Nauman Raza

Physical Model Study of Living Breakwaters

Stability and Ecological Analysis of Green-Grey Hybrid Structure Concept for Climate Change Adaption

Master's thesis in Coastal and Marine Engineering and Management
Supervisor: Dr. Raed Lubbad
August 2019

Master's thesis

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Norwegian University of Science and Technology
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ERASMUS +: ERASMUS MUNDUS MOBILITY PROGRAMME

Master of Science in

COASTAL AND MARINE ENGINEERING AND MANAGEMENT

CoMEM

PHYSICAL MODEL STUDY OF LIVING BREAKWATERS;
STABILITY AND ECOLOGICAL ANALYSIS OF GREEN-GREY HYBRID STRUCTURE CONCEPT FOR CLIMATE CHANGE ADAPTION

Norwegian University of Science and Technology

05 August 2019

Nauman Raza

The Erasmus+: Erasmus Mundus MSc in Coastal and Marine Engineering and Management is an integrated programme including mobility organized by five European partner institutions, coordinated by Norwegian University of Science and Technology (NTNU).

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CoMEM Thesis

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Abstract

A vast majority (84%) of all countries in the world have coastlines and 80-100% of their population resides within 100 km of the shoreline. Studies show a major growth in population in low-elevation coastal zones and a scenario of rising sea level may force millions of people to relocate. To deal with the increased frequency of extreme events and sea level rise, coastal vegetation (mangroves, salt marches and coral reefs) has been observed to act as an effective natural barrier. Coral reefs are believed to reduce upto 90% of wave energy but increasingly warming oceans and acidification are destroying this barrier by coral bleaching. Apart from a social, ecological and environmental damage, this will also result in an increase in environmental loading on coastal structures.

This study focuses on the development of a climate change adaption measure for existing structures on the principles of Sustainability. In order to do so, a representative existing breakwater at Kiberg Norway is chosen. A brief ecology study of the area is conducted and based on economic value and vulnerability, Red King Crabs and Capelin are chosen as target species. A green-grey hybrid structure consisting of an existing breakwater with additional Artificial Reefs (AR) as toe elements is hypothesized to be the suitable solution. However, hydraulic performance of AR is still not understood properly and to utilize them to enhance the stability of existing breakwater may create tension between hydrodynamic and ecological performance.

In order to investigate the hydraulic behaviour of hybrid structure, physical model study is conducted. A traditional method of using transmission coefficient to quantify energy dissipation over submerged/non-submerged AR breakwater is not suitable for this hybrid structure. Therefore, stability of existing breakwater is measured in terms of damage level (Ahrens and Cox, 1990) and indirectly by turbulent kinetic energy (Mukaro and Govender, 2013) for 9 plunging and 6 surging wave conditions. Four configurations of experimental setup are finalized with four types of AR units (AR1, AR2, AR3 and AR4) and in total 175 tests are carried out. Behaviour of breaking and non-breaking waves is observed to be different especially over config-3 and config-4. Landward vortex and breaker tongue are not fully developed in config-3 due to depth limited scenario. Additional non-linearities in the flow, due to interaction of incoming and secondary waves, are observed for config-4, which resulted into higher reflection coefficient than other configurations.

Behaviour of a hybrid structure can be predicted by Van der Meer stability formulas for plunging and surging waves at lower wave heights. However, higher waves exhibit greater damage reduction and formulas show larger deviations. Results indicate that one row of AR placed as toe, does not reduce much damage (10%). A comparison of all the configurations indicate that config-3 and config-4 show an average damage reduction of 38% and 51% respectively. Critical stability number of config-4 (i.e. 1.45) is lower than of config-1 (i.e. 1.7), indicating that disturbing forces are becoming weaker due to the presence of

AR. Residence time of wave on reef is believed to be of much importance and with a 15m reef length a damage reduction upto 45% is observed. Reef porosity is observed to have dependency on placement location and reef length. Ecological performance is predicted to increase by 25% in 10 years of construction. However, differently chosen indicator species might have shown better results.

It is concluded from the study that green-grey hybrid structures can be a suitable short-term climate change adaption measure.

Acknowledgments

With the completion of my masters thesis, an exciting journey of two years will come to an end. Getting accepted into CoMEM, was an ideal start of my professional life. I would like to thank Dr. Øivind and Ms. Sonja for their constant support and guidance in all the administrative issues. Getting so far would have never been this easier without their help. Thanks to them I got to be a part of CoMEM trips and waffle presentations, the exciting memories that I will always cherish.

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I would like to thank my mom, dad and my siblings for their love, support and encouragement. Even though we are half of the world apart but we are connected and this connection has got me going through every trouble I faced so far. Finally, I would like to thank the great group of friends throughout the world which I got because of CoMEM. The time I spent with all of them is the highlight of my life.

Nauman Raza
Trondheim, August 2019

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Symbols and Abbreviations

Symbol	=	**Definition**
AR	=	Artificial Reef
TBW	=	Traditional Breakwater
BwN	=	Building with Nature
SLR	=	Sea Level Rise
N_L	=	Length Scale Factor
F_r	=	Froude Number
C_r	=	Reflection Coefficient
C_t	=	Transmission Coefficient
TKE	=	Turbulent Kinetic Energy
r_u	=	Turbulence Intensity
ξ	=	Iribarren Number
KC	=	Keulegen-Carpenter Number
D_{N50}	=	Median Nominal Stone Diameter
S_d	=	Damage Level Parameter
H_s	=	Significant Wave Height
H_o	=	Deepwater Wave Height
H_i	=	Incident Wave Height
T	=	Wave Period
L_o	=	Deepwater Wave Length
α	=	Seaward Slope of Structure/Model
ADV	=	Acoustic Doppler Velocimetry
d_r	=	Water Depth over AR
H_r	=	AR Height/Relief
H_{ref}	=	Reflected Wave Height
P	=	Van der Meer Nominal Permeability Factor
Ω	=	Breaker Height Index
LCS	=	Low-crested Submerged Breakwaters
ADV	=	Acoustic Doppler Velocimeters
MSL	=	Mean Sea Level
R_e	=	Reynolds Number
HAT	=	Highest Astronomical Tide
$RMSE$	=	Root Mean Square Error
u', v', w'	=	Turbulent Velocities in x, y and z direction
$\overline{u}, \overline{v}, \overline{w}$	=	Mean Velocities in x, y and z direction
r_u, r_v or r_w	=	Turbulence Intensities in x, y and z direction
$u'_{rms}, v'_{rms}, w'_{rms}$	=	Root Mean Square of velocity fluctuations in x, y and z direction
FFT	=	Fast Fourier Transformation

1 Introduction

> "The challenge is not to find the best policy today for the next 100 years, but to select a prudent strategy and to adjust it over time in the light of new information."
>
> *(IPCC, 1996)*

Coastal areas define the boundary between land and oceans/seas. The dynamic interaction between the oceans and land is causing a continuous change in coastal zones, which are the habitat to various species of flora and fauna. In this age of globalization and global warming, coastal zones are constantly experiencing increased pressure from landward and seaward side due to enhanced economic development activities and sea level rise (SLR). In order to keep up with changing environmental conditions (SLR, temperature pH changes etc.), marine habitats are forced to move landwards. At the same time, economic development is forcing to push the business development seawards resulting in the destruction of marine habitats due to this coastal squeeze. This also results in more severe consequences on the elements of coastal zone management, e.g. increased and frequent loading on structure etc.

1.1 Background

A vast majority (84%) of the countries in the world have coastlines and 80-100% of their population resides within 100 km of the shoreline (Martinez et al., 2007). Neumann et al. (2015) concluded from the study on population growth for 2030 and 2060 that a major increase in population is expected in low-elevation coastal zones and a scenario of rising sea level may force millions of people to relocate. Along with this, changing climate will cause increase in weather extremes (Mann et al., 2017). Hemer et al. (2013) predict an increase in mean value of peak period of 30% at certain locations around the world. In fact, its not only peak periods that could change, given the expected climate change scenario, but also wave heights and wave directions.

In this context, coastal vegetation has been shown to resist the climate change in a very effective manner, acting as a natural barrier. Mangroves, salt marches and coral reefs are believed to damp the energy of storm waves and reducing their impact. But, an increase in oceanic temperature and pH is effecting their growth. A warmer planet have been observed to have huge implications on marine ecosystem such as coral reefs. Three major events of coral bleaching have been recorded so far (1998, 2002 and 2012). More acidic ocean will show reduction in the saturation state of aragonite which leads the coral reef skeletons to become fragile, prone to erosion and exhibit lower growth rate. Many marine organisms, including commercially important fish species during planktonic larvae phases, are also threatened by this situation. Doney et al. (2009) suggest that ocean warming and acidification, threaten current food webs and, consequently, the livelihood of communities that depend on the ocean for a source of protein. Therefore, loss of these natural barriers will enhance the risk of social damage (coastal erosion, flooding, loose of food source), ecological damage (loose of marine habitats, migration of species) and environmental damage.

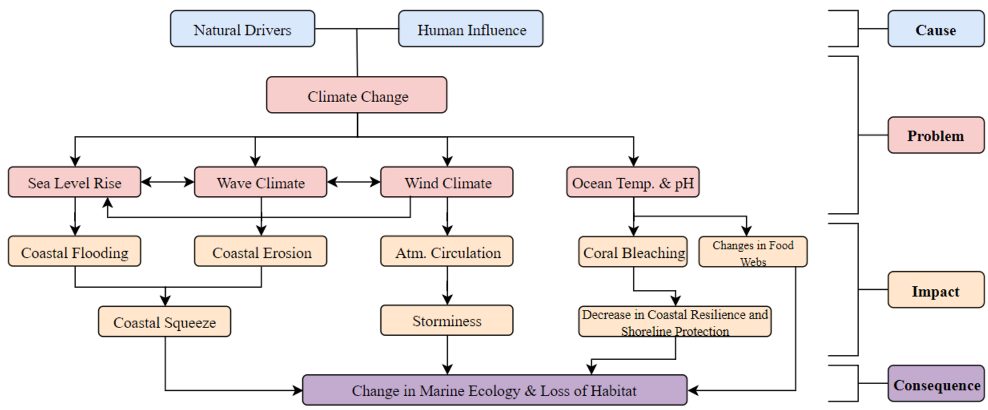


Figure 1.1: Causes, Impact and Consequences of Climate Change.

Humans have accelerated the climate change situation through changing the natural behaviours of water bodies (e.g. river damming) and seaward development (land reclamation) which have resulted in coastal erosion and flooding at many locations along with destruction of marine ecosystem.*The process of loss of intertidal habitats that are positioned between increasing human pressure landward and rising water level seaward is known as coastal squeeze* (Pontee, 2013). Figure 1.1 presents a flow chart for climate change situation. It links the climate change associated problems with the aforementioned impacts and consequences.

1.1.1 Motivation

A couple of decades ago, coastal development was only considered with perspective of economic development, ignoring the coastal squeeze and its consequences on marine ecology. However, the scenarios have changed now, new developments in coastal zones are being carried out in accordance with the policies on climate change and conservation of natural habitats of the species in the construction area, but the problem lies with the adaption for existing structures. There are numerous existing structures which require constant excessive maintenance due to increasingly changing environmental loads and intensity of these loads.

A **sustainable future** is currently the focus of most of the developments in the coastal areas. Every coastal management activity should focus on building social resiliency within the society, reducing risk due to changing environmental conditions and it should also give the opportunity for growth of ecological resiliency. These three basic elements of sustainability (see Figure1.2) are interrelated. Human safety and economic development should have to go in hand with ecological resilience. Awareness about environmental sustainable development as an indicator of sustainability is increasing. However, the concept of harmonizing ecology with coastal protection still requires alot of research and especially for existing coastal structures.

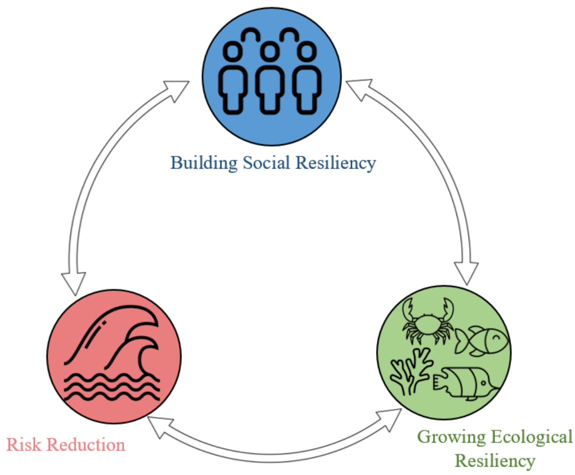


Figure 1.2: Elements of Sustainability in Coastal Zones, (Scott et al., 2018).

1.1.2 Study Area

The study is based on a fishery harbour located in Kiberg in the Finnmark county, along the Barents Sea, in northern Norway. A location map is shown in Figure 1.3. In the area, two breakwaters with varying stone quality were constructed in 1960s to provide tranquil conditions for Kiberg port. Due to the concentration of waves, northern convex shaped breakwater suffered damage and temporary repairs have been carried out. However, it is expected that with the changing climate along with increased frequency of extreme events, the breakwater is going to suffer more damage unless some adoptive measures are taken.

Figure 1.3: Location Map

1.1.3 Ecology of the Area

Ecology of Barents Sea is changing due to climate change which is causing the change in patterns of biodiversity, through variation/alteration in species distribution. The Barents sea has a shelf ecosystem, which is highly effected by the ice cover. Almost 40% of the sea is covered with ice but it varies with season, August/September being the lowest and March/April being the highest. This ecosystem is situated at a border between the North Atlantic Oceans and the Arctic. If it is seen as in the perspective of Arctic Ocean then it is highly productive, deep, inflowing shelf sea (Carmack and Wassmann, 2006). However, if compared to North Atlantic shelf ecosystem, Barents Sea has low productivity and low biodiversity (Frank et al., 2007). Highly variable ice-cover is assumed to be the cause of low productivity, but ice melt in summer initiates phytoplankton bloom which attracts high concentrations of zooplankton. Due to this high concentrations, these areas are targets for the northbound feeding migrations of capelin, red king crabs, North-East Arctic (NEA) cod, juvenile herring, haddock, blue whiting, seabirds and marine mammals in late summer and early autumn (Elisabet et al., 2009). Therefore, Barents Sea is identified as short-lived, intense and spatially concentrated pulse in terms of biodiversity.A complete picture of Barents Sea food web is presented as Figure 1.4.

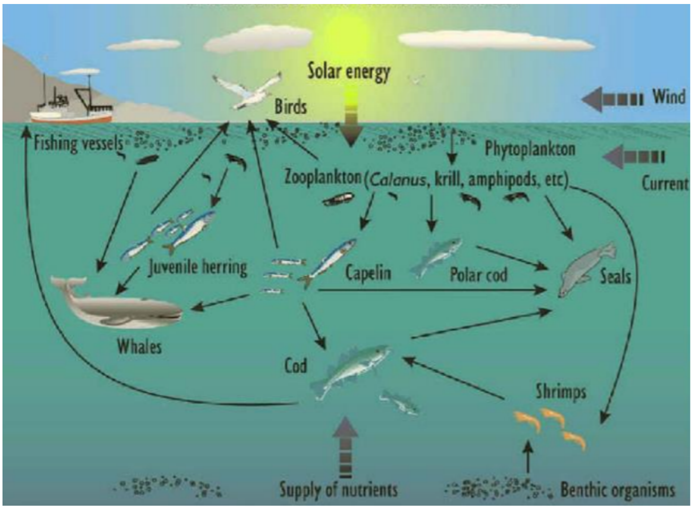


Figure 1.4: Simplified Food Web for Barents Sea, (Espen et al., 2016).

1.1.4 Target Species

Target species will be used as an indicator to evaluate ecological performance of the study concept. In Norwegian waters around 292 fish species are found but to limit the extent of the study, only two of the most relevant marine species are selected.

Barents Sea Capelin

In northern Norway, many major commercial fish stocks are found in the Barents sea and the Norwegian Sea, with cod being one of the most important fish. Capelin plays a major role in the Barents Sea ecosystem as food for cod, seabirds and marine mammals (Elisabet et al., 2009). Espen et al. (2016) suggest that 40-50% of the diet of cod consists on capelin. As per Espen et al. (2016), due to the warming of the Barents Sea, the cod stock has increased and became distributed over larger area, depending on capelin to a higher degree than before. Length of overlap period for cod and capelin is greater than other prey species (polar cod) for cod, and capelin is also fat and energetically more valuable prey. Same study has indicated that capelin is decreasing, see Figure 1.5. In 2016, total stock of capelin is estimated around 0.3 million tonnes and it is the lowest one after 2005. In the last 30 years, four collapse periods have been observed. In the period of first collapse, cod was not able to compensate reduced amount of capelin and severe growth decline was observed. A similar situation can be expected for this fourth collapse period.

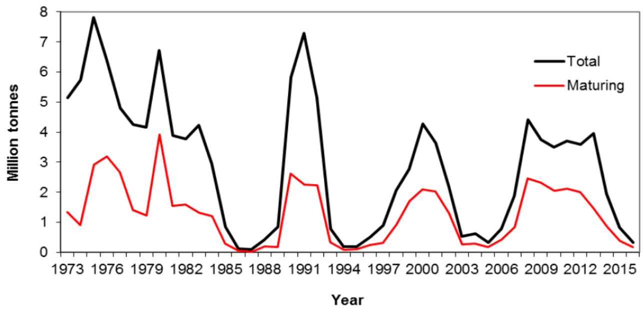


Figure 1.5: Capelin biomass 1973-2016. Maturing stock (>14cm) and total. (Espen et al., 2016)

Capelin has a northern distribution with major spawning locations from Vesterlen and northwards, including the location of Kiberg port. Figure 1.6 shows the location of spawning areas for capelin in green. The inclusion of capelin as an indicator specie in this study can be seen as a measure for its growth by providing shelter to the eggs and larvae. Artificial Reefs can provide more complex hiding places to the fish, giving them a chance to avoid being preyed on.

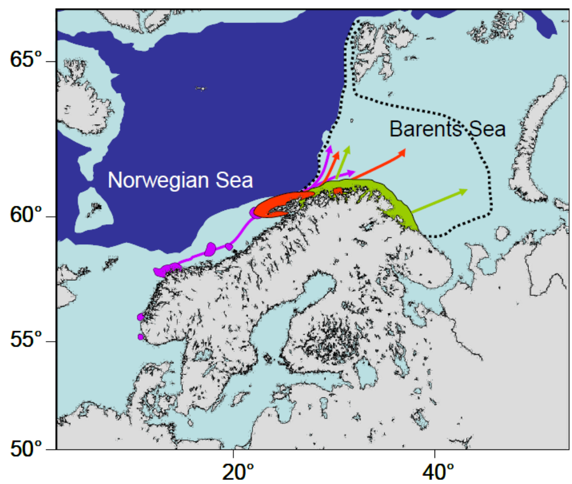


Figure 1.6: Map showing spawning locations and advection routes of eggs and larvae of three fish stocks:Barents Sea capelin (green), North East Arctic cod (red) and Norwegian spring-spawning herring (purple). (Elisabet et al., 2009)

Red King Crab (RKC)

A population of red king crab was introduced in the Barents Sea in 1960s by Soviet scientists in order to establish a valuable pot fishery. This invasive specie is seen as both valuable fishery resource and also a potential threat to native biota but despite its negative impacts it is now a permanent component of benthic life in the north Norwegian coasts.

Norway has complex and evolving management roles for crab fishery, due to the dual nature of biological invasion and profitable resource. Most of the red king crabs caught in the Norwegian waters are exported especially to the United States which makes Norway as one of the major sources of RKC in the US market. Despite this Monterey Bay Aquarium (MBA), Seafood Watch (2015) argues that RKC quota is decreasing world-wide and it is expected that RKC will be in much demand in the days to come.

Nina and Torstein (2012) suggest that RKC are very cryptic during the early stages and they try to find refuge in complex habitats which can help them survive from predators. They prey on lumpsucker eggs which is hampering the lumpsucker recruitment in the Norwegian waters. Recent studies have found that the ecosystem has improved in the invasion areas of RKC and it can be considered as a sign of gradual adjustment between this invasion specie and local prey species. However, deployment of artificial reefs in the area, can be helpful in a way that it can provide shelter to both RKC and lumpsuckers.

Jorgensen (2013) studied the historic distribution of RKC in the Barents Sea (see Figure 1.7). The figure shows that in 1992, RKC invaded Varanger fjord and Kiberg area. RKC has been considered as one of the indicator species for the study because of its economic importance and the fact that artificial reefs will enhance the opportunities for them to hide and hence survive from prey in early stages of their life. Along with this, artificial reefs will provide an enhanced biodiversity in the area, attracting more species, which will be helpful for the growth of RKC.

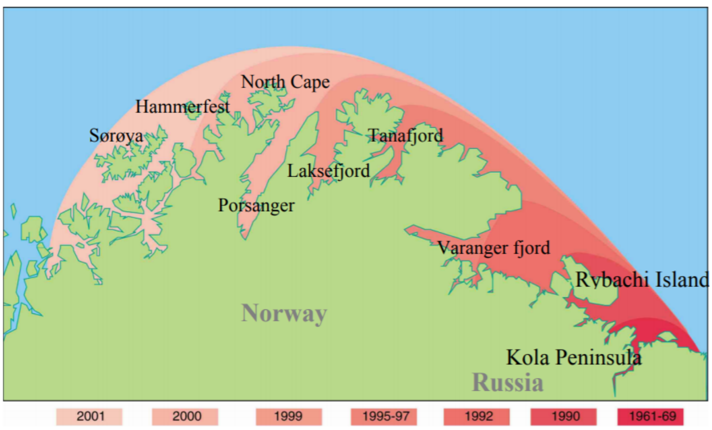


Figure 1.7: Distribution and spread of the red king crab from its release region in the Barents Sea, (Jorgensen, 2013).

1.2 Problem Description

In the situation of climate change, the risk to the societies living in coastal zones is increasing manifolds, especially in a scenario where coastal management/coastal protection measures involve existing coastal structures which were not designed for climate change scenarios.

One of the leading consultancy firms in Norway, Norconsult, was looking for innovative ideas to make one of their existing breakwater projects, in Finnmark county Norway, climate change adoptive. This study tries to find a solution for this problem by using Artificial Reefs (AR) as the toe elements on the seaward side of the existing breakwater. Hydraulic performance of AR is still not understood completely and to assess the stability of an existing breakwater through this concept, keeping ecological improvement of the areas as an important goal, is a challenge in itself.

Basically, this study is a step towards the incorporation of Building with Nature concept into Coastal Engineering. Typical engineering practices, utilize hard structures for protection against wave attack, where the geometry of the structure has an impact on wave dampness and other hydrodynamic aspects. Wave breaking is the most important phenomenon in the process of wave dampness, for any engineered modification in the bathymetry or profile of structure. Standard wave theories become invalid in the region of breaking and broken waves, therefore knowledge about wave breaking properties and energy dissipation has to be gained with the help of physical model studies. On the other hand, in terms of ecology, artificial reefs are believed to restore/improve the ecology of the area. The major factors contributing towards this improvement are the porosity and geometry (configuration, shape etc.) of the AR. These elements placed in water influence the hydrodynamic conditions. Therefore, a combination of AR elements on an existing structure may create such hydrodynamic conditions which can benefit the stability of structure. Based on this hypothesis, the problem statement of this research is stated as :

> *In order to improve stability of existing breakwaters in the scenario of climate change, integrated solution with ecological enhancement can be utilized in terms of Artificial Reefs but hydrodynamic conditions achieved through this concept may create tension between ecology and stability of breakwater.*

1.3 Research Objectives and Questions

The aim of this study is to explore the connection between the risk reduction and ecological enhancement for existing structures. It focuses on the climate change adaption for existing coastal structures by adopting a nature friendly measure i.e. AR, which is expected to not only enhance structural integrity but also to improve the ecology around the grey structure.

Derived from the above discussion, main research question of the study is:

> ***"How existing coastal structures can be made climate change adaptive through a measure which is not only technically viable but also feasible***

in terms of ecology of the area?"

Aiming towards the main research question, following sub-questions are formulated:

1. Artificial Reef units are believed to reduce wave energy when placed as submerged or non-submerged offshore breakwaters. However, how would they behave if they are integrated in the toe of an existing structure in the form of a continuous layer?

2. Quantification of physical damage to the hybrid structure under various storm conditions. Does the Van der Meer formulas for stability also hold good for this hybrid structure ?

3. What is the effect of reef length on wave energy for an integrated AR structure scenario ?

4. What is the effect of reef porosity on wave impact reduction?

5. What would be the criteria to assess the ecological suitability of AR incorporated existing structure ?

The goal of the study is to provide an integrated solution for existing coastal protection systems which will improve the stability along with enhanced ecological values. AR are expected to act like traditional coastal protection structures in near-shore areas, but they will have an advantage of creating less/no damage to the environment/ecology as compared to hard structures. This research will also try to explore the reason behind the added advantage of AR while maintaining technical stability of the structure.

1.4 Research Methodology

Approach

Figure 1.8 represents the flowchart of the approach followed to meet the objectives of this study. Initially in order to get in depth view of the research questions and aims of the study, literature review is conducted. On the basis of the literature review, climate change data for the study location are acquired and modeling scenarios are established. In the third phase, scaling laws are used to interpret the modeling choices into a physical model and with the help of suitable stone size model is constructed. Tests are performed as per the pre-defined test matrix. Data obtained from the physical model tests are then analyzed and interpreted to get the answers of research questions.

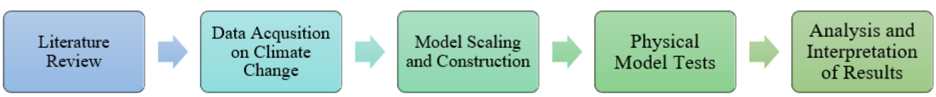


Figure 1.8: Flowchart of Research Approach

Physical Modeling Choices

Wave Breaking is one of the most important aspects in evaluating the hydrodynamic behaviour of AR. Classical wave theories become invalid in the region of breaking and broken waves, therefore reliance is placed on two dimensional tests in the laboratory to assess the behaviour of AR (Smith and Kraus, 1991). In most of the cases performance of an AR submerged breakwater, in terms of wave energy reduction, is measured with the help of transmission coefficient, C_t (Fauzi et al.,2017; Armono, 2004; Bleck,2006). C_t is the ratio of transmitted wave height to the incident wave height. This method can not be employed for this study as AR units will be placed in the continuation of the toe of the structure, so there is a possibility that for certain wave conditions, breaking may either occur on AR units or after AR. In this scenario, measurement of wave heights towards the breakwater side of AR units may not be true representation because of wave breaking. Along with this, additional wave breaking phenomena on AR like vortex shredding, eddies generation etc. are not possible to measure and quantify. Bleck (1997) and Bleck (2006) presented many concepts to evaluate hydraulic performance of AR but non of these describe the complete description of wave evolution on AR on the basis of hydrodynamic processes occurring on reef (Bleck, 2006).

Considering aforementioned aspects, for the measurement of wave energy reduction over AR following approaches will be used;

1. After a storm, eroded area profiles will be measured with the help of a laser scanner which will give an indication of damage to the structure. It is the similar approach as adopted by Ahrens and Cox (1990). Further detail on it is provided in Chapter 2.

2. Turbulent velocity fluctuations, in and around the AR units will be measured with the help of Vectrino Acoustic Doppler Velocimeters (ADVs). These values will be processed to get Turbulence Intensity and Turbulent Kinetic Energy (TKE). Which will give an idea about the turbulence and indirectly the energy loss in different hydrodynamic processes around AR which can not be measured directly. It is adopted after (Mukaro and Govender, 2013).

1.5 Living Breakwaters

Traditional breakwaters are hard structures designed to reduce/limit/eliminate wave energy between shoreline and open water. However, in 1960s a concept of living breakwaters was introduced, these are the breakwaters which are designed to accommodate natural habitats and improve ecology while still performing the intended functions of traditional breakwaters. Artificial Reefs are utilized on these breakwaters as the elements to provide complex structural components for the marine and aquatic species to thrive/hide, as well as to provide colonization of hard corals/marine growth.

The effectiveness of a living breakwater is determined by it width, height, size, depth and position from shoreline. Depending on the area of construction, a mix of various species can be expected to inhibit the breakwater but it may take years to develop a stable benthic community.

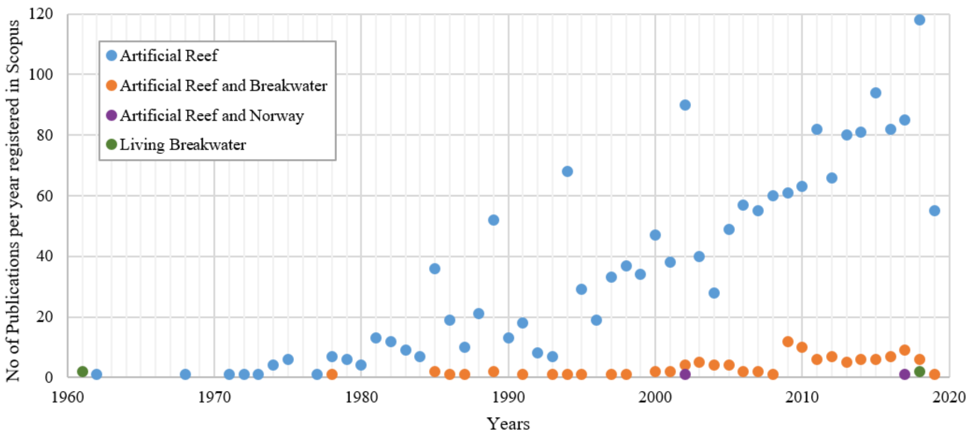


Figure 1.9: Evaluation of No. of Publications Registered per year in Scopus about AR

After the initial introduction of the concept in 1960s, there has not been much research on this topic. However, research about the use of artificial reef has been increasing since then. Figure 1.9 shows the number of research publication registered in Scopus from 1960 to 2019. Research about use of artificial reefs on breakwaters has somewhat constant trend with a boom in the last decade. More recently, a US based landscape architecture company, SCAPE, picked up this concept for their project in Tottenville Staten Island, US which has resulted in the increased focus on this concept again.

No studies have been conducted to check the implications of living breakwaters on Norwegian coasts, which is mainly because of the rocky/non-eroding/non-receding conditions of the shoreline. Recently, Norway has implemented artificial reefs for the enhancement of certain fish species. However, no studies have been conducted to check the concept's applicability on the existing structures, which make the objectives of this study unique.

1.6 Reference Project

Living Breakwaters- Tottenville Pilot Project

After the horrific superstorm "Sandy" in 2012, US Department of Housing and Urban Development (HUD) initiated a design competition in June 2013 to help design more resilient communities for future. Living Breakwater- Tottenville Pilot Project was one of the seven winning proposals who got funding from HUD. SCAPE Landscape Architecture, led a design team with Arcadis being responsible for coastal modeling and COWI led the design work for coastal engineering.

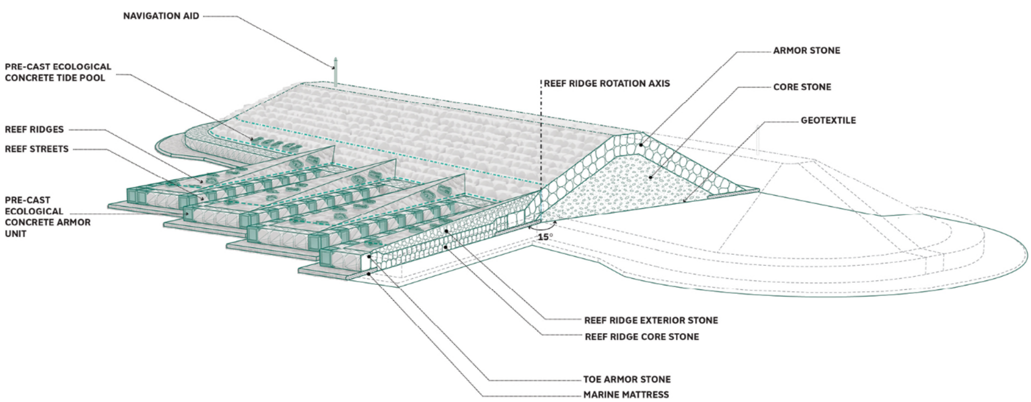


Figure 1.10: Proposed Design of Living Breakwater with Bio-enhancing Concrete Units, (Scott et al., 2018).

These breakwaters are 1.61km long with specifically designed artificial reefs which are capable of attenuating damaging storm waves, reducing or reversing coastal erosion, enhancing ecosystem and fostering social resilience (Scott et al., 2018). Different bio-enhancing concrete units are used on the toe of the structure to make it nature friendly. Water depths at the site range from 1.8m to 3.35m and tides range from -0.8m to +0.63m. Sea level rise of 0.76m is considered along with a severe storm surge level of +4.69m. A significant wave height of 1.62m with peak wave period of 5 sec is considered for the design on the basis of 100-year design storm wave. A physical model study was also conducted to optimize and finalize the design. One of the finalized design options is presented as Figure 1.10.

1.7 Structure of the Report

Details and contents presented in different chapters of the report are briefly described below.

Chapter 1 : A brief introduction of the study along with background, motivation, problem description, methodology and objectives of the study is presented. A description of studies conducted so far on living breakwaters is provided and a reference project is stated.

Chapter 2 : Literature review is conducted to place this research in proper perspective. Different aspects of research related to the project are discussed including climate change, climate change adaption, design of artificial reefs, hydrodynamics of artificial reefs etc.

Chapter 3 : This chapter is dedicated to physical modelling, different similitude rules and physical modeling techniques. Selection of model scale for this study is also elaborated.

Chapter 4 : The chapter presents details of experimental setup adopted for this study. Test matrix and different test configurations along with the construction of breakwater model in lab are dealt in detail.

Chapter 5 : Results obtained for physical model tests and ecological studies are presented in this chapter. Techniques adopted for post processing of raw data are also presented.

Chapter 6 : A detailed discussion on the results of the physical model tests is presented supported by literature.

Chapter 7 : This chapter consists of conclusions and recommendations. Research questions are answered and further research aspects, that emerged during this study are recommended.

2
Literature Review

> "The future is not someplace we are going to, it is a place we are creating. The path to the future is not found, it is made."
>
> *Peter Elyard*

In this chapter, a literature review is conducted in order to place this study in a proper prospective. The chapter entails concepts like building with nature, climate change, artificial reef design and construction along with physical and ecological performance evaluation of artificial reef structures. Hydrodynamic aspects of artificial reefs and reasons behind wave attenuation/reduction are discussed in detail.

From literature review, design basis for AR units to be used for this study will be selected. Different physical and ecological parameters will be identified and a method for quantification of ecological and physical performance of AR will be chosen to be employed for this study.

