvae *P. Sibogae*. It was found that the wave-driven velocities were lower in canopy 2 and generally fell within the acceptable thresholds for *P. Sibogae* recruitment. This illustrated the importance of the canopy length and water column depth above the canopy. With a lower canopy, almost the same net wave height reduction occurred due to the extended canopy length across which the wave-driven velocity can dissipate. Although *P. Sibogae* is not a coralline larva, it was found to share similar patterns in recruitment to that of the coral species *Fungia scutaria* also found at Kaneohe Bay.

The GC structure is rather open and porous compared to more monolithic type coral features. This creates high initial internal wave-drive velocities at the offshore end of the canopy. The outer edge of the GC canopy is therefore unattractive for settlement and growth of more delicate marine species. The study makes an initial estimate of larval recruitment within the canopy using only 1 species. Although this species is often considered the “model” species for larval recruitment studies, and is most often cited and used in the types of investigations, a larger variety of species should be studied. To fully understand the relationship between
wave-driven flows in the GC canopy and how those are related to natural canopy flows, with their associated environments for larval recruitment, additional field and laboratory studies must be undertaken to parameterize more species and scenarios.

c. Provide recommendation as to which environments would provide the most successful hydrodynamic conditions for the GC concept

Given some of the high energy-wave climates experienced by the canopy, the overall canopy resistance and/or material strength may become a limitation before the actual in-canopy velocities become too large for the establishment of marine organisms. This was found to be the case with some of the tests that experienced large wave driven flows. Visual observations confirmed significant movement of the canopy in the vertical in addition to horizontal migration of hooks as the water level reached the canopy crest. It is therefore recommended to deploy the GC canopy in calmer conditions with the primary purpose of providing a marine habitat and the secondary objective of providing wave dampening properties. This is also reinforced by the porous nature of the canopy which results in high-wave driven velocities at the offshore end of the canopy.

Furthermore, it is recommended to place the canopy close to the bottom providing more substrate for larval settlement. Lower energy intertidal areas would also provide an excellent habitat for GC canopy instillation as this would facilitate the growth of more resistant species such as muscles, limpets and urchins. Although, sufficient circulation of nutrients is required to maintain these populations.

Additional findings
Some notable additional findings observed during this study are:

- The Shaw & Trowbridge method for turbulence decomposition is applicable outside its suggested range of validity due to the micro-structure of turbulence in the canopy. It was found that there was little to no turbulence interaction within 5 cm from a measured point. This allows a Vectrino profiler to be placed at smaller intervals in the canopy in addition to increasing the flexibility of which points can be used to decompose the signal.
- This thesis introduces the relatively novel idea of using a numerical model to generate tailored wave time-series for a physical modelling campaign. This method was developed after it was deemed unpractical to replicate the steep fringing reef edge in a physical model.
- Numerical modeling using a non-hydrostatic individually wave-resolving model can produce wave conditions for a flume hydraulic wave paddle within a confidence limit of 95%.
- A large database of global fringing reef characteristics was not readily available. For the purpose of this study, this newly developed data set was assembled. Such a collection of information can prove to be useful in future studies.
The Vectrino II was placed almost exactly in the position where most of the shoaling on top of the canopy occurred. As a result the wave-driven flows are considerably larger at this location, penetrating deeper into the canopy and at times lifting the canopy from the flume bottom.

- GC volume ratio to total canopy volume consistently ranged between 30-34%.
- A local shoaling effect occurs on top of the canopy.
- Mechanical limits of the wave-paddle at the TU Delft hydraulics laboratory were explored. It was found that long waves with a period up to 7 seconds could be generated with an amplitude of 0.4m +/- 0.05m. Irregular shorter wave signals could be generated more easily. It was also found that the higher harmonics in shorter period waves were difficult to generate due to the short-interval successive accelerations.

