MINIMIZING WAVE REFLECTION IN THE ATLANTIC BASIN

Evaluation of different wave absorption methods to minimize wave reflection in Deltares' facilities

R. A. Abbasi

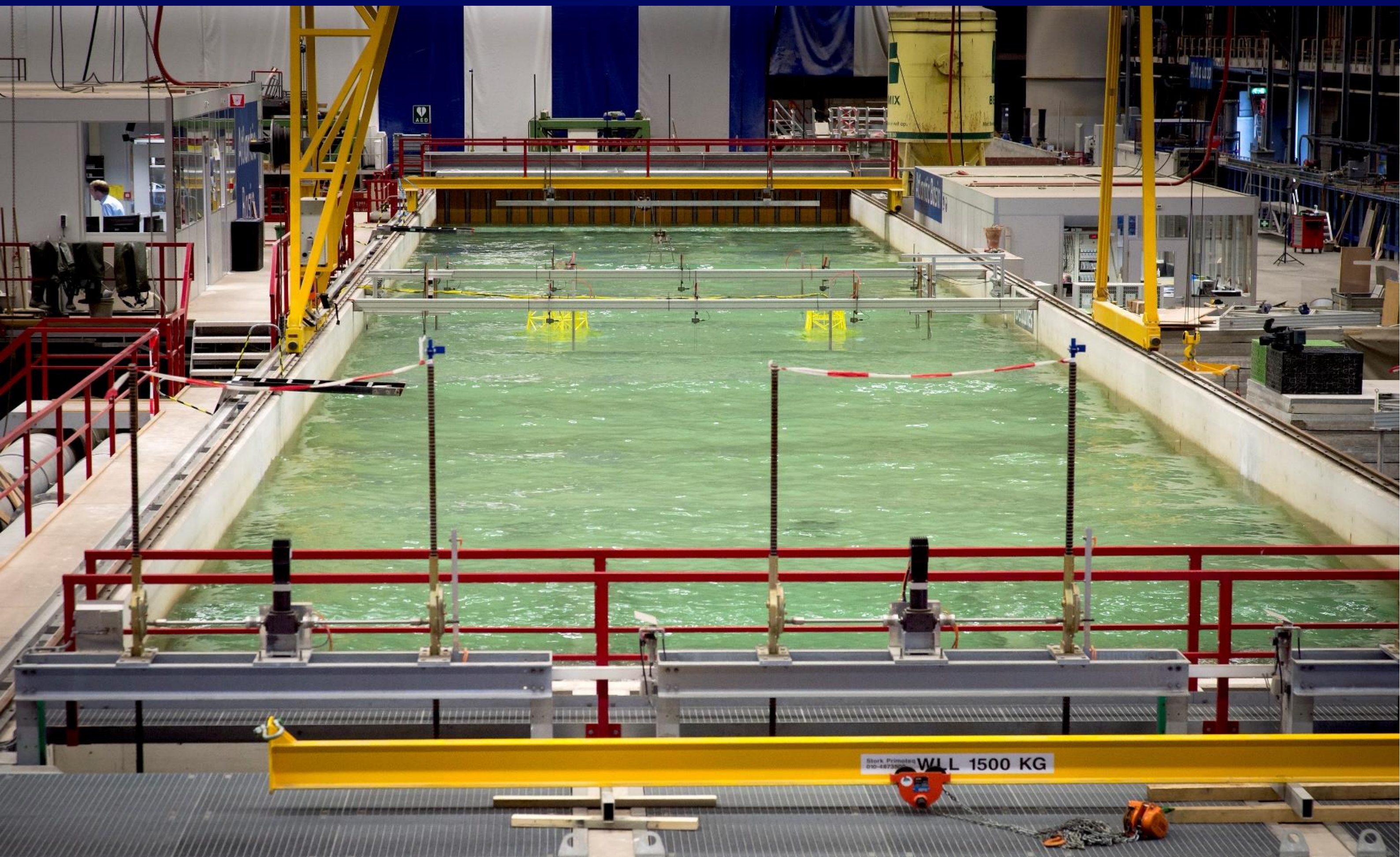

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Figure front page: The Atlantic Basin of Deltares where ocean waves are simulated.
Courtesy: Deltares Photo

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BSc Thesis

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Abstract

When waves interact with surfaces of different structures they are reflected, and these reflections are mainly caused due to less wave energy being dissipated by the surface of the structure. Naturally, rock slopes or permeable structures (mangroves forests, brushwood material, etc.) are used around the world to dissipate wave energy. Generally, wave energy in hydraulic facilities is dissipated using passive absorption methods as they are economical and efficient in reducing reflections. In hydraulic basins, that are used for replicating ocean/sea waves and conditions, ARC (Active reflection compensation) is also used, however, wave dampening beach slopes are still widely popular due to the high costs of ARC devices.

The Atlantic basin, a facility in Deltares, has a beach slope consisting of large rocks in the wave dissipation zone. To improve the wave dissipation zone's efficiency for minimizing wave reflections, certain methods consisting of several models with different configurations were investigated in a small-scale flume to find the best performing method, that improves the energy dissipation ability. Hence, the main research question reads as:

What optimizations can be made in the wave dissipation zone to enhance wave absorption and minimize wave reflection in the Atlantic Basin?

To answer this question, the current situation, geometry, and different wave energy absorption methods were examined. During the research, a few hydraulic specialists from Deltares were interviewed. In addition, the measures taken in similar hydraulic facilities around the world were investigated. Based on the gathered information, three variants were devised that would optimize wave energy dissipation by minimizing wave reflections. In the 1st variant, smaller and uniform rock sizes are used for a 1:4 rock slope. In the 2nd variant, a parabolic damper slope is used and lastly, in the 3rd variant, a 10cm layer of the permeable mattress is placed over a 1:4 rock slope.

Experiments were conducted in the 7-meter long wave flume inside the Pacific basin, located at the hydro-hall in Deltares, Delft. Various tests were concluded for two different water depths, and several different wave conditions, to analyse and examine the variants based on reflection performance. The winning variant is a decision based on an assessment using an evaluation matrix, for which the criterion are performance, cost-efficiency, and viability. With the help of these criteria, it was concluded that in given boundary conditions and limitations, variant 3 is an effective solution for enhancing wave absorption and minimizing wave reflection in the Atlantic Basin.

Possible future research could be to analyse the effect of different rock sizes on permeability and wave reflections and to examine milder slopes in a longer flume.

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1 Introduction

1.1 Deltares and hydraulic facilities

Deltares is a renowned knowledge institute for applied research in the field of water and subsurface. The organization operates worldwide on smart innovations, solutions and applications for people, the environment and society. As the management of vulnerable and densely populated areas is complex, the institute works closely with governments, companies, research institutions, universities, and NGOs in the Netherlands and abroad.

Several state-of-the-art hydraulic facilities exist at the location in Delft for research and innovations. The most famous is the Delta flume, a 300-meter-long man-made flume with a wave generator that can produce waves as tall as five meters, the world's largest artificial wave. Atlantic basin, Delta Basin, Scheldt flume and Pacific basin are some of the others, each with different configurations and performance capabilities.

Figure 1: Deltares Building, Courtesy: Fedor Baart, Feb. 2019

Figure 2: The Atlantic basin in Deltares. Courtesy: Author, 2022

1.1.1 Atlantic basin

The Atlantic Basin is one of the multifunctional facilities located in the hydraulic labs of Deltares. The total area of the basin which was built in 2009 is approximately 650 m2. The facility can simulate both waves and (tidal) currents. The wave generator is attached to one of the short sides and consists of 20 corrugated bulkhead segments that are hydraulically driven. (Deltares , 2022) As the segments can be controlled independently, it is possible to generate short-framed and oblique waves. Using a pump system, a flow can be generated that follows the wave direction or goes against it. The layout of the basin can be adapted to the specific requirements of a project.

The Atlantic Basin can be used for coastal, river, port, and offshore projects. The basin is a wide gutter in which research can be done into flow forces, discharge coefficients, specific design details, soil protection and the morphological consequences of hydraulic structures. A few research studies and projects for which the Atlantic Basin is used are the following:

- Stability of breakwaters: both middle pieces and breakwater heads
- Scour protection and forces on offshore structures
- Protection against excavation and pipeline cladding
- Stability of cribs, ground beams, ground protection, inlet, and outlet structures
- Excavation around pillars, jackets, elevations, gravity-base structures, and pipelines

1.2 Problem description

Deltares is currently investigating several improvements to its hydraulic facility, the Atlantic basin. Currently, small differences in wave height over the width of the basin are observed, partly caused by wave reflections from the rock slope at the end of the basin. For offshore structures that are regularly tested in the facilities, these wave reflections are preferably minimized to simulate realistic sea-states as reflected waves are typically not present offshore and should therefore be as small as possible on the model scale to scale down the effects. To have accuracy in the testing facilities, Deltares would therefore like to further investigate alternative solutions to improve the absorption of wave energy at the end of the basin and therewith minimize wave reflections.

1.3 Research goal

This study aims to develop and design an optimized method of wave absorption to minimize wave reflection in the wave dissipation zone of the Atlantic basin. This will be done by testing and evaluating various designs for wave energy dissipation for several wave cases in the basin.

1.4 Research question

For this bachelor thesis, the main research question that will be answered is:

What optimizations can be made in the wave dissipation zone to enhance wave absorption and minimize wave reflection in the Atlantic Basin?

Additionally, the following sub-questions have been formulated:

- What is the range of typical wave conditions that should be absorbed in the wave dissipation zone?
- What kind of methods can be used for wave dissipation?
- What designs can be made from the different methods that are promising and worthwhile to physically test to evaluate the wave reflection?
- What method can be used to measure the wave reflection?
- What recommendations can be made based on the results of the test programme for the practical design?

1.5 Research approach

The approach aims to design, and construct alternatives using wave absorption methods and test them efficiently in a small 1 m wide test section in the Pacific basin. An attempt will be made to improve the hydrodynamic performances (lower reflection and higher dissipation) using a flexible, practical, and feasible design of these methods.

A physical model test programme will be carried out with different wave conditions to assess which variant minimises the reflections in the basin the most. The results will provide a basis for understanding the variant, its limitations, and its effects on wave energy dissipation. Based on these experiments a practical design will be recommended that can be implemented in the Atlantic basin which will be based on a trade-off between performance, feasibility, and cost-efficiency.

1.6 Content of the report

A literature review is presented in form of a theoretical framework in the next chapter. It also includes literature on waves, slopes, and detection methods for wave reflection. Chapter three presents the details of the facilities, restrictions, and boundary conditions for the research. In chapter four, the methodology and approach toward the results are given.

In chapter five, variants, the test program, and model setup are explained including the translation of various hydrodynamic conditions in the experiment setup. In the next chapter, the test results are presented, and interpretation of these test results is discussed which shall provide recommendations for the final design. Chapter seven includes discussions of the research and in the final chapter of the report, the conclusion and recommendations of this research are presented.

2 Theoretical Framework

2.1 Wave generation and absorption

2.1.1 Waves in oceans/sea

Waves are generated on water surfaces under the action of wind. Therefore, the sea surface is generally covered by wind waves, these are produced locally by the wind, or else are swell waves that have come from distant storms. Waves consist of certain wave height, period, and propagation direction, which are known as wave characteristics. The wave characteristics are a function of the wind field, the fetch, and the local water depth. The wind field includes speed, duration, and direction.

The fetch is the maximum length of open water over which the wind blows, which is determined by meteorological and geographical conditions. It generally holds that the higher the wind speed and duration, the larger the wave height and period. Wave height and wave period relation can be seen in figure 3. The wind waves span a range of frequencies and wavelengths, with dominant periods typically between 1s and 10s, and they travel mainly in or close to the wind direction.