2.1 Building With Nature; A Sustainable Coastal Zone Management Approach

Building with Nature (BwN) has emerged as a design philosophy for sustainable coastal zone management in the last decade. The philosophy emphases on construction of multipurpose structures which create benefits for not only society but also for the nature at the same time by a proactive approach. The concept was initially introduced by Dutch engineer Honzo Svasek in 1979 and Ronald E. Waterman added his efforts to expand the concept later on by publishing the ideas in his book "Integrated Coastal Policy via Building with Nature" in 2008. He defined the essence of BwN as:

"*Flexible integration of land-in-sea and of water-in-the-new-land, making use of materials, and forces interactions present in nature, taking into account existing and potential nature values, and the bio-geomorphology geo-hydrology of the coast and seabed.*" (Waterman, 2008)

BwN concept is based on two principals, first principal is to use ecosystem or natural forces as a part of solution for engineering problems and second principal is related to development of nature as an integrated part of the solution. Second principal basically promotes further development of ecosystem along with mitigation measure of problems. Traditional design approaches are generally focused on single purpose development (flood protection, defence etc.) which may be combined with mitigation of negative impact of development. However, BwN considers the entire system as the starting point and aims to develop multipurpose designs which are proactive in utilizing natural processes and they are designed to create additional opportunity for nature to develop. ***"Based on the BwN approach, marine infrastructure development can be carried out adaptively, in line with natural dynamics systematically seeking win-win solutions."*** Waterman (2008). Therefore, this approach may lead to solution which are not only flexible and cost effective but also environmental friendly.

2.1.1 Ecosystem-Based Coastal Defense System

There is a growing body of evidences that BwN based solutions, either in terms of integrated strategies or hybrid portfolios, can be effective in risk reduction for coastal structures (Borja et al., 2014). In this world of climate change, risks for coastal structures are increasing and degradation of ecosystem has worsen the situation which has put assets and communities in much risk. Borja et al. (2014) states that 50% of marshes, 35% of mangroves, 30% of coral reefs and 29% of sea grasses are either damaged or lost. With the loss of these coastal vegetation, the benefits that they provide in terms of coastal protection (attenuation of wave energy etc.) is also lost. Reefs and wetlands are in constant threat but there are ways to resort them or adopt mitigation measures to keep this first line of defense in action.

Elements of Ecosystem Based Coastal Defense System

Susan et al. (2006) suggest that coastal areas with natural protective features (green solution) can re-establish themselves after natural traumas or long-term changes such as sea level rise. Main components of a natural protection system (ecosystem-based coastal defense system) of coastal areas are presented in Figure 2.1. Laboratory and numerical studies have shown that the coastal vegetation, if present in certain density, can considerably attenuate wave heights and protect coast. Mangroves are estimated to reduce 13-66% of wave height and even upto 100% if present up to 500m or more width. Similarly, salt marshes can add up to 50% in the reduction of smaller waves with a barrier width of just

10m.

As per findings of Filippo et al. (2014), coral reefs are believed to reduce wave energy upto 97% with 86% wave height reduction. But, scientists believe that, 30% of coral reef has been lost world wide due to nutrient pollution, habitat conversion and mainly due to increasingly acidic sea waters due to climate change. With the current projections of climate change, it is expected that 80% of coral reefs may die withing few decades.

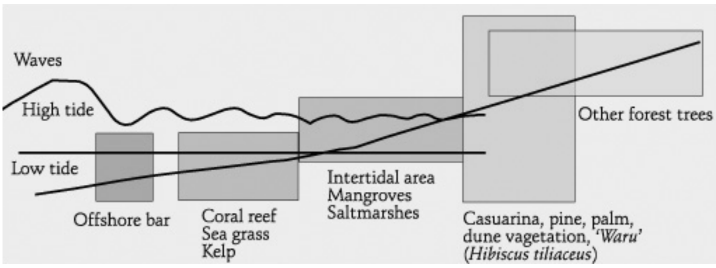


Figure 2.1: Natural Protective Features of Coastal Systems, (Susan et al., 2006).

2.1.2 Restrictions in Application of Fully Green Solution

In certain scenarios, fully green solutions are sometimes not feasible to apply. These scenarios may include space limitations, high wave energy or presence of existing coastal structures. In such situations, **"Green-Grey Hybrid Solutions"** may provide a suitable alternative for a sustainable future approach (*publicwiki.deltares.nl/display/BTG/Green-grey+solutions*). These structures are sometimes more suitable in terms of efficiency, economy and environment. In principal, instead of just having a hard structure, ecological value of a grey structure can be improved by adopting certain measures under the umbrella of design of green-grey structures. Examples of some of these measure are listed below;

- Combination of beach nourishment and artificial headlands/groynes to tackle erosion issues.
- Re-vegetation along with temporary offshore breakwaters/artificial reefs.
- Implementation of artificial reef units on the toe of a grey structure.

For this study, a green-grey hybrid solution is adopted, in terms of application of artificial reefs to increase the ecological value and structural stability of an existing grey structure.

2.2 Climate Change

Escalation in greenhouse gases is causing warming of air and ocean which consequently cause acidification of oceans. According to climate change adaption study conducted by

United States Agency for International Development (USAID), air and sea temperatures will keep on increasing even if greenhouse gases are capped today because these gases have a lifetime between 10 to several thousand years and past emissions will keep causing the rise in temperature, USAID (2009). The temperature increase causes the change in precipitation, frequency and magnitude of extreme events and sea level rise (SLR) with huge influence on coastal erosion, droughts, flooding, ecosystem changes and saltwater intrusion. A summary of climate change observations and current trends of SLR change, sea surface temperature change, increased frequency of extreme weather events, precipitation changes and ocean acidification rates is presented in Appendix A.

2.2.1 Climate Change; a Norwegian Perspective

There is a huge geographical and season variability in Norwegian climate; it tends to be very mild as compared to other areas on same latitude. Major cause behind this mild weather is the heat transfer with Westerlies and Gulf Streams. Meteorological measurements are quite reliable in Norway and they go back to 150 years. All these meteorological stations have sufficient data to provide a good picture on the variability of temperature and precipitation. The data series show major annual and decade-on-decade fluctuations. Many data series indicate trends over longer periods of time which may be attributed to natural or climate forcing (NOU, 2010). Some of the highlights of climate variability in Norway during last 100 years, as presented by NOU (2010), are listed below;

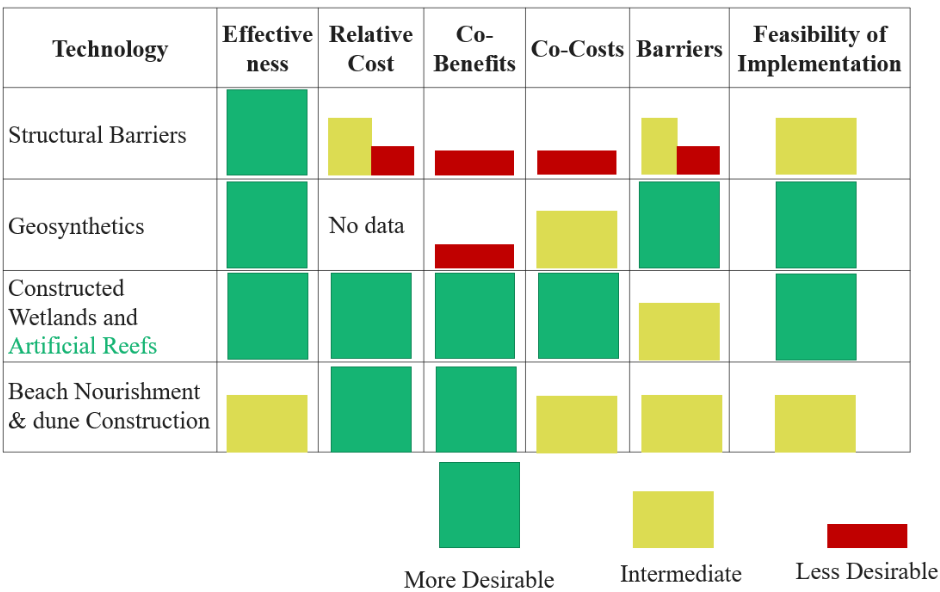
- A rise in annual mean temperature of about 0.8° is observed.
- Annual precipitation has increased by about 20%.
- During 20th century, snow season at most areas have become shorter.
- Permafrost is rapidly warming up at a rate of about 0.3° per decade.
- Increased streamflow during winter and spring and rainfall floods have become more frequent after 1987.
- ***Frequency of storms has increased for many areas.***
- ***A gradual warming of ocean temperature is observed from 100year long time series.***
- ***In the last 100 years, on average 14cm sea level rise is observed***, after subtracting glacial isostatic adjustments.
- Over the past 30 years, size of the Arctic summer ice has decreased by about 30%.

2.3 Climate Change Adaption Techniques

Main purpose of climate change adaption for coastal areas, in relation to nature-based coastal defense system, is to minimize damage to livelihood, resources, infrastructure and ecosystem. Asian Development Bank (ADB) on its report on climate change adaptation, categorizes adaption measures into three categories namely; protect, accommodate, or retreat (ADB, 2014). *Protection* adaption measures utilize structural (e.g. groynes, dikes, seawalls, breakwaters etc.) or nonstructural solutions (e.g. constructed wetlands, artificial reefs, beach nourishment, dune construction etc.) to protect coastal areas from inundation and flooding. *Accommodation* measures allow flooding/inundation up to certain extent and these are more focused on flood proofing and flood alleviation strategies. However, *Retreat* adaption measures requires changing in the coastal zoning and they are more focused on management.

A comparative overview of protective climate change adaption measures (structural and non-structural) is provided in Table 2.1, after ADB (2014) report. Comparison among different measures is made in terms of their effectiveness regarding protection of settlements and infrastructure from rising sea level, relative cost (cost of construction, maintenance etc.) which depends on material and scale of project, co-benefits which refers to the benefits apart from main function of protection (i.e. generation of new habitats, tourism, food security, groundwater filtration etc.), co-costs concerns the economic and ecological advantages/disadvantages (e.g. blocking of natural evolution of beaches, effect on the adjacent communities, pollution, re-use of certain material for adaption etc.), barriers deal with integration of the measure within coastal zone management (i.e. property value, required effective construction area, construction equipment etc.) and feasibility of implementation (i.e. technical expertise required for design, ecological information, required technology for construction etc.).

Table 2.1: Summary of Climate Change Adaption Measures (ADB, 2014).



It is evident from the Table 2.1 that **constructed wetlands and artificial reefs are the**

most desirable climate change adaption measures.

2.3.1 Future-Proofing of Existing Structures

Long-term adaption strategies of most coastal situations involve a combination of different planning and management options. Significant existing development is also taken into count for these options. Generally, existing structures are equipped with short-term adaption measures, however planning and identification of transition mechanisms towards long-term and sustainable approaches is always kept as first priority.

Britton et al. (2011) identifies different adaption options for existing coastal structures. These measures/options can help reduce risk on the structures, some of these options are listed below;

- Removal or relocation of the existing structure and constructing more greener and sustainable structure can be an option for long-term solution.
- Identification of hazards associated with 'do-nothing' approach.
- Construction of hard structures may be the only possible solution and for these scenarios development should be carried out considering its social, environmental and ecological implications. Form and location of structure should be designed in a way that it minimizes the effects on coastal environment.
- Adopting a green-grey hybrid solution as a short-term adaption measure and keep working on transiting the structures towards long-term sustainability.

Adaptation measures which use hard-structures are often implemented in order to protect existing development and infrastructure or future development areas. These options may provide an immediate remedy to the problem but they are not sustainable in longer run as many of these options have severe negative impact on ecosystem. Green-grey structures can be a ray of hope in these situations in terms of short-term sustainable solution.

For this research, a non-structural protection adaption measure in the form of Artificial Reefs is chosen as a short-term adaption option for an existing structure.

2.4 Artificial Reefs (AR)

European Artificial Reef Research Network (EARNN) defines AR as the submerged structures which are intentionally placed on sea bed to imitate some features/characteristics of natural reefs. Various studies show that AR provide shelter, food and breeding area for marine species along with providing shoreline protection and coastal defense.

Since 17th century different AR have been used to attract fish in Japan. The concept was implemented in Europe in 1900s and ever since many countries have deployed AR for various purposes. Fabi et al. (2011) presented an overview of different types of AR employed in different European countries (see Figure 2.2).

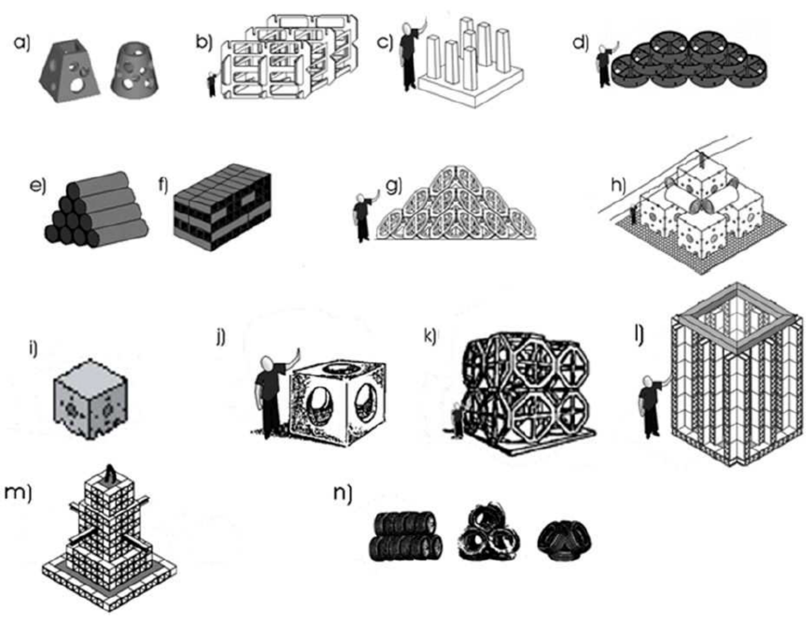


Figure 2.2: Examples of artificial reef construction in Europe. a) Cyprus; b), c) France; d) Germany; e), f) Greece; g), h) Italy; i) Poland; j), k) Portugal; l), m) Spain; n) United Kingdom. (Fabi et al., 2011).

Figure 2.3: "Rundle Reef" deployed in Norfjorden and Hammerfest, Norway (Fabi et al., 2011).

The concept of AR is quite new in Norway and it is still in the experimental stage. However, in 2002 first ever AR in Norwegian waters were deployed in Nordfjorden and its primary purpose was to investigate the effects of AR on flora and fauna (Fabi et al., 2011). These "Rundle Reef" are made of hollow concrete cylinder filled with stones along with 14 rows of plastic pipes and have a surface area of $250m^2$ (see Figure 2.3). In 2004, two reefs were placed to attach fish in Lofoten and the most recent deployment was in 2006 durin which two Rundle reef were deployed at Hammerfest, with a purpose to promote the development of seaweeds and kelp.

Given the rocky coastline of Norway, no AR has been deployed, so far, for the purpose of coastal protection. This research tries to explore this option.

2.5 Artificial Reef Design Considerations

Various factors influence the design of AR and its placement with one motive to make AR biologically and structurally successful. Some of these parameters/factors are described in the following section. Most of the studies have found an optimum range of these parameters in which the efficiency of AR is considered to be maximum.

2.5.1 Area Covered

Volume and bottom covered area of AR are one of the key design factor. Marine species show more attraction towards AR greater in size, however small reefs are also shown to have good performance. Ogawa et al. (1977) conclude that marine biomass/ production increases directly from 400 m^3 to 4,000 m^3 volume of AR. An exact range for optimum size of an individual AR unit has not been determined so far. *Most of the blocks employed nowadays have a volume ranging from 1m^3 to 5m^3 but the upper limit also reached to 60m^3*. Bohnsack and Sutherland (1985) suggest that effective size of reef set (structure formed by the assembling many/some individual AR units) is around 400m^3.

2.5.2 Vertical Height/Relief

A conflicting results have been found about the importance of reef height for ecological gains but in terms of hydrodynamics, its an important parameter limiting water depth above the reef, effecting the flow conditions especially when AR are employed in shallow waters. On small experimental reef, greater vertical relief are found to be more attractive to fish. Ogawa et al. (1977) *suggest that 3m-4m are sufficient from ecological point of view*. Effectiveness of height depend on the species and shallow water condition(AR height less important for ecology) or deep water condition (increasing AR height has pronounced effect on ecology).

2.5.3 Complexity

Complexity is one of the most important parameter for the ecological success of AR. Complexity counts for number size of openings/chambers, interstitial spaces and arrangements of openings. Crowder (1979) predicates that feeding and growth efficiency of fish is maximum for intermediate levels of structural complexity. Size and number of opening spaces depends on the size and behaviour of the species which are suppose to inhabit the AR. Bohnsack and Sutherland (1985) *suggest that best size opening ranges from 0.15m to 1.5m*. However, more porous structure may not be much suitable for wave reduction/coastal defence.

2.5.4 Texture/Rugosity

Abundance of benthic species on AR is effected by texture and material of AR. Uneven surface, holes and narrow openings show increased biodiversity. Abalone are found in larger quantities on relatively rougher surfaces and sharp edges are believed to be effective for kelp and seaweed growth. Newly settled growth on AR require microhabitat from grazing marine animals, in this scenario higher rugosity can present a better recruitment area for attachment of early growth (MScience, 2015). It is an important factor in terms of drag forces and flow friction on the reef. A rougher structure can enhance the wave dissipation.

2.5.5 Spatial Arrangement and Orientation

It is suggested that most efficient AR orientation is if units are perpendicular to currents direction. AR should be oriented to present their maximum area to incoming waves because corals and algae have a tendency to develop in well oxygenated and clear water. On most of the AR projects, it has been observed that coral colonization is larger seaward side facing incoming waves than the landward side. Turner et al. (1969) suggested that there should be 15-18m open spaces between in AR set.

2.5.6 Stability

Stability of a AR unit is dependent on its weight, material density and unit complexity(i.e. number of holes etc.). Other factors that may effect AR stability include loading intensity (current and wave motion), substrate composition and sedimentation. On a muddy substrata, extensive wave and current action may cause scouring and sinking issues which may lead to destruction of AR structure/community. Another effect of excessive wave and current action can be toppling and sliding leading to displacement of AR units.

In terms of material different materials being used for AR worldwide include; wood, shell,rock, concrete, steel, fiberglas, ash, recycled inert material, vehicle tires, vessels and vehicles. All these material are suitable under certain conditions based on location of placement. However, some of these can not be used to achieve structural benefits. Eco-concrete is an emerging environment friendly solution for these type of structure. This is a very high performance concrete which enhances ecological and biological value of coastal and marine infrastructure while increasing their strength and durability (*www.econcretetech.com*).

2.6 Site Selection for Artificial Reef

According to Ogawa et al. (1977), the selection of site for AR is more important than their design. Environmental loading conditions (wave direction, oceanic and tidal currents etc.) have huge influence on the successful design of AR. Nakamura (1982) suggests that it is more beneficial to place AR in an area with current turbulence (area of upwelling, downwelling, ascending currents and vortex currents). Further, Nakamura (1982) concluded that topography and temperature gradients also have huge influence on success of a reef structure. *Gentle slopes and relatively flat areas are best for AR placement.* Studies show that ARs placed in an isolation from natural reefs are more effective because of more food availability for benthic organisms.

Apart from aforementioned considerations, factors affecting site selection for AR can be classified into three groups; physio-chemical factors, biological factors and anthropological factors.

2.6.1 Physio-Chemical Aspects

Water Depth and Wave Exposure

Depth of the site is important in a prospective of light requirements for the habitat development, degree of wave action, tidal range and navigability, if applicable. MScience (2015) suggests that an AR is very unlikely to be successful at much greater depths. Depth criteria along with tidal range is essential for light attenuation and ultimately growth of ecology. Required depth should be enough to protect AR from wave action. *Nakamura (1982) suggests that target depth ranges from 5-9.9m however, 10-15m is also accepted for certain cases.* Site with frequent cyclonic activity may not be suitable for AR deployment.

Water Quality

The chosen site should have low turbidity because light penetration is essential for productivity. Seasonal variation in turbidity should be taken into account. Light attenuation is linked to turbidity and MScience (2015) suggests that a higher turbidity rate (>5NTU) can severely suppress the marine growth in shallow waters. Along with these consideration, importance should be given to salinity and water temperature. Period of low salinity due to rain runoff or lake water etc. should be taken in account. In terms of temperature coral reefs are observed to shown growth in temperatures ranging from 18°C to 30°C. However, cold water coral reefs can survive in temperatures as low as 4°C. One of such corals, **Lophelia Pertusa** are in found deep waters of Barents sea (and North Atlantic Ocean).

Sedimentation

Apart from climate change factors, sedimentation is considered to be the one of the most anthropogenic causes of loss of coral reefs. Few corals species have the ability to survive in constant high sedimentation but most of them struggle for survival.

2.6.2 Biological Aspects

Existing Community

One of the primary drivers in the decision of employing AR is the presence of existing coral community (or a lost community) in the surrounding areas of construction site. This can be helpful in the design of artificial reefs and its management in a way that it can give an idea about the species that inhabit or use to inhabit in that area. Natural regeneration may take some time but traces of existing communities can give an idea about the survival of regenerated community. MScience (2015) suggests that the absence of corals from a place are generally due to some environmental reason which may not be immediately obvious point out that reason unless studies are conducted on the lost community.

Competition

Similar to natural corals, many benthic organisms look for a hard strata to settle and grow. Macroalgae and invertebrates may complete with corals to grow, which can consequently cause reduction in surface area. While checking the suitability of an AR site, macroalgae abundance should be checked properly (Nakamura, 1982).

Predation

There are certain marine species (e.g.Drupella spp. gastropods, thorns starfish etc.) which may hinder the growth of corals/marine growth on artificial reefs. Therefore, a site offering the less predation from aforementioned species can be a suitable site.

2.6.3 Anthropological Factors

Commercial and recreational activities have the potential to hinder the development of coral community on an AR. Land reclamation, seaward construction, dredging, vessel traffic, vessel traffic etc. have the tendency to increase sedimentation and turbidity at the thriving AR community location, and all these factors then negatively affect the development. Similarly, AR should not be at a location which is expected to go through development in near future.

2.7 Hydrodynamic Aspects of Artificial Reefs

Complex geometry of reef elements (either coral reef or artificial reef) causes difference in the flow behaviour around and through the reef. Magnitude of turbulence and currents relies on wave presence and location of reefs. AR are supposed to mimic the hydrodynamic behaviour of coral reef. Therefore, depending on the hydraulic conditions at coral reefs, hydrodynamic of AR is divided into 3 scales; micro, meso and macro, respectively representing conditions within the reef, just outside the reef in boundary layer and behaviour of reef community.

Flow Conditions at Micro Scale

The scale of coral colonies at a reef structure is referred to as Micro Scale in this report. Similar to coral reefs, AR with more complexity and less number of holes tend to drive flow to the exterior and reefs with less complexity and greater number of holes tend to allow more flow through the unit. However, this behavior changes when waves are present. Monismith (2007) suggests that in the presence of waves, velocities inside reef tend to be similar to outside, leading to a wave enhancement of interior mass transfer as compared to steady flow condition. This enhancement can be quantified by Keulegan-Carpenter (KC) number, described as Equation 2.1.

$$KC = \frac{u_w}{wS} \tag{2.1}$$

Where, u_w is orbital wave velocity, w is wave frequency and S is the term presenting the porosity of the unit/reefs (it is spacing of cylinders used in experiments by Monismith (2007)). A larger KC value presents a drag dominated flow condition with velocities in the reef units being much lower than outside the units. On the other hand, a smaller value of KC indicates inertia dominated flow with velocities inside the units being nearly equal to the exterior velocities which results in enhanced total mass transfer.

Flows at Meso Scale

Meso scale in represented as $1 - 10m$ in terms of length scale and it is generally the scale of boundary layer flow. At this scale, most important feature is the roughness of reef with a bottom drag coefficients which are generally larger than the representative values of 0.0025 for muddy or sandy beds (Monismith, 2007). Studies have shown that an equivalent sand grain roughness, k_s, of about 0.28m is observed from experimental setup using coral reef skeletons. However, the values of k_s are generally chosen in a way that observed velocity (u_z) matches with the law of wall (equation 2.2).

$$u_z = \frac{u_o}{k} \ln(\frac{30z}{k_s}) \tag{2.2}$$

Where k is von kamran constant with a value of 0.41 and z is the height above seabed. For steady flows, velocity profiles and turbulent stresses follow law of wall and a roughness value can be predicted from this indirect way. However, Monismith (2007) suggests that so-far there is no accepted way of measuring roughness of a reef structure which can be translated into k_s or drag coefficient value.

When waves have an interaction with reef structure in shallow waters, changes in flow pattern can be observed in the form of orbital velocities pattern changing to elliptical in shallow water and then to varying patterns on reefs. The enhanced turbulence due to AR may cause some issues with the for certain species to access the units. This accessibility factor is important for the ecological advantages assessment of AR.

Flows at Macro Scale

Macro Scale refers to the scale of total reef system which is translated as $100 - 1000m$ in terms of length scale. On this large scale, most of the research is carried to access rate and patterns of transport in relation to reef geometry. Studies show that models of wave-driven flows over a reef system, at macro scale, are based on the concept of change in spatial gradient in radiation stresses making them similar in dynamics to long shore flow on beaches due to incident waves (Lentz et al., 1999).

Hydrodynamics of reefs at micro and meso scale will be the main focus of this research, as this is the scale for the ecological development and coastal protection measures.

2.7.1 Wave Impact Reduction Due to Artificial Reefs

It is derived from preceding sections, that AR height and roughness are two major aspects that govern wave dampness. Reef units with larger relief (i.e. greater height) have the ability to damp larger wave heights and so is the case for rugosity. Fabi et al. (2011) made a comparison of different studies and came to a conclusion that reef structures have the tendency to reduce 51-74% wave heights. These submerged units dissipate the energy by forcing the waves to break at the top of the reef crest due to decrease in freeboard (Armono, 2004). Turbulence generated by complex geometry of AR and nonlinear interactions of incoming waves with reef structures are also the causes of wave attenuation.

Wave Breaking Type and Wave Action

"Breaker type" is form of depth-limited wave at breaking. There are several classification of breaking types, however spilling, plunging, collapsing and surging are the most generally accepted types. Smith and Kraus (1991) defines these types as:

- ***Spilling Breakers*** are specified if crest of wave spills over or roll down the from face of wave.
- ***Plunging Breakers*** are specified in scenario when wave become vertical, rotate forward and plunge into the base of the wave.
- ***Collapsing/surging Breakers*** are specified when only lower part of the front face become vertical and plunge forward, resulting into an unbroken wave crest collapsing onto the wave base.

Stability of a breakwater is an indication of damage level (S_d) to armour layer which is measured in the form of displaced rocks in a certain area after storm. It can be expressed in terms of eroded area (A_e) in response to stormy conditions and nominal diameter of armour stone (D_{N50}) as;

$$S_d = \frac{A_e}{{D_{N50}}^2} \tag{2.3}$$

Hydraulic conditions for this study are based on the damage calculation by Van der Meer formulas for breakwater stability defined in Van der Meer (1998). The main parameter of focus in these formulas is Iribarren number or breaker parameter, which is the ratio of slope of the structure ($tan\alpha$) to square root of wave steepness (ratio of wave height and wave length, H/L or $2\pi H/gT^2$) and it defines the wave action on the slope. Depending on the location of wave period and wave heights used, different type of Iribarren number are defined e.g. for deepwater wave data it is denoted as ξ_o and for wave parameters at breaker point it is ξ_b. Based on these Iribarren number, different forms of aforementioned wave breaking on beaches or coastal structures are defined (spilling: $\xi_o < 0.5$,plunging: $0.5 < \xi_o < 3.3$ and surging or collapsing: $\xi_o > 3.3$).

$$\xi = \frac{tan\alpha}{\sqrt{\frac{2\pi H}{gT^2}}} \tag{2.4}$$

Another most important parameter for the wave action is the relation between wave condition and structure in terms of **Stability Number**, which is defined as : $H_s/\Delta D_{N50}$. Effect of density of the material on stability is expressed here in terms of relative buoyant density (Δ), which is expressed as;

$$\Delta = \frac{\rho_r}{\rho_w} - 1 \tag{2.5}$$

Where, ρ_r and ρ_w are mass density of the rock or concrete and water, respectively.

Van der Meer (1998) defined two different formulas for plunging and surging waves, which are presented as Equation 2.6 and Equation 2.7 respectively. In order to distinguish, plunging and surging behaviour of a certain wave condition, critical breaker parameter is used which is defined as Equation 2.8. If $\xi < \xi_c$ then its a plunging case and 2.6 is used and on the other hand if $\xi > \xi_c$ then waves are showing surging behaviour and Equation 2.7 is used.

$$\frac{H_s}{\Delta D_{N50}} = 6.2P^{0.18}\left(\frac{S}{\sqrt{N}}\right)^{0.2} \xi^{-0.5} \tag{2.6}$$

$$\frac{H_s}{\Delta D_{N50}} = 1.0P^{-0.13}\left(\frac{S}{\sqrt{N}}\right)^{0.2} \sqrt{cot\alpha}\ \xi^{P} \tag{2.7}$$

$$\xi_c = \left[6.2P^{0.31}\sqrt{tan\alpha}\right]^{\frac{1}{P+0.5}} \tag{2.8}$$

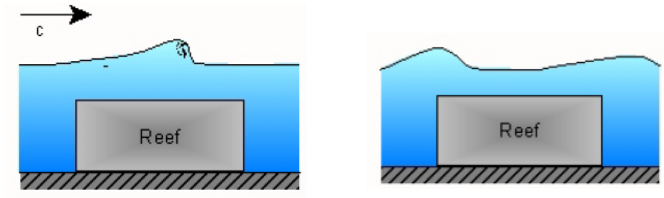
In these equation, P is notional permeability factor, which incorporates the effect of permeability of structure on the stability. Storm duration is incorporated in terms of number of waves in a storm (denoted as N in the formula).

Apart from the above mentioned typical wave breaking classification by Van der Meer, Bleck (2006) defined three types of breaking specifically for AR units, which are;

- ***Spilling Breaker***, wave steepness is caused by the return flow on AR due to which wave skewness increases and it breaks at the crest. The broken wave propagates landwards in the form of bore.

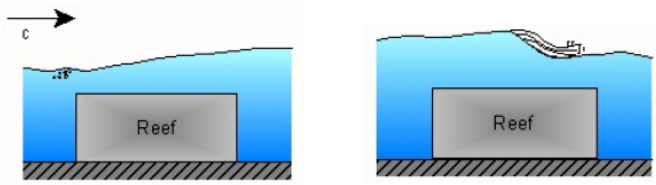
- ***Two-Step Breaker***, Incident wave is encountered by strong return flow and a zone of turbulence develops seaward of AR which travels with the wave. As wave skewness increases over the AR, it breaks and the zone of turbulence decays in front of AR. Broken wave travels like a bore landwards.

- ***Drop-Step Breaker***, In this type return flow is stronger than previous two types, and it creates a large vortex on the seaward edge of AR. Incident wave hit the vortex and they travel together. Due to this vortex, wave generally breaks before reaching shallow region on top of AR.



(a) Before Breaking **(b)** After Breaking

Figure 2.4: Spilling Breaker



(a) Before Breaking **(b)** After Breaking

Figure 2.5: Two-Step Breaker

2.7.2 Stability Concept for AR

Stability Defined by the Reduction in Crest Height

For the AR breakwaters helping protecting the shores, stability is defined in terms of free-board above AR (Ahrens and Cox, 1990). This criterion links the stability with the prime motive of such breakwaters, wave transmission reduction, a phenomenon which is very sensitive to the relative reef height in water. Different models are present, for the submerged and non-submerged cases, which depends on wave conditions and stone size.

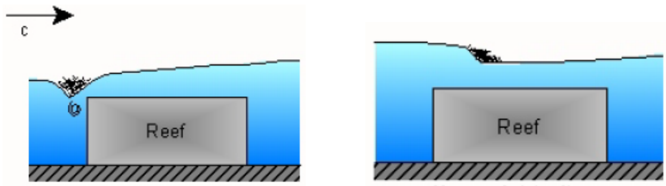
Stability Defined by the Number of Stones Removed

Ahrens and Cox (1990) developed a reef breakwater with various type of stones and run different tests in laboratory. Reef stability was defined in terms of equivalent number of stones moved by the wave action and expressed as the ratio of damaged area A_e and stone size D_{N50}, ($S_d = \frac{A_e}{D_{N50}}$). Sheppard and Hearn (1989) used a same approach and consolidated the damage into reef exposure number, which is a function of reef height, water depth and damage.

For this study, a similar approach as of Ahrens and Cox (1990) is used based on the similarity of the models

2.7.3 Performance Characteristics

Effectiveness/efficiency of an AR breakwaters are measured in terms of Transmission Coefficient (C_t), Reflection Coefficient (C_r) and Dissipation Coefficient (C_d). All these



(a) Before Breaking **(b)** After Breaking

Figure 2.6: Drop Type Breaker

parameters can define the energy dissipation for submerged/non-submerged offshore AR breakwaters and the green-grey hybrid structures.

Wave Transmission

Wave transmission is associated with the degree to which AR disturb incident waves and reduce their energy. AR cause wave breaking which shift wave energy into higher harmonic of incident wave frequencies resulting into lower transmitted period than incident. Transmission coefficient is measured as the ratio of transmitted wave height to incident wave height.

Wave Reflection

Reef structures posses high porosity with rough texture which results into a low reflection coefficient than a stone made structure. It is considered advantages because it reduces toe scour. Main parameters influencing wave reflection from reefs include relative water depth and relative reef height. For high structures, C_r ranges from 0.3 (short waves) to 0.6 (for long waves). C_r is the ratio of reflected wave height to incident wave height.

Energy Dissipation

There is not much information/research on wave energy dissipation of AR even though this is considered as on of their main advantages over other structures (Ahrens, 1987b). The reason behind is that the energy dissipation can not be measured directly but parameters like C_t and C_r are used from experiments for the indication.

2.8 Artificial Reefs Construction and Deployment

AR construction and deployment can be quite challenging due to the weight of the units and difficulties of marine operations in stormy conditions. Suitable techniques for a given location and situation greatly depend on AR configuration, susceptibility of units to damage, placement orientation and proximity of existing habitats. MScience (2015) suggests following set of guidelines for the construction and deployment period of AR/living Breakwaters;

- If possible, construction should preferably be carried out in calmer months to avoid any hazard during marine operation.
- A combination of a crane on a barge can be used as an effective method to load and deploy the units.
- Prior deployment, AR units should be cleaned for fine sediments attached to them. Screening with loader bucket can be utilized for effective results. Sediments lesser than 2mm diameter can become suspended and impact locations at considerable distance from site.
- Techniques of deployment can be as simple as non-controlled placement by pushing units.
- For precise placement, sea divers are used to map the area and then individual components are placed with the help of differential GPS.

2.9 Effectiveness Assessment of AR Structures

Ecological and structural performance evaluation of an AR, can give an idea about integration of AR into marine resource management. Despite a significant research and development in design and construction, AR still lack efficient performance and monitoring measures. Fabi et al. (2015) give some guidelines for monitoring program to assess the effectiveness of ARs;

- Water quality should not be compromised.
- Structural stability and integrity should be checked and maintain over time.
- Presence of any invasion species in reef community should be checked and reported and remedial measures should be taken , if necessary.
- Navigational safety should be maintained.

2.9.1 Physical Performance

Artificial reefs bring changes into physical and biological features of the deployment area, by changing the velocities and creating more turbulence which consequently may cause scouring. Bathymetric changes in seafloor can physically impact AR structure. Therefore, efficiency of an AR system depends on balance of scour, settlement and burial resulting from variable environmental loading (Fabi et al., 2015). In order to quantify this aspect acoustic survey systems such as single-beam echosounder, side scan sonar etc. can be used. These systems have the capabilities to monitor physical and biological evolution around an AR.

On a green-grey structures, a combination of topographic and bathymetric surveys can give a complete picture about the damage to the structure after an extreme weather event.