### 8.1.1 Limitations

The following limitations were observed in addition to those initially outlined in section 1.3:

- Most of the larval species which were used in the analysis were found in the Pacific Northwest down to the Mexican pacific coast. This is primarily due to the fact that this region is very well studied with a lot of valuable data readily available for this study. Although not applicable on a global level, these thresholds should give a good indication of survivorship in the GC MAUS in high energy wave environments typical to the North American Pacific coast.
- As previously noted, the Mendez and Losada (2004) method uses a number of assumption to parameterize the canopy geometry. This method employed for the current study is not entirely correct, as it does not take the three-dimensional nature of the hooks into account. Introducing alternative theories such as the Forcheimer method discussed earlier may be a feasible alternative.
- The species examined in analysis (e.g. larvae of barnacles, bryozoans, some cnidarians) settle on surfaces in intertidal zones and therefore require some time of exposure without inundation – this was not the case with flume test studies, where only about 1/3 of the test exposed the canopy crests. Additional information on species with full permanent submergence would be beneficial to a more representative investigation.
- During post processing and analysis of results, it was found in literature that many critical recruitment indicators can be observed by analyzing the flow structure just above the canopy. This was not done in the experiments, where the velocities were only measured within the canopy. It would be beneficial to understand the turbulent flow structures just above the canopy.
- A larger variety in testing conditions may have provided a better fit to $C_d$ values
- Velocity recorded with the Vectrino I is at a lower frequency than that of the Vectrino II, therefore turbulent the signal is not comparable. The wave-driven component is averaged over a series of turbulent fluctuations and may therefore be relatively comparable for both instruments.
- The ribbed structure of the GC's may provide additional protection from high velocity bursts. This may decrease the shear stresses experienced on those surfaces. Further testing would be required to verify this at a pilot level scale.
8.1.2 Advancements

The results presented in this investigation help to advance the following concepts:

- Applying canopy theory developed for mangroves, sea grasses and other conventional natural canopies, to an artificial reef canopies.
- Deriving a $C_d$ relationship for the GC concept.
- Designing a research methodology and structure which incorporates a number of scientific fields intended to bridge various gaps of research to deliver more complete and comprehensive design recommendations.
- A more thorough oversight of required changes and additions in canopy schematization, research and interpretation was explored.
- A more flexible application of the Shaw & Trowbridge turbulence decomposition scheme was introduced in a porous canopy scenario.
- A data-base of fringing reef characteristics was compiled introducing a larger data set than currently available in the public domain.
- First use of XBeach vegetation canopy module in a research application, relying on the theory from Mendez & Losada (2004).
- Validation and demonstration of successful application of unconventional method to produce a custom wave climate in a flume using waves transformed in a numerical model.
- This research provides evidence needed to determine which factors are most critical in advancing the understanding of current and future requirements for internal canopy computational flow models.

Ultimately, given the above considerations and limitations, it was found that a GC canopy can perform some of the key functions of a natural canopy, if adapted to the local wave climate and aquatic species. In a reef environment coral recruitment is usually higher on vertical or inclined surfaces as compared to horizontal ones, mainly due to lower sedimentation levels and increased water circulation on the former. These types of surfaces are abundant in a GC structure. Furthermore, the structural complexity of a natural reef (like a GC MAUS) greatly affects the species diversity, density and size distribution of both invertebrates and fish, as a more complex and heterogeneous canopy structure offers a greater array of niches.

8.2 RECOMMENDATIONS

The following recommendations are made for the outcome of this investigation:

- Focus on designing a low crested structure to maintain structural integrity, aesthetic appeal whilst maximizing reef top substrate for settlement
- Conduct a small pilot study focusing on coralline larval adhesion
- Deploy the GC canopy in calmer conditions with the primary purpose of providing a marine habitat and the secondary objective of providing wave dampening properties.
- Explore alternative methods to find the $C_d$ values for the canopy, such as methods used for permeable breakwaters or dams. These methods employ a Forchheimer’s friction factor. Such investigations may improve the fitted relationship to the $C_d$ values.
• Validating the XBeach module with the fitted $C_d$ value will create a useful tool to design GC canopies at various locations around the world.

• Continue to develop the links between the wave-driven flows and $C_d$ values above the canopy and the internal flow velocities and larvae survivorship.