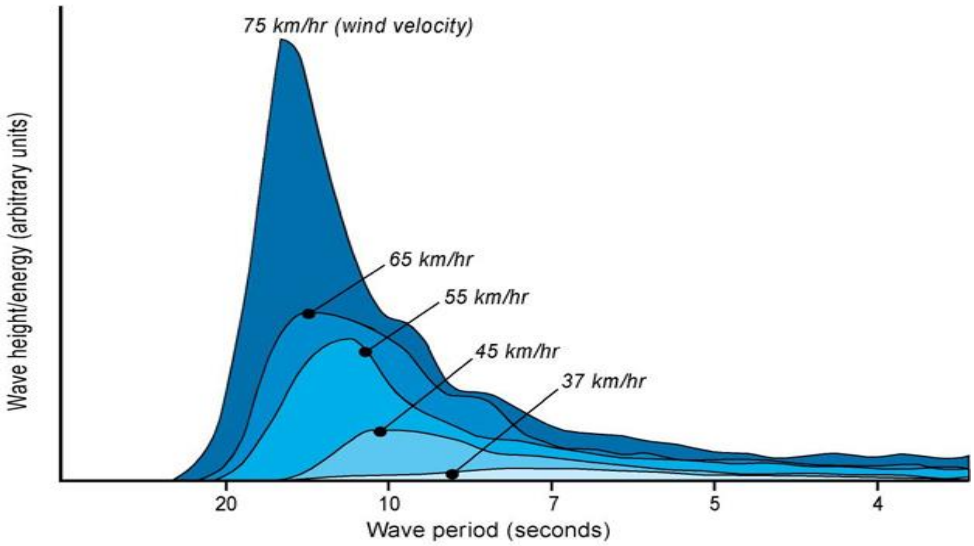

Figure 3: As wind velocity increases, the period or time between waves, and wavelength, increases, and the amount of energy transferred to the waves increases exponentially. Note how as wind velocity doubles from 37 to 75 km/hr the amount of energy increases exponentially. Very strong winds are therefore required to generate the biggest waves. Courtesy: Nature Education, 2012

Wave energy involves a balance of processes leading to the transfer of energy into and from waves, the topic involves reference to both how wind causes waves to become bigger and to accompanying processes that lead to their loss of energy or 'dissipation.' Not considering other external factors affecting this process and only considering the ones directly related to wind, such as surface wave interaction with fronts or internal waves, there are three main factors which lead to changes in the energy of the waves in each narrow frequency band. (Stive & Bosboom, 2022)

These factors are the following:

- There is a growth in wave energy through the action of wind which is related to the transfer of momentum from the air into the sea and consequently with wind stress.
- There occur certain interactions, such as waves of a particular frequency that may lose or gain energy because of nonlinear resonant interactions with other waves, and their propagation may be affected by interaction with currents.
- Wave dissipation is also an important factor. Wave dissipation occurs due to waves breaking either in deep water or as waves approach shallow water or shore. Dissipation can occur through waves' interaction with turbulence or through vicious action, the latter particularly if they are of small wavelength such as capillary waves.

Wave fields disperse (spread out) since the different harmonic components travel at different speeds that depend on their frequency, which is referred to as frequency dispersion. (Krogstad & Arntsen, 2000)

The dispersion relation for waves is given by:

$$\omega^2 = gk\tanh(kd) \qquad \text{or} \qquad L = g/2\pi\, T^2 \tanh(2\pi\, d/L)$$

From a coastal perspective, which is at a certain distance from the storm centre, one would experience long travelling waves first. At a later stage, the increasingly shorter waves appear. At long distances from the storm centre, the shorter waves are filtered out. Therefore, longer waves travel faster than shorter waves. It is mainly due to dissipation processes (due to currents, white capping) more strongly affecting the shorter waves. Therefore, only long and (fairly) regular swell waves remain. (Waves at Sea, 2021)

The distinction between sea and swell is usually made based on the average wave period, i.e. the average time taken for the passage of two successive wave crests to pass a fixed point. Sea has wave periods less than 8-10s, and swell has periods equal to that or greater. The wave period is directly related 2 to the average wavelength, which is the average distance between two successive wave crests (figure 4). Wave height is the vertical difference in elevation between the wave crest and the adjacent wave trough. (Hughes, 2016)

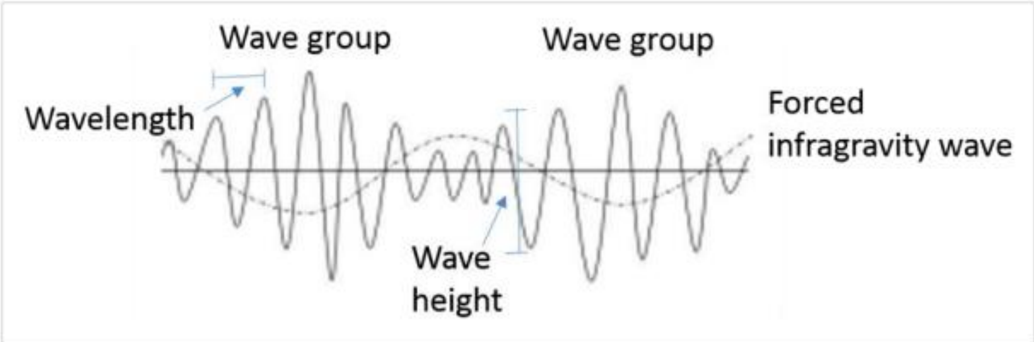

Figure 4: Wave record showing wave groups and the associated forced group-bound infra-gravity wave. Wavelength and wave height are also defined. Courtesy: *(Hughes, 2016)*

Furthermore, the swell waves are unidirectional crested because only waves travelling in a certain direction end up at a certain location away from the storm centre. The spreading due to different directions of propagation is called direction dispersion. The spectrum of swell waves is narrow in both frequency and direction due to frequency and direction dispersion respectively. The swell waves are relatively low because of spreading and energy dissipation.

Some coasts around the world experience mainly swell waves as storms are generated at a location far away, for example, the Australian coast. On other coasts, storms are generated more locally, and these wind-sea waves can dominate the wave climate. This is, for instance, the case for the Dutch coast. The waves are irregular and short crested. Most of the time, wave records of the Dutch coast show both swell waves as generated in distant storms and storm waves locally generated. (Haage, 2018)

2.1.2 Waves in hydraulic basins

There are wave basins throughout the world, almost most of them rectangular in geometry. Dr W. Froude first carried out a resistance test in still water within a rectangular towing tank due to this the rectangular configuration of the basins became popular. Gradually as the world advances and the offshore structures are being designed and built the demand for testing these offshore structures' performance has increased. This has given wave-makers a chance to become standard equipment for testing these structures in most of the world's hydraulic facilities. A tank equipped with a wave-maker at one end is called a wave-making basin, which is an excessive help for the ocean engineering research groups. To assess the economic, safety and reliability aspects of offshore structures more accurately, it is important to evaluate their performance when subjected to directional waves.

Naturally, the scope of experiments using wave-making basins has expanded over time to consider the performance of offshore structures in real-sea conditions. However as discussed earlier in the problem statement, the basin is unable to simulate accurate real-sea conditions because of the existence of reflected waves from the basin end.

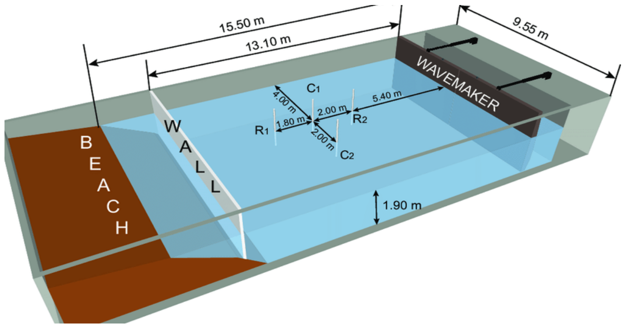

Figure 5: Example Sketch of a wave basin. The wavemaker is located. The boundary opposite to the wavemaker is either a beach or a permeable wall/structure. Courtesy: Eric Falcon

Generally, there are two main methods of wave absorption within these basins. Firstly, by creating beach slopes or maintaining permeable structures at the end of the basin, and the second one by a body with an external dynamic system (Naito S. M., 1999). Creating a beach and permeable structures are known as passive absorption methods. Whereas the external dynamic system is an active absorber, with which it is possible to absorb waves by tuning the external dynamic system over a wide range of frequencies. (Naito S. , 2006).

Deltares has developed an active reflection compensation method in their wave makers, which is discussed in a further sub section, this method dissipates the reflected wave energy well. This shows that an active solution is possible for wave reflections by placing a second wave machine at the opposite end instead of a wave dissipation beach. However, this initiative is not economical and therefore passive absorption methods are preferred.

2.1.3 Wave energy

Waves consist of two main types of total energy, potential energy (PE) and kinetic energy (KE). The potential energy of a wave is due to the displacement of the free surface from the still water level and the kinetic energy occurs due to the movement of the water particles on wave action. According to the wave theory, the two forms of wave energy are equal. The average energy contained in a wave per unit plan area is given according to this:

Total Energy: = PE + KE

= $1/16 pgh^2 + 1/16 \; pgH^2$

= $1/8 pgH^2$

In the formulas, p is the density of water. It is important to indicate that wave energy does not depend on the water depth or wavelength, however, depends only on the square of the wave height.

2.1.4 Reflection of waves

All types of waves encounter obstructions at some point, when this happens the waves are reflected from the surfaces of the obstructing objects/structures. Several characteristics such as the absorbing capability of the surface, the slope of the surface, the steepness of incident waves, etc. typically define the reflected waves. The reflection coefficient of the surface is a parameter that is defined as the ratio of the height of the reflected wave to that of the incident wave. For an idea, the reflection coefficient of a perfectly reflecting vertical surface is 1, and that of a round mound breakwater is typically 0.4 to 0.5. (W.W. Massie, 1976)

2.2 Wave-structure interaction

This section considers the theory related to the interaction of incident waves with permeable (porous) structures. It is indeed a vast subject, so therefore the focus is kept on researching the transmission of incident waves through vertical permeable structures. These are used mainly to damp incident waves parallel to the shoreline, making sure not to generate a fully reflective structure, therefore they are considered permeable structures.

The wave interaction with a structure is elaborated through the following simplified sketch, which is illustrated in figure 6. The incident, reflected, and transmitted waves are considered on both sides of the structure. As the incoming wave with wave energy Ei is approaching a permeable structure, the energy is translated into reflection, dissipation, and transmission. Within the permeable structure, the flow that was generated by wave propagation encounters resistance forces due to the added mass of discrete grains with the porous medium.

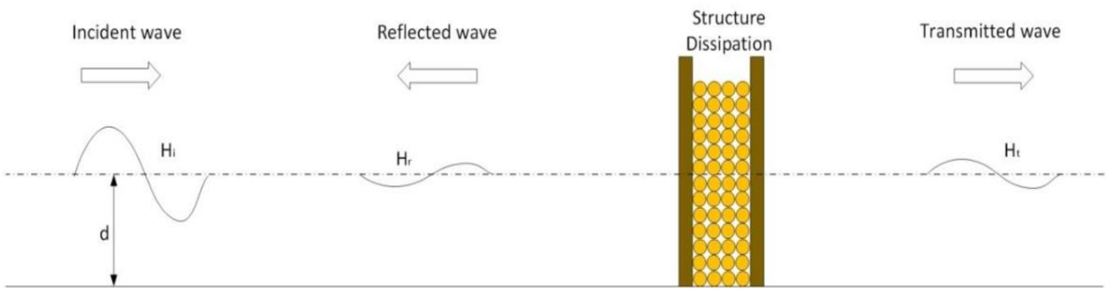

Figure 6: Simplified sketch of a theoretical model of a permeable structure. Courtesy: *(Haage, 2018)*