For this study, damage level evaluation of the hybrid structure, after an extreme event, is considered as a measure for physical performance.

2.9.2 Ecological Performance

Radius of influence of an AR on the marine ecosystem can be assessed by taking samples (inside AR unit, near the edges and at some distance from the unit) for a reasonably longer period of time to evaluate temporal and spatial variations in marine environment. Samples are generally taken by scuba divers, therefore sampling techniques should be simple, fast and standardize. From these samples, major aspects to be test for benthic/epibenthic and algal communities are presence/absence, luxuriance and fertility rate (Fabi et al., 2015). Different sampling techniques (e.g. underwater observations, grab and box-corer sampling, suction samplers, scraping technique etc.) are used depending on location and expected type of benthic communities.

For assessment of fish different technical in-situ visual methods are applied because of their accuracy, ability to record broad range of variables (abundance, size, density, specie composition etc.) and time efficiency. Diver-based methods are observed to have physical limitations (e.g. visibility, water depth etc.) and ability to see and record fish accurately. Advanced in-situ methods may include techniques such as baited remote underwater video and hydroacoustic techniques. Recent development in stationary/mobile hydroacoustic technology (e.g.MBES, echosounder for fish etc.) are proven to be the most efficient so far in determining distribution, behaviour and abundance of fish in a specific area.

A quantitative measure for ecological performance is difficult to establish because of sensitivity of ecology on number of factors (variation in inhabiting marine species, algae community, seabed conditions etc.). Because of this, research does not say much about qualification, however a comparison can be drawn with a structure similar to artificial reefs i.e. fish screens at at water intake structures. Simplification of this method is that fish screens are generally designed for constant uniform flow but in an AR structure presence of waves may hinder in the application of this method. However, considering the shallow water flow case with elliptical velocity patterns, this method can be applied for a first estimate. Katopodis (1992) provided an approach for the design of fish screens at water intakes. For the intake screens placed in perpendicular direction to flow, approach velocity is considered as the water velocity. For fish, criteria for approach velocity is linked to swimming speed of fish. Katopodis (1992) studied swimming performance of 20 fish species and came up to the following relationship;

$$V_a = 0.02L^{0.56} \tag{2.9}$$

In the equation 2.9, V_a represents the approach velocity in m/s and L is fish length in mm. It should be kept in mind that, this formula is developed for unidirectional flow, when we will apply it to waves, it will underestimate the approach velocities. Velocity patterns achieved by this approach will be checked with general design parameters to get a better idea of the ecology.

3
Physical Modelling

"Be part of the solution, not part of the problem."

Stephen R. Covey

Most of the coastal engineering problems and flow conditions are so complex that a suitable mathematical model can not be generated, reason behind this can be the nonlinear character of governing equations, turbulence, complex wave breaking etc. In such situations, in order to predict the behavior of a coastal structure under certain loading, physical models are constructed to predict the scenarios which can not be readily examined. Hughes (1993) defines a physical model as:

"***A Physical Model is a physical system reproduced (usually at a reduced size) so that the major dominant forces acting on the system are represented in the model in correct proportion to the actual physical system.***" , Hughes (1993).

A physical model study for this research is carried out to achieve three main goals;

1. Obtain data on the stability of a hybrid green-grey structures.

2. Quantify and gain insight of phenomena like turbulence intensity in and around AR units, wave breaking on AR units under different loading conditions etc.

3. Obtain some useful co-relations for stability of hybrid structures with changing climate.

3.1 Model Scaling

In an ideal situation, a well designed fluid flow model should act in exact similarity to the prototype, this similarity generally includes the similitude in acceleration, velocity, mass transport and fluid forces. This state of similitude is believed to be achieved when all the major factor related to fluid action are in proportion between model and prototype (Hughes, 1993). Requirement to establish a similarity for a physical model (dynamic considerations, dimensional analysis and differential equations) are broadly classified into following two categories;

- **Criteria of Similitude**, are based on physical relations between different parameters. These are mathematical conditions and they must be met by a ratio of certain parameters of prototype and model. These criteria are also referred as "**Scale Laws**".
- **Conditions of Similarity**, are the chosen set of rules to make the results of physical models acceptable. One or more criteria of similitude can also be chosen as similarity condition.

A physical model should be like a precision device with a possibility to predict behaviour of different physical phenomena. If the model is not scaled in a proper way then, even a small error in measurement/instrumentation can lead to large inaccuracies in predicted results. Therefore, it is of much importance to select a suitable scale which can not only present the situation properly but also reduce scaling effects in results. In order to have a proper understanding of scaling, following points should be kept in mind;

- *Scale* represents a ratio of a certain parametric values in prototype and similar parametric value in model. This is the constant characteristic of any physical model study.
- *Scale Effects* are variations/differences in the response of prototype and model, which may derive from certain reasons (e.g. inability to properly simulate all relevant mechanism/forces in a physical model at an appropriate scale).
- *Laboratory Effects* are generated due to limitations of facilities in the laboratory. These may include flow and wave generation issues/techniques, solid/non-realistic boundaries etc.

A model is said to be in "similarity" to the prototype, if both gives similar response and this can be achieved even in a situation when model is not in strictly following similitude criteria. Hughes (1993) suggests that a model can have similarity without meeting similitude in a situation when certain features of interest are satisfactorily represented in model. There are three criteria that a model has to fulfill to achieve similarity, namely geometric, kinematic and dynamic similarity.

Geometric Similarity

Warnock (1950) defines geometric similarity as "a similarity between two objects or systems if the ratios of all corresponding linear dimensions are equal. This relationship is independent of motion of any kind and involves only similarity in form." The model is often miniature of prototype. It can be quite challenging sometimes to achieve a correct geometric similarity for all the aspects of consideration. These geometrically similar models are also known as "**geometrically undistorted models**", however a model which has different scales for vertical and horizontal dimensions is known as "**geometrically distorted models**".

$$N_L = \frac{L_m}{L_p} \tag{3.1}$$

Equation 3.1 represents the similarity in length, where N_L represents length scale factor, L_m is length of a particular dimension in model and L_p is the length of the same dimension in prototype.

Kinematic Similarity

The similarity of particle motion in model and prototype is known as kinematic similarity and it is much dependent on geometric similarity. A model can be said to achieve kinematic similarity if streamlines at a particular location and time, in model and prototype behave in a similar manner. The kinematic ratio (velocities ratio) N_v has to be constant and it can be defined as

$$N_v = \frac{v_m}{v_p} \tag{3.2}$$

Where, v_m and v_p represent velocities in model and prototype respectively.

Dynamic Similarity

Warnock (1950) suggests that "Dynamic similarity between two geometrically and kinematically similar systems requires that the ratios of all vectorial forces in the two systems be the same." Dynamic similarity imply that ratios of all forces and masses should be constant. This similarity derive its basis from Newton's second law of motion. It is important that both magnitude and direction of forces are represented correctly in model and prototype.

3.1.1 Froude Scaling

For wave models, various scaling numbers are defined based on the importance of attacking forces on the structure, some of these are Froude Number (F_r), Reynolds Number (R_e), Mach Number (M_a), Weber Number (W_e), Euler Number (E_u) and Strouhal Number ((S_t). The most relevant forces for wave models include gravity, inertia, friction and surface tension and to have a dynamic similarity F_r, R_e and W_e must be similar for model and prototype. These numbers are defined as:

$$F_r = \sqrt{\frac{InertialForce}{GravitationalForce}} = \sqrt{\frac{\rho L^2 V^2}{\rho L^3 g}} = \frac{V}{\sqrt{gL}} \tag{3.3}$$

$$R_e = \frac{InertialForce}{ViscousForce} = \frac{\rho L^2 V^2}{\mu V L} = \frac{\rho L V}{\mu} \tag{3.4}$$

$$W_e = \frac{InertialForce}{SurfaceTensionForce} = \frac{\rho L^2 V^2}{\sigma L} = \frac{\rho V^2 L}{\sigma} \tag{3.5}$$

where;
V = Velocity of flow
L = Length
g = Gravitational Acceleration
ρ = Fluid Density
μ = Kinematic Viscosity of Fluid
σ = Surface Tension

It is not possible to satisfy F_r, R_e and W_e for both prototype and model at the same time. For a F_r - R_e model the ratio of kinematic viscosity are fixed by geometric scales (Frostick et al., 2011). For most of the physical models, it is impossible to find an appropriate fluid and hence exact similarity is not possible. Effect of friction is often not much pronounced, as waves have to propagate a long distance before the serious action of bottom friction and for the cases with dominant drag forces, there are ranges of R_e which represent a constant drag coefficient.

As gravity and inertia are the dominant parameters in the wave field at model, therefore Froude modelling law is generally applied , keeping R_e in the same range (Frostick et al., 2011). Surface tension in an actual wave field is not dominant in wave action, therefore W_e similitude can be neglected in the model provided that model satisfies certain conditions (wavelength $>$ 2cm, water depth should be higher than 2cm)(Frostick et al., 2011). Therefore, in most of the Coastal Engineering problems Froude scaling laws have to be satisfied. F_r should be same in model and prototype and this condition leads to :

$$\left(\frac{V}{\sqrt{gL}}\right)_p = \left(\frac{V}{\sqrt{gL}}\right)_m \tag{3.6}$$

This results in:

$$\frac{V_p}{V_m} = \sqrt{\left(\frac{g_p}{g_m}\right)\left(\frac{L_p}{L_m}\right)} \tag{3.7}$$

Equation 3.7 can be rearranged in terms of scale ratios (N) as;

$$\frac{N_v}{\sqrt{N_g N_L}} = 1 \quad or \quad N_{Fr} = 1 \tag{3.8}$$

Froude scaling is important for surface waves as these are gravity driven, so scaling by Froude laws can ensure that wave forces/resistance and other forces are properly translated from prototype to model. Relations for scaling based on Froude law can be expressed in therms of length scale factor (N_L). Table 3.1 show similitude ratios for Froude scaling in terms of N_L.

Table 3.1: Froude Scaling Laws

Character	Units	Froude Scaling
Length /Wave Height	m	N_L
Area	m^2	N_L^2
Time	s	$N_L^{0.5}$
Velocity	m/s	$N_L^{0.5}$
Acceleration	m/s^2	1
Mass	kg	N_L^3xN_ρ
Volume	m^3	N_L^3
Discharge	m^3/s	$N_L^{1.5}$
Force	N	N_L^3xN_ρ
Pressure	N/m^2	N_LxN_ρ

3.2 Environmental Loading in the Study Area

Norconsult conducted a study to assess the feasibility of a submerged breakwater seawards of the existing breakwater at Kiberg. Design data that will be discussed in this section are derived from studies conducted by Norconsult and Sasikumar et al. (2018).

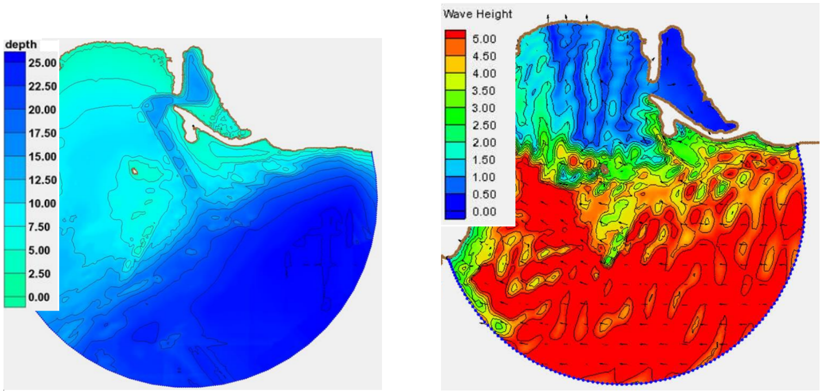
3.2.1 Water Levels

Water level is an important design consideration for coastal structures in shallow waters as depth and wave heights are dependent on it. In order to assess water level at Kiberg, a Mean Sea Level(MSL) of 6m with reference to NN2000 is considered. This level included a the sea level rise value of about 36cm, predicted for next 100 years with most extreme climate change scenario and after subtracting glacial isostatic adjustments (Simpson et al., 2017). Along with this, MSL of 6m also incorporates the effects of extreme storm surges (Sasikumar et al., 2018). Considering all these aspects, water depth of around 8-8.5m is calculated at the toe of the existing structure at highest astronomical tide (HAT) with storm surge, water and wind induced currents and sea level rise.

3.2.2 Wave Heights

Wave height, period and wavelength are the most important parameters for the design of any coastal engineering structure. A scenario of existing wave conditions with current water depths is depicted in Figure 3.1. It can be observed from the figures that at the breakwater location wave heights of 3-4m are expected at normal conditions on a water depth around 7.5m-10m. However, frequency of extreme events is expected to increase in the future, as the highest temperature change in Norway is observed at Finnmark county.

Use of current wave conditions for the design is not recommended, therefore it is necessary to predict the wave heights atleast at design life period. This can be done by carrying out



(a) Depth Profile at Kiberg

(b) Wave Height Profile at Kiberg

Figure 3.1: Depth Profile (left) and Wave Height Profile (right) at Study Area (Sasikumar et al., 2018)

long term statistical analysis (e.g. extreme value analysis) if sufficient hindcast data are available at design location. Sasikumar et al. (2018) carried out such analysis and came up with Figure 3.2. The figure represents significant wave height values for dominant wave directions at different return periods (R_p). At 100 year return period, significant wave height value corresponds to around 6.5m. Peak wave period is predicted as 15 seconds.

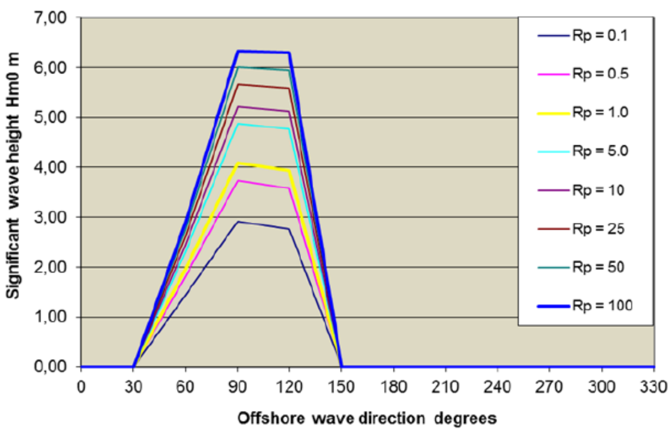


Figure 3.2: Extreme Value Analysis for Swell Waves at Kiberg, (Sasikumar et al., 2018)

3.3 Scale Selection

Froude modeling laws will be implemented for this study. In order to ensure geometric similarity, existing breakwater at Kiberg is used as reference. A representative sketch of the breakwater is shown in Figure 3.3. There is not much details available for this case as the breakwater was constructed in 1960s. Existing breakwater is rubble mound breakwater with varying stones quality in the armour layer. It is believed that the breakwater was damaged by 6m wave height which corresponds to 50 year return period conditions.

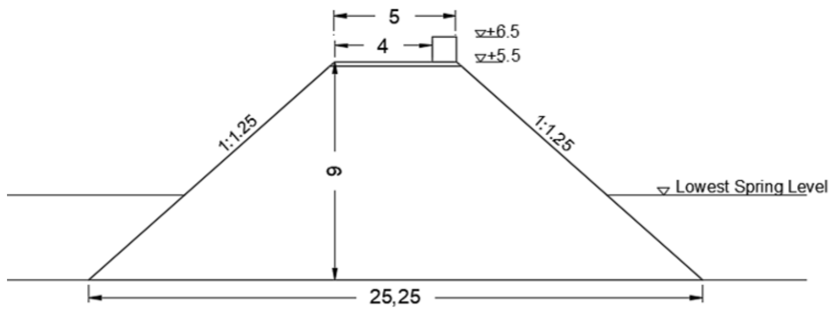


Figure 3.3: Representative Sketch of Kiberg Breakwater

Physical Testing Facility and Limitations

Wave Flume is a channel which consists of wave maker, a rectangular open channel prism, pumps for oscillation of water or to generate collinear currents and wave absorbing mechanism (permeable mesh/beach etc.). Generally, an active absorption system with wave paddle responding to incident waves is also used (Frostick et al., 2011).

Testing for this research is carried out at one of the ocean research facilities, at NTNU with the largest available flume, see Figure 5(a). Its effective dimensions are 20m x 0.6m x 0.85m (length x width x height). Largest flume is chosen because it will reduce the discrepancies in scaling between geometric design of model and fluid viscosity.

After trying different options, a scale ratio of 1:25 (N_L=25), has been chosen for this study. The reasons behind this choice are;

- There is not sufficient information on stone size used for the Kiberg breakwater, however some sources suggests that 2-3m^3 largest stones are present in the first armour layer. Therefore, a practical scenario can be to model these stones at a suitable scale which gives a true picture of hydrodynamics of AR along with existing breakwater.
- Frostick et al. (2011) suggests that, "It is advisable to operate at larger scales whenever possible. A large model scale is often also necessary for the accurate modelling

of wave loading and structure responses." Large scales models offer smaller/ lesser/ negligible scale effects.

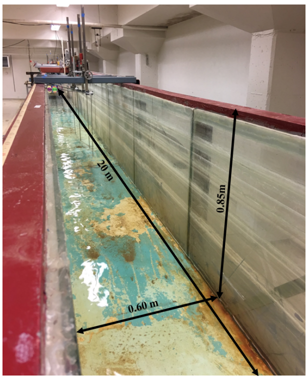
- In order to check the suitability of wave flume with the hydraulic conditions mentioned in previous section, performance curve of wave flume is generated at a scale of 1:25 (see Figure 5(b)). This curve describes the maximum limit of wave conditions that can be generated with the help of wave paddle at a particular scale. Actual water depth of 8.5m (around 35cm at model) at the toe of structure is considered for this performance curve. The curve suggests that maximum achievable wave height in the flume with 35cm water depth is 15cm, which corresponds to 3.75m waves. This value is much lesser than the waves at study location. At this point, two options were considered;

  - **First Option**: Change the scale to represent the exact geometric similarity. A distorted model scale can also be selected. But a scale smaller than this may cause problems for the accuracy of results
  - **Second Option**: Considering the non-availability of data at the site, a truly representative model can not be constructed. But the objectives of the study can be achieved using the same scale (due to lesser scale effects) considering fictitious wave conditions which may generate accurate results.

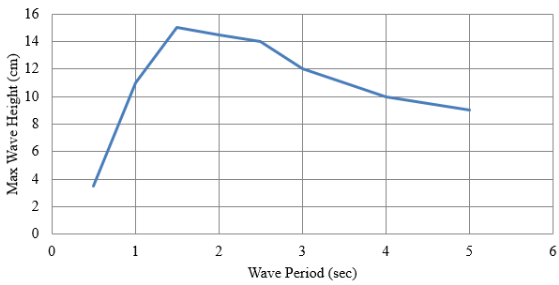
  Considering the importance of wave loading and stability analysis for the study, second option is chosen.

- One of the main objectives of the study is to check the integration of AR with existing structures. To achieve this, partial factors from site (e.g. factors related to geometric similarity) are chosen from the site data and water depths being one of the most important considerations are chosen from the site to be used in model. However, as the exact hydraulic conditions can not be modeled on the same scale. Therefore, a set hydraulic conditions which will ensure the damage to the structure will be selected for this study (based on the situation that Kiberg breakwater was damaged by 50years return period waves).

Scale of the physical model study is chosen as 1:25, N_L***=25***



(a) Wave Flume



(b) Performance Curve

Figure 3.4: Wave Flume with performance curve at scale 1:25

4

Description of the Experiments

This chapter defines the essential equipment and experimental setup adopted to establish a breakwater model study based on the literature mentioned in Chapter 2 and Chapter 3. It starts with the details of velocity and damage measurement techniques utilized for this study. A summary on the breakwater model is presented along with the finalized design of AR units and at the end, different tests configurations, tests matrix and test methodology are discussed in details.

4.1 Test Measurements

Velocity, wave heights and damage level are three main parameters that are needed to evaluate physical and ecological performance of proposed green-grey hybrid structure.

4.1.1 Velocity Measurement

Velocity measurements are essential part of this study. Their values at reef describe the velocity field in and around reef structures. Three Vectrino, Acoustic Doppler Velocimetry (ADV) are used for this purpose. These ADVs work on the doplar effect of sound waves that hit the moving particles in the water. An ADV consists of one transmitters/transducer and four receivers (see figure 4.2). Transmitter emits a sounds signal/wave and receivers are oriented in a way that they record the signal from a well-defined volume (sample volume, $0.25cm^3$). With this approach, three dimensional velocity vector is measured in a sample volume located at 5cm from the center of the probe.

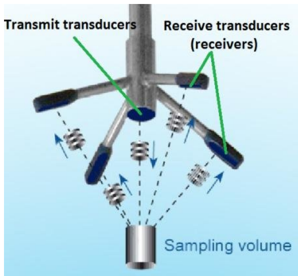


Figure 4.1: Vectrino ADV

Sampling rate for Vectrino ADVs is 25Hz. A higher sampling rate with higher sensitivity can result in a signal which is prone to disturbance. Therefore, velocity measure by ADVs is comprised of three components:

$$u_t = \bar{u} + u' + u_{noise} \tag{4.1}$$

Where, u_t is total velocity, $\bar{u}$ is mean velocity, u' represents turbulence and u_{noise} is the noise in the measure velocity signal. Noise is high or low frequency disturbances due to any source of error. $\bar{u}$ and u' will be used further for this study.

Considering the 2DV nature of experiment, only two of the three directions of velocity are considered, which are u-velocity and w-velocity, in the longitudinal and vertical direction of the flume respectively.

4.1.2 Wave Height Measurement

Wave gauges are used to measure wave heights. These probes consist of two stainless steel bars with a small box connected at the bottom. Bars act as electrodes for the small box which measures the current that flows between the bars immersed in water. This analogue signal is linearly proportional to the water level at that instant of measurement. Wave gauges can have a sample frequency of 0-10Hz.

Before the start of experiment, wave gauges are calibrated. To do so, wave gauges are immersed into water upto a certain level and this level is set as zero in voltmeter. By repeatedly changing the immersion depth and adjusting the values of gain, coarse and fine adjustments on voltmeter all wave gauges are calibrated to give a factor of 2cm/1volt (which is the same as used in Wave Synthesizer for the analysis). Filter is adjusted at 20 Hz for all the experiments.

4.1.3 Damage Measurement

For the measurement of damage of structure before and after storm conditions, a laser profiler is used. Laser assembly is mounted on beam placed over the flume with the help of two cross beams/supporting beams. It is connected to a computer on which a Fortran based code is developed which controls the movement of laser scanner. The same code generates a file in terms of measurements of vertical distance which can be interpreted to develop a damage profile of the breakwater. Laser was initially marked to measure the profiles at 5cm interval and profiles for 10 initial experiments are measured with the same setting. However, latter on it was decided to reduce the interval to 4cm, considering the D_{N50}=4.5cm. Therefore, in order to check the error a few experiments from initial 10 experiments were repeated with reduced interval. It was observed that the measured damage is within the standard deviation. However, for the rest of the experiments interval between scan profiles is kept as 4cm.

Figure 4.2: Laser Profiler Assembly

4.2 Breakwater Model

A scaled traditional breakwater is constructed on the guidelines mentioned in Rock Manual and in order to convert it to a living breakwater AR units are added. These units are designed based on the literature mentioned in Chapter 2.

4.2.1 Traditional Breakwater

For the construction of rubble mound breakwater model in flume, different calculations/ trials were made with the available rock sizes in the laboratory. However, a grading sample was chosen with D_{N50} of 4.5cm. Initially, the geometric design of prototype was translated into model scale with N_L=25 and by using a stone size of 4.5cm and packing density of 85%, total number of stones required for the armour layer were calculated (around 1500 stones for the model). The grading of the stones being used is adjusted as per EN 13383 criterion for heavy grading armour stones category and later on it was checked for Rosin-Rammier rules for mass and size distribution of idealized grading. The selected stone size translate to 3-6ton rock category in prototype scale. A detailed gradation adjustment calculation is given as Appendix-B. For the upscaled adjusted grading, distribution curve is presented as Figure 4.3. Nominal upper limit (NUL) and nominal lower limit (NLL) are defined as masses corresponding to 70% and 10% passing. The total mass calculated for prototype scale comes out to be 4886148kg for armour layer. Cumulative passing mass at NUL (3433496 kgs) and NLL (4725149 kgs) corresponds to 9.67% and 70.27% values for NUL and NLL respectively for the adjusted grading.

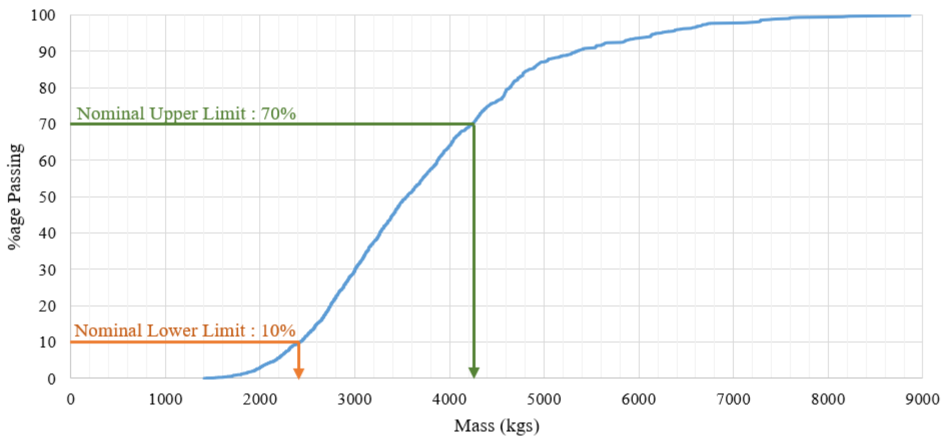


Figure 4.3: Standardized rock grading as per grading test-Prototype Scale

For the construction of filter and core layer, trial calculations were made with available material in lab by keeping in mind the size of armour stone layer (4.5cm). Retention criteria ($W_{50(filter)}/W_{50(core)} < 15-20$) to prevent the loss of core material and permeability criterion ($D_{15(filter)}/D_{15(core)} > 4-5$) to reduce hydraulic gradient are applied in the selection of filter and core material gradations. A finalized design is achieved with D_{N50} of 3cm and 1.2cm for filter and core layer respectively. As per the usual design practice and Rock Manual recommendations, a two stone layer of armour stone and filter is considered. Finalized model sketch along with grading for each layer is shown in Figure 4.4. Pictures taken during the construction of core, filter and armour layer in the flume are shown as Figure 4.5.

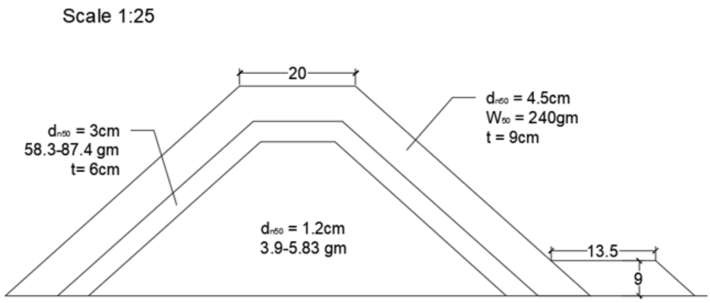


Figure 4.4: Scaled Breakwater Model

(a) Construction of Core

(b) Construction of Filter

(c) Construction of Armour

Figure 4.5: Construction of Breakwater Model Step-by-Step

4.2.2 Designed of AR Units

For this study four different type of Artificial reef units are designed based on the design guidelines mentioned in section 2.5 and literature review. A pictorial representation of the designed elements is shown in Figure 4.6. Main highlights of the design are mentioned below:

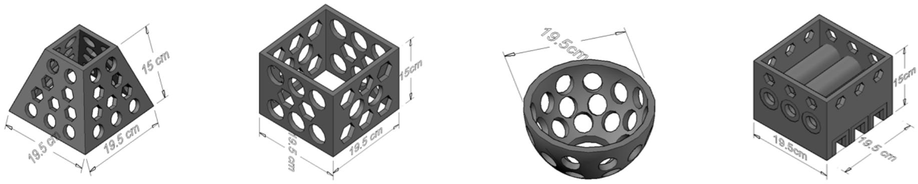
- On the recommendations of Ogawa et al. (1977) for effective ecological development (h=3-4m), vertical relief/height of all AR units is designed as 3.75m and 15cm for scaled model.
- On the recommendations of Bohnsack and Sutherland (1985) opening size in all the AR units is kept in between 0.75m to 1.25m (3-5cm on scale). Another factor in deciding the size of holes is the maximum size of target species (Barents Sea Capelin and Red King Crabs) which ranges from 0.25m to 0.30m.
- Complexity of units, especially AR4 is designed for the fish to hide in order to avoid being preyed upon.
- Elements are 3D printed at NTNU using PA2200 material (density = 930kg/m^3) by using Fused Disposition Modelling (FDM) technology. The technology was used because it produces a relatively rougher surface, even for PA2200. So the unit produced have some rugosity, which may contribute in the drag and friction forces.

These forces are not quantified in this research, but the total effect of wave force in terms of damage is observed. Pictures of 3D printed units, during and after printing are presented in Appendix E.

- Dimensions of AR units are decided on the basis of AR that are employed in European Waters. Based on the recommendation of Fabi et al. (2011) and suitability of the scaled AR units to fit in the wave flume width (0.6m), AR1, AR2 and AR4 are designed as the 4.875m x 4.875m base area, while AR3 with 4.875m diameter. The scaled dimensions are 19.5cm X 19.5cm , therefore it is possible to fit 3 scaled units in one row in wave flume.

- Three units of each AR are 3D printed, which are further used in different configurations for the testing. (see section 4.3)

- Because of the 2D nature of experiments, all AR are placed in way that they face waves.



(a) Type 1 : AR1 **(b)** Type 2 : AR2 **(c)** Type 3 : AR3 **(d)** Type 4 : AR4

Figure 4.6: Scaled Artificial Reef Units with Designed Dimensions

4.3 Experimental Setup

Tests are performed in two dimensional wave flume which has a total length of around 26m, including the regions of absorption beach and wave paddle. A representative sketch of test assembly is shown in Figure 4.7. On the suggestion of DHI (Danish Hydraulic Institute) four resistance type wave gauges are placed at a constant distance of 5.5m, 5.8m, 6.15m and 6.5m from wave paddle. Basic purpose of using these wave gauges is to separate incoming and reflected waves, which can be done with the help of DHI provided software, Wave Synthesizer. The distance between wave paddle and center line of breakwater is around 19.4m. Three ADVs are installed at different locations along the wave flume. ADV3 is placed at 6m from the toe of the structure. Location of ADV1 ADV2, along with the location of three additional wave gauges will be discussed in the later sections. The placement of four initial wave gauges and ADV3 will be constant for all test configurations.
Taking the leverage of different AR units, four different test configurations are used for this study.

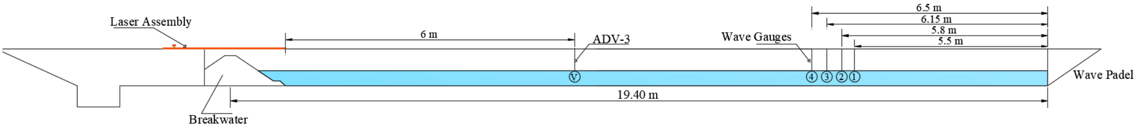


Figure 4.7: Test Setup in Laboratory

Configuration 1: Traditional Breakwater (TWB)

Configuration 1 of the testing scheme is based on the tests on traditional breakwater model without any AR unit. This configuration will serve as the base case for comparison of advantages/disadvantages of AR incorporated living breakwaters and traditional breakwaters. TBW will serve as the existing structure in this study. The damage values after experiments for this configuration are expected to be similar to the values calculated from Van der Meer stability formulas (equation 2.6 and equation 2.7). Three wave gauges are placed at the beginning of toe, end of toe and 12cm from waterline. ADV1 and ADV2 are respectively placed at left and right of the toe, if seen from plan view. A detailed sketch showing the submerge distance and placement location of wave gauges and ADVs is presented as Figure 4.8.

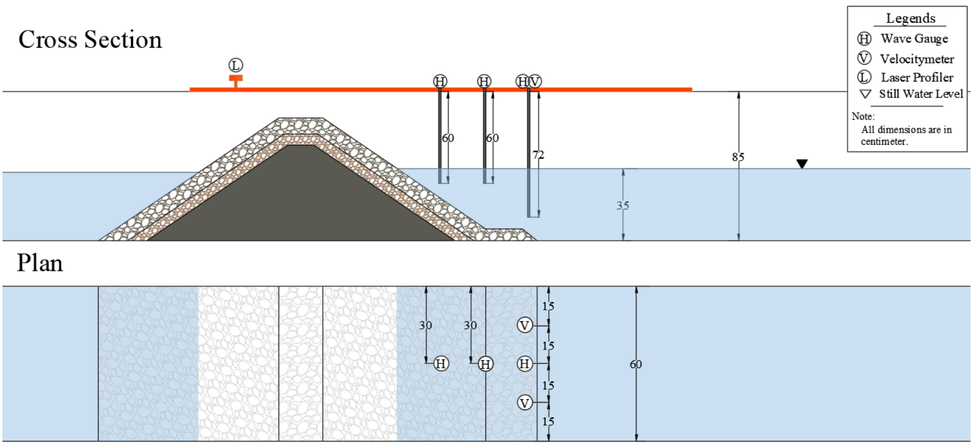


Figure 4.8: Test Configuration 1 : Traditional Breakwater

Configuration 2 : One Row of AR Units

Configuration 2 is the first step towards the implementation of living breakwater concept. One row of different AR elements (AR1, AR2, AR3 and AR4) will be placed at the end of the toe of TBW and then configuration 2 will be tested for different hydraulic conditions. ADV1 is placed inside the AR elements to measure the velocities inside the reefs and ADV2 is placed at around 8cm away from edge of AR (in the wake of AR). Placement of ADV2 is crucial because velocity at the hiding places is important for fish recruitment on AR units. The wave gauge which was initially placed the the toe of breakwater in configuration 1 is now placed at the top of the AR units. A representative sketch is presented in Figure 4.9. The green structure in the figure represents AR units.

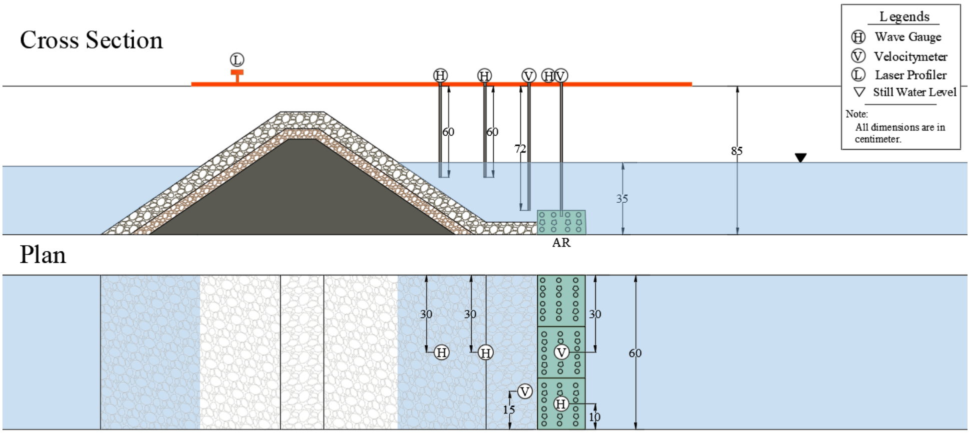


Figure 4.9: Test Configuration 2: One Row of AR Units

Configuration 3: Three Rows of AR Units

Configuration 3 is basically the extension of the toe of breakwater with the help of various AR units. In this configuration, AR units will be placed in rows in front of the toe based on the performance in damage reduction assessed during testing with configuration 2. The AR elements showing the highest performance (reduce more wave energy) will be placed immediate to the toe structure and AR unit showing least reduction in wave energy will be placed at the farthest to the toe of the breakwater. Locations of wave gauges, ADV1 and ADV2 are similar to configuration 2. A sketch is presented in Figure 4.10 for reference.