The following recommendations are made for continued work:

• An apparent disconnect exists within research in relating the large scale hydrodynamic processes occurring in and around fringing reef systems to the larval scale hydrodynamic processes occurring on the surfaces of natural and artificial structures. This link must be better understood with a combination of field and laboratory research.

• There is an apparent need to study more species of aquatic larvae and how large-scale and local hydrodynamic process influence their recruitment.

• Measure turbulent structures and flows just above the canopy as this is a critical region dictating successful larval recruitment.

• Future work could consist of closer collaboration with ecologists and marine biologists to measure larval recruitment and adhesions thresholds for a variety of species. It would be beneficial to start this analysis at a global reef scale and narrow it down to a larval scale using a combination of CFD (computational fluid dynamics) modelling in programs such as open FOAM. This model could be fed by canopy profiles acquired in field surveys where detailed local hydrodynamic conditions are recorded and observed. The global hydrodynamic conditions around the canopy can then be modeled, calibrated and validated in a CFD type application and more carefully studied at a larval-scale on the object’s surface using a high resolution canopy mesh in the CFD model.

• Improve parameterization of vegetation. The widely used Mendez and Losada (2004) method uses an Re number averaged over the water column, and as a result the water velocities are too high, which means the $C_d$ values become too low. It is better to use a method which derives local $C_d$ values on the surface of the canopy.

• There are currently limited available computational models which can resolve wave-driven velocities within a canopy. Such developments are required for a more reliable understanding of the forces and velocities experienced on larvae in the canopy. Until adequately developed, this connection must be made using approximations, physical model testing and field-observations.
Roll on, thou deep and dark blue Ocean, roll!  
Ten thousand fleets sweep over thee in vain;  
Man marks the earth with ruins, his control  
Stops with the shore...  
Lord Byron, “Childe Harold’s Pilgrimage” 1812


Hu Z., Suzuki T., Zitman T., Uittewaal W., Stive M., Laboratory study on wave dissipation by vegetation in combined current–wave flow, Coastal Engineering, Volume 88, June 2014, Pg 131-142


Schmidt, D., A Review of California Mussel ("Mytilus californianus") Fisheries Biology and Fisheries Programs, Canadian Stock Assessment Secretariat Research Document 99/187


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Climate Change And The Great Barrier Reef: A Vulnerability Assessment (pp. 667-716). Townsville, Qld., Australia


APPENDIX

The following appendix provides additional material discussed in the thesis and can be used to add background and context to the presented information.

1.0 Global Reef Survey

The following material supports the information presented in section 3.1.

Figure A1: Reef profiles collected in literature
Figure A2: Various reef top spectra recorded worldwide

Figure A3: In-situ recorded offshore wave heights at various locations worldwide
Figure A4: In-situ recorded offshore period at various locations worldwide

Figure A5: In-situ recorded reef top wave height at various locations worldwide
Figure A6: In-situ recorded reef top wave periods at various locations worldwide

Figure A7: Reef top and offshore conditions recorded for use at John Brewer Reef - Australia
Figure A8: Reef top and offshore conditions recorded for use at Guam – South Pacific

2.0 Wave calibration

Figure A9: Calibration of TU Delft wave paddle for bichromatic conditions
Figure A10: Calibration of TU Delft wave paddle for irregular conditions

3.0 Example input DELFT-AUKE/GENERATE

A typical input for DELFT-AUKE/GENERATE in the measurement setting is show:

```
WAVETYPE,MEASUREMENT
\{[[AUKEPC]]<ASCII,\{DT=dt|FREQ=freq\},SCALE=scale-meas[1.]>\}
DATAFILE,filenedcriptor
SCALE-FOR-GENERATION, scale-stir
POSITION,x,y
ANGLE,angle
\{LONGCRESTED}\}
BAND-PASS,LOW=value,HIGH=value
END:WAVETYPE
```

The $dt$ value is in seconds and the $freq$ value is the reciprocal value. The scale to nature of the measurement is given with the $SCALE$ parameter in $scale-meas$. The scaling has already been completed prior to this step and therefore this value will be set to 1. The $POSITION$ directive sets the coordinate where the wave field to generate must be realised. The position is given as $x,y$ in the user coordinate system. In these tests, the signal has been generated with the intention that it is the signal found at the wave paddle, therefore $POSITION$ will be set to 0.
4.0 Wave dissipation at various water levels