The wave energy balance is described as follows (Thornton & Calhoun, 1972):

$$E_i = E_r + E_{diss} + E_t$$

According to the wave linear theory, it can be determined that the wave energy is proportional to the wave height squared:

$$E = 1/8\ \rho g H^2$$

With ρ and g remaining constant, the translation from the incoming wave energy into reflection, dissipation and transmission can directly be derived from the change in wave height:

$$H_i^2 = H_r^2 + H_{diss}^2 + H_t^2$$

Now if this equation is divided by the incoming wave height and then squared, that gives us the following equation:

$$1 = (H_r/H_i)^2 + (H_{diss}/H_i)^2 + (H_t/H_i)^2$$

$$1 = C_r^2 + C_{diss}^2 + C_t^2$$

In the above equation, C_r is the reflection coefficient, C_{diss} is the dissipation coefficient and C_t is the transmission coefficient. The wave heights H_i , H_r and H_t are usually determined in experiments, from which the percentage of dissipated wave energy can be calculated using the following equation:

$$C_{\text{diss}}^2 = 1 - (H_r/H_i)^2 - (H_t/H_i)^2$$

2.3 Beach slopes

The slope of the beach face is a critical parameter for coastal scientists and engineers studying coastlines and waves' effects on them. Slopes dampen the wave energy and this way helps in reducing wave reflection, however that depends on their design and placing. Beach systems where most wave energy is dampened through the process of breaking are usually known as dissipative beaches. In 1974, Guza was the first to use the term dissipative beach and present his research on it. His study showed that the wave-energy status of a nearshore system could be studied and understood using the surf-scaling parameter. The primary cause for wave breaking in deep water is that the wave steepness exceeds the fundamental limit given for individual waves by (Allsop, Durand, & Hurdle, 1998):

$$(H/L)_{max} = 0.142$$

The main processes of interest in wave breaking within shallow water are divided into two aspects. The first processes are those of wave transformations up to, but not beyond, the point of breaking. These include refraction and diffraction, and shoaling. This process is essentially reversible and has no significant loss of energy. The second set of processes is those which occur from breaking onwards. These processes involve a significant loss of energy and are not reversible. (Allsop, Durand, & Hurdle, 1998)

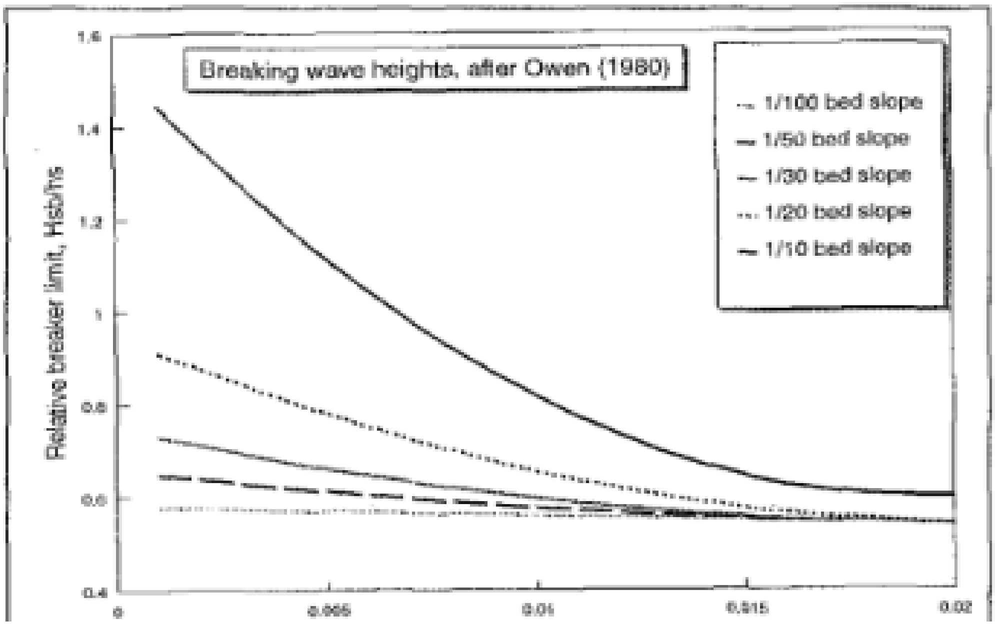

Figure 7: Simple breaking curves after Owen. Courtesy: *(Owen, 1980)*

Noting that for steep bed slopes, waves may shoal substantially before breaking starts, Owen in 1980 developed a simple method to provide first estimates of the upper limit to the (significant) wave height H_{Sb} in any water depth h_s for each five-bed slope. The method was derived as a part-way point in predicting wave overtopping of seawalls and was not itself validated against any data on breaking wave heights. Owen's simple curves were derived graphically, see figure 7, but were later described by empirical equations relating breaker index H_{st}/h_s to relative depth h_s/gT_m^2 (Owen, 1980):

Slope	Breaking limit, H_{sb}/h_s	
1/100	$H_{sb}/h_s = 0.58 - 2\ (h_s/\ gT_m^2)$	(5a)
1/50	$H_{sb}/h_s = 0.66 - 10.583\ (h_s/\ gT_m^2).\ + 229.17\ (h_s/\ gT_m^2)^2$	(5b)
1/30	$H_{sb}/h_s = 0.75 - 20.083\ (h_s/\ gT_m^2) + 479.17\ (h_s/\ gT_m^2)^2$	(5c)
1/20	$H_{sb}/h_s = 0.95 - 38.417\ (h_s/\ gT_m^2) + 895.83\ (h_s/\ gT_m^2)^2$	(5d)
1/10	$H_{sb}/h_s = 1.54 - 97.83\ (h_s/\ gT_m^2) + 2541.67\ (h_s/\ gT_m^2)^2$	(5e)

The interaction between waves and slopes is also dependent on the local wave height and period, the external structure geometry (water depth at the toe), slope with/without berm, the crest elevation etc. The type of structure wave interaction is defined by the surf similarity parameter (or breaker parameter) which is defined as:

$$\xi_{op} = \tan\alpha / \sqrt{s_{op}}$$

With:
ξ_{op} = breaker parameter
α = slope angle
s_{op} = $\dfrac{2\pi H_s}{gT_p^2}$ = wave steepness
T_p = wave period, peak period of the wave spectrum
H_s = significant wave height, being the average value of the highest 1/3 part of the wave heights. This H_s is the significant wave height at the toe of the structure.

The wave steepness is a computation quantity, especially meant to describe the influence of a wave period. This quantity is fictitious as the wave height at the location of the toe is related to the wavelength in deep water. Several wave periods can be taken from a spectrum, among them the peak period T_p, the mean period T_m (computed from the spectrum) and the significant period T1/3. Applicable here is that the ratio T_p/T_m mostly lies between 1.1 and 1.25 and that Tp and T1/3 are virtually equal. With ξ_{op2}, 2 - 2.5 the waves break on the slope. This is mostly the case with slopes of 1:3 or milder. For larger values of ξ_{op3}, the waves do not break on the slope any longer. (Pilarczyk, 1998)

In that case, the slopes are often steeper than 1:3 and/or the waves are characterized by a smaller wave steepness (for example swell). For large values of the wavelength or large values of slope angle (steep slopes), the wave behaves like a long wave, which reflects against the structure without breaking known as the surging wave. For shorter waves and medium slopes, waves will short and break, causing plunging breakers for ξ_{op4} values in the range of 1 to 2.5. This figure is common along the Dutch coast with slope angles of 1 to 3 to 1 to 5, wave periods 6 to 8s and wave heights of 3 to 5m. For mild slopes wave breaking becomes a more continuous process, resulting in a more gradual dissipation of wave energy. This type of breaking is called "spilling". (Pilarczyk, 1998).

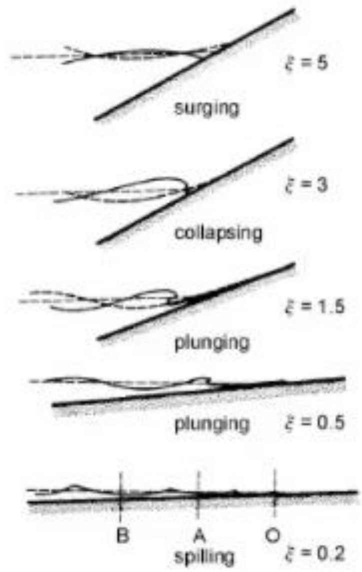

Figure 8: Wave interaction with structure on a slope. Courtesy: *(Pilarczyk, 1998)*

2.4 Permeable mattresses

Permeable mattresses are made of permeable textile materials designed rather than engineered specifically for use in civil engineering and geotechnical applications like erosion control, soil stabilization, reinforcement, separation, and slope and shore protection and drainage. It has a flexible framework of fabric made with high-strength geotextile. During the last decade, the use and application of geotextile mattresses have extended worldwide. Due to the technological advancements, geotextiles have entered several domains and have gained confidence around the world because of their integral advantages like easiness and flexibility of use, softness (in comparison to rock constructions), speediness of installation and long-term efficiency. Geotextiles yield financial advantages and benefits such as reducing construction times, material costs and the costs of maintaining structures. The permeable mattress is easy in handling and installing; besides that, it is also durable and has ductile formwork.

Deltares representatives visited a Chinese hydraulic facility that was using the geotextile mattresses as a wave absorber at the end of their basin. In figures 9 and 10, the material and idea can be seen. Based on this idea, a variant will be formed using geotextile mattresses. Deltares is in contact with a local supplier, discussions with them about the idea will take place and once the design is finalized in the next phase, the order can be placed for testing of the material as a variant. The design, layout and geometry can be adjusted according to the needs and requirements which will be discussed in the following chapters.

Figure 9: Mattress placed vertically at the end of the basin for wave absorption in China, Courtesy: Deltares

Figure 10: Close up of the Permeable mattress. Courtesy: Author, 2022

2.5 Detection methods for wave reflections

As many hydraulic laboratories nowadays have the capability of generating irregular sea waves for their experimental investigations, the necessity for figuring reflections in an irregular sea state is important. In past, the techniques that were used for this purpose were a 2-point method which was found by (Thornton & Calhoun, 1972), (Goda & Suzuki, 1976), and (Morden, et al., 1976), which consisted of measuring simultaneously the co-existing wave spectra at two known positions on a line parallel to the direction of wave propagation and deriving from this the incident and reflected spectra.

This method had limitations and new studies were built upon further. A three-point method that used a least-square analysis for decomposing the measured spectra into the incident and reflected spectra with greater accuracy and range was designed. This method was originally derived by Mansard and was used extensively for reflections with periodic waves and yielded reliable results. It requires simultaneous measurement of the waves at three positions in the flume which are in reasonable proximity to each other and are on a line parallel to the direction of wave propagation. Experimental investigations have shown that there is good agreement between the incident spectra calculated by the least-squares method and the incident spectra measured concurrently in a side channel. (Mansard & Funke, 1976)

The gauges will measure the surface elevation of the water at a fixed location and determine surface elevation by measuring the electrical resistance between the wires, which is a function of the water level. Signals from a set of three-wave gauges are used to determine a few wave characteristics which will be discussed in the next chapters.

2.6 Active reflection compensation

An ARC functionality reduces unwanted re-reflections of waves against the wave board by absorbing the waves coming from the flume or basin when they reach the wave board. Active reflection compensation (ARC) refers to the use of the wavemaker not only as a wave generating device but also as a wave absorbing device. Nowadays wave generation and active wave absorption can be performed concurrently which is considered the default way of working. There are various reasons for having the ARC:

- In case to eliminate spurious re-reflections from the wavemaker, thereby spoiling the target incident waves.
- To prevent resonant oscillations in the flume or basin, which reduce the maximum test operation.
- To make the experimental results less sensitive to the placing of artificial boundaries constituted by wavemakers, and thus to make them easier to interpret.
- To be able to reduce the stilling time in the basin between tests significantly (usually from an hour to a couple of minutes). This can be done by quickly removing the otherwise slowly damped low-frequency oscillations.

A significant improvement in the wave field of the hydraulic facilities and wave basins can be made by equipping the wave generator with the Active Reflection Compensation (ARC) functionality. This is usually done by also equipping the basin with the ARCH functionality. In the ARCH software, the Active reflection compensation software by Deltares cooperates with the HyPCoS wave generator control software by Bosch Rexroth. These have been operating around the world (Marin, Coppetec, Deltares (two equipment), Hannover). (Expert Environmental, n.d.). This software facility is designed and developed by Deltares and has been a remarkable achievement in the wave reflection field.