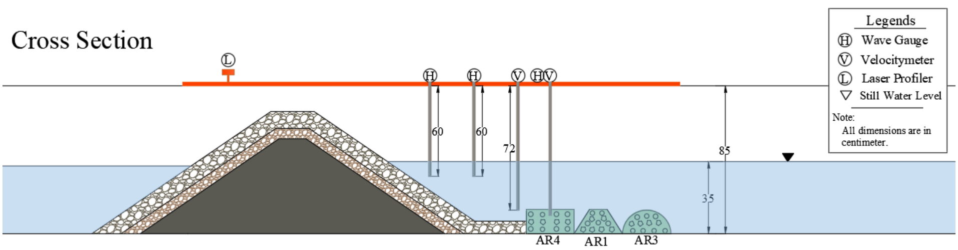


Figure 4.10: Test Configuration 3: Three Rows of AR Units

Configuration 4 : AR Submerged Breakwater

This configuration is actually a representation of low crested submerged (LCS) AR breakwater seawards of existing traditional breakwater. A set of three rows of AR will be deployed at 2m from the toe of TBW. The locations of wave gauges are changed, One wave gauges is present at 20cm from waterline, one at the toe of TBW and one at the middle of TBW and and submerged breakwater (1m from toe of TBW). ADV1 is placed in the middle of the AR units and ADV2 is placed at 20cm in the wake of submerged AR breakwater. Figure 4.11 presents the plan and cross section of configuration 4 along with the location of wave gauges and ADVs.

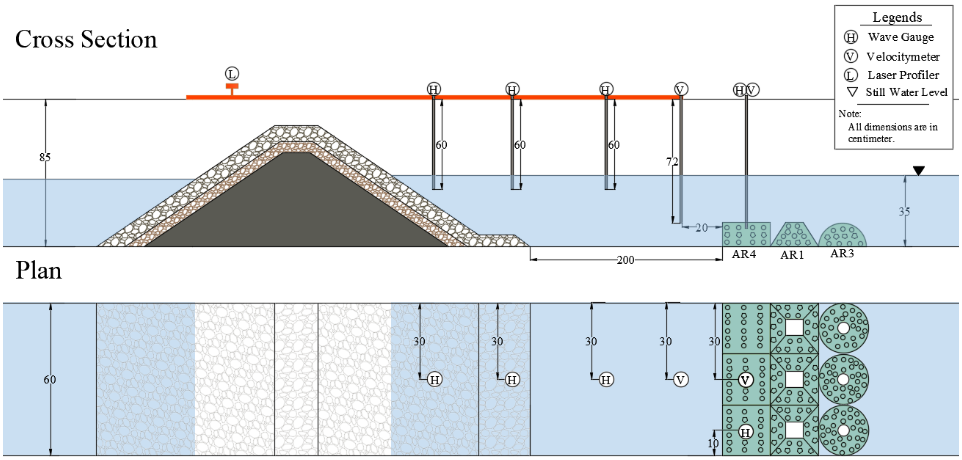


Figure 4.11: Test Configuration 4 : Low Crested Submerged AR Breakwater

4.4 Hydraulic Conditions

For this study, a traditional breakwater model with one filter layer and permeable core is constructed with armour layer D_{N50} of 4.5cm. Literature review suggests that a storm duration of 2-3 hours is considered for most studies, therefore for this study a storm duration of 2.5 hours is considered and it would be translated as 30min for model. Based on aforementioned parameters and geometric parameters of Kiberg breakwater (defined in section 3.3), different damage curves corresponding to different wave heights and wave periods are plotted for prototype in Figure 4.12 using Van der Meer formulas for plunging and surging scenarios. Two horizontal at S=2 and S=8 in figure, respectively indicate start of damage and failure of the structure, by completely removing armour layer and showing filter layer for a structures with slopes steeper or equal to 1:2 (Van der Meer, 1998).

Test Matrix

Based on these damages curves (Figure 4.12), a test matrix is defined which contains hydraulic conditions most of which are expected to cause damage to TBW. This matrix would be used to assess initially the stability of traditional breakwater and then stability of AR incorporated living breakwater. Table 4.1 presents the selected wave conditions in

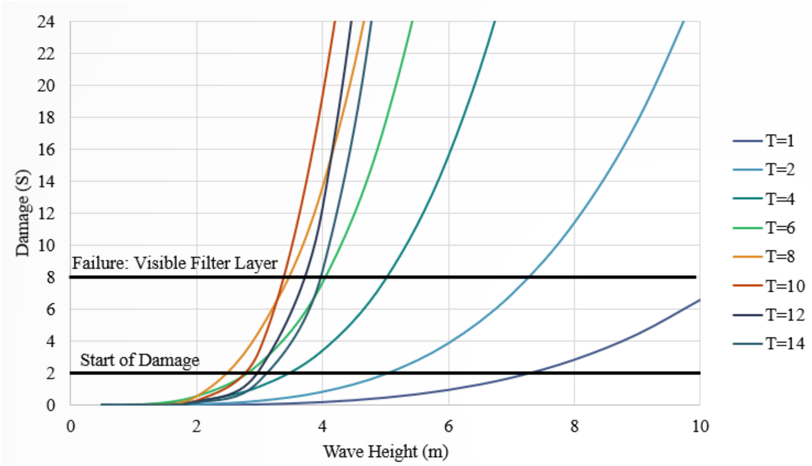


Figure 4.12: Damage at Various Wave Conditions

actual and scaled values. Three wave heights of 2m, 3m and 3.5m are modeled with wave periods ranging from 4 second to 11 seconds. There are total 15 combinations to be tested, which are respectively highlighted as blue and green in actual and scaled conditions tables. Values have been scaled using scale ratio, N_L= 25. The scaled values will be provided as wave paddle input for a water depth of 35cm in the model.

Wave Period (s)			
11	(2, 11)	(3, 11)	(3.5, 11)
10	(2, 10)	(3, 10)	(3.5, 10)
8	(2, 8)	(3, 8)	(3.5, 8)
6	(2, 6)	(3, 6)	(3.5, 6)
4	(2, 4)	(3, 4)	(3.5, 4)
Wave Height (m)	2	3	3.5

(a) Actual Wave Conditions

Wave Period (s)			
2.2	(8, 2.2)	(12, 2.2)	(14, 2.2)
2	(8, 2.0)	(12, 2.0)	(14, 2.0)
1.6	(8, 1.6)	(12, 1.6)	(14, 1.6)
1.2	(8, 1.2)	(12, 1.2)	(14, 1.2)
0.8	(8, 0.8)	(12, 0.8)	(14, 0.8)
Wave Heigth (cm)	8	12	14

(b) Scaled Wave Conditions

Table 4.1: Actual and Scaled Wave Conditions

Number of Tests

As mentioned earlier, there are total 15 wave conditions that are planned to be tested for each of the configurations described in section 4.3. However, carrying out one experiment for one wave condition may not give a true representation of the exact damage. Therefore, three test for one wave conditions in a particular configuration are planned to be performed. But considering that one experiment takes upto 4hours to execute and limited time is available for the study, number of experiments have to be reduced. Total experiments performed for the study are indicated in the Table 4.2. In total 175 tests are performed. A detailed description on skipping certain tests will be provided in the Chapter 5.

Table 4.2: Number of Tests Performed

Configuration	Tests in Test Matrix	No of Tests Performed	Remarks
Configuration 1	15	45	All wave conditions repeated thrice
Configuration 2 : AR1	15	45	All wave conditions repeated thrice
Configuration 2 : AR2	15	3	Only 3 wave conditions tested
Configuration 2 : AR3	15	3	Only 3 wave conditions tested
Configuration 2 : AR4	15	45	All wave conditions repeated thrice
Configuration 3	15	17	All wave conditions repeated once + 2tests on one wave condition
Configuration 4	15	17	All wave conditions repeated once + 2tests on one wave condition

4.5 Methodology

Activities to be performed for a test in flume are described below;

1. First of all, initial profile of breakwater is measure with the help of laser profiler in an empty flume.
2. Water is pumped in the flume to reach a 35cm depth.
3. Wave gauges and ADVs are fixed at the locations described in section 4.3
4. Wave gauges are calibrated and seeding material for ADVs is added to get a signal to noise ratio higher than 15.
5. Wave paddle input is provided with the help of DHI wave synthesizer software and experiment is run for 30minutes.
6. After experiments, data collection is stopped and ADVs along with wave gauges employed on breakwater are taken out of the flume.
7. Flume is emptied again and damage profile is measured.

5
The Experiments' Results

Results from physical model tests are presented in this chapter. Initially, data processing techniques used for this study are mentioned along with brief description of the concepts behind the techniques. This resulted into data which are further interpreted to get the results for different test configurations.

Engineering changes in the bathymetric profiles , such as reef breakwater and sandbars etc, modify the behaviour of incident waves including its breaking characteristics. However, deep water wave steepness ($s_o = H_o/L_o$) controls the breaking and therefore it was desired to generate waves with a wide range of steepness for this study. Maximum deep water steepness is determined by deep water wave height (H_o) and wavelength (L_o) calculated using linear wave theory and type of breaking over artificial reef is determined based on the modified Miche (1951) criterion described as Equation 5.2. This modified criteria is based on the critical depth for shallow water regions on the top of reef. As there are no bathymetric changes incorporated in the experiment before the toe/ AR units of the breakwater therefore the incident waves heights (H_i) are considered to be equal to the deepwater wave heights (H_o). Water depth over AR units (d_r) is simply the difference of water depth (h) and AR relief (H_r).

$$L_o = \frac{gT^2}{2\pi} = 1.561T^2 \tag{5.1}$$

$$\left(\frac{d_r}{H_i}\right)_{critical} = \left(\frac{h - H_r}{H_o}\right)_{critical} = 1.51 \tag{5.2}$$

Wave conditions for this study are mentioned in section 4.4 which translates into 15 wave steepness values defined in the Table 5.1. Apart from Van der Meer criteria of breaking waves, the scenario of breaking over the reef structure based on the recommendations of

Bleck (2006) is also considered. The wave conditions are checked for type of breaking based on wave steepness and ratio of water depth over AR (d_r) and wave length. This is shown in Figure 5.1, red dots indicate the wave conditions mentioned in Table 5.1. This graph presents d_r and H_i normalized by deep water wave lengths. Based on this plot, it is observed that 9 out of 15 wave conditions are not showing any breaking behaviour however remaining 6 wave conditions exhibit spilling breaking behaviour over the artificial reef which is believed to be caused by wave skewness due to the return flow/reflected wave over the reef. This was further verified during the tests and a description on it is presented in Chapter 6.

Table 5.1: Actual and Scaled Wave Condition

Actual Wave Conditions					Scaled Wave Condition				
T_o	H_o	L_o	s_o	ξ	T_o	H_o	L_o	s_o	ξ
sec	m	m			sec	cm	m		
4.0	2.0	25.0	0.080	2.8	0.8	8.0	1.0	0.080	2.8
4.0	3.0	25.0	0.120	2.3	0.8	12.0	1.0	0.120	2.3
4.0	3.5	25.0	0.140	2.1	0.8	14.0	1.0	0.140	2.1
6.0	2.0	56.2	0.036	4.2	1.2	8.0	2.2	0.036	4.2
6.0	3.0	56.2	0.053	3.5	1.2	12.0	2.2	0.053	3.5
6.0	3.5	56.2	0.062	3.2	1.2	14.0	2.2	0.062	3.2
8.0	2.0	99.8	0.020	5.7	1.6	8.0	4.0	0.020	5.7
8.0	3.0	99.8	0.030	4.6	1.6	12.0	4.0	0.030	4.6
8.0	3.5	99.8	0.035	4.3	1.6	14.0	4.0	0.035	4.3
10.0	2.0	156.0	0.013	7.1	2.0	8.0	6.2	0.013	7.1
10.0	3.0	156.0	0.019	5.8	2.0	12.0	6.2	0.019	5.8
10.0	3.5	156.0	0.022	5.3	2.0	14.0	6.2	0.022	5.3
11.0	2.0	188.8	0.011	7.8	2.2	8.0	7.6	0.011	7.8
11.0	3.0	188.8	0.016	6.3	2.2	12.0	7.6	0.016	6.3
11.0	3.5	188.8	0.019	5.9	2.2	14.0	7.6	0.019	5.9

5.1 Data Post Processing

Post processing of the collected data is one of the most crucial steps in the physical model study. Techniques employed can greatly influence the results.

5.1.1 Damage Profiles

Figure 5.2 presents a sample plot obtained after processing the data from the laser profiler. The data were in the form of vertical distances from laser beam to the first encountered object in the path of beam ray. This data in $text.txt$ format files are processed with the help of a matlab code to generate the damage plots along with the values of the damage level after storm. The damage values represents the ratio of eroded area after the storm (A_e) and square of stone diameter D_{N50}. In a unit strip it is more or less equal to the

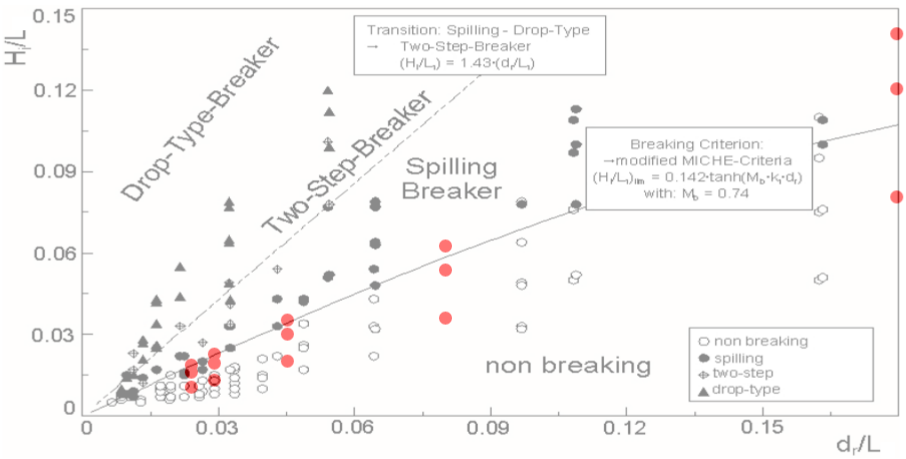


Figure 5.1: Identification of breaking type for wave breaking over AR, (X-axis; water depth over AR normalized by deep water wave length, y-axis; incident wave height normalized by deep water wave length), (Bleck, 2006)

number of stones removed.

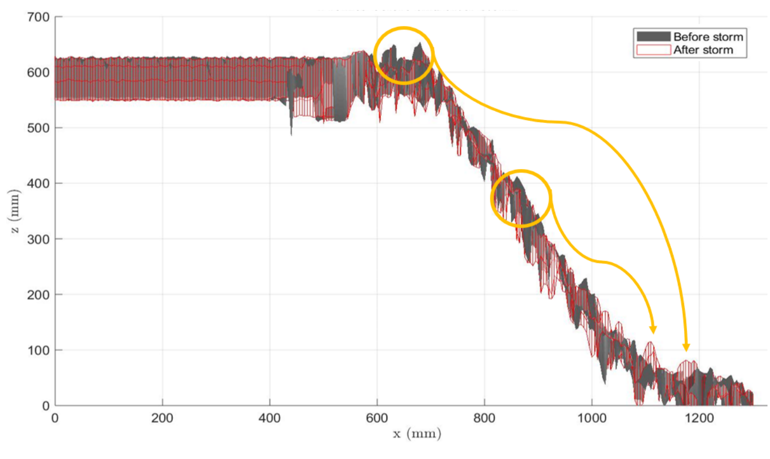


Figure 5.2: Profile of Breakwater Before and After Storm

Damage values obtained by this approach are further used in a slightly modified form of Van der Meer stability formulas (Equation 2.6 and Equation 2.7). All the known predefined parameters are summed up into a factor $\frac{H_s}{\Delta D_{N50}}.P^{-0.18}.\xi^{0.5}$ for plunging waves and $\frac{H_s}{\Delta D_{N50}}.\xi^{-P}.\sqrt{tan\alpha}$ for surging waves. (Van der Meer's definition of plunging and surging waves is considered for the interpretation of the results.) These factors are then plotted for the measured parameters $S_d/\sqrt{N}$. The plots obtained will be analyzed for the stability assessment of hybrid structure for various wave conditions. Behaviour of the waves as per Bleck (2006) criteria of breaking will be also be evaluated from the same curves.

5.1.2 Velocity Signals

Analog velocity signals is captured with the help of same DHI software as used for wave gauge data, therefore the water levels are coupled with velocity signal. As described earlier, Vectrino ADV is very sensitive and this has resulted in some noise in the velocity signals which can be due to the deficiency of seeding material/particles to deflect the acoustic signal to receiver. This situation was limited by adding sufficient seeding so that signal to noise ratio become higher than 15. However, there was noise in the velocity signals which was eliminated with the help of curve fitting.

Fast Fourier Transformation (FFT) is used to separate the velocity components, as mentioned in Equation 5.3. Spectral analysis plots are used to identify and verify the components in the signal before and after filtering of noise. The quality of fit was checked with the help of Root Mean Square Error (RMSE), which is expressed as Equation 5.4. Numerator in RMSE equation represents the sum of squares due to error, if it is closer to zero then fit is considered to have smaller random error. n indicates the number of independent bins involved in calculating the sum of squares. If RMSE is close to zero then a fit is considered more valuable. This has been done with the help of curve fitting tools in Matlab. A detailed description along with matlab code is given in Appendix-C.

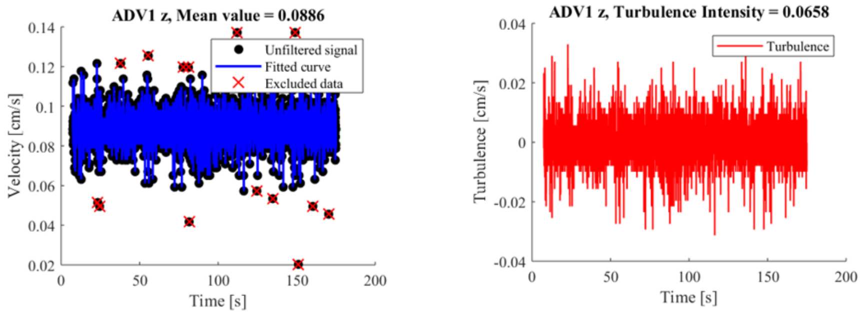
$$y = a_o + \Sigma(a_i Cos(iwx) + b_i(iwx)) \tag{5.3}$$

$$RMSE = \sqrt{\frac{\Sigma_{i=1}^{n} w_i (y_i - \hat{y}_i)^2}{n}} \tag{5.4}$$

A signal with eliminated noise data along with fitted curve can be seen in Figure 5.3 (a). Turbulent velocities (u', v', w') signal after excluding mean velocities ($\overline{u}$, $\overline{v}$, $\overline{w}$) and noise are presented in the form of sample plot shown in Figure 5.3 (b), along with the values of turbulent intensity values (r_u, r_v or r_w).

Velocity values (mean and turbulent) are used to analyze ecological and physical performance of breakwater. Mean velocities obtained from this analysis will be used to check the suitability of target species to inhabit AR units. For the assessment of turbulence in the flow, most of the researchers either use relative turbulence intensity or turbulent kinetic energy (TKE). Turbulence intensity is the ratio of root-mean-square of the velocity fluctuations (u'_{rms}, v'_{rms}, w'_{rms}), to the mean flow velocity, however TKE is defined as mean kinetic energy per unit mass associated with eddies in turbulent flow. Mathematically these terms, for only velocity component in longitudinal direction of flume, are expressed as:

$$r_u = \frac{u'_{rms}}{\overline{U}} \tag{5.5}$$



(a) Filtered Velocity Signal

(b) Turbulence in Signal

Figure 5.3: Processing of Velocity Signal

$$u'_{rms} = \sqrt{\overline{u'^2}} = \sqrt{\frac{1}{N}\sum_{i=0}^{i=N-1}(u-\overline{u})^2} \tag{5.6}$$

$$TKE = \frac{1}{2}(u'^2 + v'^2 + w'^2) \tag{5.7}$$

As only two components of fluctuating velocities (u' and w') will be used for further analysis therefore, TKE is estimated as suggested by Mukaro and Govender (2013) from Equation 5.8. This value of 1.33 is based on the assumption that turbulence characteristics for plane and breaking wave are similar (Bleck, 2006). A similar estimation approach for TKE is also used by Shin Cox (2006) and Liiv Lagemaa (2008). In order to make TKE value dimensionless, it is normalized by gh on the recommendations of Mukaro and Govender (2013) (see Equation 5.9). These non-dimensional values are use to get an idea about turbulence.

$$TKE = \frac{1.33}{2}(u'^2 + w'^2) \tag{5.8}$$

$$NormalizedTKE = \sqrt{\frac{TKE}{gh}} \tag{5.9}$$

For most of the measurements, it is observed that mean velocities ($\bar{u}$ and $\bar{w}$) are relatively higher in respect to the turbulent fluctuations (u' and w'). This ensures that the r_u and r_w and TKE can be used for further analysis. In this study, TKE is reported for the comparison of turbulence in flow for different wave conditions and experimental setup. However, similar trends were observed for r_u and r_w .

5.1.3 Wave Reflection Analysis

Wave gauges in experiments are used to obtain data regarding incident-wave height and reflected wave height. Goda and Suzuki (1976) presented a method of separating the incident and reflected waves on the basis of wave measurements at two known positions on a line parallel to the direction of wave propagation. In order to do so, wave gauges have to placed at specific distance from each other. Based on the recommendation of experts from DHI, the distance between four wave gauegs closer to the wave paddle is set as:

$$\Delta l_{1,2} = 40cm \qquad \Delta l_{1,3} = 75cm \qquad \Delta l_{1,4} = 100cm \tag{5.10}$$

Where, l represents the distance between wave gauges mentioned in subscript.

5.2 Results for Configuration 1: TBW

On traditional breakwater 45 total tests have been conducted with variable wave conditions repeating each test in test matrix three times. This is the base case for comparison to other configurations.

Damage Profiles

Three values of damage to the structure are obtained for each test conditions which are further used for analysis. Mean of these values are presented below in Figure 5.4. Highest damage is observed at a period of 2 second with a wave height of around 14cm, and damage is valued at 8. Figure 5.5 shows the relative values of damage as compared to modified Van der Meer stability formulas for plunging and surging waves. The results show a good comparison for plunging waves however, the damage associated for surging waves is higher for lab measurements. The damage values associated with non-breaking waves lies above the main trend-line of the measured values, indicating a higher damage. Stability number ($H_s/\Delta D_{N50}$) calculated for all these values experiments comes out to be around 1.7.

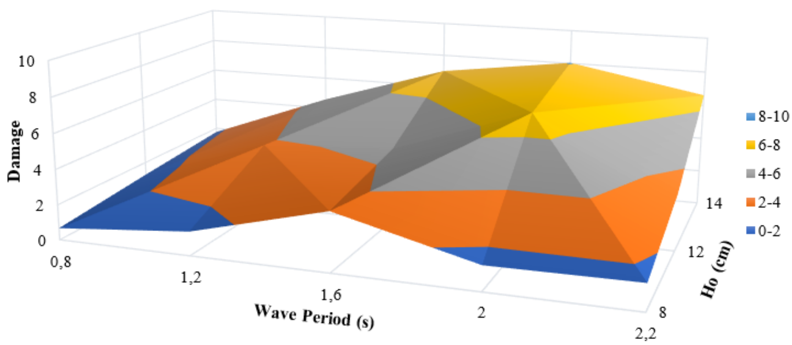
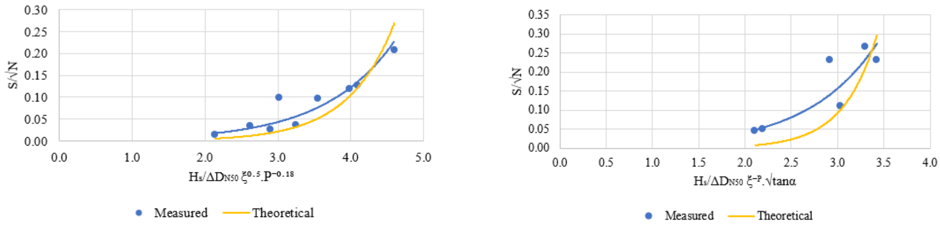


Figure 5.4: Damage Profile of Configuration 1

Turbulence

TKE for two locations, 15cm from left and 15cm from right wall of the flume, were calculated with the help of the velocities measured at the same locations with ADV1 and ADV2.



(a) Plunging Waves **(b)** Surging Waves

Figure 5.5: Damage Comparison for Configuration 1

Normalized TKE values are then plotted against non-dimensional wave height (H_s/h). At lower wave heights there are differences in the values for ADV1 and ADV2 but for most of the data the values at both locations conform with each other. It was anticipated as the flow conditions are similar at both locations. Figure 5.6 represents the plot for this scenario. Each point on the curve represents an average value obtained from measured velocities for three repetitions.

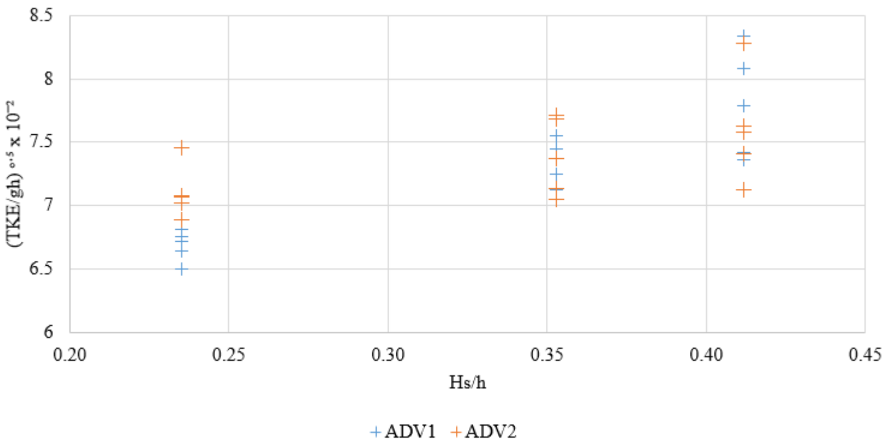


Figure 5.6: Turbulence for Configuration 1

5.3 Results for Configuration 2: One Row of AR

Four different AR units are used to attain four setups of configuration 2. Three units, consisting of one row of AR of similar type, are placed in front of the toe for one setup. Initially, the highest damage producing combination for configuration 1 ($T_o = 2s$ and $H_o = 14$) is used to perform tests for each setup in order to identify the most efficient AR unit for damage reduction. These initial results depicted that AR4 is the most efficient followed by AR1, AR3 and AR2 respectively. Therefore, on this basis AR1 and AR4 are chosen to investigate further for more wave conditions and AR2 and AR3 are eliminated from configuration 2 test scheme due to time limitations.

5.3.1 Configuration 2: AR1

Damage

Highest damage is observed at the same wave condition ($T_o = 2s$ and $H_o = 14$) as of configuration 1 but with a relatively lower value of around 7.5. A spread of mean values of damages is shown in Figure 5.7. Figure 5.8 relative damage plot compared with theoretical values from modified Van der Meer formulas. The curves for plunging show a good similarity on lower wave heights however on higher wave heights the energy dissipation effect of AR is more prominent making the damage lesser than theoretical values. A similar behaviour is observed for surging waves however at lower wave heights the difference with theoretical values is still present. From these calculations it was derived that breaking waves exhibit a higher stability number (range from 1.75 to 1.85) as compared to non-breaking waves (range from 1.45 to 1.60).

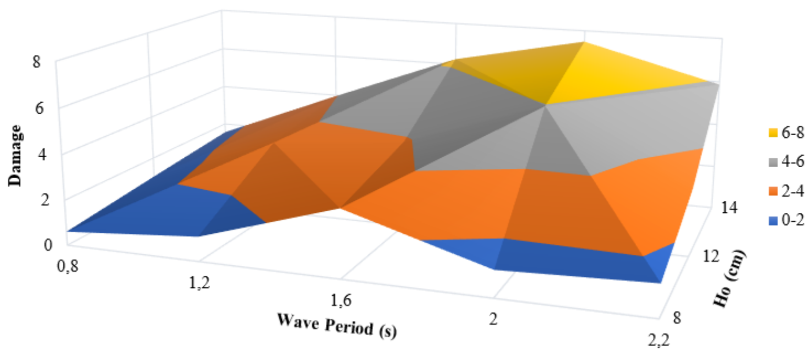
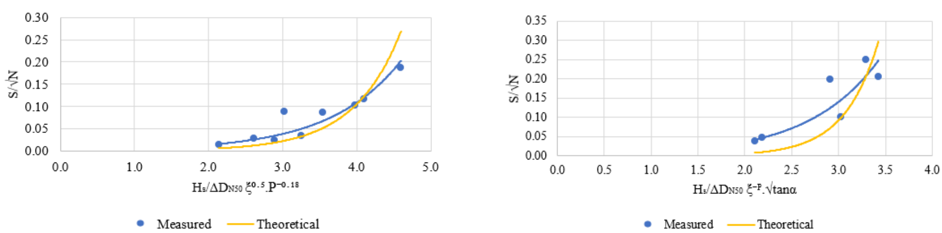


Figure 5.7: Damage Profile of Configuration 2: AR1



(a) Plunging Waves

(b) Surging Waves

Figure 5.8: Damage Comparison for Configuration 2 - AR1

Turbulence

Figure 5.9 represents the turbulence situation for in configuration 2 (AR1). Values inside AR are measure with help of ADV1 and outside AR with ADV2. It can be seen that the velocity fluctuations outside the reef are relatively higher than inside the AR structure. This is specially prominent at lower wave heights. In general the turbulence values are higher than config-1. Each point in Figure 5.9 is the mean value of fluctuations measured by repeating test matrix three times.

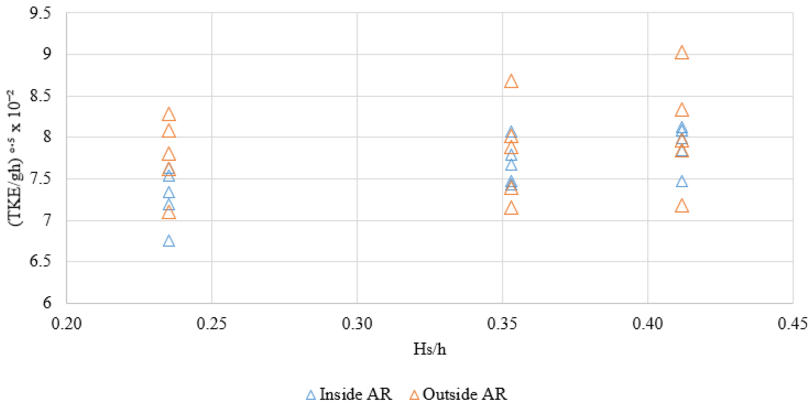


Figure 5.9: Turbulence for Configuration 2 (AR1)

5.3.2 Configuration 2: AR2

In total 3 experiments are performed on one wave condition ($T_o = 2s$ and $H_o = 14$). Which has resulted into a mean damage value of 8.1 and this value is very close to the damage value calculated for the same wave condition in configuration 1. Therefore no reduction in wave energy is observed. One of the reason behind this aspect can be a larger porosity of AR2 (64%), which does not change flow conditions and breaking of waves.

5.3.3 Configuration 2: AR3

As discussed for AR2, a similar situation is observed for AR3 units. Mean damage value from 3 tests is calculated as 7.94 which does not differ much from AR2 and configuration 1. A lesser reduction of the energy can be attributed to the more open structure of the AR3.

5.3.4 Configuration 2: AR4

Damage

A highest mean damage of 7.2 is observed at ($T_o = 2s$ and $H_o = 14$) wave condition. Representative envelope of damage is plotted as Figure 5.10. Figure 5.11 presents the comparison plots for plunging and surging waves. Waves for this configuration behave almost similar to Config2- AR1. A similarity on lower wave heights and divergence of trend on higher can be observed from the plots. Surging waves still does not fully follow the theoretical curves. Stability number for all wave conditions is calculated as 1.65 from the measurements.

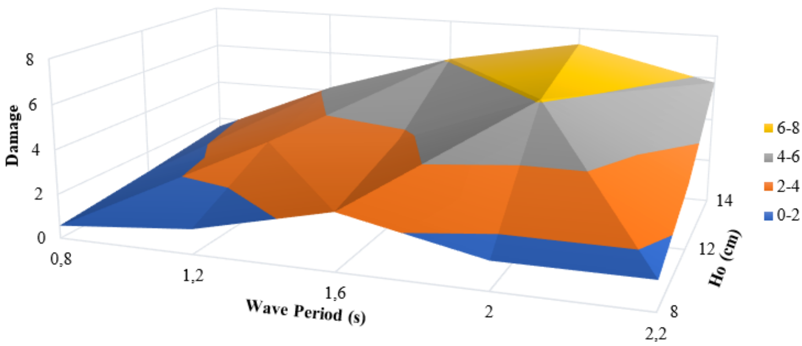
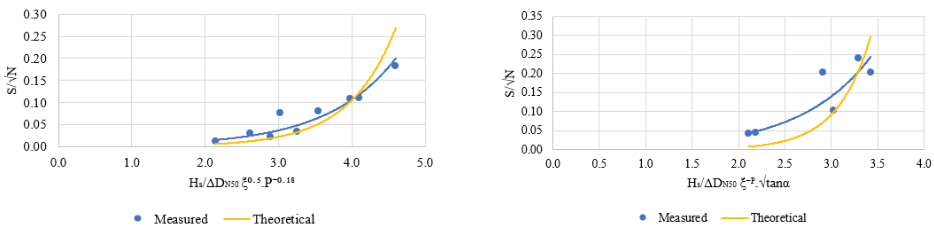


Figure 5.10: Damage Profile of Configuration 2: AR4



(a) Plunging Waves

(b) Surging Waves

Figure 5.11: Damage Comparison for Configuration 2 - AR4

Turbulence

For AR4, there a clear distinction between inside and outside fluctuations which can be observed from Figure 5.12. In general, there is a clear pattern of rise in turbulence with increase of wave heights. TKE in the wake of AR units is higher than the turbulence inside AR units. Each point represents the average value of measured fluctuations during three repetitions of test matrix.