**Figure A11:** Wave dissipation across reef 1 & 2, WL 0.38m & 0.36m

**Figure A12:** Wave dissipation across reef 1 & 2, WL 0.42m
Figure A13: Wave dissipation across reef 1 & 2, WL 0.48m

Figure A14: Wave dissipation across reef 1 & 2, WL 0.52m
5.0 In-canopy flows

Dislodgement due to wave-driven forces in the canopy - Field measurements vs. Reef 2 monochromatic laboratory results -

Figure A15: Observed forces - monochromatic wave conditions in canopy 2

Dislodgement due to wave-driven forces in the canopy - Field measurements vs. Reef 2 bichromatic laboratory results -

Figure A16: Observed forces - bichromatic wave conditions in canopy 2
Another method which can be used to compare turbulence decomposition techniques is to analyze the resulting turbulent kinetic energy (TKE) and shear stress profiles. The TKE budget can be described Poggi D., Katul G.G., Albertson J.D. (2004):

$$0 = P_s + P_w + P_t + P_d$$  \[1-0\]

Where $P_s$, $P_w$, $P_t$, and $P_d$ are the shear production, wake production, turbulent transport, and viscous dissipation rates, respectively. Each of these terms is given by:

$$P_s = -2\langle u'w' \rangle \frac{d\langle u \rangle}{dz}$$ \[2-0\]

$$P_w = 2C_d a\langle u \rangle^3$$ \[3-0\]

$$P_t = \frac{d}{dz} \left[ q_{13} \left( \frac{d\langle u'w' \rangle}{dz} + \frac{d\langle v'v' \rangle}{dz} + \frac{d\langle w'w' \rangle}{dz} \right) \right]$$ \[4-0\]

$$P_d = -2 q^3 \frac{3}{a^3}$$ \[5-0\]

From equations [2-0] to [5-0] it can be seen that velocity is considered in the $u,v,w$ directions. These measurements can be made using the Vectrino profilers. The individual components of the TKE budget can be analyzed in the post processing stage of the modeling campaign. During the testing phase, initial indications of the stream wise turbulence intensity $T_u$, vertical...
turbulence intensity $T_v$, and turbulent kinetic energy $k$ can be computed using the following relationships (Leu J.M., Chan H.C., Chu M.S., 2008):

$$ T_u = \left( \overline{u'^2} \right)^{1/2} $$ \hspace{1cm} [6-0] 

$$ T_v = \left( \overline{v'^2} \right)^{1/2} $$ \hspace{1cm} [7-0] 

$$ k = \frac{1}{2} \left( \overline{u'^2} + \overline{v'^2} + \overline{w'^2} \right) $$ \hspace{1cm} [8-0]

In expressions [6-0] to [8-0] $u'$ is the fluctuation of $u$, $v'$ is the fluctuation of $v$ and $w'$ is the fluctuation of $w$. These fluctuations can be computed using a combination of data collected from the GHM wave height profilers, vectrino profilers and the EMS units. Figure A18 presents the TKE and Reynolds stress profiles for the various turbulence decomposition schemes. It can be seen that the Shaw & Trowbridge method provides the most reliable result for the Reynolds profile because its profile average is 0, which is expected.

![Figure A18: TKE and Re profiles for various turbulence decomposition techniques](image)

The profiles presented in figure A18 are often used in turbulence studies. However, these profiles were not required to answer the research questions and were therefore abandoned.

Another way to analyze these turbulent fluctuations is presented in figure A19 where location B is the top of the canopy and location C is the bottom of the canopy. The data from the Vectrino II profiler is plotted as a plan view where turbulent fluctuations $u'$ and $w'$ can give an indication of the direction in which turbulent burst or sweeps travel in the canopy at a given time step. Again, such profiles, although very informative, were not required to answer the research questions and were therefore abandoned.
Figure A19: Turbulent fluctuations in the canopy at various locations