In basins, it is expected that additional boundaries are present. These boundaries are in form of the sidewalls of the facility and the wavemaker. The model boundaries lead to unwanted reflections (very less in real-life situations). Therefore, at the sidewalls or the ends of basins often rocky beaches are placed to provide additional passive damping. Besides this, the wave board itself gives, (without ARC) significant reflections. In other words, in the testing facility the wavefield consists of two parts:

- The required part consists of the target incoming waves (provided by the wavemaker) and the reflected waves (the target waves that have reflected at the structure and may interact with the target incoming waves).
- The undesirable part, consists of the re-reflected waves (reflection of the reflected waves at the wave board), the re-re-reflected waves (reflection of the re-reflected waves at the structure), and the re-re-re-reflected waves (reflection of the re-re-reflected waves at the wave board), and so on.

This leads to a polluted wave field, as clearly indicated in figure 11.

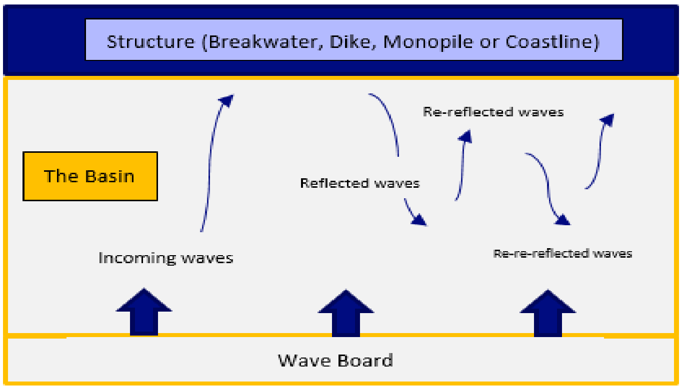

Figure 11: Testing facility situation without ACR

Wavefield near structure = Incoming waves + reflected waves + re-reflected waves + Re-re-reflected waves + …

3 Boundary conditions

3.1 Current situation

The Atlantic Basin has a length of 75m, a width of 8.7m and a height of 1.3m. The maximum water depth the Atlantic basin can attain is 1.0m. It has a wave maker at one end that has a width of 8.7m as well and is a cradle wave board. It includes a max. wave height of 0.25 m for time-period: 2s and a max. wave height of 0.45 m. (Deltares , 2022)

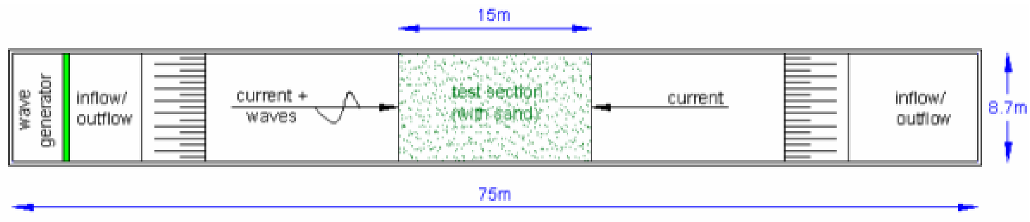

Figure 12: Layout of Atlantic Basin with a sandy test section in the middle of the basin

At the end of the basin exists currently a rock slope with rock sizes of approx. 150-200mm, that was placed to minimize wave reflections. The ocean wave simulations are produced in the testing facilities, to maintain as accurate as possible conditions of the open sea for the projects. However, at present, the rock slope causes significant reflections which lie between 16-29%, with an average value of 22% and they slightly affect the results. The rock slope can be seen in figure 13 below. Ideally, as the result of this research, these wave reflections will be minimized so that basin can produce accuracy in research results.

Figure 13: The rocky beach slope at the end of the Atlantic basin. Courtesy: Author, 2022.

3.2 Wave dissipation zone

The area for modification is only the end of the Atlantic basin, therefore when designing and testing this should be kept in mind throughout. This area is referred to as the wave dissipation zone. Therefore, all the variants need to be designed according to the geometry of the dissipation zone. No other modifications to the geometry or equipment of the basin shall take place for this research. The length of the zone is 5.8m and the width is 8.7m. The wave dissipation zone can be seen in figure 14 within the red square.

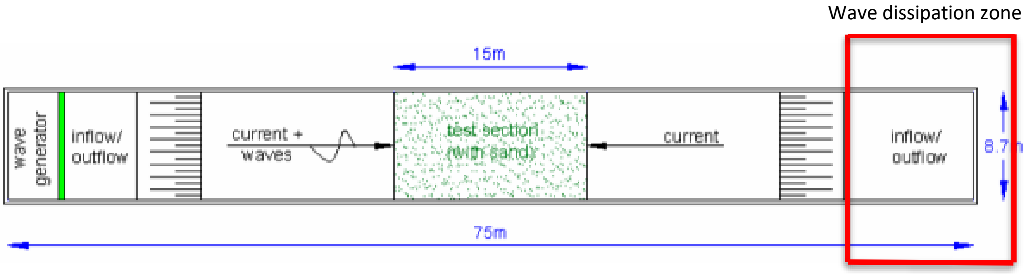

Figure 14: Wave dissipation zone indicated in red square. Courtesy: Author, 2022

3.3 Pacific basin

The hydro-hall consists of another important hydraulic facility, the Pacific basin which is used for test experiments for research from bachelor/master's students. This basin is relatively small-scaled in size, and therefore it is practical and economical to test design setups for various researches there. It is equipped with a wave generator that can generate different irregular waves. Below the figure shows the WHMs, rock slope and the flume with detailed dimensions.

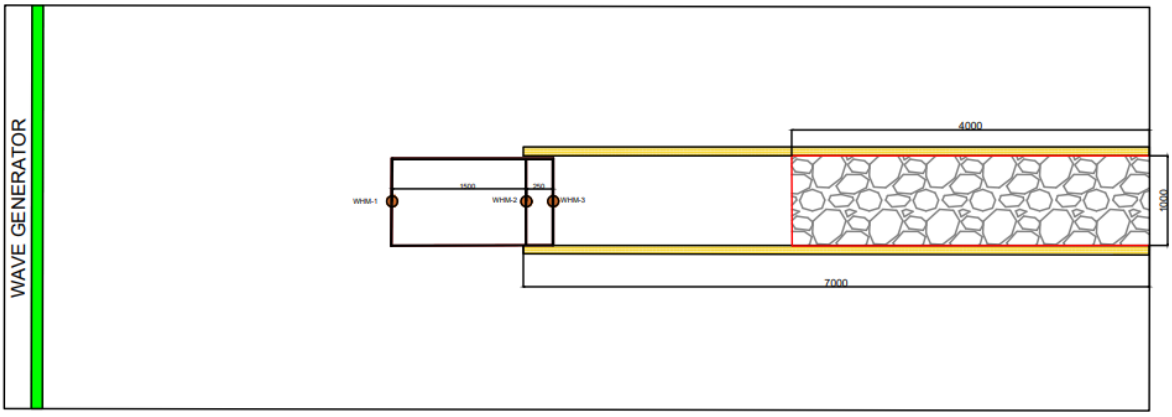

Figure 15: Detailed drawing of Pacific basin, including the flume inside

Before recommending a design for the Atlantic basin, test experiments are carried out in the Pacific basin. The idea is to test the variants with various hydrodynamic conditions. If the testing and design give ideal results, then a final selection of the design will be recommended for the Atlantic basin.

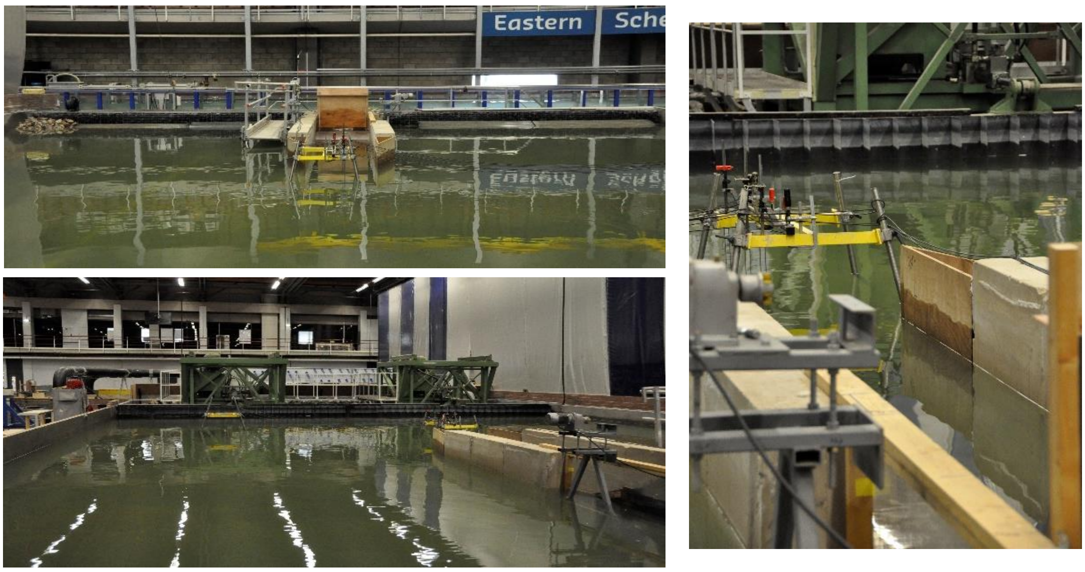

Figure 16: Pacific basin visuals. Courtesy: Author 2022

3.4 Wave ranges and water depth

The Atlantic basin tests offshore structures and reciprocates the sea wave conditions, hence waves are produced within certain ranges and water depths. For the significant wave height, the physical depth-limited wave height (approximately 40% of the water depth in offshore conditions) can be assumed as the upper limit. However, generally slightly smaller significant wave heights are observed. Based on a 50-year hindcast of significant wave heights at the North Sea significant wave heights of 6-12m are representative of water depths of 15-40m.

The period T_p also depends on the wave height H_s. For larger waves, usually, longer wave periods exist. In practice, the Tp for testing processes is given by the clients. However, for the variants of this research, an estimation is considered based on these principles. The first consideration for the wave period is the upper bound presented in (DNV, 2014):

$$T_p = 14.3 \cdot \sqrt{\frac{H_{m0}}{g}}$$

In which:

T_p= peak wave period (s)

H_m= significant wave height (m)

Next to the 14.3, for slightly shorter waves 12.3 can be considered and for longer waves, the value 16.3 can be considered.

According to the dataset available from Deltares, the typical wave generation, water depth and peak period range for testing in the Atlantic basin are following:

Wave Parameters	**Ranges**
Water depth (d)	0.4 – 0.9 m
Significant wave height (H_{m0})	0.13 – 0.25 m
Wave peak period (T_p)	1.5 – 3 s

These are derived from the excel file that has a large range of tests done in the Atlantic basin over the past years with details of wave parameters. These ranges will be used for testing the design so that in practice the variant can withstand and dissipate the waves when offshore structures are tested within the facility. The database is presented in appendix B.

3.5 General limitations

Any kind of natural vegetation cannot be used in the design as the facilities don't exist within the nature area and have no access to direct sunlight. Ideally, the design must need the least maintenance and is a fixed structure, so any materials that are floating must be avoided. Besides waves, currents also exist in the basin hence no such design should be executed that affects the current movement in the basin. Technically, the design needs to be maintained in geometric scales, so that it covers the complete width of the basin, withstands the wave energies and forces, and is sustainable in its design. The existing rock slope can be kept in the new design, can be altered, or modified if the results minimize wave reflections.

4 Methodology

4.1 Desk research

For this research, multiple literature and information sources were thoroughly investigated and studied. This was done using the desk research approach. That resulted in a basis of the theoretical framework to gather objective information from trustworthy and relevant open sources. The information was then used as a foundation for the rest of the report.

4.2 Interactive research

During the research, various forms of interactions with professionals within the department were carried out, namely formal meetings and brainstorming sessions. To understand the previous research or study carried out before, an interaction kick-off meeting with Deltares specialists was conducted. They explained the current situation and the similar reflection issues from the side walls behind the wavemaker. The hydraulic specialist gave suggestions on slope designs and their optimizations, that could be investigated. To gain more insight into the availability and design of permeable mattresses, a meeting with a supplier was arranged to see what kind of materials would be available to absorb wave energy.