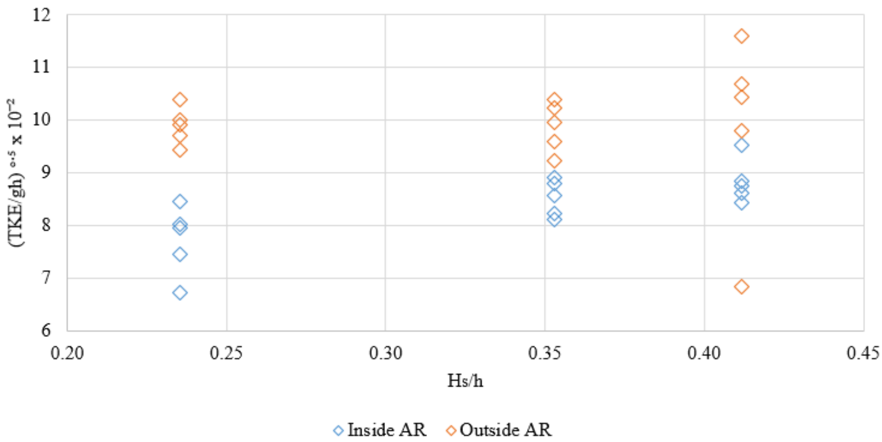


Figure 5.12: Turbulence for Configuration 2 (AR4)

5.4 Results for Configuration 3: Three Rows of AR

Damage

This configuration is more efficient in terms of damage reduction on breakwater than configuration 2. Highest damaged is recorded as 4.4 on the wave condition ($T_o = 2s$ and $H_o = 14$). This configuration has reduced the damage value for all the wave conditions significantly (see Figure 5.13.) Figure 5.14 represents the damage comparison for this configuration and its deviation from theoretically calculated values. It can be observed that at lower wave heights, model study results are much aligned with theoretical values for both plunging and surging conditions. However, at higher wave heights a very huge difference can be observed. Stability number for this configuring is calculated as 1.55 which is lesser than config-2, indicating that the restoring forces are becoming more prominent than disturbing forces.

Turbulence

The trend of turbulence is different than configuration 2. Figure 5.15 represents that the velocity fluctuations inside the reef structure are higher than outside. This is the opposite behaviour as of configuration 2, where higher fluctuations were observed outside the reef structure. Along with this, there is an increasing trend of fluctuations with wave heights. Each point on the plot presents the results of measurement obtained from single repetition of test matrix.

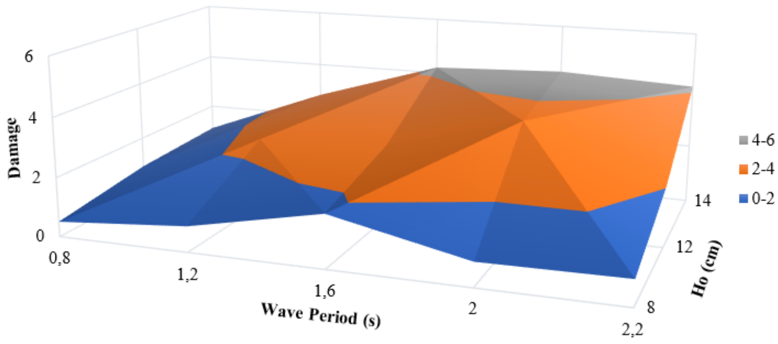
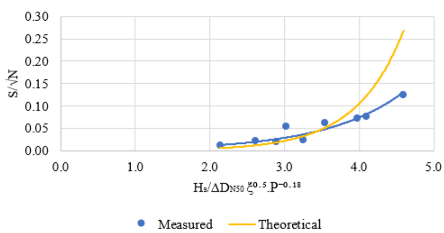
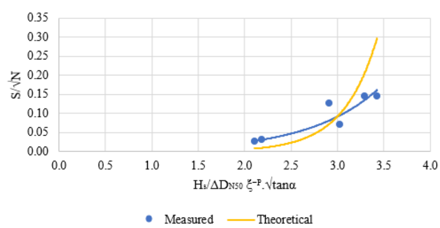


Figure 5.13: Damage Profile of Configuration 3



(a) Plunging Waves



(b) Surging Waves

Figure 5.14: Damage Comparison for Configuration 3

5.5 Results for Configuration 4: Submerged AR Breakwater

In total 15 test are performed using this configuration, with one test for each condition in test matrix.

Damage

Out of all the configurations, highest reduction in wave energy is observed for this scenario and a highest damage of 3.4 is recorded for $T_o = 1.6s$ and $H_o = 14$ wave condition. Figure 5.16 represents the envelope for damage for all wave conditions. Comparative output of the results is shown in Figure 5.17, which shows that modified Van der Meer formula and test results are similar at lower wave heights but higher wave heights indicate much more reduction in energy for both plunging and surging waves. Reduction in stability number (1.45) is also observed indicating the empowering balancing/restoring forces.

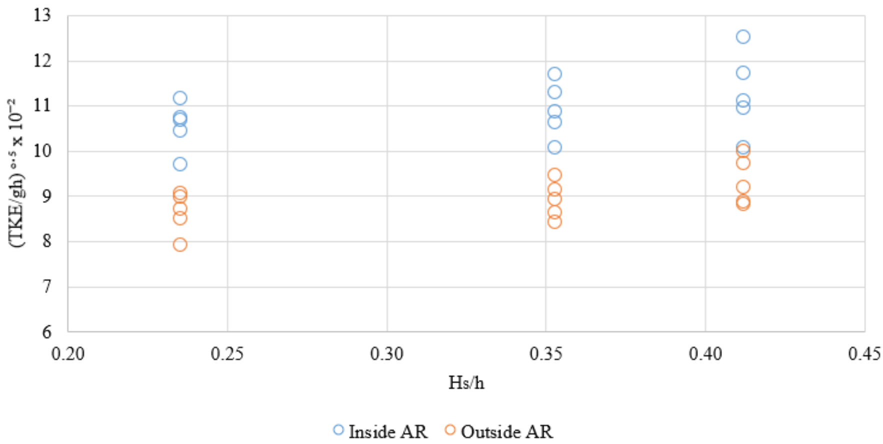


Figure 5.15: Turbulence for Configuration 3

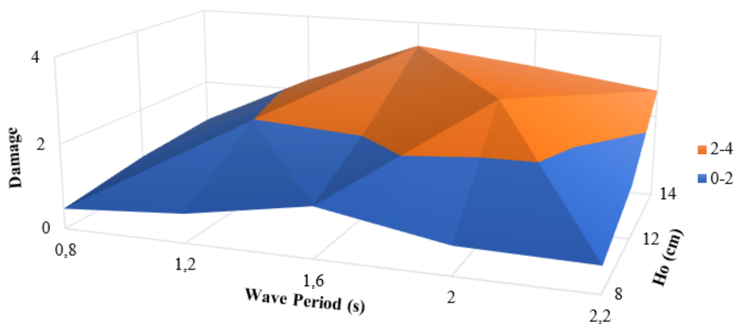
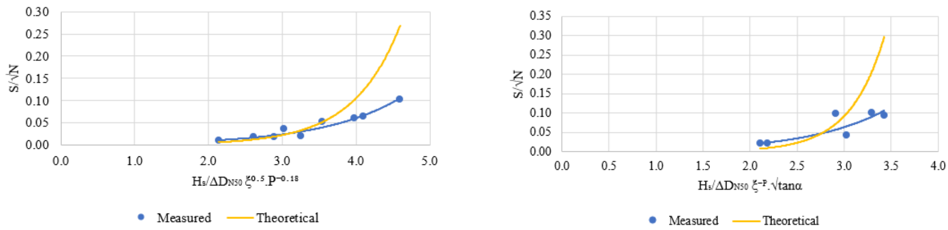


Figure 5.16: Damage Profile of Configuration 4

Turbulence

Figure 5.18 represents the velocity fluctuations for configuration 4. It can be seen that a higher fluctuations are present present outside the AR reef with a higher trend by increase of wave height. Each point in the figure presents the results of measurements obtained from single repetition of test matrix.



(a) Plunging Waves **(b)** Surging Waves

Figure 5.17: Damage Comparison for Configuration 4

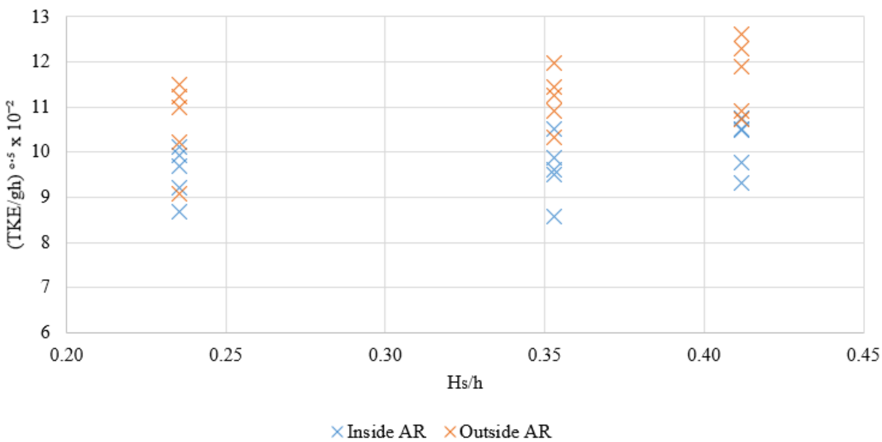


Figure 5.18: Turbulence for Configuration 4

6
Discussion

A logical explanation of the results of the study in the light of literature is presented in this chapter. Observations made during performance of tests and the reasons behind the exhibited trends of results are discussed.

Analysis of results show a clear trend of damage reduction from configuration 1 to configuration 4, with configuration 4 begin the most efficient in reduction. Plots showing an overall picture of damage reduction for different configuration are presented as Figure 6.1 and Figure 6.2 for plunging and surging waves respectively (as per Van der Meer definition). All the configurations show similar behaviour in plunging at lower wave heights but with the increase in wave heights wave energy increased and so as the damage. However, configuration 4, shows much better efficiency than other in reducing the damage for plunging waves. In comparison with theoretical curve, all the configurations does not show much deviation at the lower wave heights but at higher wave heights a significant difference can be observed. In case of surging waves Figure 6.2 indicates that behaviour of configuration 2 is closer to configuration 1 and there is not much difference in damage. On the other hand, configuration 3 and 4 show significant reduction, with config-4 being the most efficient. Measured values for surging waves are relatively dispersed from theoretical values as compared to plunging waves. However, a similar trend of higher difference at high wave heights can also be observed for surging waves.

In order to quantify the damage for different configurations Figure 6.3 shows the percentage damage reduction for the different configurations compared to configuration 1, i.e.

$$\%Reduction = \frac{S_{config_x} - S_{config_1}}{S_{config_1}} 100 \tag{6.1}$$

An average value of damage reduction over all wave conditions along with maximum ob-

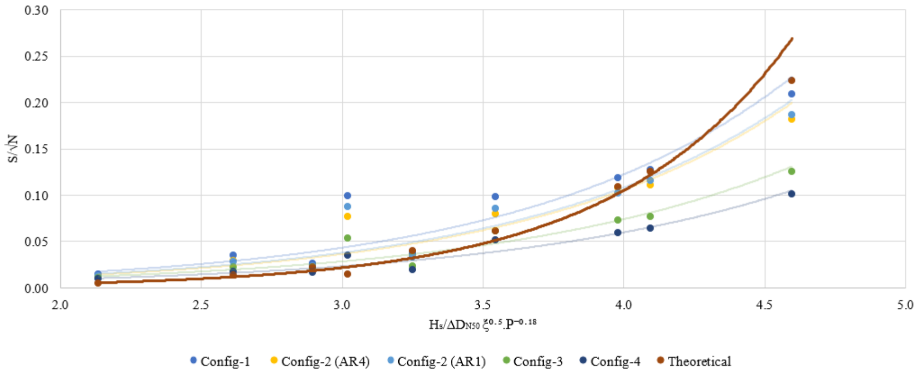


Figure 6.1: Damage Reduction Comparison for Plunging Waves

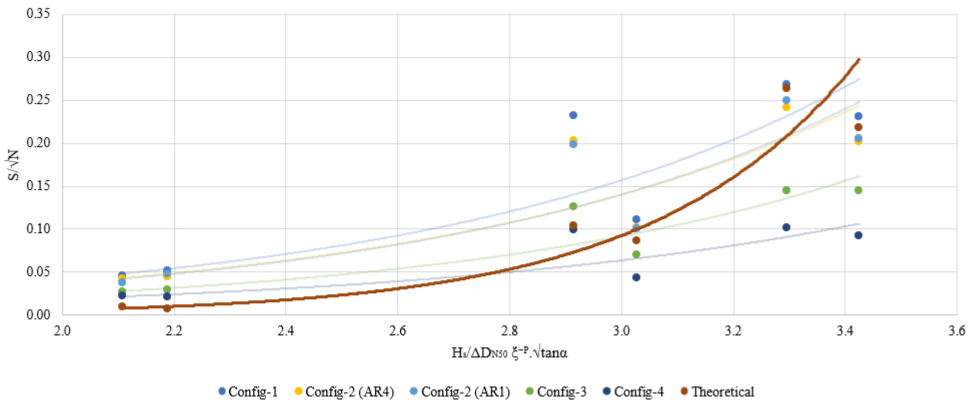


Figure 6.2: Damage Reduction Comparison for Surging Waves

served damage reduction value and reduction at highest wave steepness are plotted in the Figure 6.3. Plot clearly indicates that configuration 4 presents a damage reduction upto 50%, which is less than wave energy reduction percentages for submerged low crested AR breakwater reported in literature (upto 74% reported by Fabi et al. (2011)). However, configuration 3 presents damage reduction upto 40% as compared to 10% value for configuration 2. The results for config-2 are within the standard deviation of results obtained for configuration 1, which emphasizes that ***placement of just one AR row is not very effective in wave energy reduction***, making width of AR structure an important parameter.

The increased reduction of damage for hybrid structure is an indication of increased energy loss for breaking and non-breaking waves. Figure 6.4 shows different phenomena of energy dissipation for breaking and non-breaking waves on AR. Wave reflection from AR units causes less high wave heights on AR, making the breaking more convenient. A secondary wave is generated landward of AR, which may cause constructive or destructive interference with incoming wave causing a highly non linear behaviour, reflected

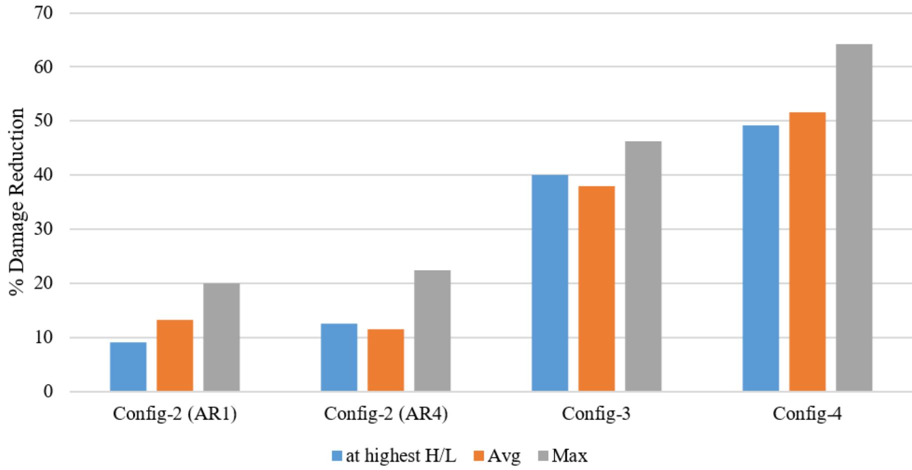
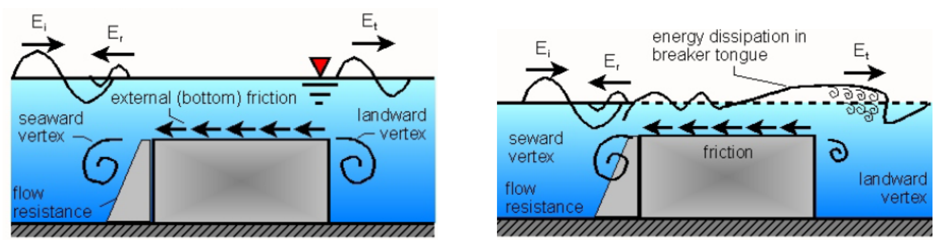


Figure 6.3: Comparison of Configurations for Damage Reduction

waves from breakwater add more non-linearity to it (see Figure 6.5). Apart from these non-linearities the phenomena involved in the wave reduction on AR are following:

- **Non-Breaking Waves** loose energy by forming landward and seaward vortex, flow resistance due to AR bottom friction and other internal and external friction losses.

- **Breaking Waves** dissipate energy by landward and seaward vortex, breaker tongue, flow resistance over reef and friction losses. Landward vortex is generally dominated by breaker tongue



(a) Non Breaking Waves

(b) Breaking Waves

Figure 6.4: Phenomenon Contribution to Energy Loss at Artificial Reef, (Bleck, 2006).

In order to assess the non-linear interaction and reflection from reefs and breakwater, reflection coefficient for different wave setups are plotted. Reflection coefficient (C_r) is simply a ratio of reflected wave height (H_{ref}) to the incoming wave height (H_i).

$$C_r = \frac{H_{ref}}{H_i} \tag{6.2}$$

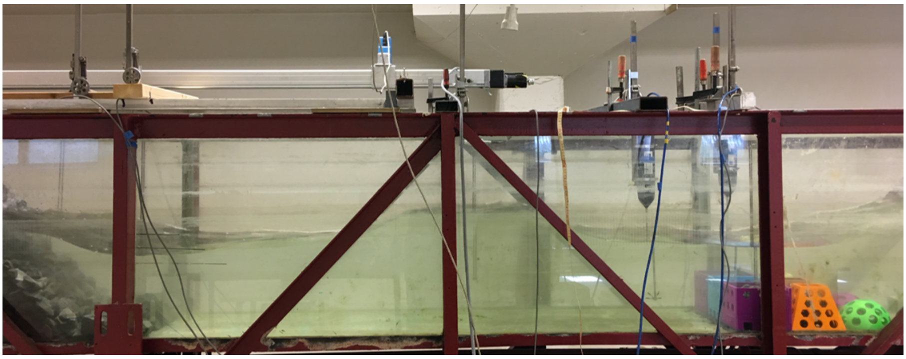


Figure 6.5: Nonlinear Behaviour due to interferes of incoming wave with secondary waves.

For a rubble mound structure C_r vary with relative wave height and with wave steepness. However, because of high porosity, rough texture and low profile AR breakwater generally tend to have low reflection coefficients.

C_r for this study is computed with the help of MIKE Zero, WS Wave Reflection Analysis Tool. The data obtained from Wave Synthesizer (dfs0 files) are used as an input in connection with wave gauges set closer to the wave paddle. Based on Fast Fourier Analysis, reflected waves are separated from incoming waves and C_r values corresponding to different wave conditions are determined. The values obtained from physical model study are compared with Van der Meer (1992) formula for rouble mound breakwaters with steep front face (Equation 6.3). Representative plots for config-3 and config-4, from model study results, are plotted as Figure 6.6.

$$C_r = 0.07(P^{0.88} + \xi) \qquad Where, \;\; \xi = \frac{tan^{0.62}\alpha}{(H/L_o)^{0.46}} \tag{6.3}$$

Figure 6.6 depicts that as compared to reflection from TBW, green-grey hybrid structure (config-3) exhibit much more reflective behaviour. However, LCS AR breakwater (config-4) show even a stronger reflection behaviour than config-3. The difference in behaviour of plunging waves for both configurations does not vary much, especially at smaller ξ. The difference at higher ξ is quite significant, which suggest that *reflection is more pronounced in for LCS AR breakwaters*. The difference between the C_r, increased reflection can be explained with the help of Figure 6.7. A secondary wave shoreward of main incoming wave is generated due to which breaking occurs even before incident wave has reached to depth limited breaking criteria. Due to the presence of strong return flow, breaker height index ($\Omega_b = H_b/h_b$) increases. Armono (2004) observed that this return flow is strongest if the slope of the reef, facing incoming wave, is steeper. This is the case for current study. 2 out of 4 AR units are vertical and AR1 is with a very steep slope and AR3 is semi circle. Due this a very non-linear behaviour of waves is observed during physical model test. It may also be the reason that C_r at certain wave conditions is higher than 1.

Decrease in damage can also be explained in terms of increased turbulence in and around

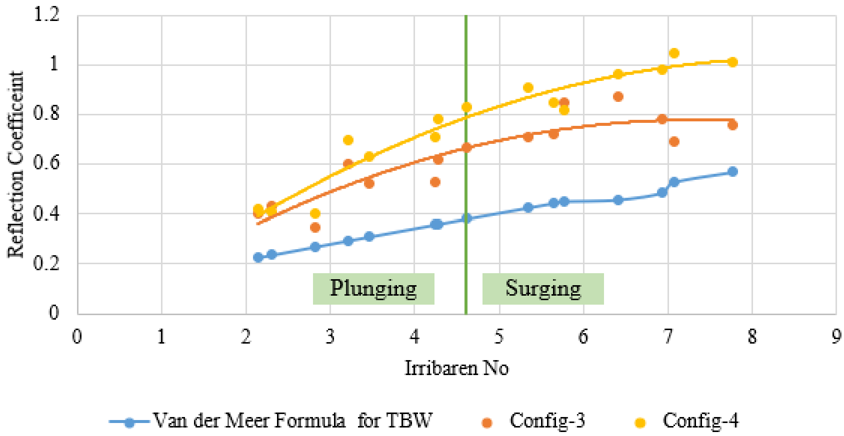


Figure 6.6: Comparison of Reflection Coefficient for Config-3 and Config-4

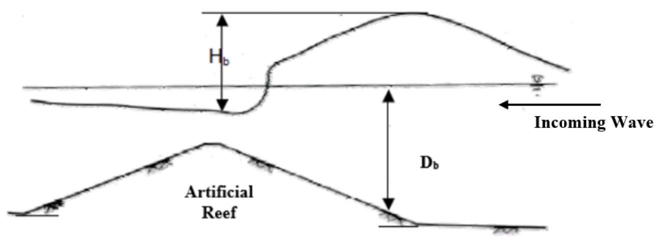


Figure 6.7: Incident Wave Behaviour on AR

AR structures, as this increase is associated with the loss of wave energy. Figure 6.8 and Figure 6.9 present a comparison of turbulence inside and outside AR for all configurations. Outside fluctuations are measured by ADV2 in the wake of reef structures. It can be observed that configuration 3 shows highest turbulence among all cases when measured inside AR. This can be associated with the decreased depth immediate next towards the breakwater, as AR are placed in the extension of breakwater toe. Vortex shredding at the edge of reefs is influenced by this limited water depth and as Bleck (2006) suggested that in such conditions deformation of waves become stronger leading to higher turbulence. However, due to limited length for the development of vortex in the wake, landwards vortex in configuration 3 is believed to be not as stronger as in configuration 4. Along with this, breaker tongue also does not develop due to the immediate presence of structure and this situation combined with reflected waves cause the waves to break on the AR. Therefore even waves with lower steepness are observed to break on the middle of AR instead of the breakwater ward edge of AR. This caused a higher fluctuations within the AR units for configuration 3, which can be observed from Figure 6.8.

Figure 6.9 depicts the comparison of turbulence in the wake of AR units for all configurations. It can be seen that configuration 4 presents the most higher values. This behaviour can be attributed to the fact that as a wave breaks a very high turbulent mixing zone of air and water can be observed. On landward side this is indicated in breaker tongue. It can be seen from Figure 6.10, a very high turbulent zone is observed on the landward edge of reefs and it is one of the main sources of dissipating wave energy leading towards the breakwater.

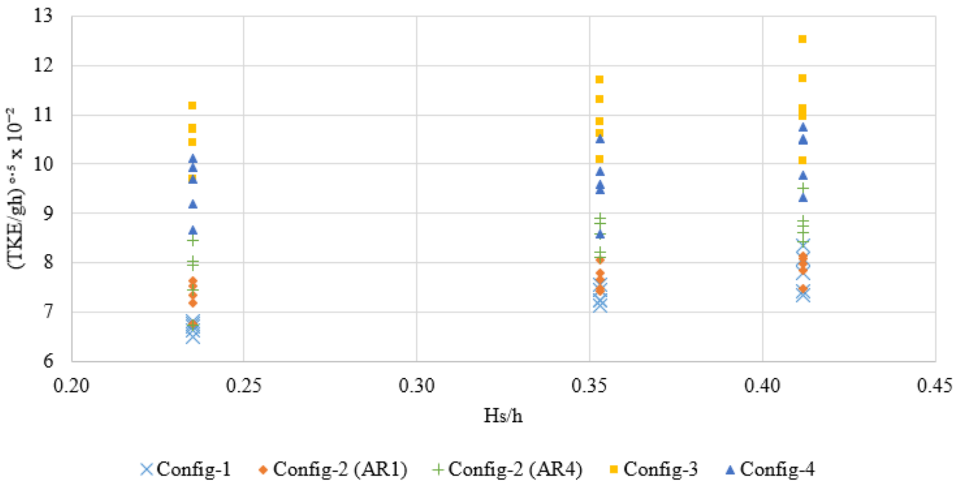


Figure 6.8: Comparison of Turbulence (Inside AR) for all Configurations

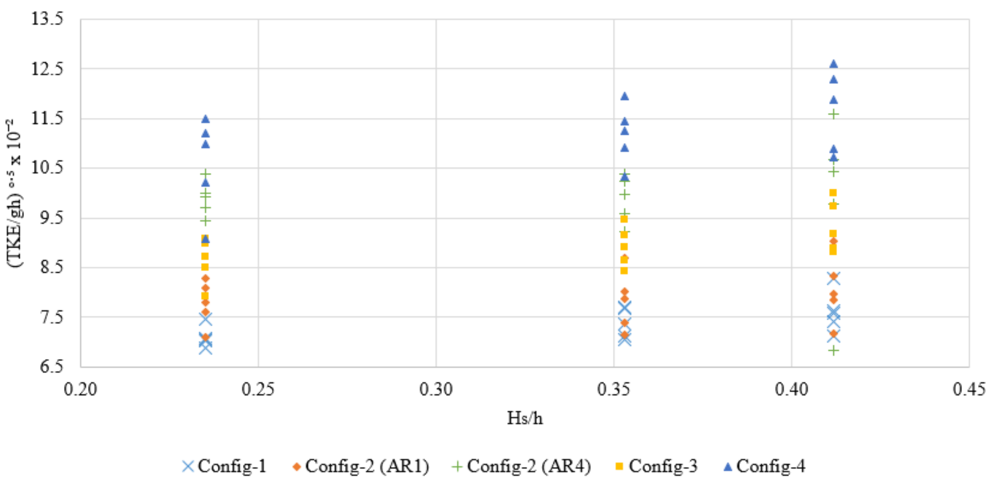


Figure 6.9: Comparison of Turbulence (Outside AR) for all Configurations

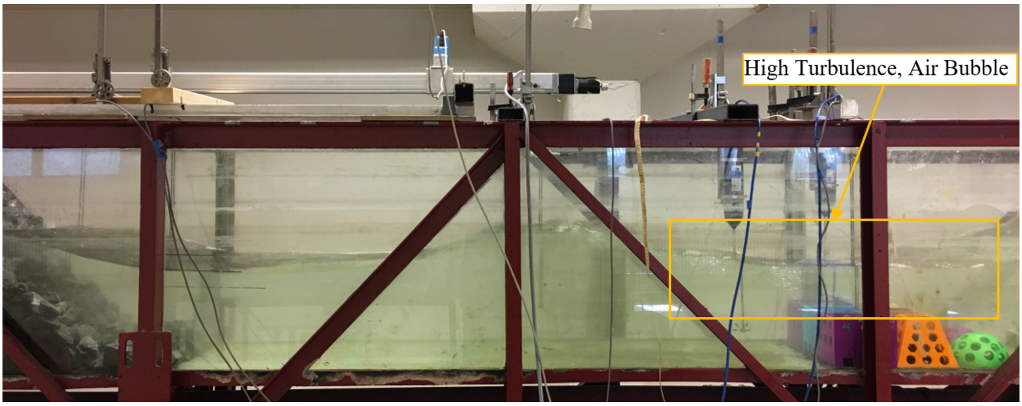
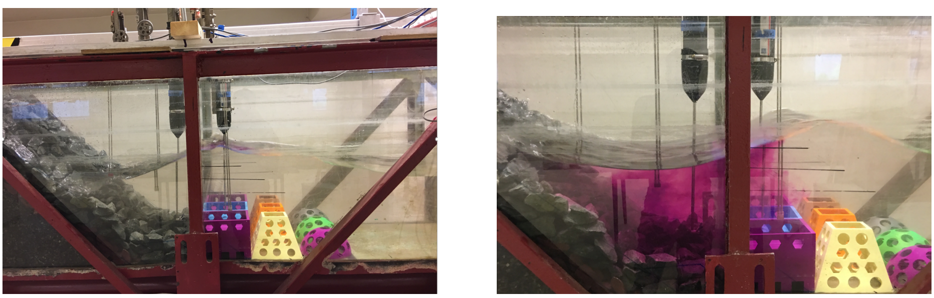


Figure 6.10: High Turbulence Regions on and around AR in Config-4

From the velocity and damage discussions, it is evident that configuration3 and 4 are more efficient, and configuration 2 show almost similar behaviour as of TBW. On major difference between these configurations is the reef length, which seems to play major role in energy dissipation. AR length characterizes the residence time of wave on reef. Increased residence time enhanced the water circulation which are mainly driven by wave breaking. Strength of these circulations increase almost linearly with the increase in offshore wave height and it depends weakly on wave period and bottom drag coefficient (Lowe and Falter, 2015). Apart from its role in breaking, generated circulations contribute towards the improvement of ecology around the AR structure. For most of the wave conditions it was observed for configuration 3 that wave peaks start to crumble or break at the seaward last unit of AR and a very high circulations were examined with the help of dye dispersion (see Figure 6.11). However, for configuration 2 with less residence time, peaking/shoaling/breaking of most of the wave were observed after the AR unit (Figure 6.12). Figure 6.13 shows a comparison for this effect of wave residence and AR length in terms of energy dissipation and it is observed that **a 15m wide AR can reduce upto 45% of the incoming wave energy**.



(a) Shoaling/Breaking

(b) Circulations

Figure 6.11: Wave Shoaling/Breaking with Circulations

(a) Configuration 2 (AR4) **(b)** Configuration 2 (AR1)

Figure 6.12: Wave Shoaling/Breaking for Configuration 2

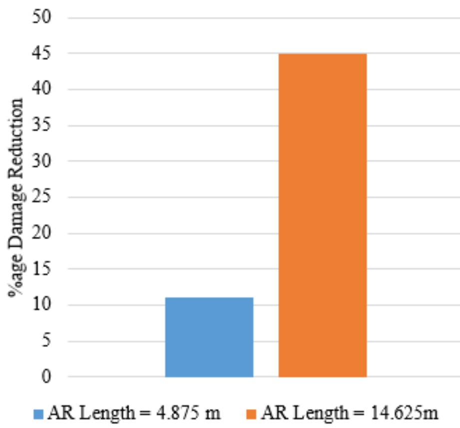


Figure 6.13: Effect of AR Length on Damage

Another important aspect for the wave reduction is the porosity of AR units. Table 6.1 indicates the porosity values of AR units and different configuration as a ratio of area of holes to the total area of AR. In order to link these values with the reduction in wave energy, Figure 6.14 is plotted which indicates that even if some AR have similar porosity their effectiveness can vary. Porosity individually can not suggest anything about the damage reduction, however if combined with length and location information of AR then it can give some promising results. Different results for same porosity has been observed for different locations of AR units (offshore or at toe).

Table 6.1: Porosity Values for AR units

Artificial Reef Type	Porosity (%age)
AR1	42
AR2	64
AR3	53
AR4	28
Config-2 (AR1)	42
Config-2 (AR4)	28
Config-3	44
Config-4	44

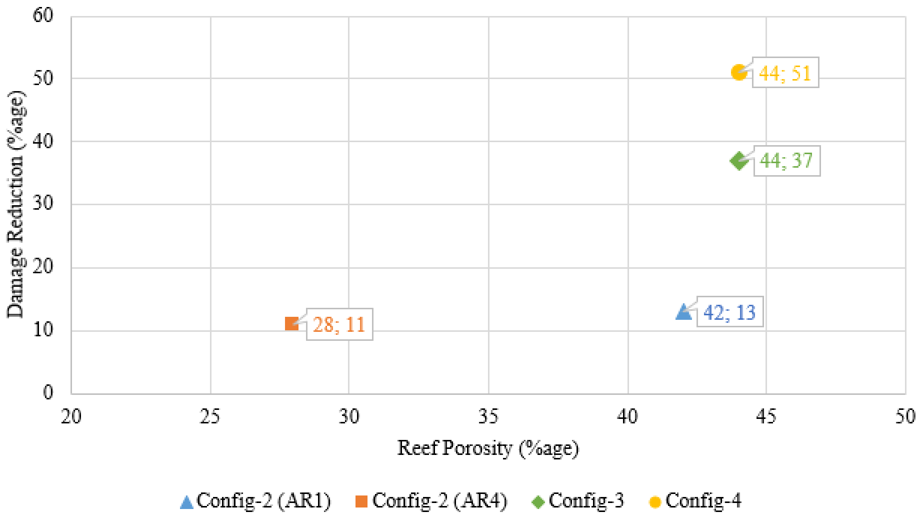


Figure 6.14: Effect of AR Porosity on Damage

6.1 Cost Benefit Analysis

Bio-Economic Effects of AR

Along with the structural performance enhancement advantages, Fabi et al. (2011) concluded that AR cost less than other structural alternatives. The authors made a comparison of AR projects and found that cost of building a breakwater is 15 times more than AR deployment or reef restoration. Apart from this, economic evaluation of AR also included socio-economic impact and efficiency. Whitmarsh et al. (2008) concluded that in Portugal, revenue from fishing at AR sites is 1.7 times higher than the control sites. In Japan, two sites indicated a 4% per 1000m^3 increase in octopus catch. A wide range of benthic organisms are found to be attracted to AR sites and it is verified by various studies. However, Osenberg et al. (2002) suggested that fish recruitment, aggregation and diversity on AR are strongly linked with physical attributes of reef structures, such as AR size, complexity, depth, sedimentation load, water circulation, predation and competition etc. Ecological improvement is highly dependent of the location and it is most probably not the same a two location at different altitudes.

Ecological Performance

Target species considered in this study are RKC and Capelin. An average length of both of these species ranges from 25cm to 30cm. Based on the criteria of Katopodis (1992) an approach to measure suitable velocities for these species is indicated in section 2.9.2. Using the approach, suitable velocities for these species turn out to be in the range of 0.13 m/s to 0.14 m/s for these species. However, velocities observed for most of the wave conditions when scaled up indicate higher values than these due to the increased turbulence probably. This indicates a non suitability for these species. As the indicator species are selected based on a general study it would be advantages to conduct a thorough ecological study and based on that select the target species, which can be different than this result. On the other hand, a more robust techniques for the quantification of ecology may also improve the results.

An ecological community development prediction model by MScience (2015) is presented in Figure 6.15. The model predicts marine community growth on AR with the passage of time. It is evident from the model that even after 10 years of construction, 25% of the AR will be inhabited by different marine species. It may not be the targeted species of this study, but despite that it shows ecological improvement with the passage of time.