4.3 Practical experiments

To understand the effect of different models with various designs in terms of arrangement and orientation, these are tested in a practical hydraulic facility, the Pacific basin. Several effects on wave energy dissipation and structure prototypes consisting of various slopes for energy absorption will be tested in the wave flume. Measurements of wave reflection and dissipation will be analysed and then a design based on a trade-off between performance, feasibility, and cost efficiency will be chosen for the Atlantic basin.

The experiments focus on regular or in-line configurations since they simplify the analysis of the physical processes. Deltares has modern methods available to measure the wave reflections that will be used during the testing programme. The Mansard and Funke (1980) method will be used to compute the reflection coefficient, the theory for which has already been explained earlier in sub-section 2. The experiment setups and data measuring processes are discussed in sub-section 5.2. Software programs such as Delft-measure will be used to collect data for processing. For post-processing, the in-house software known as Auke-process will be used to process the results for analysis.

4.4 Design methodology

As it is globally known that design methodology is vital for any kind of research. It refers to the development of a system or method for a unique situation that needs improvisation, improvements, or fixture. To be able to design variants for our research, a design methodology is developed as shown in figure 17.

Based on the main objectives of the research a set of boundary conditions & functional requirements are assessed. Then keeping in mind, the main functions, the following aspects, and goals were considered:

- The design should minimize wave reflection in the basin

- It must be practically possible to construct and execute the design
- The construction cost should be minimized to an acceptable/responsible level

Based on these main objectives, variants/solutions are discussed (conceptual design) and then preliminary designs are made. These designs are then tested and modified according to the findings and improvements during the testing.

Once, the results are satisfactory or according to the objectives, based on post-processed results a final design will be recommended, in case the results are not up to standards, the re-design and retesting process shall follow. Below in detail, a complete strategy is given for this research.

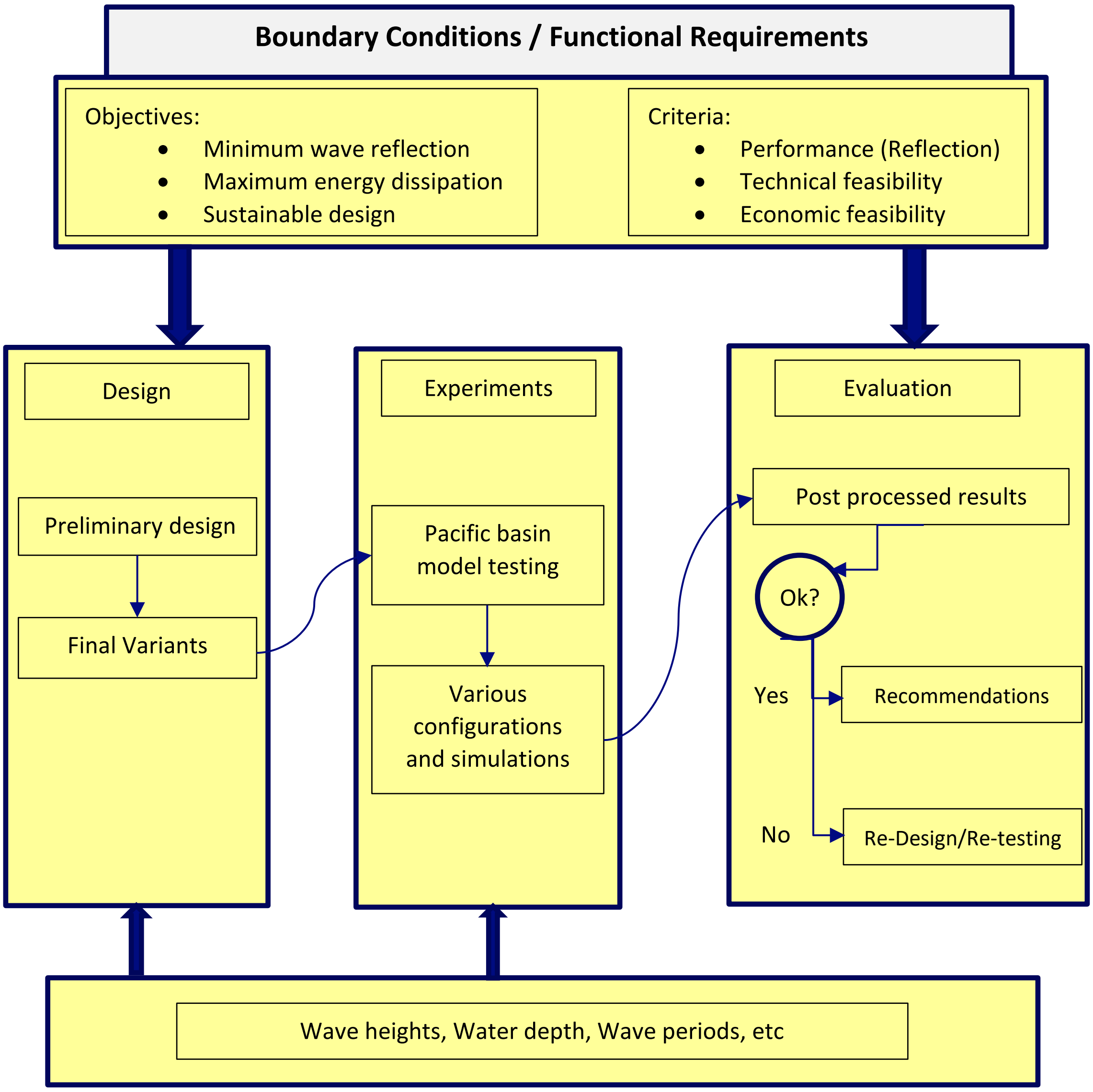

Figure 17: Design Methodology

4.5 Project planning

To make sure the research project follows a decent timeframe for execution, a schedule and planning is made. To be able to execute the experiments in the testing facility, a work schedule is needed so that other client projects are not disturbed. The schedule for this project is a brief one to keep into account the basic activities and deadlines. Besides that, individual time planning was also done for carrying out the graduation thesis on a professional level.

The schedule needs to consist of all relevant activities as well as limitations, like a client project disturbance, etc. It also needs to include public holidays like Christmas, Easter, etc. Briefly, the major event breakdown is bellowed:

- Literature research and study must be carried out for understanding design concepts and materials. (To be finished by March).
- The variants are designed for experiments (To be finished by March).
- The experiment setup is discussed and understood (Before April)
- Budget allocation and procurement of materials are done. (Before mid-April)
- Models are constructed in the testing facility (April)
- Experiments are carried out with different hydrodynamic conditions. (May)
- Results and discussions for the recommendation for the Atlantic basin (June)

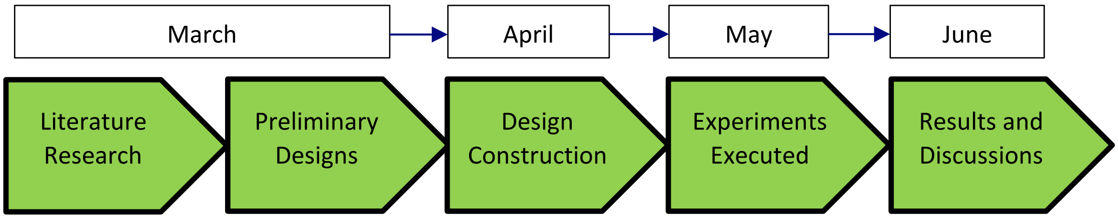

Figure 18: Planning and activities for the research

5 Design & Experimental setup

5.1 Variants and their configurations

In this sub-section, the design of the variants is explained. It describes the different configurations used in various models that were designed and tested in the flume for the absorption of wave energy and minimizing wave reflection. To be able to answer the third sub-question, the designs are formulated in this section. The information and sources gathered in chapter two are used as the foundation for the design of the variants. There are three main variants, and each of them contains several models with various configurations.

5.1.1 Variant 1

Variant 1 is based on the original idea, the beach slope with rocks to damp wave energy. As mentioned earlier, the current rock slope has 150-250 mm-sized rocks. However, this variant has a different and uniform rock size. The 32-50mm rocks are used for creating several slopes with a mesh on the top to keep them protected from rolling if the wave forces are too high. The five models that are tested under this variant are based on different configurations. These include different consistent slopes and a combination of slopes with different lengths and steepness. This is done to find the most ideal rock slope and use it for evaluation with the other two variant’s ideal configurations to find the most optimized solution for minimizing wave reflection. The detailed AutoCAD drawing for all models is made for a better understanding of the design and visual comparison of the models.

5.1.1.1 Model 1A

Model 1A consists of rocks which are uniformly spread over a slope of 1:3. This means the length of the model is 3m and the height is 1m, and as the testing flume has a width of 1m, the rocks are spread over this width. The detailed drawing in figure 19, shows a clear understanding of the design.

A photograph taken before the execution of the tests of the model is shown in figure 20. The current slope at the Atlantic basin is 1:4 (Tanα = 0.25), hence this slope is slightly steeper, however with uniform rock diameter.

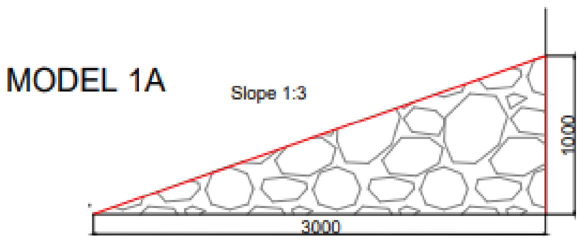

Figure 19: Detailed design of model 1A.

Figure 20: Physical design of model 1A.

5.1.1.2 Model 1B

Model 1B consists of a combination of two slopes. These combinations are created to test 1:5 & 1:6 rock slopes. Due to the limited testing space in the flume 1:5 & 1:6 rock slopes cannot be constructed as individual consistent slopes. This is because WHMs in the fume need to be placed at a minimum distance away from the rock slope to be able to measure accurately.

At 1.5m, the midpoint of the total length of this model a transition between new slope occurs. The first slope has a steepness of 1:2 and the second slope has a steepness of 1:5. The length of both the first and second slopes is 1.5m, however, the height of the first slope is 0.7m and the height of the second slope is 0.3m. This model configuration was chosen to analyse the effects on wave energy when the combination of the slope has a transition point at 0.7m which occurs between both the testing water depths. Figure 21 indicates the design with its dimensions and figure 22 shows the physical design before testing.

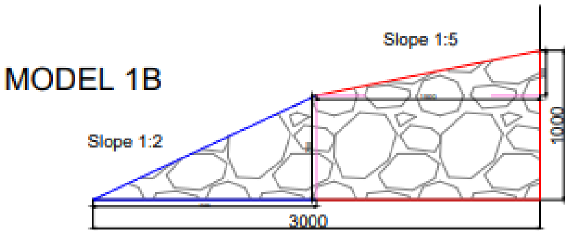

Figure 21: Detailed design of model 1B.

Figure 22: Physical design of model 1B.

5.1.1.3 Model 1C

This model also consists of a combination of slopes; however, the first slope is until the height of 0.4m and with a length of 1m, and the second slope which is indicated in red is 0.6m high and 3m in length. To test the energy dissipation on a 1:5 slope, but with a larger length and height, this model was designed. This model configuration analyses the effects on wave energy at both water depths 0.6m and 0.8m when the combination of the slope has a transition point 0.2m below the minimum testing water depth. The first slope has a steepness of 1:2.5 and then the second slope has a steepness of 1:5.

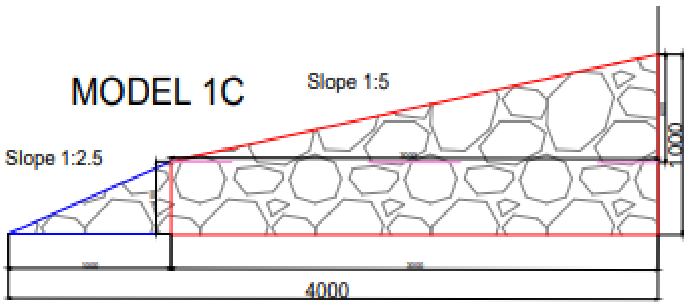

Figure 23: Detailed design of model 1C.

Figure 24: Physical design of model 1C.

5.1.1.4 Model 1D

In model 1D, the second slope has a steepness of 1:6 slope with a length of 3m and a height of 0.5m. Both slope 1 and slope 2, have heights equal to 0.5m but the lengths are different, creating space for a mild second slope. This model configuration is designed to test the impact of a mild second slope on energy dissipation. Slope 1 indicated in blue has a steepness of 1:2 and the second slope has a steepness of 1:6 which is indicated in red in figure 25. As water depths of 0.6m and 0.8m are to be tested, therefore evaluation is done to see the effects on wave energy by creating a steeper second slope with a transition point just 0.1m below the minimum testing water depth.

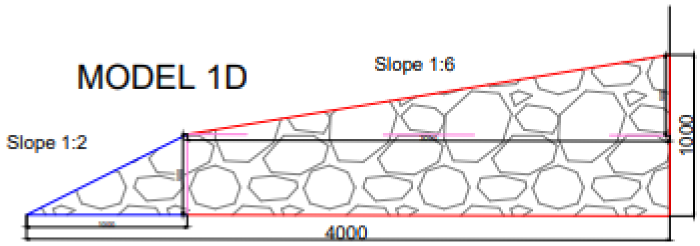

Figure 25: Detailed design of model 1D.

5.1.1.5 Model 1E

Model 1E replicates the current situation at the basin, with a 1:4 slope. However, uniform rocks of smaller size have been used for all other models as well. The rocks are 32-50mm in diameter, this way the comparison is fair with other models, and parameters are not changed. This design model is tested to have a comparative reference and to see if having smaller and uniform rock size affects the wave dissipation positively or negatively. This is also tested to see the steepness effect of 1:4 consistent rock slope with smaller rock size. The slope is indicated in the design in figure 26.

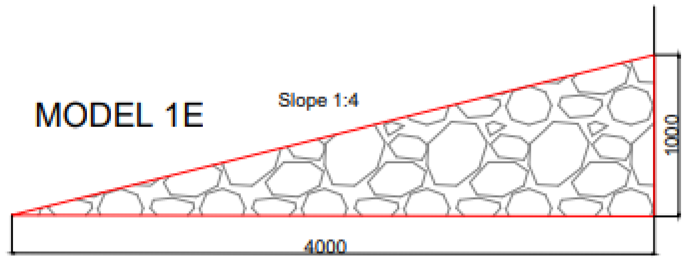

Figure 26: Detailed design of model 1E.

5.1.2 Variant 2

An adjustable parabolic damper slope is currently being used in the Deltares hydraulic facility, the Scheldt flume. The damper slope is designed in a parabolic shape to damp wave energy with a steep and then a mild slope, with little bumps on its surface and having a slightly higher height in the centre of the structure to replicate the parabolic shape. This slope has been effective in dissipating wave energy in the Scheldt flume, and it is easy to install. In this variant, the parabolic slope will be installed and made adjustable using a pully attached to it which can adjust its heights. It will be tested with two different configurations to see its effects on wave reflection and then the winning model shall be used for further comparison with other variants. The configurations are explained further in detail.

5.1.2.1 Model 2A

Model 2A has its end point adjusted at a height of 0.8m, which is the height of the highest testing water level. This configuration is tested to evaluate and see the effects of parabolic damper slope on wave reflection when kept aligned with the testing water level. This means using a pully, the slope could be adjusted for each water level that is being tested in the basin. The rock slope is also kept underneath the parabolic damper to improve its overall efficiency. As the shape is parabolic, it is noticeable that the damper is slightly higher from the centre and then gets lower towards the end. The design can be viewed in Figures 27 and 28 below.

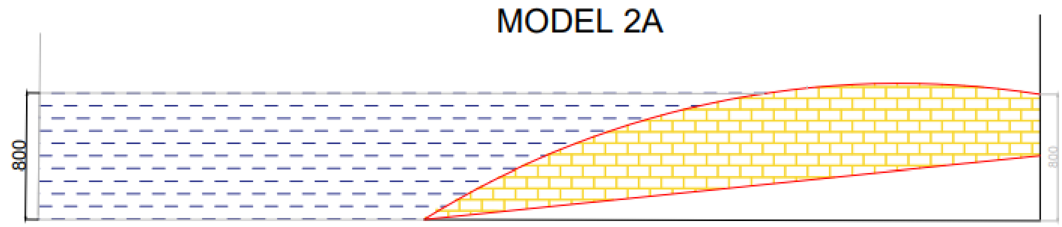

Figure 27: Design of slope that is used for model 2A.

Figure 28: Physical design of the Parabolic damper slope used as model 2A and 2B.

5.1.2.2 Model 2B

Model 2B, has its end height adjusted at 1m. This means that the centre point is even slightly higher than 1m, and therefore the slope is steeper for both water levels. This configuration is tested to analyse for two main purposes, the parabolic slope effects on reflection compared to rock slopes which also exist in a combination of slopes and its efficiency when installed at a static position in the flume.

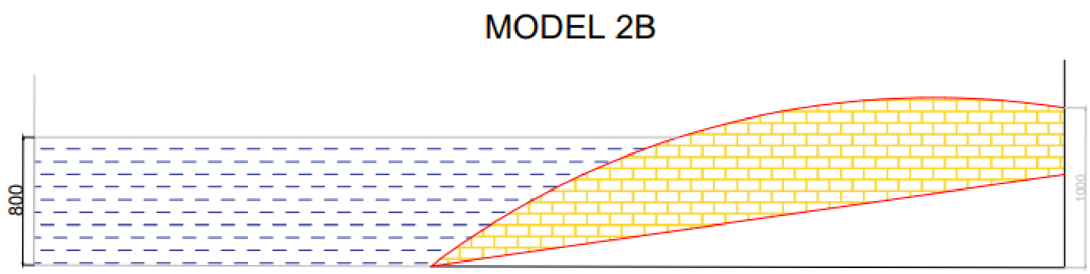

Figure 29: Detailed design of slope that is used for model 2B.

5.1.3 Variant 3

Variant 3 is based on the use of permeable mattresses as wave energy dissipators. The background of the material is already explained in sub-section 2.4. The Chinese hydraulic facilities have been using this in their flume as a wave damper. Based on that, this is also tested with various configurations to see the influence of permeable mattresses on wave energy. The supplier delivered three different material types, A = 400g/m2, B=700g/m2 and C=260g/m2. Model A, B and C, have each different material used with the same thickness layer of 10cm placed on the rock slope. Besides this, D a 4th model is also tested, however in this case the mattresses are placed vertically in front of a 1:4 rock slope. The models are further explained below.

Figure 30: Three different type of permeable mattress materials

5.1.3.1 Model 3A

A 10cm thick layer of a permeable mattress made of material that weighs 400g/m2 is placed on the top of the 1:4 rock slope throughout the width using tie wraps and mesh on the top which clips the mattresses and mesh with the rocks. This is tested to examine the influence of the permeable mattress on the reflection. This can then be compared with the normal 1:4 rock slope which is used in model 1E to find out the influence of this specific mattress on wave reflection.

Figure 31: 10cm layers of materials created.

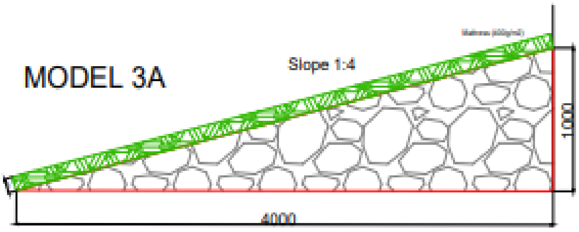

Figure 32: Detailed design of the Model 3A.

5.1.3.2 Model 3B

Model 3B has a similar configuration to model 3A, however, the material used is different. It is stiffer as the weight is also more (700g/m2) and the permeability varies due to this. Similarly, it is placed over a 1:4 rock slope to see the material effect.

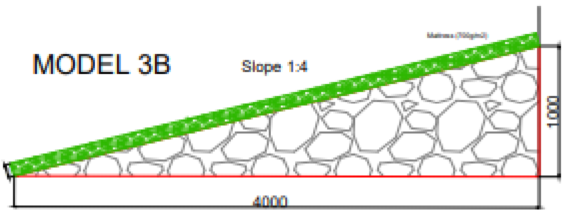

Figure 33: Detailed design of the Model 3B.

5.1.3.3 Model 3C

Model 3C used a mattress made up of a material that is denser but light as well. It is 260g/m2 and has very less permeability. This is tested on top of a rock slope with 10cm thickness to see its effect on wave reflection in comparison with the other type of mattress material.

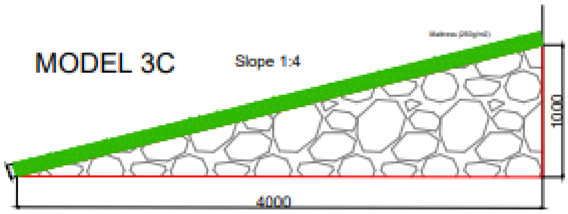

Figure 34: Detailed design of the Model 3C.

Figure 35: Physical design of the Model 3C.

5.1.3.4 Model 3D

Model 3D includes a layer of mattresses rolled in a rectangular shape and placed vertically in the front of the 1:4 rock slope. The rock slope at the back will be used to dissipate the wave energy that still passes through the permeable structure. This design is based on the concept from sub-section 2.2 (Wave interaction with structures) and the general principles of the mangrove forests. The material used for this is type A (400g/m2) due to its permeability and stiffness. The mattresses need enough permeability, so they don't act as an opaque vertical wall. This model will be tested to examine the results of the material as a permeable structure to dissipate energy and its effects on reflection. This can also be later used as a material on the side and back walls of the basins in the facilities to dampen the extra energy that causes certain side and back reflections that cause pressure on the wave makers from the back walls. The configuration is shown below in figure 36.

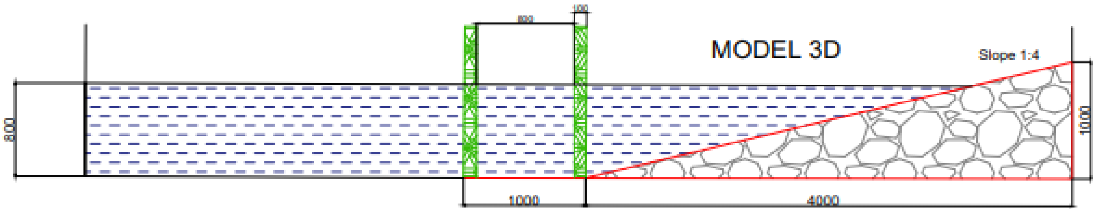

Figure 36: Detailed design of the Model 3D.

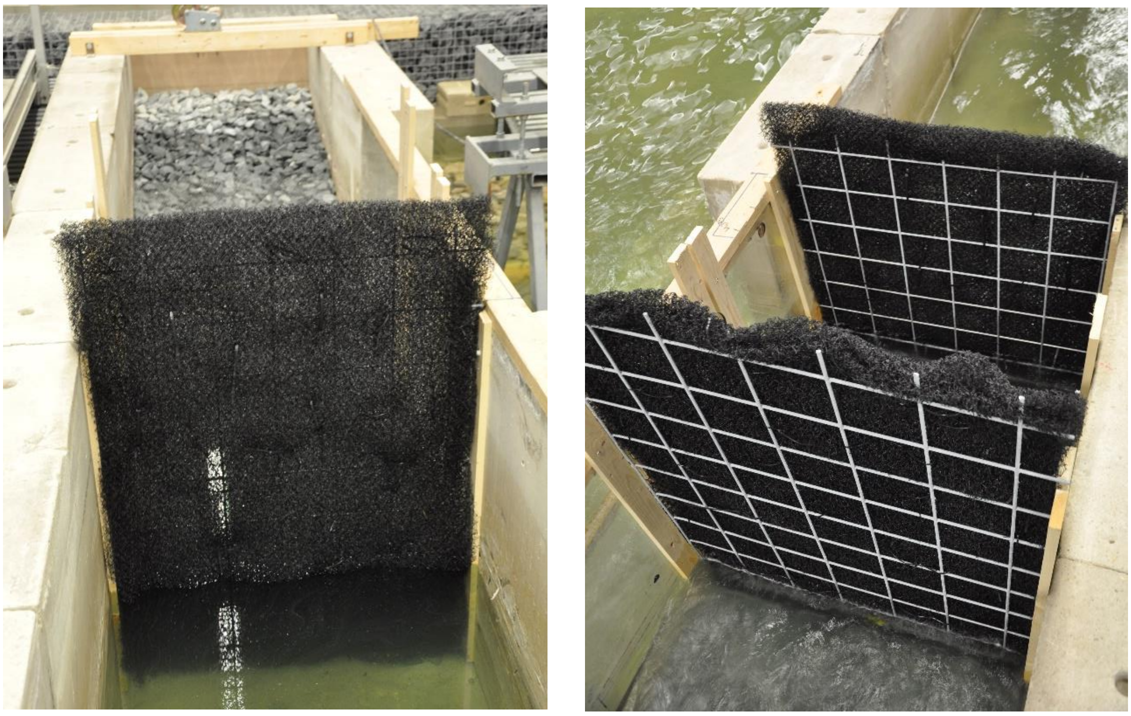

Figure 37: Physical design of the Model 3D.