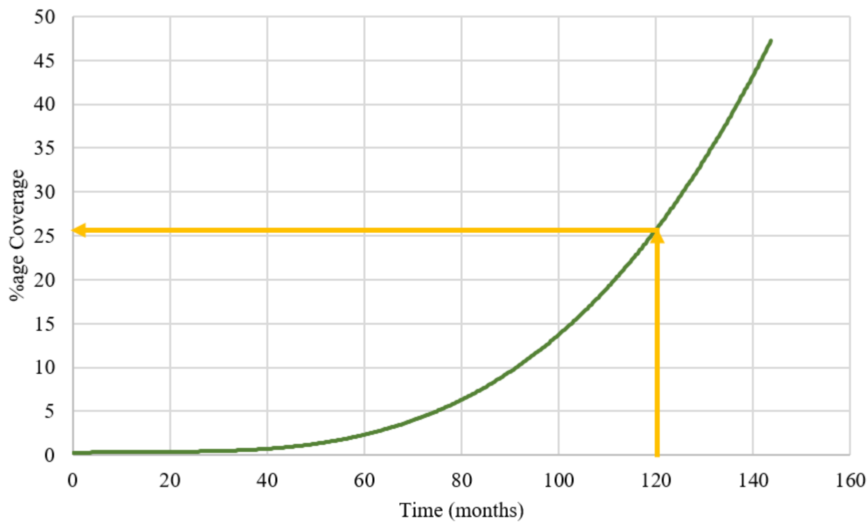


Figure 6.15: Prediction of Community Growth on Artificial Reef (MScience, 2015)

7
Conclusions and Recommendations

The chapter contains conclusions derived from the results of physical model study and their analysis along with the recommendation for future work.

7.1 Conclusions

Conclusion from the study including the answers to the research sub-questions, main research question and related findings are mentioned below;

- Like offshore LCS breakwaters, AR are also effective as green-grey hybrid structures. They are found to reduce the wave energy but with some modified mechanisms than LCS. When AR placed as the toe elements, vortex development and shredding on the landward side of the reef are believed to reduce because of the depth limited situation. This results into lower turbulence in the wake of the AR as compared to the offshore situation.

- **Configuration 1**; is traditional breakwater. The results of damage are compared with the theoretical values calculated from Van der Meer formulas for plunging and surging waves. Measured and theoretical results showed an almost similar behaviour. However, measured values depicted slightly higher damage for surging waves.

- **Configuration 2**; Damage values obtained for different sub-configurations of config-2 are compared with config-1 and results are described below;

  - **One row of AR1** This configuration has shown on average 12% reduction in wave energy. However, TKE inside and outside the reef units are observed to be almost similar, and the values does not vary much from TKE at TBW. This behaviour can be attributed to the more open type of the structure (porosity = 43%). Lower damage than theoretical values is observed for plunging and surging waves at high wave heights.

  - **One row of AR2** This configuration has shown the lowest damage reduction with a value of 7%. On the initial test of the configuration, it was dropped due to the lower reduction value as compared to other units. Therefore, it was not utilized in study after initial tests.
  - **One row of AR3**, 9% damage reduction was observed for this configuration. This was the second lowest reduction value among all the units therefore it was also dropped from the study due to time limitations.
  - **One row of AR4**, Among all the sub-configurations of config-2, AR4 showed the highest damage reduction, this is mainly due to the lower porosity (28%). Due to less flow passing situation, turbulence in the wake of the units is measured to be higher than inside the units. Behavior of plunging and surging waves corresponds very well with theoretically determined values on the lower wave heights. But, for higher wave heights, this configuration shows wave dissipation by predicting lower damage.

- **Configuration 3** show a average damage reduction upto 38%. Waves are observed to break on the AR units which make the turbulence and circulation in the AR units higher than in the wake of AR structure. Plunging and surging waves behave very closely to the theoretical values from formulas but only for relatively lower wave heights. For higher wave heights as clear reduction in energy is observed for both type of waves.

- **Configuration 4**, This is the configuration with the most damage reduction (average 51%, but maximum measured is 63%). Turbulence measured in the wake of the structure is higher than inside AR units, which is probably due to a properly developed landward vortex and breaker tongue. Behaviour of plunging and surging waves vary significantly from theoretical values with measured results being lower than the theoretical values.

- From the behaviour of plunging and surging waves on all configurations, it is observed that Van der Meer stability formulas can predict quite good results for lower wave height on green-grey hybrid structures. However, for higher wave heights the formulas does not remain valid probably due to increased nonlinear behaviour of waves on the AR units and increased energy reduction.

- Configuration 4 clearly is the configuration with the highest wave reduction but results indicate that turbulence in the wake of AR in config-4 is higher than the turbulence in the wake of config-3. This suggests higher scour protection measures for config-4. Therefore, config-3 may be a suitable economic option in certain situations.

- Another factor contributing towards the reduced energy is the reflection from hybrid structure. It is observed that for all wave conditions, reflection coefficient of green-grey hybrid structure (config-3) varies from 0.4 to 0.8 , which is much higher than the normal rubble mound breakwater values calculated from Van der Meer formula (0.2-0.58).

- LCS AR breakwater (config-4) shows highest reflection coefficients (0.4 - 1.1). At higher iribarren numbers reflection vales exceeding 1 are noted, which does not seem appropriate. However, increase reflection is attributed to the secondary waves generated landward from the LCS structure along with the seaward reflected waves from AR. The constructive interference of these secondary waves with incoming waves can lead to higher reflection coefficients.
- AR length is observed to be effective in wave reduction. With a AR of 15m a reduction of 45% wave energy is observed.
- Porosity of the structure is observed to be a less effective parameter when AR are placed in more than one rows. A signal row with 42% reef porosity is not as effective in damage reduction as a row of 3 AR units with 44% porosity combined (damage reduction 11% and 37% respectively). Location of the AR units and unit placement act enhance the energy dissipation.
- Based on Katopodis (1992) analyses, an approach to evaluate the ecological performance of the AR was developed. By this approach, velocities measured for most of the wave conditions does not satisfy the suitable velocity criteria for indicator species. However, various studies show enhanced ecology for AR sites globally.

Based on all these conclusions, main research question is answered as:

Artificial Reefs can be a technically viable and ecologically feasible option for short-term climate change adaption of existing structures.

7.2 Recommendations

- It is believed that the seaward edge of AR experiences more turbulence due to return flow generation and seaward vortex formation. In this study no measurements were taken on the seaward side turbulence. It would be interesting to know the turbulence in the seaward side to assess the situation of scour to the structure.
- Stability of AR units itself was not evaluated in this research. Units were fixed to the bottom of the flume with the help of a plate and it was done due to the lower density of 3D printed material PA2200. A study should be conducted with some reasonably heavier material depicting the actual weight of AR in order to assess the complete stability of green-grey hybrid structure.
- Rugosity is one the main properties of AR which help enhance the friction and hence drag forces on the AR units. This further contribute in the reduction of wave energy. AR units used in this study were printed through a technique (FDM) which generates rougher surface, however a study on the quantification of the enhanced drag forces due to the rougher surface can give a more proper idea about the hydrodynamics around AR units.

- More experiments may be conducted on AR2 and AR3, in order to evaluate their comprehensive behaviour.

- Configurations based on mixed designed units of AR units are generally recommended (like config-3 or config-4). However, in order to check their impact configurations with similar AR units and more than one rows can be tested.

- A detailed ecological study may be conducted in the study area for a proper choice of indicator spices and a suitable approach to quantify the ecological parameters should be looked for.

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Appendices

Appendix A
Climate Change Projections

An overview of current climate change impacts and their projections is presented in Table 1.

Table 1: Global Climate Change Projections (USAID, 2009)

Climate Impact	Observations	Projected Trends
Sea Level Rise	1. For the 20th century, sea level rise rose at a rate of 1.7 to 1.8mm/year 2. In the last decade, the worldwide average rate was measured to be 3.0 mm/yr. 3. Coastal erosion is increasingly observed around the world; it can be related to either sea level rise or subsidence, or both.	a) Sea levels are expected to rise by at least 0.6 meters by the centurys end; glacial melt is expected to increase this rise. b) Coastal flooding could grow tenfold or more by the 2080s, affecting more than 100 million people per year due to SLR, especially in Southeast Asia c) It is projected that seawater intrusion due to SLR could severely affect aquaculture in heavily populated mega-deltas, such as in Southeast Asia d) A one-meter rise in sea level could inundate 17% of Bangladesh and completely flood the Republic of Maldives, reduce Bangladeshs rice farming land by half and affect millions of livelihoods e) A 2C increase in temperature could result in the loss of a number of island states
Sea Surface Temperature Change	1. Between 1970 and 2004, sea surface temperatures around the planet rose between 0.2-1.0C, with a mean increase of 0.6C 2. The Caribbean Sea has warmed by 1.5C in the last 100 years 3. Observations since 1961 show that the ocean has been absorbing more than 80% of the heat added to the climate system 4. Changes in water temperature caused wide scale coral bleaching in the Asia region, damaging as much as 75-100% of coral in the Philippines in 1998	a) By 2100, temperatures are projected to rise in the tropical Atlantic (2-4C), Pacific (1.5-3.5C) and Indian (3C) Oceans b) Increases in sea surface temperature of about 1-3Care projected to result in more frequent coral bleaching events and widespread mortality. c) Studies project that with a 1C increase in sea surface temperatures, all coral reefs in the Great Barrier Reef, Southeast Asia and the Caribbean could be bleached

Table 1 continued from previous page

Ocean Acidification	Since 1750, an average decrease in pH of 0.1 units has been observed	It is projected that the pH of the worlds oceans could fall by up to a further 0.3 0.4 units by 2100, resulting in the lowest ocean pH levels in 20 million years
Increased Frequency of Extreme Weather Events	1. Increases in category 4 and 5 tropical cyclones, hurricanes and typhoons during the 20th century have been reported 2. Tropical cyclone activity has increased since 1970, with a trend towards longer lived storms and storms of greater intensity. 3. Mass mortality of mangrove species in the Caribbean has been attributed to the increased frequencies of hurricanes in the region 4. El Nio events have become more frequent, persistent and intense during the last 20 years compared to the previous 100	a) Models project a likely increase of peak wind intensities and increased mean and peak near-storm precipitation in future tropical cyclones b) The population exposed to flooding by storm surges will increase over the 21st century, especially in South, Southeast and East Asia
Precipitation Change	1. Precipitation has increased by up to 10% in the Northern Hemisphere and decreased in other regions (e.g., North and West Africa, parts of the Mediterranean and the Caribbean) 2. The frequency and severity of drought has increased in some regions, such as parts of Asia and Africa. 3. Very dry areas have more than doubled since the 1970s 4. Australia incurred over US$13 billion in drought damage between 1982-2003	a) Projections for Latin America show a general year round drop in seasonal precipitation of up to 60% with the greatest effects felt in Mexico and Central America b) Precipitation change is very likely to increase the frequency of flash floods and large-area floods in many regions c) In Tarawa, Kiribati, it is projected that drought damages could to reach 18% of the gross domestic product by 2050

Appendix B
Gradation Curve

Due to the non-availability of the sieve set which can separate a portion of stone as large as D_{N50}=4.5cm from the quarry run, the stones are measured individually with the help of a weighing gauge. From the sorted stones, a gradation curve was developed which was further adjusted as per Rosin-Rammier criterion by adding stones to represent NUL and NLL of 70% and 10% passing respectively. Table 2 represents the final table after adjustments.

Table 2: Gradation Curve Calculation

Weight (gm)	Diameter (cm)	%age Retained	Cumm. Weight (gm)	%Cumm. Retained	%Passing
567.160	5.982	0.198	567.160	0.198	99.802
526.770	5.836	0.184	1093.930	0.381	99.619
521.530	5.817	0.182	1615.460	0.563	99.437
492.330	5.706	0.172	2107.790	0.734	99.266
485.950	5.681	0.169	2593.740	0.904	99.096
485.740	5.680	0.169	3079.480	1.073	98.927
475.770	5.641	0.166	3555.250	1.239	98.761
471.940	5.626	0.164	4027.190	1.403	98.597
466.360	5.604	0.163	4493.550	1.566	98.434
466.270	5.604	0.162	4959.820	1.728	98.272
466.170	5.603	0.162	5425.990	1.891	98.109
465.160	5.599	0.162	5891.150	2.053	97.947
460.080	5.579	0.160	6351.230	2.213	97.787
454.480	5.556	0.158	6805.710	2.371	97.629
432.190	5.464	0.151	7237.900	2.522	97.478
430.300	5.456	0.150	7668.200	2.672	97.328
429.790	5.453	0.150	8097.990	2.822	97.178
426.960	5.441	0.149	8524.950	2.971	97.029
426.630	5.440	0.149	8951.580	3.119	96.881
426.090	5.438	0.148	9377.670	3.268	96.732
423.510	5.427	0.148	9801.180	3.415	96.585
423.190	5.425	0.147	10224.370	3.563	96.437
422.150	5.421	0.147	10646.520	3.710	96.290
420.080	5.412	0.146	11066.600	3.856	96.144
419.180	5.408	0.146	11485.780	4.002	95.998
413.990	5.386	0.144	11899.770	4.147	95.853
412.180	5.378	0.144	12311.950	4.290	95.710
409.580	5.367	0.143	12721.530	4.433	95.567
408.440	5.362	0.142	13129.970	4.575	95.425
408.170	5.360	0.142	13538.140	4.717	95.283

Table 2 continued from previous page

Weight (gm)	Diameter (cm)	%age Retained	Cumm. Weight (gm)	%Cumm. Retained	%Passing
406.990	5.355	0.142	13945.130	4.859	95.141
403.940	5.342	0.141	14349.070	5.000	95.000
401.170	5.330	0.140	14750.240	5.140	94.860
399.970	5.324	0.139	15150.210	5.279	94.721
398.740	5.319	0.139	15548.950	5.418	94.582
395.010	5.302	0.138	15943.960	5.556	94.444
394.960	5.302	0.138	16338.920	5.693	94.307
393.120	5.294	0.137	16732.040	5.830	94.170
392.690	5.292	0.137	17124.730	5.967	94.033
392.190	5.290	0.137	17516.920	6.104	93.896
392.060	5.289	0.137	17908.980	6.240	93.760
391.910	5.288	0.137	18300.890	6.377	93.623
391.700	5.287	0.136	18692.590	6.514	93.486
389.040	5.275	0.136	19081.630	6.649	93.351
386.690	5.265	0.135	19468.320	6.784	93.216
384.380	5.254	0.134	19852.700	6.918	93.082
381.400	5.241	0.133	20234.100	7.051	92.949
380.420	5.236	0.133	20614.520	7.183	92.817
378.290	5.226	0.132	20992.810	7.315	92.685
377.170	5.221	0.131	21369.980	7.446	92.554
376.080	5.216	0.131	21746.060	7.578	92.422
374.810	5.210	0.131	22120.870	7.708	92.292
374.360	5.208	0.130	22495.230	7.839	92.161
374.300	5.208	0.130	22869.530	7.969	92.031
373.680	5.205	0.130	23243.210	8.099	91.901
371.900	5.197	0.130	23615.110	8.229	91.771
362.390	5.152	0.126	23977.500	8.355	91.645
361.150	5.146	0.126	24338.650	8.481	91.519
360.810	5.145	0.126	24699.460	8.607	91.393
360.210	5.142	0.126	25059.670	8.732	91.268
359.880	5.140	0.125	25419.550	8.858	91.142
358.880	5.135	0.125	25778.430	8.983	91.017
358.410	5.133	0.125	26136.840	9.108	90.892
355.430	5.119	0.124	26492.270	9.231	90.769
355.210	5.118	0.124	26847.480	9.355	90.645
355.130	5.117	0.124	27202.610	9.479	90.521
354.930	5.116	0.124	27557.540	9.603	90.397
354.460	5.114	0.124	27912.000	9.726	90.274
354.130	5.113	0.123	28266.130	9.849	90.151
349.330	5.089	0.122	28615.460	9.971	90.029
346.550	5.076	0.121	28962.010	10.092	89.908

Table 2 continued from previous page

Weight (gm)	Diameter (cm)	%age Retained	Cumm. Weight (gm)	%Cumm. Retained	%Passing
346.390	5.075	0.121	29308.400	10.213	89.787
345.770	5.072	0.120	29654.170	10.333	89.667
344.880	5.068	0.120	29999.050	10.453	89.547
344.210	5.064	0.120	30343.260	10.573	89.427
342.770	5.057	0.119	30686.030	10.693	89.307
342.710	5.057	0.119	31028.740	10.812	89.188
341.620	5.052	0.119	31370.360	10.931	89.069
341.360	5.050	0.119	31711.720	11.050	88.950
340.570	5.046	0.119	32052.290	11.169	88.831
340.350	5.045	0.119	32392.640	11.287	88.713
338.800	5.038	0.118	32731.440	11.405	88.595
338.400	5.036	0.118	33069.840	11.523	88.477
338.390	5.036	0.118	33408.230	11.641	88.359
338.130	5.034	0.118	33746.360	11.759	88.241
336.860	5.028	0.117	34083.220	11.876	88.124
335.510	5.021	0.117	34418.730	11.993	88.007
335.360	5.021	0.117	34754.090	12.110	87.890
332.400	5.006	0.116	35086.490	12.226	87.774
331.560	5.002	0.116	35418.050	12.342	87.658
331.330	5.000	0.115	35749.380	12.457	87.543
330.150	4.994	0.115	36079.530	12.572	87.428
330.110	4.994	0.115	36409.640	12.687	87.313
327.800	4.983	0.114	36737.440	12.801	87.199
326.950	4.978	0.114	37064.390	12.915	87.085
325.500	4.971	0.113	37389.890	13.029	86.971
324.730	4.967	0.113	37714.620	13.142	86.858
322.870	4.957	0.113	38037.490	13.254	86.746
322.660	4.956	0.112	38360.150	13.367	86.633
322.390	4.955	0.112	38682.540	13.479	86.521
322.300	4.955	0.112	39004.840	13.591	86.409
322.130	4.954	0.112	39326.970	13.704	86.296
322.080	4.953	0.112	39649.050	13.816	86.184
320.710	4.946	0.112	39969.760	13.928	86.072
320.590	4.946	0.112	40290.350	14.039	85.961
317.810	4.931	0.111	40608.160	14.150	85.850
317.570	4.930	0.111	40925.730	14.261	85.739
317.120	4.928	0.111	41242.850	14.371	85.629
316.860	4.927	0.110	41559.710	14.482	85.518
316.590	4.925	0.110	41876.300	14.592	85.408
316.310	4.924	0.110	42192.610	14.702	85.298
315.820	4.921	0.110	42508.430	14.812	85.188

Table 2 continued from previous page

Weight (gm)	Diameter (cm)	%age Retained	Cumm. Weight (gm)	%Cumm. Retained	%Passing
315.420	4.919	0.110	42823.850	14.922	85.078
315.350	4.919	0.110	43139.200	15.032	84.968
314.940	4.917	0.110	43454.140	15.142	84.858
314.640	4.915	0.110	43768.780	15.251	84.749
314.380	4.914	0.110	44083.160	15.361	84.639
314.130	4.912	0.109	44397.290	15.470	84.530
313.490	4.909	0.109	44710.780	15.580	84.420
313.480	4.909	0.109	45024.260	15.689	84.311
313.470	4.909	0.109	45337.730	15.798	84.202
313.250	4.908	0.109	45650.980	15.907	84.093
312.870	4.906	0.109	45963.850	16.016	83.984
311.960	4.901	0.109	46275.810	16.125	83.875
311.030	4.896	0.108	46586.840	16.233	83.767
309.960	4.890	0.108	46896.800	16.341	83.659
309.440	4.888	0.108	47206.240	16.449	83.551
309.100	4.886	0.108	47515.340	16.557	83.443
308.930	4.885	0.108	47824.270	16.665	83.335
308.000	4.880	0.107	48132.270	16.772	83.228
307.390	4.877	0.107	48439.660	16.879	83.121
307.290	4.876	0.107	48746.950	16.986	83.014
307.000	4.875	0.107	49053.950	17.093	82.907
306.520	4.872	0.107	49360.470	17.200	82.800
306.230	4.871	0.107	49666.700	17.307	82.693
305.830	4.869	0.107	49972.530	17.413	82.587
305.780	4.868	0.107	50278.310	17.520	82.480
305.720	4.868	0.107	50584.030	17.626	82.374
305.650	4.868	0.107	50889.680	17.733	82.267
305.590	4.867	0.106	51195.270	17.839	82.161
305.410	4.866	0.106	51500.680	17.946	82.054
305.330	4.866	0.106	51806.010	18.052	81.948
305.230	4.865	0.106	52111.240	18.158	81.842
305.150	4.865	0.106	52416.390	18.265	81.735
303.920	4.859	0.106	52720.310	18.371	81.629
303.830	4.858	0.106	53024.140	18.477	81.523
303.780	4.858	0.106	53327.920	18.582	81.418
303.740	4.858	0.106	53631.660	18.688	81.312
303.070	4.854	0.106	53934.730	18.794	81.206
302.460	4.851	0.105	54237.190	18.899	81.101
302.270	4.850	0.105	54539.460	19.005	80.995
302.200	4.849	0.105	54841.660	19.110	80.890
302.190	4.849	0.105	55143.850	19.215	80.785

Table 2 continued from previous page

Weight (gm)	Diameter (cm)	%age Retained	Cumm. Weight (gm)	%Cumm. Retained	%Passing
302.100	4.849	0.105	55445.950	19.320	80.680
301.900	4.848	0.105	55747.850	19.426	80.574
301.330	4.845	0.105	56049.180	19.531	80.469
301.270	4.844	0.105	56350.450	19.636	80.364
300.350	4.839	0.105	56650.800	19.740	80.260
300.200	4.839	0.105	56951.000	19.845	80.155
299.610	4.835	0.104	57250.610	19.949	80.051
299.530	4.835	0.104	57550.140	20.054	79.946
299.290	4.834	0.104	57849.430	20.158	79.842
299.110	4.833	0.104	58148.540	20.262	79.738
299.070	4.833	0.104	58447.610	20.366	79.634
299.020	4.832	0.104	58746.630	20.471	79.529
298.990	4.832	0.104	59045.620	20.575	79.425
298.590	4.830	0.104	59344.210	20.679	79.321
298.370	4.829	0.104	59642.580	20.783	79.217
298.210	4.828	0.104	59940.790	20.887	79.113
298.170	4.828	0.104	60238.960	20.991	79.009
297.980	4.827	0.104	60536.940	21.094	78.906
297.870	4.826	0.104	60834.810	21.198	78.802
297.620	4.825	0.104	61132.430	21.302	78.698
297.330	4.823	0.104	61429.760	21.405	78.595
297.290	4.823	0.104	61727.050	21.509	78.491
297.280	4.823	0.104	62024.330	21.613	78.387
297.080	4.822	0.104	62321.410	21.716	78.284
296.690	4.820	0.103	62618.100	21.820	78.180
296.510	4.819	0.103	62914.610	21.923	78.077
295.850	4.815	0.103	63210.460	22.026	77.974
295.760	4.815	0.103	63506.220	22.129	77.871
295.690	4.814	0.103	63801.910	22.232	77.768
294.590	4.808	0.103	64096.500	22.335	77.665
294.400	4.807	0.103	64390.900	22.437	77.563
294.220	4.806	0.103	64685.120	22.540	77.460
294.200	4.806	0.103	64979.320	22.642	77.358
294.150	4.806	0.102	65273.470	22.745	77.255
294.150	4.806	0.102	65567.620	22.847	77.153
294.140	4.806	0.102	65861.760	22.950	77.050
293.840	4.804	0.102	66155.600	23.052	76.948
293.760	4.804	0.102	66449.360	23.155	76.845
293.660	4.803	0.102	66743.020	23.257	76.743
293.420	4.802	0.102	67036.440	23.359	76.641
293.380	4.802	0.102	67329.820	23.461	76.539

Table 2 continued from previous page

Weight (gm)	Diameter (cm)	%age Retained	Cumm. Weight (gm)	%Cumm. Retained	%Passing
293.370	4.802	0.102	67623.190	23.564	76.436
293.330	4.801	0.102	67916.520	23.666	76.334
293.230	4.801	0.102	68209.750	23.768	76.232
293.210	4.801	0.102	68502.960	23.870	76.130
292.930	4.799	0.102	68795.890	23.972	76.028
292.860	4.799	0.102	69088.750	24.074	75.926
292.690	4.798	0.102	69381.440	24.176	75.824
292.680	4.798	0.102	69674.120	24.278	75.722
292.580	4.797	0.102	69966.700	24.380	75.620
292.450	4.797	0.102	70259.150	24.482	75.518
292.070	4.795	0.102	70551.220	24.584	75.416
291.990	4.794	0.102	70843.210	24.686	75.314
291.570	4.792	0.102	71134.780	24.787	75.213
291.390	4.791	0.102	71426.170	24.889	75.111
291.280	4.790	0.101	71717.450	24.990	75.010
291.180	4.790	0.101	72008.630	25.092	74.908
291.150	4.790	0.101	72299.780	25.193	74.807
290.830	4.788	0.101	72590.610	25.295	74.705
289.610	4.781	0.101	72880.220	25.395	74.605
289.340	4.780	0.101	73169.560	25.496	74.504
288.840	4.777	0.101	73458.400	25.597	74.403
288.450	4.775	0.101	73746.850	25.697	74.303
287.960	4.772	0.100	74034.810	25.798	74.202
287.890	4.772	0.100	74322.700	25.898	74.102
287.380	4.769	0.100	74610.080	25.998	74.002
287.380	4.769	0.100	74897.460	26.098	73.902
287.050	4.767	0.100	75184.510	26.198	73.802
286.610	4.764	0.100	75471.120	26.298	73.702
285.560	4.759	0.100	75756.680	26.398	73.602
285.100	4.756	0.099	76041.780	26.497	73.503
283.970	4.750	0.099	76325.750	26.596	73.404
283.840	4.749	0.099	76609.590	26.695	73.305
283.790	4.749	0.099	76893.380	26.794	73.206
283.440	4.747	0.099	77176.820	26.893	73.107
283.240	4.746	0.099	77460.060	26.991	73.009
282.740	4.743	0.099	77742.800	27.090	72.910
282.470	4.741	0.098	78025.270	27.188	72.812
282.290	4.740	0.098	78307.560	27.287	72.713
281.700	4.737	0.098	78589.260	27.385	72.615
281.660	4.737	0.098	78870.920	27.483	72.517
281.400	4.735	0.098	79152.320	27.581	72.419

Table 2 continued from previous page

Weight (gm)	Diameter (cm)	%age Retained	Cumm. Weight (gm)	%Cumm. Retained	%Passing
281.080	4.734	0.098	79433.400	27.679	72.321
280.980	4.733	0.098	79714.380	27.777	72.223
280.800	4.732	0.098	79995.180	27.875	72.125
280.700	4.732	0.098	80275.880	27.973	72.027
279.790	4.726	0.097	80555.670	28.070	71.930
279.750	4.726	0.097	80835.420	28.167	71.833
279.530	4.725	0.097	81114.950	28.265	71.735
279.510	4.725	0.097	81394.460	28.362	71.638
279.440	4.724	0.097	81673.900	28.460	71.540
278.950	4.722	0.097	81952.850	28.557	71.443
278.900	4.721	0.097	82231.750	28.654	71.346
278.690	4.720	0.097	82510.440	28.751	71.249
278.100	4.717	0.097	82788.540	28.848	71.152
278.030	4.716	0.097	83066.570	28.945	71.055
278.000	4.716	0.097	83344.570	29.042	70.958
277.670	4.714	0.097	83622.240	29.139	70.861
277.630	4.714	0.097	83899.870	29.235	70.765
277.280	4.712	0.097	84177.150	29.332	70.668
277.020	4.711	0.097	84454.170	29.428	70.572
276.810	4.710	0.096	84730.980	29.525	70.475
276.770	4.709	0.096	85007.750	29.621	70.379
276.730	4.709	0.096	85284.480	29.718	70.282
276.510	4.708	0.096	85560.990	29.814	70.186
276.470	4.708	0.096	85837.460	29.910	70.090
276.310	4.707	0.096	86113.770	30.007	69.993
276.130	4.706	0.096	86389.900	30.103	69.897
275.790	4.704	0.096	86665.690	30.199	69.801
275.740	4.703	0.096	86941.430	30.295	69.705
275.700	4.703	0.096	87217.130	30.391	69.609
275.630	4.703	0.096	87492.760	30.487	69.513
275.490	4.702	0.096	87768.250	30.583	69.417
275.200	4.700	0.096	88043.450	30.679	69.321
275.000	4.699	0.096	88318.450	30.775	69.225
274.850	4.698	0.096	88593.300	30.871	69.129
274.700	4.698	0.096	88868.000	30.966	69.034
274.340	4.695	0.096	89142.340	31.062	68.938
274.180	4.695	0.096	89416.520	31.158	68.842
274.030	4.694	0.095	89690.550	31.253	68.747
273.960	4.693	0.095	89964.510	31.349	68.651
273.860	4.693	0.095	90238.370	31.444	68.556
273.770	4.692	0.095	90512.140	31.539	68.461

Table 2 continued from previous page

Weight (gm)	Diameter (cm)	%age Retained	Cumm. Weight (gm)	%Cumm. Retained	%Passing
273.700	4.692	0.095	90785.840	31.635	68.365
273.380	4.690	0.095	91059.220	31.730	68.270
273.340	4.690	0.095	91332.560	31.825	68.175
273.020	4.688	0.095	91605.580	31.920	68.080
272.850	4.687	0.095	91878.430	32.015	67.985
272.780	4.687	0.095	92151.210	32.111	67.889
272.660	4.686	0.095	92423.870	32.206	67.794
272.420	4.685	0.095	92696.290	32.300	67.700
272.220	4.683	0.095	92968.510	32.395	67.605
271.720	4.680	0.095	93240.230	32.490	67.510
271.690	4.680	0.095	93511.920	32.585	67.415
271.590	4.680	0.095	93783.510	32.679	67.321
271.490	4.679	0.095	94055.000	32.774	67.226
271.430	4.679	0.095	94326.430	32.868	67.132
271.120	4.677	0.094	94597.550	32.963	67.037
270.740	4.675	0.094	94868.290	33.057	66.943
269.870	4.670	0.094	95138.160	33.151	66.849
269.170	4.666	0.094	95407.330	33.245	66.755
268.980	4.665	0.094	95676.310	33.339	66.661
268.960	4.665	0.094	95945.270	33.433	66.567
268.890	4.664	0.094	96214.160	33.526	66.474
268.890	4.664	0.094	96483.050	33.620	66.380
268.830	4.664	0.094	96751.880	33.714	66.286
268.480	4.662	0.094	97020.360	33.807	66.193
267.880	4.658	0.093	97288.240	33.901	66.099
267.460	4.656	0.093	97555.700	33.994	66.006
267.130	4.654	0.093	97822.830	34.087	65.913
267.030	4.653	0.093	98089.860	34.180	65.820
266.660	4.651	0.093	98356.520	34.273	65.727
266.650	4.651	0.093	98623.170	34.366	65.634
266.530	4.651	0.093	98889.700	34.459	65.541
266.440	4.650	0.093	99156.140	34.551	65.449
266.180	4.648	0.093	99422.320	34.644	65.356
265.500	4.645	0.093	99687.820	34.737	65.263
264.510	4.639	0.092	99952.330	34.829	65.171
264.100	4.636	0.092	100216.430	34.921	65.079
263.780	4.634	0.092	100480.210	35.013	64.987
263.660	4.634	0.092	100743.870	35.105	64.895
263.470	4.633	0.092	101007.340	35.196	64.804
263.240	4.631	0.092	101270.580	35.288	64.712
263.180	4.631	0.092	101533.760	35.380	64.620

Table 2 continued from previous page

Weight (gm)	Diameter (cm)	%age Retained	Cumm. Weight (gm)	%Cumm. Retained	%Passing
263.120	4.631	0.092	101796.880	35.472	64.528
262.690	4.628	0.092	102059.570	35.563	64.437
262.620	4.628	0.092	102322.190	35.655	64.345
262.560	4.627	0.091	102584.750	35.746	64.254
262.310	4.626	0.091	102847.060	35.838	64.162
262.050	4.624	0.091	103109.110	35.929	64.071
261.490	4.621	0.091	103370.600	36.020	63.980
261.470	4.621	0.091	103632.070	36.111	63.889
261.430	4.621	0.091	103893.500	36.202	63.798
260.930	4.618	0.091	104154.430	36.293	63.707
260.660	4.616	0.091	104415.090	36.384	63.616
260.330	4.614	0.091	104675.420	36.475	63.525
260.210	4.613	0.091	104935.630	36.565	63.435
260.190	4.613	0.091	105195.820	36.656	63.344
260.100	4.613	0.091	105455.920	36.747	63.253
259.850	4.611	0.091	105715.770	36.837	63.163
259.190	4.607	0.090	105974.960	36.927	63.073
259.170	4.607	0.090	106234.130	37.018	62.982
259.110	4.607	0.090	106493.240	37.108	62.892
259.100	4.607	0.090	106752.340	37.198	62.802
258.990	4.606	0.090	107011.330	37.289	62.711
258.850	4.605	0.090	107270.180	37.379	62.621
258.840	4.605	0.090	107529.020	37.469	62.531
258.580	4.604	0.090	107787.600	37.559	62.441
258.510	4.603	0.090	108046.110	37.649	62.351
258.310	4.602	0.090	108304.420	37.739	62.261
258.250	4.602	0.090	108562.670	37.829	62.171
258.030	4.601	0.090	108820.700	37.919	62.081
257.960	4.600	0.090	109078.660	38.009	61.991
257.930	4.600	0.090	109336.590	38.099	61.901
257.600	4.598	0.090	109594.190	38.189	61.811
257.590	4.598	0.090	109851.780	38.278	61.722
257.470	4.597	0.090	110109.250	38.368	61.632
257.310	4.596	0.090	110366.560	38.458	61.542
257.180	4.595	0.090	110623.740	38.547	61.453
257.170	4.595	0.090	110880.910	38.637	61.363
257.100	4.595	0.090	111138.010	38.727	61.273
256.890	4.594	0.090	111394.900	38.816	61.184
256.830	4.593	0.089	111651.730	38.906	61.094
256.640	4.592	0.089	111908.370	38.995	61.005
256.570	4.592	0.089	112164.940	39.084	60.916

Table 2 continued from previous page

Weight (gm)	Diameter (cm)	%age Retained	Cumm. Weight (gm)	%Cumm. Retained	%Passing
256.080	4.589	0.089	112421.020	39.174	60.826
255.870	4.588	0.089	112676.890	39.263	60.737
255.810	4.587	0.089	112932.700	39.352	60.648
255.640	4.586	0.089	113188.340	39.441	60.559
255.410	4.585	0.089	113443.750	39.530	60.470
255.350	4.585	0.089	113699.100	39.619	60.381
255.290	4.584	0.089	113954.390	39.708	60.292
255.100	4.583	0.089	114209.490	39.797	60.203
254.710	4.581	0.089	114464.200	39.886	60.114
254.670	4.580	0.089	114718.870	39.974	60.026
254.550	4.580	0.089	114973.420	40.063	59.937
254.180	4.578	0.089	115227.600	40.152	59.848
253.930	4.576	0.088	115481.530	40.240	59.760
253.930	4.576	0.088	115735.460	40.329	59.671
253.770	4.575	0.088	115989.230	40.417	59.583
253.760	4.575	0.088	116242.990	40.505	59.495
253.040	4.571	0.088	116496.030	40.594	59.406
252.810	4.569	0.088	116748.840	40.682	59.318
252.450	4.567	0.088	117001.290	40.770	59.230
252.220	4.566	0.088	117253.510	40.858	59.142
252.210	4.566	0.088	117505.720	40.945	59.055
252.150	4.565	0.088	117757.870	41.033	58.967
252.140	4.565	0.088	118010.010	41.121	58.879
252.030	4.565	0.088	118262.040	41.209	58.791
252.020	4.565	0.088	118514.060	41.297	58.703
251.940	4.564	0.088	118766.000	41.385	58.615
251.690	4.563	0.088	119017.690	41.472	58.528
251.550	4.562	0.088	119269.240	41.560	58.440
251.280	4.560	0.088	119520.520	41.647	58.353
251.000	4.558	0.087	119771.520	41.735	58.265
250.980	4.558	0.087	120022.500	41.822	58.178
250.920	4.558	0.087	120273.420	41.910	58.090
250.780	4.557	0.087	120524.200	41.997	58.003
250.390	4.555	0.087	120774.590	42.084	57.916
250.240	4.554	0.087	121024.830	42.172	57.828
250.220	4.554	0.087	121275.050	42.259	57.741
250.190	4.553	0.087	121525.240	42.346	57.654
249.850	4.551	0.087	121775.090	42.433	57.567
249.580	4.550	0.087	122024.670	42.520	57.480
249.330	4.548	0.087	122274.000	42.607	57.393
249.240	4.548	0.087	122523.240	42.694	57.306