5.2 Experiment setup

To investigate various designs, the model experiments are performed inside the flume in the Pacific basin. The flume can be seen in figure 38. Inside the flume, the models are constructed/installed and then tested. The table shows the dimensions of the flume and a detailed drawing can be seen in figure 39.

Dimensions	-
Length	7m
Width	1m
Height	1.3m

Figure 38: Flume inside the pacific basin where the experiment models were installed.

The measuring equipment (wave height meters) is discussed in sub-section 5.3. The wave generator can generate irregular waves, where the user must assign the combination of wave height, water depth and wave period. All prescribed wave fields are of a JONSWAP-type with J=3.3, which is the peak enhancement factor. A water depth measuring needle is installed in the basin, via this the water level is measured in the basin for testing purposes.

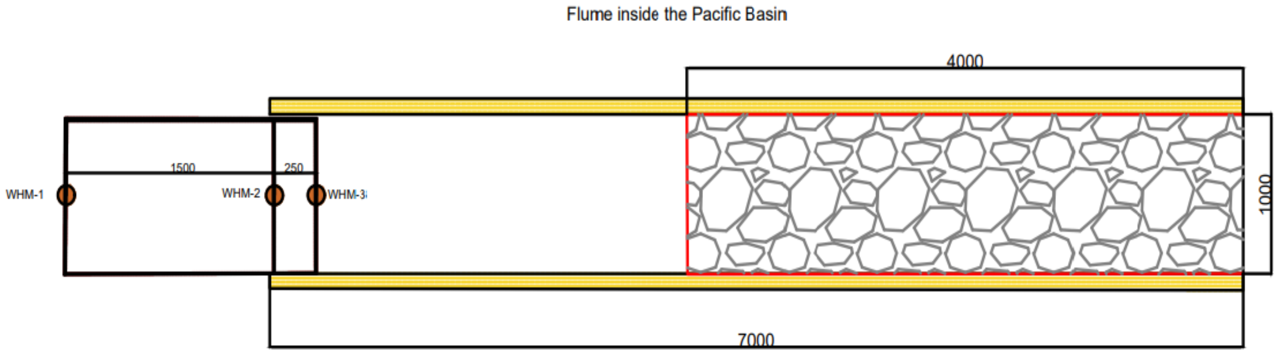

Figure 39: Pacific basin's experiment flume with WHMs installed.

5.2.1 Test programs

The tests aim to get insight into the performance of the various wave absorbing methods, that dissipate wave energy and in return minimize wave reflections. Therefore, a variety of water depths and wave periods have been studied, with a focus on different wave heights. Tests have been executed for two water depths d (0.6m & 0.8m), various peak wave periods T_p for different significant wave heights H_{m0}. T_p also depends on wave heights H_{m0} and thus is calculated concerning that. The selected values for the wave height and wave period are based on the wave ranges and water depths (sub-section 3.4). To be more precise, per wave height – T_p low, average and T_p high are taken based on the formula and values. (sub-section 3.4). In the formula, 14.3 is for avg. waves, for slightly shorter waves 12.3 value is taken and for longer waves, 16.3 is used.

$$T_p = 14.3 \cdot \sqrt{\frac{H_{m0}}{g}}$$

H_{m0}	T_p low	T_p avg.	T_p high
0.13	1.4	1.6	1.9
0.16	1.6	1.8	2.1
0.19	1.7	2.0	2.3
0.22	1.8	2.1	2.4

Steering files are generated and used to run the wave generator and the test names are given to differentiate models and wave parameters. The below shows an example for a water depth of 0.6m, three wave-heights are taken and the T_p is calculated and then a combination is used. For instance, for H_{m0} 0.13, T_p avg. and T_p high are taken, for H_m 0.16, T_p low, avg. and high all three are taken. This is done to have a combination of large and short waves that are tested for the performance of the slope.

Typical values for the wave steepness are between 1.5% and 4.0% and are calculated based on this $S_p=H_m/1.56\ T_p{}^{\wedge 2}$. The duration is also optimized and is explained further in sub-section 5.2.2. For water dept 0.6m and 0.8m, several tests were carried out. In total each model was tested several times, under different hydrodynamic conditions. Complete details regarding tests can be viewed in the excel file.

		For water depth: 0.6m				
Steering Files	Test name	d(m)	H_{m0}(m)	T_p(s)	Duration (s)	Steepness %
6H13T16	A6H13T16	0.6	0.13	1.6	1322	3.08
6H13T19	A6H13T19	0.6	0.13	1.9	1570	2.37
6H16T16	A6H16T16	0.6	0.16	1.6	1322	4.16
6H16T18	A6H16T18	0.6	0.16	1.8	702	3.08

6H16T21	A6H16T21	0.6	0.16	2.1	868	2.37
6H19T20	A6H19T20	0.6	0.19	2.0	826	3.08
6H19T23	A6H19T23	0.6	0.19	2.3	950	2.37

5.2.2 Optimization in test programs

The duration for the test to be carried out is calculated in seconds using the T_m value. The T_m value comes from T_p. $T_m=T_p/1.1$, and then the $T_m/1.1*1000$ gives the duration in seconds for the test program. The table below shows the duration values for different T_p. These time durations tested 1000 waves as 1000 in the formula represent the number of waves. This could be optimized by testing 500 waves. Few tests were carried out and processed, which showed that the reflection coefficient stayed the same for the first half (first 500 waves), the second half (second 500 waves) and the full test (1000 waves). This process was done for a few tests to make sure that the optimization doesn't affect any results.

T_p	$T_{m-1.0}$	Duration
1.4	1.3	1157
1.6	1.5	1322
1.7	1.5	1405
1.8	1.6	1488
1.9	1.7	1570
2	1.8	1653
2.1	1.9	1736
2.3	2.1	1901
2.4	2.2	1983

The optimization table is given below for reference and understanding. The table shows the tests that were carried out for the optimization practice, the results were processed via the in-house post-processing software (Auke-Process). All further tests and models were tested based on half the duration, which means 500 waves. This gave us an optimization for test programs that resulted in saving time that would have taken to carry out several tests for each model. Optimizations are always preferred as they reduce time duration which results in the ability to perform more variety of tests in a similar amount of time and reduces extra energy use.

Originally -	Duration = $((T_{m-1.0})/1.1)*1000$
Optimized -	Duration = $((T_{m-1.0})/1.1)*500$

		OPTIMIZATION FOR TEST DURATIONS				
Test name	**d(m)**	**H_{m0}(m)**	**T_p(s)**	**Parts**	**Duration(s)**	**Reflection coefficient**
A6H13T16	0.6	0.13	1.6	First half	661	0.193
A6H13T16	0.6	0.13	1.6	Second half	661	0.193
A6H13T16	0.6	0.13	1.6	Full	1322	0.193
A6H13T19	0.6	0.13	1.9	First half	785	0.193
A6H13T19	0.6	0.13	1.9	Second half	785	0.193
A6H13T19	0.6	0.13	1.9	Full	1570	0.193
A6H16T16	0.6	0.16	1.6	First half	661	0.198
A6H16T16	0.6	0.16	1.6	Second half	661	0.198
A6H16T16	0.6	0.16	1.6	Full	1322	0.198
X8H13T14	0.8	0.13	1.4	First half	578.5	0.210

X8H13T14	0.8	0.13	1.4	Second half	578.5	0.210
X8H13T14	0.8	0.13	1.4	Full	1157	0.210
A8H16T18	0.8	0.16	1.8	First half	744	0.178
A8H16T18	0.8	0.16	1.8	Second half	744	0.178
A8H16T18	0.8	0.16	1.8	Full	1488	0.178

5.3 Wave height meters

The wave height meters measure the conductivity depending on the water level and give a signal varying between -10V and 10V. Therefore, the WHMs need to be calibrated individually. This is done by creating a series of fixed water level differences and measuring the corresponding response in volts. There is a linear relationship between the water level and voltage. By using this linear relationship, the measurements in volts are translated into water level measurements. The wave gauges have an accuracy of ± 1 mm. Figure 40 shows the detailed sketch of the WHM and figure 41 shows the images of the installed WHMs in the testing facility.

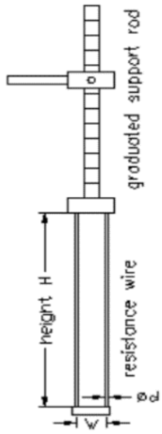

Figure 40: Sketch of the WHMs

Three wave height meters are placed in line at the end of the flume. The measured data is used to find an optimal wave height meter's length. The distance between WHM-1 and WHM-2 is 1.5m and between the WHM-2 and WHM-3 is 0.25m. Their data is used to separate wave fields into the incident and reflected components using the procedure of Mansard and Funke (1980). The wave impact on the wave height meters can, for large wave depths (0.8 m and larger), be so strong that they move with the waves. Therefore, a more stable and solid construction had to be made and this is visible in figure 41. The measured data is stored via Delft measure software and is then used in standard postprocessing software (Auke-Process) for the results of the experiments.

Figure 41: Visuals of the WHMs in the Pacific basin. Courtesy: Author, 2022.

6 Results and Analysis

6.1 Data processing (Auke-process)

Using the in-house developed Auke-process software the information was processed. The test results are presented and used to evaluate and compare the variants and their models. The software processes the information and data gathered using Delft measure software that collects the data of the WHMs which are discussed in detail in sub-section 2.5 and 5.3. A complete report of results is presented in appendix A (excel file), but below few important figures for understanding are shared. The model A data gives important parameters such as the significant wave height (H_{m0} and wave period T_p), and the most important for this research is the reflection coefficient. Processed data of each model was collected and stored in an excel file to analyse and examine their performances.

Below in the table, the test name indicates the different alphabets for different models, water depth, wave height and wave periods respectively. This table represents the input data for each variant and its different models. The blue colour indicates the optimized duration which is explained earlier in sub-section 5.2.2.

		For water depth: 0.6m				
Steering Files	**Test name**	**d(m)**	**H_{m0}(m)**	**T_p(s)**	**Duration (s)**	**Steepness %**
6H13T16	A6H13T16	0.6	0.13	1.6	1322	3.08
6H13T19	A6H13T19	0.6	0.13	1.9	1570	2.37
6H16T16	A6H16T16	0.6	0.16	1.6	1322	4.16
6H16T18	A6H16T18	0.6	0.16	1.8	702	3.08
6H16T21	A6H16T21	0.6	0.16	2.1	868	2.37
6H19T20	A6H19T20	0.6	0.19	2.0	826	3.08
6H19T23	A6H19T23	0.6	0.19	2.3	950	2.37

The results table shows the processed data from the executed experiments. The result values slightly differ from the expected values (in the above table), the difference is insignificant and can be ignored, as the wave height meters have an accuracy of ± 1 mm. The result values are average values over the complete duration of the test. For various models, these values in the tests are usually similar and if differ the value difference is insignificant, and usually when rounded up lead to the expected values. For example, T_p expected is 1.6 and T_p in results is 1.594.