Table 2 continued from previous page

Weight (gm)	Diameter (cm)	%age Retained	Cumm. Weight (gm)	%Cumm. Retained	%Passing
249.160	4.547	0.087	122772.400	42.781	57.219
249.030	4.546	0.087	123021.430	42.867	57.133
249.020	4.546	0.087	123270.450	42.954	57.046
248.670	4.544	0.087	123519.120	43.041	56.959
248.660	4.544	0.087	123767.780	43.127	56.873
248.360	4.542	0.087	124016.140	43.214	56.786
248.320	4.542	0.087	124264.460	43.301	56.699
248.310	4.542	0.087	124512.770	43.387	56.613
248.240	4.542	0.087	124761.010	43.474	56.526
247.980	4.540	0.086	125008.990	43.560	56.440
247.800	4.539	0.086	125256.790	43.646	56.354
247.760	4.539	0.086	125504.550	43.733	56.267
247.650	4.538	0.086	125752.200	43.819	56.181
247.540	4.537	0.086	125999.740	43.905	56.095
247.520	4.537	0.086	126247.260	43.991	56.009
247.440	4.537	0.086	126494.700	44.078	55.922
247.360	4.536	0.086	126742.060	44.164	55.836
247.220	4.535	0.086	126989.280	44.250	55.750
247.210	4.535	0.086	127236.490	44.336	55.664
247.160	4.535	0.086	127483.650	44.422	55.578
247.130	4.535	0.086	127730.780	44.508	55.492
247.070	4.534	0.086	127977.850	44.594	55.406
246.790	4.533	0.086	128224.640	44.680	55.320
246.520	4.531	0.086	128471.160	44.766	55.234
246.460	4.531	0.086	128717.620	44.852	55.148
246.460	4.531	0.086	128964.080	44.938	55.062
246.330	4.530	0.086	129210.410	45.024	54.976
245.730	4.526	0.086	129456.140	45.110	54.890
245.590	4.525	0.086	129701.730	45.195	54.805
245.580	4.525	0.086	129947.310	45.281	54.719
245.570	4.525	0.086	130192.880	45.366	54.634
245.380	4.524	0.086	130438.260	45.452	54.548
244.970	4.522	0.085	130683.230	45.537	54.463
244.740	4.520	0.085	130927.970	45.622	54.378
244.690	4.520	0.085	131172.660	45.708	54.292
244.420	4.518	0.085	131417.080	45.793	54.207
244.360	4.518	0.085	131661.440	45.878	54.122
244.230	4.517	0.085	131905.670	45.963	54.037
244.110	4.516	0.085	132149.780	46.048	53.952
243.490	4.512	0.085	132393.270	46.133	53.867
243.370	4.512	0.085	132636.640	46.218	53.782

Table 2 continued from previous page

Weight (gm)	Diameter (cm)	%age Retained	Cumm. Weight (gm)	%Cumm. Retained	%Passing
243.120	4.510	0.085	132879.760	46.303	53.697
243.020	4.510	0.085	133122.780	46.387	53.613
242.920	4.509	0.085	133365.700	46.472	53.528
242.820	4.508	0.085	133608.520	46.557	53.443
242.760	4.508	0.085	133851.280	46.641	53.359
242.450	4.506	0.084	134093.730	46.726	53.274
242.180	4.504	0.084	134335.910	46.810	53.190
242.020	4.503	0.084	134577.930	46.894	53.106
241.860	4.502	0.084	134819.790	46.979	53.021
241.550	4.500	0.084	135061.340	47.063	52.937
241.400	4.499	0.084	135302.740	47.147	52.853
241.230	4.498	0.084	135543.970	47.231	52.769
241.100	4.498	0.084	135785.070	47.315	52.685
241.050	4.497	0.084	136026.120	47.399	52.601
240.870	4.496	0.084	136266.990	47.483	52.517
240.840	4.496	0.084	136507.830	47.567	52.433
240.720	4.495	0.084	136748.550	47.651	52.349
240.440	4.494	0.084	136988.990	47.734	52.266
240.260	4.492	0.084	137229.250	47.818	52.182
239.920	4.490	0.084	137469.170	47.902	52.098
239.810	4.490	0.084	137708.980	47.985	52.015
239.700	4.489	0.084	137948.680	48.069	51.931
239.590	4.488	0.083	138188.270	48.152	51.848
239.270	4.486	0.083	138427.540	48.236	51.764
239.060	4.485	0.083	138666.600	48.319	51.681
239.030	4.485	0.083	138905.630	48.402	51.598
238.950	4.484	0.083	139144.580	48.486	51.514
238.540	4.482	0.083	139383.120	48.569	51.431
238.430	4.481	0.083	139621.550	48.652	51.348
238.370	4.481	0.083	139859.920	48.735	51.265
238.210	4.480	0.083	140098.130	48.818	51.182
238.130	4.479	0.083	140336.260	48.901	51.099
237.870	4.477	0.083	140574.130	48.984	51.016
237.850	4.477	0.083	140811.980	49.067	50.933
237.710	4.476	0.083	141049.690	49.149	50.851
237.620	4.476	0.083	141287.310	49.232	50.768
237.530	4.475	0.083	141524.840	49.315	50.685
237.290	4.474	0.083	141762.130	49.398	50.602
237.040	4.472	0.083	141999.170	49.480	50.520
236.920	4.471	0.083	142236.090	49.563	50.437
236.820	4.471	0.083	142472.910	49.645	50.355

Table 2 continued from previous page

Weight (gm)	Diameter (cm)	%age Retained	Cumm. Weight (gm)	%Cumm. Retained	%Passing
236.760	4.470	0.083	142709.670	49.728	50.272
236.450	4.469	0.082	142946.120	49.810	50.190
236.310	4.468	0.082	143182.430	49.893	50.107
236.230	4.467	0.082	143418.660	49.975	50.025
236.210	4.467	0.082	143654.870	50.057	49.943
236.020	4.466	0.082	143890.890	50.139	49.861
236.000	4.466	0.082	144126.890	50.222	49.778
235.950	4.465	0.082	144362.840	50.304	49.696
235.890	4.465	0.082	144598.730	50.386	49.614
235.640	4.463	0.082	144834.370	50.468	49.532
235.360	4.462	0.082	145069.730	50.550	49.450
235.360	4.462	0.082	145305.090	50.632	49.368
235.320	4.461	0.082	145540.410	50.714	49.286
235.090	4.460	0.082	145775.500	50.796	49.204
234.510	4.456	0.082	146010.010	50.878	49.122
233.900	4.452	0.082	146243.910	50.959	49.041
233.860	4.452	0.081	146477.770	51.041	48.959
233.840	4.452	0.081	146711.610	51.122	48.878
233.700	4.451	0.081	146945.310	51.204	48.796
233.660	4.451	0.081	147178.970	51.285	48.715
233.520	4.450	0.081	147412.490	51.367	48.633
233.250	4.448	0.081	147645.740	51.448	48.552
233.180	4.448	0.081	147878.920	51.529	48.471
232.670	4.445	0.081	148111.590	51.610	48.390
232.520	4.444	0.081	148344.110	51.691	48.309
232.510	4.444	0.081	148576.620	51.772	48.228
232.340	4.442	0.081	148808.960	51.853	48.147
232.310	4.442	0.081	149041.270	51.934	48.066
232.190	4.442	0.081	149273.460	52.015	47.985
232.130	4.441	0.081	149505.590	52.096	47.904
232.040	4.441	0.081	149737.630	52.177	47.823
231.980	4.440	0.081	149969.610	52.258	47.742
231.970	4.440	0.081	150201.580	52.338	47.662
231.490	4.437	0.081	150433.070	52.419	47.581
231.470	4.437	0.081	150664.540	52.500	47.500
231.100	4.435	0.081	150895.640	52.580	47.420
230.970	4.434	0.080	151126.610	52.661	47.339
230.950	4.434	0.080	151357.560	52.741	47.259
230.870	4.433	0.080	151588.430	52.822	47.178
230.770	4.432	0.080	151819.200	52.902	47.098
230.660	4.432	0.080	152049.860	52.982	47.018

Table 2 continued from previous page

Weight (gm)	Diameter (cm)	%age Retained	Cumm. Weight (gm)	%Cumm. Retained	%Passing
230.310	4.430	0.080	152280.170	53.063	46.937
230.200	4.429	0.080	152510.370	53.143	46.857
230.010	4.428	0.080	152740.380	53.223	46.777
229.950	4.427	0.080	152970.330	53.303	46.697
229.250	4.423	0.080	153199.580	53.383	46.617
229.220	4.423	0.080	153428.800	53.463	46.537
228.810	4.420	0.080	153657.610	53.543	46.457
228.650	4.419	0.080	153886.260	53.622	46.378
228.490	4.418	0.080	154114.750	53.702	46.298
228.430	4.417	0.080	154343.180	53.782	46.218
228.180	4.416	0.080	154571.360	53.861	46.139
227.880	4.414	0.079	154799.240	53.941	46.059
227.840	4.414	0.079	155027.080	54.020	45.980
227.780	4.413	0.079	155254.860	54.099	45.901
227.700	4.413	0.079	155482.560	54.179	45.821
227.700	4.413	0.079	155710.260	54.258	45.742
227.420	4.411	0.079	155937.680	54.337	45.663
227.320	4.410	0.079	156165.000	54.416	45.584
227.190	4.409	0.079	156392.190	54.496	45.504
226.960	4.408	0.079	156619.150	54.575	45.425
226.640	4.406	0.079	156845.790	54.654	45.346
226.490	4.405	0.079	157072.280	54.733	45.267
226.410	4.404	0.079	157298.690	54.811	45.189
226.330	4.404	0.079	157525.020	54.890	45.110
226.140	4.403	0.079	157751.160	54.969	45.031
226.030	4.402	0.079	157977.190	55.048	44.952
225.950	4.401	0.079	158203.140	55.127	44.873
225.880	4.401	0.079	158429.020	55.205	44.795
225.390	4.398	0.079	158654.410	55.284	44.716
224.620	4.393	0.078	158879.030	55.362	44.638
224.600	4.393	0.078	159103.630	55.440	44.560
224.430	4.391	0.078	159328.060	55.519	44.481
224.410	4.391	0.078	159552.470	55.597	44.403
224.400	4.391	0.078	159776.870	55.675	44.325
224.270	4.390	0.078	160001.140	55.753	44.247
224.180	4.390	0.078	160225.320	55.831	44.169
224.170	4.390	0.078	160449.490	55.909	44.091
223.680	4.387	0.078	160673.170	55.987	44.013
223.620	4.386	0.078	160896.790	56.065	43.935
223.480	4.385	0.078	161120.270	56.143	43.857
223.180	4.383	0.078	161343.450	56.221	43.779

Table 2 continued from previous page

Weight (gm)	Diameter (cm)	%age Retained	Cumm. Weight (gm)	%Cumm. Retained	%Passing
223.110	4.383	0.078	161566.560	56.299	43.701
222.940	4.382	0.078	161789.500	56.376	43.624
222.880	4.381	0.078	162012.380	56.454	43.546
222.770	4.381	0.078	162235.150	56.532	43.468
222.640	4.380	0.078	162457.790	56.609	43.391
222.580	4.379	0.078	162680.370	56.687	43.313
222.470	4.379	0.078	162902.840	56.764	43.236
222.410	4.378	0.077	163125.250	56.842	43.158
222.220	4.377	0.077	163347.470	56.919	43.081
222.200	4.377	0.077	163569.670	56.997	43.003
222.010	4.376	0.077	163791.680	57.074	42.926
221.590	4.373	0.077	164013.270	57.151	42.849
221.530	4.372	0.077	164234.800	57.228	42.772
221.500	4.372	0.077	164456.300	57.306	42.694
221.380	4.372	0.077	164677.680	57.383	42.617
221.360	4.371	0.077	164899.040	57.460	42.540
221.360	4.371	0.077	165120.400	57.537	42.463
221.340	4.371	0.077	165341.740	57.614	42.386
221.160	4.370	0.077	165562.900	57.691	42.309
221.080	4.370	0.077	165783.980	57.768	42.232
221.040	4.369	0.077	166005.020	57.845	42.155
220.810	4.368	0.077	166225.830	57.922	42.078
220.630	4.367	0.077	166446.460	57.999	42.001
220.140	4.363	0.077	166666.600	58.076	41.924
220.110	4.363	0.077	166886.710	58.152	41.848
220.080	4.363	0.077	167106.790	58.229	41.771
220.070	4.363	0.077	167326.860	58.306	41.694
220.040	4.363	0.077	167546.900	58.382	41.618
220.000	4.362	0.077	167766.900	58.459	41.541
219.750	4.361	0.077	167986.650	58.536	41.464
219.570	4.360	0.077	168206.220	58.612	41.388
219.490	4.359	0.076	168425.710	58.689	41.311
219.450	4.359	0.076	168645.160	58.765	41.235
219.410	4.358	0.076	168864.570	58.842	41.158
219.380	4.358	0.076	169083.950	58.918	41.082
219.330	4.358	0.076	169303.280	58.995	41.005
219.270	4.358	0.076	169522.550	59.071	40.929
219.240	4.357	0.076	169741.790	59.147	40.853
219.220	4.357	0.076	169961.010	59.224	40.776
218.880	4.355	0.076	170179.890	59.300	40.700
218.580	4.353	0.076	170398.470	59.376	40.624

Table 2 continued from previous page

Weight (gm)	Diameter (cm)	%age Retained	Cumm. Weight (gm)	%Cumm. Retained	%Passing
218.540	4.353	0.076	170617.010	59.452	40.548
218.310	4.351	0.076	170835.320	59.528	40.472
218.220	4.351	0.076	171053.540	59.604	40.396
218.170	4.350	0.076	171271.710	59.680	40.320
218.050	4.349	0.076	171489.760	59.756	40.244
218.000	4.349	0.076	171707.760	59.832	40.168
217.500	4.346	0.076	171925.260	59.908	40.092
217.420	4.345	0.076	172142.680	59.984	40.016
217.310	4.345	0.076	172359.990	60.060	39.940
217.230	4.344	0.076	172577.220	60.135	39.865
217.100	4.343	0.076	172794.320	60.211	39.789
217.090	4.343	0.076	173011.410	60.287	39.713
217.010	4.343	0.076	173228.420	60.362	39.638
216.910	4.342	0.076	173445.330	60.438	39.562
216.520	4.339	0.075	173661.850	60.513	39.487
216.450	4.339	0.075	173878.300	60.589	39.411
216.420	4.339	0.075	174094.720	60.664	39.336
216.350	4.338	0.075	174311.070	60.740	39.260
216.330	4.338	0.075	174527.400	60.815	39.185
216.240	4.337	0.075	174743.640	60.890	39.110
216.190	4.337	0.075	174959.830	60.966	39.034
216.150	4.337	0.075	175175.980	61.041	38.959
215.900	4.335	0.075	175391.880	61.116	38.884
215.900	4.335	0.075	175607.780	61.191	38.809
215.790	4.334	0.075	175823.570	61.267	38.733
215.760	4.334	0.075	176039.330	61.342	38.658
215.590	4.333	0.075	176254.920	61.417	38.583
215.450	4.332	0.075	176470.370	61.492	38.508
215.390	4.332	0.075	176685.760	61.567	38.433
215.100	4.330	0.075	176900.860	61.642	38.358
215.050	4.329	0.075	177115.910	61.717	38.283
214.830	4.328	0.075	177330.740	61.792	38.208
214.490	4.326	0.075	177545.230	61.866	38.134
214.320	4.325	0.075	177759.550	61.941	38.059
214.260	4.324	0.075	177973.810	62.016	37.984
214.260	4.324	0.075	178188.070	62.090	37.910
214.210	4.324	0.075	178402.280	62.165	37.835
214.110	4.323	0.075	178616.390	62.240	37.760
214.090	4.323	0.075	178830.480	62.314	37.686
214.030	4.323	0.075	179044.510	62.389	37.611
213.850	4.321	0.075	179258.360	62.463	37.537

Table 2 continued from previous page

Weight (gm)	Diameter (cm)	%age Retained	Cumm. Weight (gm)	%Cumm. Retained	%Passing
213.580	4.320	0.074	179471.940	62.538	37.462
213.450	4.319	0.074	179685.390	62.612	37.388
213.260	4.317	0.074	179898.650	62.687	37.313
213.240	4.317	0.074	180111.890	62.761	37.239
212.930	4.315	0.074	180324.820	62.835	37.165
212.900	4.315	0.074	180537.720	62.909	37.091
212.750	4.314	0.074	180750.470	62.983	37.017
212.740	4.314	0.074	180963.210	63.057	36.943
212.600	4.313	0.074	181175.810	63.132	36.868
212.080	4.309	0.074	181387.890	63.205	36.795
211.990	4.309	0.074	181599.880	63.279	36.721
211.800	4.308	0.074	181811.680	63.353	36.647
211.750	4.307	0.074	182023.430	63.427	36.573
211.690	4.307	0.074	182235.120	63.501	36.499
211.590	4.306	0.074	182446.710	63.574	36.426
211.580	4.306	0.074	182658.290	63.648	36.352
211.580	4.306	0.074	182869.870	63.722	36.278
211.510	4.306	0.074	183081.380	63.796	36.204
211.370	4.305	0.074	183292.750	63.869	36.131
211.340	4.304	0.074	183504.090	63.943	36.057
211.030	4.302	0.074	183715.120	64.016	35.984
210.680	4.300	0.073	183925.800	64.090	35.910
210.570	4.299	0.073	184136.370	64.163	35.837
210.490	4.299	0.073	184346.860	64.237	35.763
210.290	4.297	0.073	184557.150	64.310	35.690
210.270	4.297	0.073	184767.420	64.383	35.617
210.140	4.296	0.073	184977.560	64.456	35.544
210.100	4.296	0.073	185187.660	64.530	35.470
210.070	4.296	0.073	185397.730	64.603	35.397
210.020	4.295	0.073	185607.750	64.676	35.324
209.880	4.294	0.073	185817.630	64.749	35.251
209.700	4.293	0.073	186027.330	64.822	35.178
209.630	4.293	0.073	186236.960	64.895	35.105
209.490	4.292	0.073	186446.450	64.968	35.032
209.140	4.289	0.073	186655.590	65.041	34.959
209.130	4.289	0.073	186864.720	65.114	34.886
209.050	4.289	0.073	187073.770	65.187	34.813
208.940	4.288	0.073	187282.710	65.260	34.740
208.880	4.288	0.073	187491.590	65.332	34.668
208.840	4.287	0.073	187700.430	65.405	34.595
208.820	4.287	0.073	187909.250	65.478	34.522

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Weight (gm)	Diameter (cm)	%age Retained	Cumm. Weight (gm)	%Cumm. Retained	%Passing
208.820	4.287	0.073	188118.070	65.551	34.449
208.740	4.287	0.073	188326.810	65.623	34.377
208.730	4.287	0.073	188535.540	65.696	34.304
208.680	4.286	0.073	188744.220	65.769	34.231
208.520	4.285	0.073	188952.740	65.841	34.159
208.360	4.284	0.073	189161.100	65.914	34.086
208.350	4.284	0.073	189369.450	65.987	34.013
208.300	4.284	0.073	189577.750	66.059	33.941
208.020	4.282	0.072	189785.770	66.132	33.868
208.020	4.282	0.072	189993.790	66.204	33.796
207.940	4.281	0.072	190201.730	66.277	33.723
207.940	4.281	0.072	190409.670	66.349	33.651
207.830	4.280	0.072	190617.500	66.422	33.578
207.830	4.280	0.072	190825.330	66.494	33.506
207.690	4.279	0.072	191033.020	66.566	33.434
207.680	4.279	0.072	191240.700	66.639	33.361
207.570	4.279	0.072	191448.270	66.711	33.289
207.530	4.278	0.072	191655.800	66.783	33.217
207.160	4.276	0.072	191862.960	66.856	33.144
207.030	4.275	0.072	192069.990	66.928	33.072
206.980	4.275	0.072	192276.970	67.000	33.000
206.970	4.275	0.072	192483.940	67.072	32.928
206.810	4.273	0.072	192690.750	67.144	32.856
206.770	4.273	0.072	192897.520	67.216	32.784
206.710	4.273	0.072	193104.230	67.288	32.712
206.340	4.270	0.072	193310.570	67.360	32.640
206.130	4.269	0.072	193516.700	67.432	32.568
206.090	4.268	0.072	193722.790	67.504	32.496
205.710	4.266	0.072	193928.500	67.575	32.425
205.590	4.265	0.072	194134.090	67.647	32.353
205.450	4.264	0.072	194339.540	67.719	32.281
205.360	4.263	0.072	194544.900	67.790	32.210
205.200	4.262	0.072	194750.100	67.862	32.138
205.050	4.261	0.071	194955.150	67.933	32.067
204.980	4.261	0.071	195160.130	68.004	31.996
204.870	4.260	0.071	195365.000	68.076	31.924
204.660	4.259	0.071	195569.660	68.147	31.853
204.500	4.257	0.071	195774.160	68.218	31.782
204.400	4.257	0.071	195978.560	68.290	31.710
204.360	4.256	0.071	196182.920	68.361	31.639
204.270	4.256	0.071	196387.190	68.432	31.568

Table 2 continued from previous page

Weight (gm)	Diameter (cm)	%age Retained	Cumm. Weight (gm)	%Cumm. Retained	%Passing
204.230	4.256	0.071	196591.420	68.503	31.497
204.130	4.255	0.071	196795.550	68.574	31.426
203.780	4.252	0.071	196999.330	68.645	31.355
203.740	4.252	0.071	197203.070	68.716	31.284
203.360	4.250	0.071	197406.430	68.787	31.213
203.270	4.249	0.071	197609.700	68.858	31.142
203.180	4.248	0.071	197812.880	68.929	31.071
203.120	4.248	0.071	198016.000	69.000	31.000
202.940	4.247	0.071	198218.940	69.070	30.930
202.870	4.246	0.071	198421.810	69.141	30.859
202.870	4.246	0.071	198624.680	69.212	30.788
202.760	4.245	0.071	198827.440	69.282	30.718
202.290	4.242	0.070	199029.730	69.353	30.647
202.210	4.241	0.070	199231.940	69.423	30.577
202.150	4.241	0.070	199434.090	69.494	30.506
201.940	4.240	0.070	199636.030	69.564	30.436
201.750	4.238	0.070	199837.780	69.634	30.366
201.560	4.237	0.070	200039.340	69.705	30.295
201.500	4.237	0.070	200240.840	69.775	30.225
201.500	4.237	0.070	200442.340	69.845	30.155
201.410	4.236	0.070	200643.750	69.915	30.085
201.370	4.236	0.070	200845.120	69.985	30.015
201.350	4.235	0.070	201046.470	70.056	29.944
201.280	4.235	0.070	201247.750	70.126	29.874
201.280	4.235	0.070	201449.030	70.196	29.804
201.230	4.235	0.070	201650.260	70.266	29.734
201.160	4.234	0.070	201851.420	70.336	29.664
201.000	4.233	0.070	202052.420	70.406	29.594
201.000	4.233	0.070	202253.420	70.476	29.524
200.970	4.233	0.070	202454.390	70.546	29.454
200.950	4.233	0.070	202655.340	70.616	29.384
200.870	4.232	0.070	202856.210	70.686	29.314
200.340	4.228	0.070	203056.550	70.756	29.244
200.200	4.227	0.070	203256.750	70.826	29.174
199.960	4.226	0.070	203456.710	70.895	29.105
199.900	4.225	0.070	203656.610	70.965	29.035
199.780	4.224	0.070	203856.390	71.035	28.965
199.740	4.224	0.070	204056.130	71.104	28.896
199.730	4.224	0.070	204255.860	71.174	28.826
199.710	4.224	0.070	204455.570	71.243	28.757
199.460	4.222	0.070	204655.030	71.313	28.687

Table 2 continued from previous page

Weight (gm)	Diameter (cm)	%age Retained	Cumm. Weight (gm)	%Cumm. Retained	%Passing
199.430	4.222	0.069	204854.460	71.382	28.618
199.340	4.221	0.069	205053.800	71.452	28.548
199.300	4.221	0.069	205253.100	71.521	28.479
199.120	4.220	0.069	205452.220	71.591	28.409
198.910	4.218	0.069	205651.130	71.660	28.340
198.890	4.218	0.069	205850.020	71.729	28.271
198.880	4.218	0.069	206048.900	71.799	28.201
198.750	4.217	0.069	206247.650	71.868	28.132
198.670	4.217	0.069	206446.320	71.937	28.063
198.570	4.216	0.069	206644.890	72.006	27.994
198.540	4.216	0.069	206843.430	72.076	27.924
198.520	4.216	0.069	207041.950	72.145	27.855
198.490	4.215	0.069	207240.440	72.214	27.786
198.250	4.214	0.069	207438.690	72.283	27.717
198.170	4.213	0.069	207636.860	72.352	27.648
198.160	4.213	0.069	207835.020	72.421	27.579
198.130	4.213	0.069	208033.150	72.490	27.510
197.900	4.211	0.069	208231.050	72.559	27.441
197.840	4.211	0.069	208428.890	72.628	27.372
197.800	4.210	0.069	208626.690	72.697	27.303
197.750	4.210	0.069	208824.440	72.766	27.234
197.670	4.210	0.069	209022.110	72.835	27.165
197.580	4.209	0.069	209219.690	72.904	27.096
197.500	4.208	0.069	209417.190	72.972	27.028
197.260	4.207	0.069	209614.450	73.041	26.959
197.250	4.207	0.069	209811.700	73.110	26.890
197.210	4.206	0.069	210008.910	73.179	26.821
197.190	4.206	0.069	210206.100	73.247	26.753
197.030	4.205	0.069	210403.130	73.316	26.684
196.980	4.205	0.069	210600.110	73.385	26.615
196.870	4.204	0.069	210796.980	73.453	26.547
196.760	4.203	0.069	210993.740	73.522	26.478
196.680	4.202	0.069	211190.420	73.590	26.410
196.560	4.202	0.068	211386.980	73.659	26.341
196.360	4.200	0.068	211583.340	73.727	26.273
196.270	4.200	0.068	211779.610	73.796	26.204
196.010	4.198	0.068	211975.620	73.864	26.136
195.840	4.196	0.068	212171.460	73.932	26.068
195.690	4.195	0.068	212367.150	74.000	26.000
195.680	4.195	0.068	212562.830	74.069	25.931
195.620	4.195	0.068	212758.450	74.137	25.863

Table 2 continued from previous page

Weight (gm)	Diameter (cm)	%age Retained	Cumm. Weight (gm)	%Cumm. Retained	%Passing
195.340	4.193	0.068	212953.790	74.205	25.795
195.320	4.193	0.068	213149.110	74.273	25.727
195.130	4.191	0.068	213344.240	74.341	25.659
195.110	4.191	0.068	213539.350	74.409	25.591
195.040	4.191	0.068	213734.390	74.477	25.523
194.870	4.190	0.068	213929.260	74.545	25.455
194.750	4.189	0.068	214124.010	74.613	25.387
194.560	4.187	0.068	214318.570	74.680	25.320
194.460	4.187	0.068	214513.030	74.748	25.252
194.390	4.186	0.068	214707.420	74.816	25.184
194.100	4.184	0.068	214901.520	74.883	25.117
194.040	4.184	0.068	215095.560	74.951	25.049
193.900	4.183	0.068	215289.460	75.019	24.981
193.890	4.183	0.068	215483.350	75.086	24.914
193.800	4.182	0.068	215677.150	75.154	24.846
193.800	4.182	0.068	215870.950	75.221	24.779
193.750	4.181	0.068	216064.700	75.289	24.711
193.340	4.179	0.067	216258.040	75.356	24.644
193.210	4.178	0.067	216451.250	75.423	24.577
193.170	4.177	0.067	216644.420	75.491	24.509
193.160	4.177	0.067	216837.580	75.558	24.442
193.110	4.177	0.067	217030.690	75.625	24.375
192.850	4.175	0.067	217223.540	75.693	24.307
192.840	4.175	0.067	217416.380	75.760	24.240
192.720	4.174	0.067	217609.100	75.827	24.173
192.690	4.174	0.067	217801.790	75.894	24.106
192.650	4.174	0.067	217994.440	75.961	24.039
192.560	4.173	0.067	218187.000	76.028	23.972
192.320	4.171	0.067	218379.320	76.095	23.905
192.190	4.170	0.067	218571.510	76.162	23.838
192.190	4.170	0.067	218763.700	76.229	23.771
192.160	4.170	0.067	218955.860	76.296	23.704
192.110	4.170	0.067	219147.970	76.363	23.637
192.110	4.170	0.067	219340.080	76.430	23.570
192.070	4.169	0.067	219532.150	76.497	23.503
192.000	4.169	0.067	219724.150	76.564	23.436
191.880	4.168	0.067	219916.030	76.631	23.369
191.870	4.168	0.067	220107.900	76.698	23.302
191.860	4.168	0.067	220299.760	76.764	23.236
191.840	4.168	0.067	220491.600	76.831	23.169
191.650	4.166	0.067	220683.250	76.898	23.102

Table 2 continued from previous page

Weight (gm)	Diameter (cm)	%age Retained	Cumm. Weight (gm)	%Cumm. Retained	%Passing
191.620	4.166	0.067	220874.870	76.965	23.035
191.610	4.166	0.067	221066.480	77.032	22.968
191.510	4.165	0.067	221257.990	77.098	22.902
191.380	4.164	0.067	221449.370	77.165	22.835
191.190	4.163	0.067	221640.560	77.232	22.768
191.070	4.162	0.067	221831.630	77.298	22.702
191.030	4.162	0.067	222022.660	77.365	22.635
190.950	4.161	0.067	222213.610	77.431	22.569
190.930	4.161	0.067	222404.540	77.498	22.502
190.880	4.161	0.067	222595.420	77.564	22.436
190.670	4.159	0.066	222786.090	77.631	22.369
190.520	4.158	0.066	222976.610	77.697	22.303
190.370	4.157	0.066	223166.980	77.764	22.236
190.160	4.156	0.066	223357.140	77.830	22.170
189.880	4.153	0.066	223547.020	77.896	22.104
189.880	4.153	0.066	223736.900	77.962	22.038
189.650	4.152	0.066	223926.550	78.028	21.972
189.530	4.151	0.066	224116.080	78.094	21.906
189.500	4.151	0.066	224305.580	78.160	21.840
189.050	4.147	0.066	224494.630	78.226	21.774
189.050	4.147	0.066	224683.680	78.292	21.708
188.880	4.146	0.066	224872.560	78.358	21.642
188.860	4.146	0.066	225061.420	78.424	21.576
188.550	4.144	0.066	225249.970	78.489	21.511
188.400	4.143	0.066	225438.370	78.555	21.445
188.370	4.142	0.066	225626.740	78.621	21.379
188.340	4.142	0.066	225815.080	78.686	21.314
188.190	4.141	0.066	226003.270	78.752	21.248
188.180	4.141	0.066	226191.450	78.817	21.183
188.090	4.140	0.066	226379.540	78.883	21.117
188.070	4.140	0.066	226567.610	78.949	21.051
187.970	4.139	0.065	226755.580	79.014	20.986
187.840	4.139	0.065	226943.420	79.079	20.921
187.830	4.138	0.065	227131.250	79.145	20.855
187.640	4.137	0.065	227318.890	79.210	20.790
187.570	4.137	0.065	227506.460	79.276	20.724
187.510	4.136	0.065	227693.970	79.341	20.659
187.360	4.135	0.065	227881.330	79.406	20.594
187.180	4.134	0.065	228068.510	79.472	20.528
187.140	4.133	0.065	228255.650	79.537	20.463
187.050	4.133	0.065	228442.700	79.602	20.398

Table 2 continued from previous page

Weight (gm)	Diameter (cm)	%age Retained	Cumm. Weight (gm)	%Cumm. Retained	%Passing
187.040	4.133	0.065	228629.740	79.667	20.333
187.020	4.133	0.065	228816.760	79.732	20.268
187.000	4.132	0.065	229003.760	79.797	20.203
186.750	4.131	0.065	229190.510	79.863	20.137
186.620	4.130	0.065	229377.130	79.928	20.072
186.410	4.128	0.065	229563.540	79.992	20.008
186.370	4.128	0.065	229749.910	80.057	19.943
186.120	4.126	0.065	229936.030	80.122	19.878
186.090	4.126	0.065	230122.120	80.187	19.813
186.010	4.125	0.065	230308.130	80.252	19.748
185.950	4.125	0.065	230494.080	80.317	19.683
185.830	4.124	0.065	230679.910	80.381	19.619
185.800	4.124	0.065	230865.710	80.446	19.554
185.790	4.123	0.065	231051.500	80.511	19.489
185.760	4.123	0.065	231237.260	80.576	19.424
185.720	4.123	0.065	231422.980	80.640	19.360
185.690	4.123	0.065	231608.670	80.705	19.295
185.270	4.120	0.065	231793.940	80.770	19.230
185.160	4.119	0.065	231979.100	80.834	19.166
185.050	4.118	0.064	232164.150	80.899	19.101
185.040	4.118	0.064	232349.190	80.963	19.037
184.840	4.116	0.064	232534.030	81.028	18.972
184.720	4.116	0.064	232718.750	81.092	18.908
184.670	4.115	0.064	232903.420	81.156	18.844
184.590	4.115	0.064	233088.010	81.221	18.779
184.500	4.114	0.064	233272.510	81.285	18.715
184.490	4.114	0.064	233457.000	81.349	18.651
184.450	4.113	0.064	233641.450	81.413	18.587
184.450	4.113	0.064	233825.900	81.478	18.522
184.310	4.112	0.064	234010.210	81.542	18.458
184.290	4.112	0.064	234194.500	81.606	18.394
184.280	4.112	0.064	234378.780	81.670	18.330
184.250	4.112	0.064	234563.030	81.735	18.265
184.220	4.112	0.064	234747.250	81.799	18.201
184.020	4.110	0.064	234931.270	81.863	18.137
183.910	4.109	0.064	235115.180	81.927	18.073
183.810	4.109	0.064	235298.990	81.991	18.009
183.710	4.108	0.064	235482.700	82.055	17.945
183.540	4.107	0.064	235666.240	82.119	17.881
183.270	4.105	0.064	235849.510	82.183	17.817
183.200	4.104	0.064	236032.710	82.247	17.753

Table 2 continued from previous page

Weight (gm)	Diameter (cm)	%age Retained	Cumm. Weight (gm)	%Cumm. Retained	%Passing
182.950	4.102	0.064	236215.660	82.310	17.690
182.930	4.102	0.064	236398.590	82.374	17.626
182.820	4.101	0.064	236581.410	82.438	17.562
182.360	4.098	0.064	236763.770	82.501	17.499
182.300	4.097	0.064	236946.070	82.565	17.435
182.200	4.097	0.063	237128.270	82.628	17.372
181.970	4.095	0.063	237310.240	82.692	17.308
181.810	4.094	0.063	237492.050	82.755	17.245
181.810	4.094	0.063	237673.860	82.819	17.181
181.480	4.091	0.063	237855.340	82.882	17.118
181.410	4.091	0.063	238036.750	82.945	17.055
181.350	4.090	0.063	238218.100	83.008	16.992
181.330	4.090	0.063	238399.430	83.071	16.929
181.330	4.090	0.063	238580.760	83.135	16.865
181.250	4.090	0.063	238762.010	83.198	16.802
181.110	4.089	0.063	238943.120	83.261	16.739
181.080	4.088	0.063	239124.200	83.324	16.676
180.980	4.088	0.063	239305.180	83.387	16.613
180.980	4.088	0.063	239486.160	83.450	16.550
180.880	4.087	0.063	239667.040	83.513	16.487
180.810	4.086	0.063	239847.850	83.576	16.424
180.630	4.085	0.063	240028.480	83.639	16.361
180.510	4.084	0.063	240208.990	83.702	16.298
180.430	4.083	0.063	240389.420	83.765	16.235
180.430	4.083	0.063	240569.850	83.828	16.172
180.350	4.083	0.063	240750.200	83.891	16.109
180.240	4.082	0.063	240930.440	83.953	16.047
180.110	4.081	0.063	241110.550	84.016	15.984
179.750	4.078	0.063	241290.300	84.079	15.921
179.670	4.078	0.063	241469.970	84.141	15.859
179.450	4.076	0.063	241649.420	84.204	15.796
179.420	4.076	0.063	241828.840	84.266	15.734
179.380	4.075	0.063	242008.220	84.329	15.671
179.370	4.075	0.063	242187.590	84.391	15.609
179.350	4.075	0.062	242366.940	84.454	15.546
179.330	4.075	0.062	242546.270	84.516	15.484
179.280	4.075	0.062	242725.550	84.579	15.421
179.270	4.075	0.062	242904.820	84.641	15.359
179.270	4.075	0.062	243084.090	84.704	15.296
179.110	4.073	0.062	243263.200	84.766	15.234
178.870	4.072	0.062	243442.070	84.829	15.171

Table 2 continued from previous page

Weight (gm)	Diameter (cm)	%age Retained	Cumm. Weight (gm)	%Cumm. Retained	%Passing
178.790	4.071	0.062	243620.860	84.891	15.109
178.720	4.070	0.062	243799.580	84.953	15.047
178.530	4.069	0.062	243978.110	85.015	14.985
178.500	4.069	0.062	244156.610	85.078	14.922
178.260	4.067	0.062	244334.870	85.140	14.860
178.170	4.066	0.062	244513.040	85.202	14.798
178.160	4.066	0.062	244691.200	85.264	14.736
178.120	4.066	0.062	244869.320	85.326	14.674
178.000	4.065	0.062	245047.320	85.388	14.612
177.990	4.065	0.062	245225.310	85.450	14.550
177.970	4.065	0.062	245403.280	85.512	14.488
177.840	4.064	0.062	245581.120	85.574	14.426
177.810	4.064	0.062	245758.930	85.636	14.364
177.730	4.063	0.062	245936.660	85.698	14.302
177.480	4.061	0.062	246114.140	85.760	14.240
177.350	4.060	0.062	246291.490	85.821	14.179
177.210	4.059	0.062	246468.700	85.883	14.117
177.140	4.058	0.062	246645.840	85.945	14.055
176.950	4.057	0.062	246822.790	86.007	13.993
176.850	4.056	0.062	246999.640	86.068	13.932
176.760	4.056	0.062	247176.400	86.130	13.870
176.690	4.055	0.062	247353.090	86.191	13.809
176.660	4.055	0.062	247529.750	86.253	13.747
176.480	4.053	0.061	247706.230	86.314	13.686
176.440	4.053	0.061	247882.670	86.376	13.624
176.420	4.053	0.061	248059.090	86.437	13.563
176.250	4.052	0.061	248235.340	86.499	13.501

Appendix C
Data Processing

Raw Data

Tables 3 and 4 present raw wave gauge and ADV data for only half minute run of one of the tests. Similar data series for 30minutes are collected from 175 physical model tests. Those time series are further processed to get wave heights and velocity values which are used in the analysis.

Table 3: Raw Wave gauge Data from Wave Synthesizer

Time	WG1	WG2	WG3	WG4	WG5	WG6	WG7
0	0.0788096	0.0781605	0.0418094	0.0294759	0.0710201	0.0262303	-0.071788
0.025	0.0768623	0.0911431	0.0411602	0.0275285	0.0677745	0.0294759	-0.0685424
0.05	0.0677745	0.0963361	0.0372655	0.0294759	0.0677745	0.0353181	-0.0581563
0.075	0.0658271	0.095687	0.039862	0.0255812	0.0638797	0.0379146	-0.0549107
0.1	0.0528445	0.0995817	0.0411602	0.0255812	0.0586867	0.0418094	-0.0516651
0.125	0.0483006	0.109319	0.045055	0.0320724	0.0547919	0.0424585	-0.0477703
0.15	0.0366163	0.10802	0.050248	0.0320724	0.0515463	0.0392128	-0.0386825
0.175	0.0275285	0.10867	0.0560902	0.0314233	0.0541428	0.039862	-0.0302438
0.2	0.024932	0.0995817	0.0619323	0.0359672	0.050248	0.0418094	-0.0224543
0.225	0.0132477	0.0976344	0.0658271	0.0359672	0.0495989	0.045055	-0.0179104
0.25	0.0171425	0.0898448	0.0729675	0.0359672	0.050248	0.039862	-0.0140156
0.275	0.0119495	0.0781605	0.0781605	0.0385637	0.0495989	0.0418094	-0.00947175
0.3	0.0151951	0.070371	0.0859501	0.045055	0.0534937	0.045055	0.00156342
0.325	0.0119495	0.0645288	0.0898448	0.0508971	0.0444059	0.0385637	0.00351081
0.35	0.0184407	0.0508971	0.0917922	0.055441	0.0508971	0.0333707	0.00221255
0.375	0.0242829	0.0411602	0.0963361	0.0612832	0.0528445	0.0307742	-0.00298047
0.4	0.0216864	0.0353181	0.0982835	0.0632306	0.0483006	0.0268794	0.00286168
0.425	0.0392128	0.0314233	0.095687	0.070371	0.0457041	0.0268794	0.00156342
0.45	0.0333707	0.0184407	0.0937396	0.0697219	0.0405111	0.0275285	0.00156342
0.475	0.0463533	0.0184407	0.0891957	0.0729675	0.0340198	0.0242829	0.00740557
0.5	0.0515463	0.0203881	0.0937396	0.0697219	0.0294759	0.0210373	-0.00882262

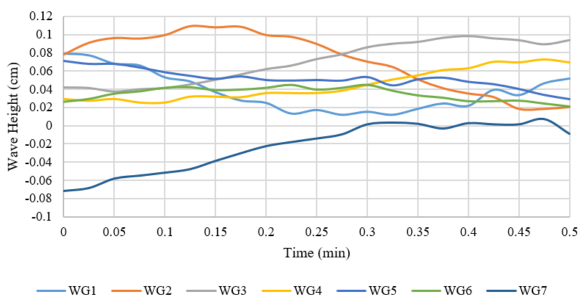


Figure 1: Raw Wave Height Plot from Data in Table 3

Table 4: Raw ADV Data from Wave Synthesizer

ime	ADV1x	ADV1y	ADV1z	ADV2x	ADV2y	ADV2z	ADV3x	ADV3y	ADV3z
0	0.0533749	0.0650592	0.0884278	0.0572696	0.0475327	0.0533749	0.105954	0.113744	0.0533749
0.025	0.0572696	0.0670066	0.0903752	0.0572696	0.0397432	0.0786909	0.0923225	0.113744	0.033901
0.05	0.0572696	0.0670066	0.0903752	0.0494801	0.0455853	0.0611644	0.0962173	0.109849	0.0553222
0.075	0.0514275	0.0689539	0.0884278	0.0553222	0.0533749	0.059217	0.0942699	0.105954	0.0514275
0.1	0.0670066	0.0670066	0.0903752	0.059217	0.059217	0.059217	0.0962173	0.105954	0.0611644
0.125	0.0747961	0.0650592	0.0864804	0.0397432	0.0416906	0.0553222	0.107902	0.109849	0.0514275
0.15	0.0572696	0.0650592	0.0903752	0.0553222	0.0514275	0.0611644	0.0962173	0.117639	0.0514275
0.175	0.0553222	0.0786909	0.0923225	0.0631118	0.0455853	0.0631118	0.0923225	0.0786909	0.0455853
0.2	0.0494801	0.0689539	0.0962173	0.059217	0.0455853	0.033901	0.0981647	0.107902	0.0475327
0.225	0.0494801	0.0533749	0.0962173	0.0514275	0.0436379	0.0475327	0.0923225	0.100112	0.0475327
0.25	0.059217	0.0767435	0.0962173	0.0611644	0.0436379	0.0572696	0.0806382	0.0981647	0.0533749
0.275	0.0436379	0.0416906	0.0923225	0.0572696	0.033901	0.0611644	0.0903752	0.104007	0.0631118
0.3	0.059217	0.0689539	0.0981647	0.0553222	0.0436379	0.0533749	0.0884278	0.107902	0.0494801
0.325	0.0572696	0.0611644	0.0884278	0.0514275	0.0455853	0.0572696	0.0884278	0.111796	0.0436379
0.35	0.059217	0.0709013	0.0923225	0.0494801	0.0436379	0.0611644	0.0981647	0.104007	0.0494801
0.375	0.0514275	0.0611644	0.0923225	0.0455853	0.0416906	0.0514275	0.0884278	0.105954	0.059217
0.4	0.0553222	0.0709013	0.100112	0.059217	0.0436379	0.0553222	0.0884278	0.105954	0.0533749
0.425	0.0533749	0.0631118	0.0923225	0.0533749	0.0436379	0.059217	0.0806382	0.109849	0.0533749
0.45	0.0553222	0.0709013	0.0962173	0.0475327	0.0416906	0.0533749	0.0923225	0.105954	0.0533749
0.475	0.059217	0.0650592	0.084533	0.0416906	0.0455853	0.0670066	0.0962173	0.104007	0.0553222
0.5	0.0494801	0.0650592	0.0903752	0.0475327	0.0436379	0.0572696	0.0923225	0.107902	0.059217

Matlab Code for Wave Height and Velocity Processing

```
close all; clear all; clc;
%Use Breakints in lines 31, 100, 170, 220 to verify the sig-
nal spectrum before and after filtering
filename = 'T0050Nauman2.txt';
data = readtable(filename);

  WG = [6]; %from 1 to 7
ADV= [1:3]; %from 1 to 3
Time = table2array(data(:,1)); %time extraction from data file

  [numRows,  ] = size(Time);
numWG = length(WG);
numADV = length(ADV);

  %data prelocation
ADVdata = zeros(numRows,numADV*3);

  WGdata = table2array(data(:,WG + 1));
SampleStart = 300;
SampleEnd = 2500; % change this value to adjust the sample plot
size.  Its valus can go up to 72032

  %% WG data treatment
fs=10000; % this is the sampling frequency.  This parameter is
assumed and if it changes the results can also change
```

```
for WGcounter = 1 :  numWG
fc = 700; %cutoff frequency(Hz).  we suppose a hig frequency
noise
%This frequency can be altered to adjust the filtering

   %Spectrual information
SpAnWG = dsp.SpectrumAnalyzer('YLimits',[-0.5 3.5],'PowerUnits','Watts')
;
step(SpAnWG,WGdata(:,WGcounter));

   % ANALYSIS 1
% Ploting file data without filtering to eliminate noise, then
adding the envelope information % andfinally the envelope mi-
nus the envelope mean value.
figure('Color','w');
scatter(Time(SampleStart:SampleEnd),
WGdata(SampleStart:SampleEnd,WGcounter),'ok','filled')
   y,
= envelope(WGdata(:,WGcounter),34,'peak') ; %'rms','analytical'
or 'peak'
% y = hilbert(WGdata(:,WGcounter));
env = abs(y);
hold on
plot(Time(SampleStart:SampleEnd),env(SampleStart:SampleEnd),'-
b','LineWidth',2)
hold off
hold on
plot(Time(SampleStart:SampleEnd),env(SampleStart:SampleEnd) -
mean(env),'-r','LineWidth',2)
hold off
legend('Unfiltered signal','Envelope','Envelope-mean')
title(strcat('WG',num2str(WG(WGcounter))),'FontSize', 11);
xlabel('time [s]','FontSize', 11)
ylabel('wave height [m]','FontSize', 11)
set(gca,'fontname','times') % Set it to times new roman

   % ANALYSIS 2
% Piloting file data without filtering to eliminate noise, then
adding the curve fitting information %Curve fitting configu-
ration
UpperLimit = 6;
LowerLimit = -4;
ExcludedData = find(or(WGdata(SampleStart:SampleEnd,WGcounter)
>=
UpperLimit,WGdata(SampleStart:SampleEnd,WGcounter) <= Lower-
Limit));
```

```
SmothPar = 0.9999;
%------------------------------------------------------------
---------------------------------------
figure('Color','w');
curve = fit(Time(SampleStart:SampleEnd),
WGdata(SampleStart:SampleEnd,WGcounter)
,'smoothingspline','SmoothingParam',SmothPar,'Exclude', Excluded-
Data);
% curve = fit(Time(SampleStart:SampleEnd),
WGdata(SampleStart:SampleEnd,WGcounter)
,'smoothingspline','SmoothingParam',SmothPar,'Span',0.2,'Exclude',
ExcludedData);
scatter(Time(SampleStart:SampleEnd),
WGdata(SampleStart:SampleEnd,WGcounter),'ok','filled')
hold on
plot(Time(SampleStart:SampleEnd),
feval(curve,Time(SampleStart:SampleEnd)),'-b','LineWidth',2)
hold off
Times = Time(SampleStart:SampleEnd);
WGdatas = WGdata(SampleStart:SampleEnd);
hold on
plot(Times(ExcludedData),WGdatas(ExcludedData)
,'xr','LineWidth',2,'MarkerSize',10)
hold off
legend('Unfiltered signal','Fitted curve','Excluded data')
title(strcat('WG',num2str(WG(WGcounter))),'FontSize', 11);
xlabel('time [s]','FontSize', 11)
ylabel('wave height [m]','FontSize', 11)
set(gca,'fontname','times') % Set it to times new roman

% ANALYSIS 3
% Plotting fitted curve without filtering to eliminate noise,
then adding the envelope information % and finally the enve-
lope minus the envelope mean value.
figure('Color','w');
% set(gca,'fontname','times') % Set it to times new roman
plot(Time(SampleStart:SampleEnd),
feval(curve,Time(SampleStart:SampleEnd)),'-b','LineWidth',2)
  y,
= envelope(feval(curve,Time(SampleStart:SampleEnd)),34,'peak')
; %'rms','analytical' or 'peak'
% y = hilbert(feval(curve,Time(:)));
env = abs(y);
hold all
plot(Time(SampleStart:SampleEnd),env(:),'-k','LineWidth',2)
hold off
```

```
hold all
plot(Time(SampleStart:SampleEnd),env(:)  -
mean(env),'-r','LineWidth',2)
hold off
legend('Fitted curve','Envelope','Envelope-mean')
title(strcat('WG',num2str(WG(WGcounter))),'FontSize', 11);
xlabel('time [s]','FontSize', 11)
ylabel('wave height [m]','FontSize', 11)
set(gca,'fontname','times') % Set it to times new roman

   % ANALYSIS 4
% Ploting data after filtering to eliminate noise, then adding
the envelope information % andfinally the envelope minus the
envelope mean value.
figure('Color','w');
set(gca,'fontname','times') % Set it to times new roman
WGdata(:,WGcounter) = datafilter(WGdata(:,WGcounter),fc,fs);
step(SpAnWG,WGdata(:,WGcounter));
scatter(Time(SampleStart:SampleEnd),
WGdata(SampleStart:SampleEnd,WGcounter),'ok','filled')
   y,
= envelope(WGdata(:,WGcounter),34,'peak')
;%'rms','analytical' or 'peak'
% y = hilbert(WGdata(:,WGcounter));
env = abs(y);
hold on
plot(Time(SampleStart:SampleEnd),env(SampleStart:SampleEnd),'-
b','LineWidth',2)
hold off
hold on
plot(Time(SampleStart:SampleEnd),env(SampleStart:SampleEnd) -
mean(env),'-r','LineWidth',2)
hold off
legend('Denoised signal','Envelope','Envelope-mean')
title(strcat('WG',num2str(WG(WGcounter))),'FontSize', 11);
xlabel('Time [s]','FontSize', 11)
ylabel('wave height [m]','FontSize', 11)
set(gca,'fontname','times') % Set it to times new roman

   % ANALYSIS 5
% Ploting data after filtering to eliminate noise, then adding
the curve fitting information
figure('Color','w');
set(gca,'fontname','times') % Set it to times new roman
scatter(Time(SampleStart:SampleEnd),
WGdata(SampleStart:SampleEnd,WGcounter),'ok','filled')
```

```
curve = fit(Time(SampleStart:SampleEnd),
WGdata(SampleStart:SampleEnd,WGcounter),'smoothingspline');
hold on
plot(Time(SampleStart:SampleEnd),
feval(curve,Time(SampleStart:SampleEnd)),'-b','LineWidth',2)
hold off
legend('Denoised signal','Fitted curve')
title(strcat('WG',num2str(WG(WGcounter)),'.  Sample plot'),'FontSize',
11);
xlabel('time [s]','FontSize', 11)
ylabel('wave height [m]','FontSize', 11)
set(gca,'fontname','times') % Set it to times new roman

   ANALYSIS 6
% Ploting data after filtering to eliminate noise, then adding
the curve fitting information
figure('Color','w');
set(gca,'fontname','times') % Set it to times new roman
plot(Time(SampleStart:SampleEnd),
feval(curve,Time(SampleStart:SampleEnd)),'-b','LineWidth',2)
   y,
= envelope(feval(curve,Time(SampleStart:SampleEnd)),34,'peak');
%'rms','analytical' or 'peak'
% y = hilbert(feval(curve,Time(:)));
env = abs(y);
hold on
plot(Time(SampleStart:SampleEnd),env(:),'-k','LineWidth',2)
hold off
hold on
plot(Time(SampleStart:SampleEnd),env(:)  - mean(env),'-r','LineWidth',2)
hold off
legend('Fitted curve','Envelope','Envelope-mean')
title(strcat('WG',num2str(WG(WGcounter))),'FontSize', 11); xla-
bel('time [s]','FontSize', 11)
ylabel('wave height [m]','FontSize', 11)
set(gca,'fontname','times') % Set it to times new roman
end

   SpAnADV = dsp.SpectrumAnalyzer('YLimits',[-0.001 0.005],'PowerUnits',
;
for ADVcounter = 1 :  numADV
ADVidx = ADV(ADVcounter);

   % ANALYSIS 7
% Ploting file data without filtering to eliminate noise, then
adding the curve fitting information
```

```
   figure('Color','w');
for component = 1 :  3
fc = 1000; %cutoff frequency(Hz).  we suppose a hig frequency
noise
%This frequency can be altered to adjust the filtering
column = (ADVcounter-1)*3 + component;

   % To select the level at which the point are not used in the
curve fitting, the higher the % value the lesser of points are
excluded
switch ADVidx
case 1
switch component
case 1 %ADV1 x component
comp = ' x'; DiffLimit = 0.007;
case 2 %ADV1 y component
comp = ' y'; DiffLimit = 0.008;
case 3 %ADV1 z component
comp = ' z'; DiffLimit = 0.01;
end
case 2
switch component
case 1 %ADV2 x component
comp = ' x'; DiffLimit = 0.009;
case 2 %ADV2 y component
comp = ' y'; DiffLimit = 0.008;
case 3 %ADV2 z component
comp = ' z'; DiffLimit = 0.007;
end
case 3
switch component
case 1 %ADV3 x component
comp = ' x'; DiffLimit = 0.009;
case 2 %ADV3 y component
comp = ' y'; DiffLimit = 0.009;
case 3 %ADV3 z component
comp = ' z'; DiffLimit = 0.007;
end

   end
ADVdata(:,column) = table2array(data(:,column+8));

   % step(SpAnADV,ADVdata(:,column));
% Curve fitting configuration
```

```
   [U,L] = envelope(ADVdata(:,column),34,'rms') ;
%'rms','analytic' or 'peak'
Center = (U+L)/2;
TempData = abs(ADVdata(:,column) - Center);
Diff = TempData - (U-Center)*sqrt(2);
ExcludedData = find(Diff(SampleStart:SampleEnd) >= DiffLimit);
SmothPar = 1;
%-------------------------------------------------------
Times = Time(SampleStart:SampleEnd);
ADVdatas = ADVdata(SampleStart:SampleEnd,column);

   subplot(2,3,component)
scatter(Time(SampleStart:SampleEnd),
ADVdata(SampleStart:SampleEnd,column),'ok','filled')
curve = fit(Time(SampleStart:SampleEnd),
ADVdata(SampleStart:SampleEnd,column)
,'smoothingspline','SmoothingParam',SmothPar,'Exclude', Excluded-
Data);
% curve = fit(Time(SampleStart:SampleEnd),ADVdata(SampleStart:SampleEnd,
,'smoothingspline','SmoothingParam',SmothPar);
hold on
plot(Time(SampleStart:SampleEnd),
feval(curve,Time(SampleStart:SampleEnd)),'-b','LineWidth',1.5)
hold off
hold on
plot(Times(ExcludedData),ADVdatas(ExcludedData)
,'xr','LineWidth',1,'MarkerSize',10)
hold off
legend('Unfiltered signal','Fitted curve','Excluded data')
title(strcat('ADV',num2str(ADVidx),comp,', Mean value = ',
sprintf(' %2.4f',mean(feval(curve,Time(SampleStart:SampleEnd))))));
xlabel('Time [s]')
ylabel('Velocity [cm/s]')
set(gca,'fontname','times') % Set it to times new roman

   subplot(2,3,component+3)
Turbulence = feval(curve,Time(SampleStart:SampleEnd))
- mean(feval(curve,Time(SampleStart:SampleEnd)));
Te = std(Turbulence)/mean(feval(curve,Time(SampleStart:SampleEnd)));
hold on
plot(Time(SampleStart:SampleEnd),Turbulence,'-r','LineWidth',1)
hold off
legend('Turbulence')
title(strcat('ADV',num2str(ADVidx),comp,', Turbulence Inten-
```

```
sity = ', sprintf(' %2.4f',Te)));
xlabel('Time [s]')
ylabel('Turbulence [m/s]')
set(gca,'fontname','times') % Set it to times new roman
end

   % ANALYSIS 8
% Plotting data after filtering to eliminate noise, then adding
the envelope information and finally the envelope minus the en-
velope mean value.
figure('Color','w');
set(gca,'fontname','times') % Set it to times new roman
for component = 1 :  3
fc = 1000; %cutoff frequency(Hz).  we suppose a hig frequency
noise
%This frequency can be altered to adjust the filtering
switch component
case 1
comp = ' x';
case 2
comp = ' y';
case 3
comp = ' z';
end
column = (ADVcounter-1)*3 + component;

   subplot(2,3,component)
ADVdata(:,column) = datafilter(ADVdata(:,column),fc,fs);
step(SpAnADV,ADVdata(:,column));

   scatter(Time(SampleStart:SampleEnd),
ADVdata(SampleStart:SampleEnd,column),'ok','filled')
curve = fit(Time(SampleStart:SampleEnd),
ADVdata(SampleStart:SampleEnd,column),'smoothingspline');
hold on
plot(Time(SampleStart:SampleEnd),
feval(curve,Time(SampleStart:SampleEnd)),'-b','LineWidth',1)
hold off
legend('Denoised signal','Fitted curve')
title(strcat('ADV',num2str(ADVidx),comp,' component.
Mean value = ', sprintf(' %2.4f',mean(feval(curve,
Time(SampleStart:SampleEnd))))));
xlabel('Time [s]')
ylabel('Velocity [m/s]')
set(gca,'fontname','times') % Set it to times new roman
```

```
   subplot(2,3,component+3)
Turbulence = feval(curve,Time(SampleStart:SampleEnd)) -
mean(feval(curve,Time(SampleStart:SampleEnd)));
Te = std(Turbulence)/mean(feval(curve,Time(SampleStart:SampleEnd)));
hold on
plot(Time(SampleStart:SampleEnd),Turbulence,'-r','LineWidth',1)
hold off
legend('Turbulence')
title(strcat('ADV',num2str(ADVidx),comp,', Turbulence Inten-
sity = ', sprintf('%2.4f',Te)));
xlabel('Time [s]')
ylabel('Turbulence [m/s]')
set(gca,'fontname','times') % Set it to times new roman
end
end

   function [OutputData] = datafilter(InputData,fc,fs)
A = InputData;
   b,a
= butter(5,fc/(fs/2),'low');
OutputData=filtfilt(b,a,A);
end
```

Appendix D
Damage Profiles

Three values of damage to the structure are obtained for each test conditions which are further used for analysis. These values are presented below in Tables 5, 6, 7, 8 and 9 for Config-1, Config-2 (AR1), Config-2 (AR4), Config-3 and Config-4 respectively.

Table 5: Results of Damage Measurements for Configuration 1

Wave Period	Test Run 1	Test Run 2	Test Run 3
0.8	0.90	0.38	0.71
0.8	1.59	0.98	1.14
0.8	2.13	1.34	1.78
1.2	1.77	0.99	1.28
1.2	4.34	3.91	3.12
1.2	4.79	4.86	4.13
1.6	6.08	1.89	1.98
1.6	2.35	5.94	4.51
1.6	6.19	7.55	7.26
2	1.09	1.29	1.79
2	8.58	5.58	6.78
2	7.52	8.92	7.67
2.2	1.85	0.98	1.57
2.2	3.48	2.95	3.15
2.2	6.89	6.35	6.58

Table 6: Results of Damage Measurements for Configuration 2: AR1

Wave Period	Test Run 1	Test Run 2	Test Run 3
0.8	0.587	0.609	0.613
0.8	1.129	1.210	0.953
0.8	1.555	1.654	1.468
1.2	1.028	1.125	1.078
1.2	3.753	2.898	3.256
1.2	4.523	4.256	3.097
1.6	2.985	2.895	2.956
1.6	4.091	3.548	3.984
1.6	6.089	6.543	6.128
2	1.065	1.145	1.231
2	4.929	5.985	6.985
2	7.174	7.854	7.435
2.2	1.242	1.467	1.432
2.2	2.567	2.987	3.125
2.2	5.234	6.235	6.154

Table 7: Results of Damage Measurements for Configuration 2: AR4

Wave Period	Test Run 1	Test Run 2	Test Run 3
0.8	0.538	0.546	0.634
0.8	0.814	1.256	0.975
0.8	1.687	1.457	1.554
1.2	1.214	0.987	1.167
1.2	2.957	3.034	3.258
1.2	3.986	4.295	4.234
1.6	2.257	2.956	2.499
1.6	3.443	4.194	3.542
1.6	6.046	5.996	6.245
2	1.125	1.436	1.256
2	4.521	6.784	6.975
2	7.235	7.456	7.012
2.2	1.387	1.234	1.245
2.2	2.785	3.025	2.957
2.2	5.523	5.492	6.354

Table 8: Results of Damage Measurements for Configuration 3

Wave Period	Test Run 1	Test Run 2	Test Run 3
0.8	0.478	0.531	0.523
0.8	0.878	0.987	0.995
0.8	1.262	0.982	1.085
1.2	0.893	0.812	0.892
1.2	2.763	2.225	2.124
1.2	2.876	2.785	2.776
1.6	1.778	1.678	1.876
1.6	2.789	2.343	2.546
1.6	4.092	4.291	4.210
2	0.821	0.808	0.799
2	3.926	3.812	3.613
2	4.067	4.689	4.320
2.2	0.853	0.875	0.838
2.2	2.096	1.978	1.989
2.2	4.129	4.213	4.074

Table 9: Results of Damage Measurements for Configuration 4

Wave Period	Test Run 1	Test Run 2	Test Run 3
0.8	0.456	0.477	0.498
0.8	0.761	0.832	0.752
0.8	0.954	0.931	0.912
1.2	0.682	0.685	0.687
1.2	1.856	2.005	2.102
1.2	2.432	2.109	2.324
1.6	1.023	1.278	1.254
1.6	2.073	2.068	2.352
1.6	3.596	3.450	3.154
2	0.765	0.672	0.553
2	3.265	2.983	2.678
2	3.095	2.953	3.124
2.2	0.534	0.623	0.674
2.2	1.246	1.324	1.174
2.2	2.643	2.743	2.570

Appendix F
Pictures from Experimentation

(a) Core Material (D_{N50}=1.2cm)

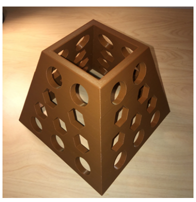
(b) Filter Material (D_{N50}=3cm)

(c) Washing of Stones

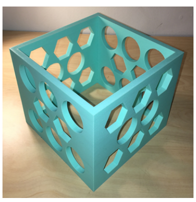
(d) Top View Filter Layer

Figure 2: Construction of Model

(a) 3D Printing

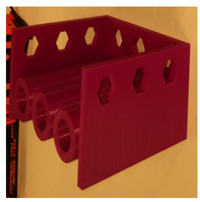


(b) AR1



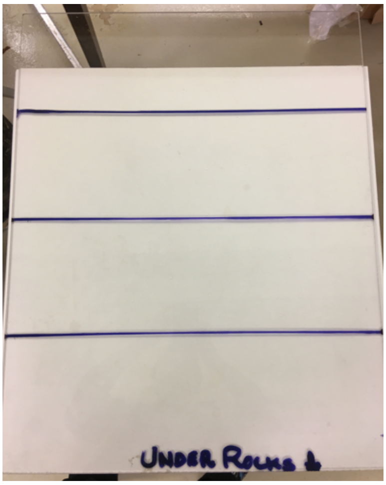
(c) AR2

(d) AR3



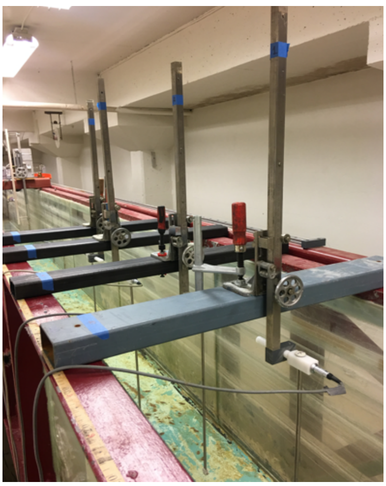
(e) AR4

Figure 3: 3D Printing of AR units

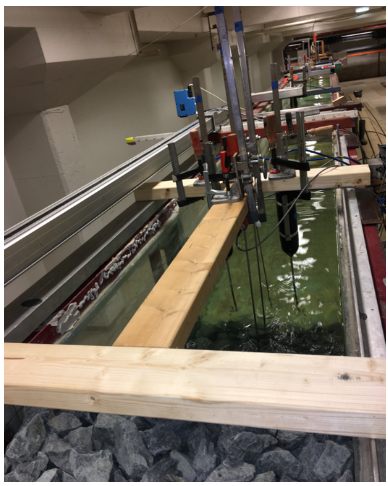


(a) Plate to Fix AR Units

(b) Config-2 (AR3)

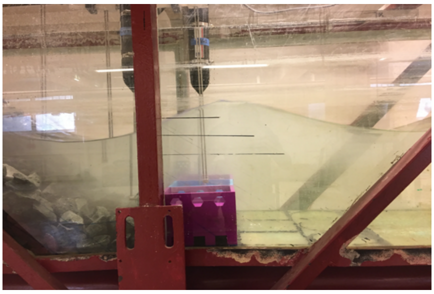


(c) 4 Wave Gauges Close to Wave Paddle

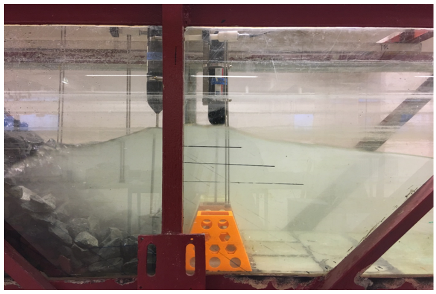


(d) Setup at Model

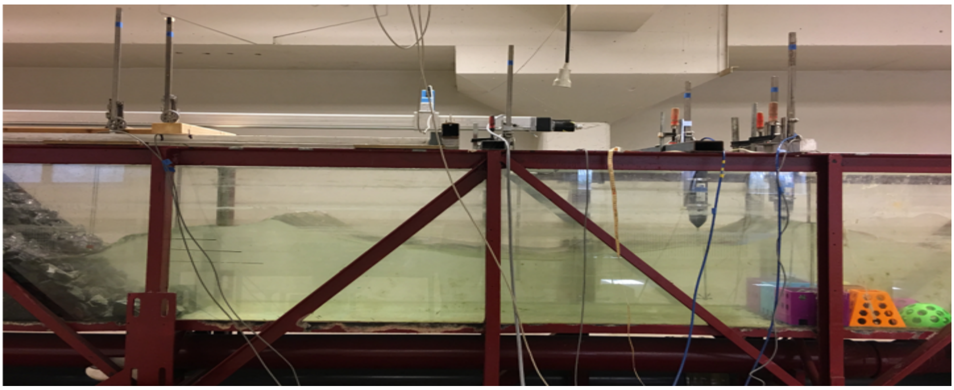
Figure 4: Experimental Setup



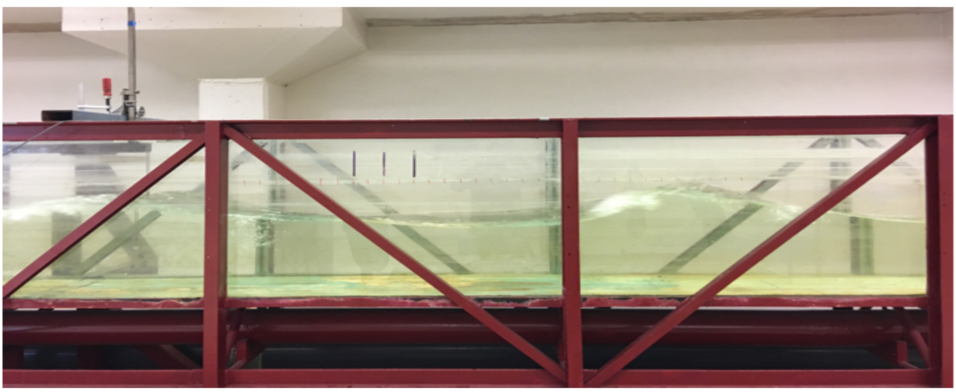
(a) Config-2 (AR4)



(b) Config-2 (AR1)



(c) Config-4



(d) Wave Reflection

Figure 5: Experiments

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Physical Model Study of Living Breakwaters

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