Results			
Test name	**H_{m0}**	**T_p**	**Reflection Coefficient**
A6H13T16	0.112	1.594	0.193
A6H13T19	0.111	1.984	0.193
A6H16T16	0.138	1.587	0.198
A6H16T18	0.139	1.739	0.191
A6H16T21	0.147	2.072	0.214
A6H19T20	0.170	2.007	0.216
A6H19T23	0.173	2.458	0.234

As we know from sub-section 5.1.2 that variant 2 has two models that are tested, due to the parabolic slope's ability to move w.r.t to the water depth via a pulley. Hence, different positions of the parabolic slope were tested. Hence, for variants 2 and 3, the tests that were carried out were chosen carefully, after comparing them with previous model tests. The criteria for choosing these tests were simple, it was based principally on reflection coefficient value differences from previous tests. The tests that had larger differences in the reflection coefficient were chosen combined with a mix of large and short-wave conditions. This was done for efficiency and to be able to perform more tests for different models with a different configuration. Below the tables present the results of models 2A and 3A. Here it can be seen the number of tests, therefore, is less as selective tests were carried out which show a combination of short and large waves.

Model 2A			
Results			
Test name	**H_{m0}**	**T_p**	**Reflection**
G6H13T19	0.117	1.977	0.229
G6H16T18	0.138	1.745	0.222
G6H16T21	0.148	2.037	0.258
G6H19T23	0.174	2.462	0.247
G8H13T19	0.118	1.922	0.150
G8H16T18	0.143	1.784	0.160
G8H16T21	0.145	2.060	0.152
G8H19T23	0.168	2.336	0.161
G8H22T24	0.197	2.395	0.172

Model 3A			
Results			
Test name	**H_{m0}**	**T_p**	**Reflection**
J6H13T19	0.114	1.980	0.187
J6H16T21	0.149	2.049	0.205
J6H19T23	0.172	2.46	0.210
J8H13T19	0.116	1.921	0.146
J8H16T18	0.144	1.788	0.151
J8H19T23	0.168	2.331	0.154
J8H22T24	0.196	2.378	0.155

6.2 Reflection coefficient

To be able to understand, what models performed well, and which were not able to perform, the reflection coefficient is used as a parameter. For this purpose, the data is collected is available in appendix A. The values are then generated in graphs, that are used to evaluate the reflection performances of different models of each variant. For each variant, the best-performing model in terms of reflection is then used to compare with the other variants using an evaluation matrix later in this chapter. Based on the evaluation matrix, a recommendation can be formulated for the best-performing variant that can be used for optimizing wave reflections in the basin.

6.2.1 Variant 1

For variant 1, which has 5 different models, a comparison of the results of these models is investigated. The purpose of this is to understand, the effects of different configurations on wave reflection. The configurations of each model are explained in detail in sub-section 5.1. Hence this sub-section includes a comparison of the results of those models. In figure 44, the graph indicates the values of reflection coefficients on the y-axis and the respective number of tests on the x-axis. As 17 tests are conducted for variant 1's each model, hence we have 17 reflection coefficient values. The graphs show the performance of each model. The first 7 tests are performed for a water depth of 0.6m and then tests 8-17 are performed for a water depth of 0.8m.

6.2.1.1 Effect of the steepness of slopes

For higher water depth the reflection coefficient values for generally all models decrease significantly, except model 1A. This primarily shows the effect of the steepness of the slopes on the wave energy as model 1A has a 1:3 slope and can be seen in figure 42. The reflection coefficient values that are higher than of model 1A, for 0.6m water depth are of models 1C, 1D and 1B. Both 1B and 1D have the first slope as a 1:2 slope, which is steeper than the model 1A's consistent slope (1:3). Model 1C has a 1:2.5 slope as its first slope.

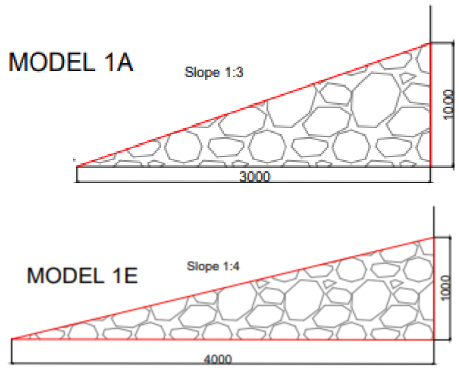

Figure 42: Detailed drawing of Model 1A & 1E.

In figure 43, the graphs shows that model 1C performs better with reflection coefficient 21.4% (at 0.6m) compared to model 1B, 27.81% (at 0.6m) and 1D, 23.01% (0.6m) that both have 1:2 slopes. Model 1A (1:3) has 20.56% reflection value and then model 1E (1:4) with 19.60%. This shows for reflection values the performance order for rock slopes is as following 1:2 > 1:2.5 > 1:3 > 1.4, 1:2 slope having the highest reflection and 1:4 slope having the lowest reflection.

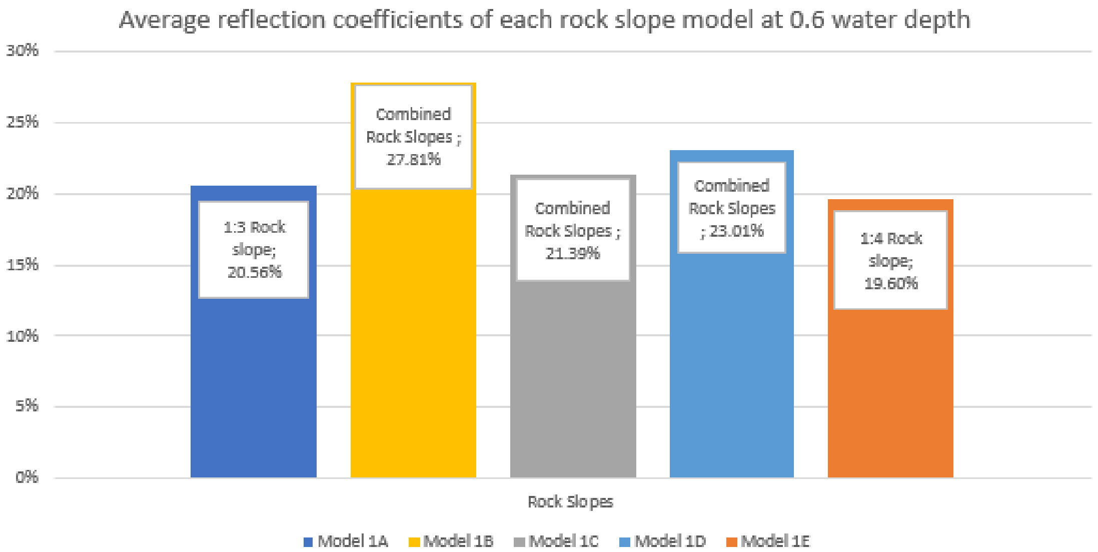

Figure 43: Average reflection coefficient values of different models of variant 1 at 0.6m water depth.

For higher water depth (0.8m), model 1E (1:4 slope) performs the best with a reflection coefficient of 16.28% (at 0.8m) followed by models with a combination of slopes and then model 1A (1:3 slope) performing the least with reflection coefficient value of 19.36% (at 0.8m).

By analysing the result values and looking at the graph in figure 44, which is representing the reflection values of each test for all the models, if space is given, the less steep the slope is constructed the better it performs for minimizing reflections. According to the graph, model 1E is over all best performing model with a consistent 1:4 rock slope. Therefore, it can be concluded from the results that if a consistent 1:5 rock slope is constructed keeping in mind the space available, it will perform even better.

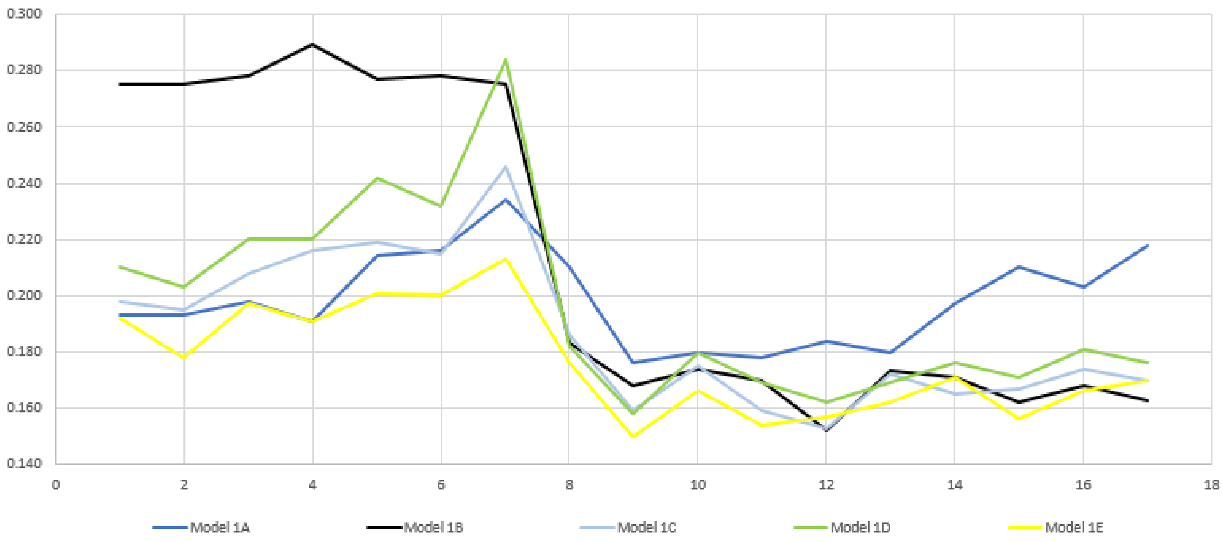

Figure 44: Reflection coefficient values of different models of variant 1 for all the executed tests

6.2.1.2 Effect of combination of slopes

Model 1B, 1C and 1D, consist of a combination of slopes. The differences among them have been discussed in sub-section 5.1 in detail. The major difference is between the heights of the transition points of the combined slopes. Model 1B, which has a 1:2 & 1:5 slope has a transition point at 0.7m, which is higher than the lower testing water depth. This model gives the highest reflection values at 0.6m water level, as at this water depth the wave energy faces a steep 1:2 slope. The second slope, however, performs better for the higher water level as the slope is less steep (1:5), and the first slope and transition point don't directly affect the wave energy, but still have impacts and therefore its reflection is lower than model 1C which has similar slopes, but the transition point is at 0.4m, rather than 0.7m. The 0.4m transition point is 0.2m below the lower testing water depth (0.6m). Therefore, this indicates that if the combination of slopes is used, the lower the transition point of slopes is kept, the better the second slope will perform for minimizing reflections.

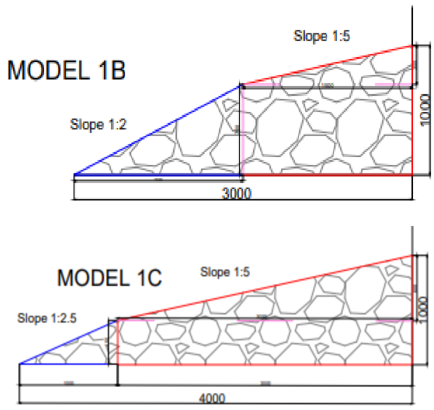

Figure 45: Detailed drawing of model 1B and 1C for reference

In the case of model 1D, the second slope of 1:6 due to space limitations did not perform well and therefore caused more reflection this was mainly because the waves ended up being reflected by the wooden wall at the back of the fume. Otherwise, model 1D with the second slope of 1:6 would perform better if space was not a limitation. A combination of slopes at higher water depth indicates that if these slopes are constructed without a combination of slopes, the reflection values can be further reduced. This is primarily due to the steepness factor. The less the steepness naturally more energy is dissipated from the waves when they are travelling towards the slope as explained earlier in detail in sub-section 6.2.1.1.

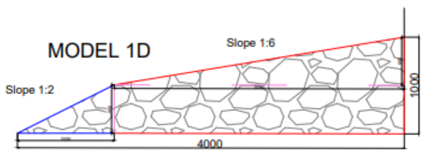

Figure 46: Detailed drawing of model 1D for reference

When a combination of slopes is constructed, the slope is not gradual, and the first slopes are usually steeper so that the second slope could be less steep. This negatively affects the wave energy and causes an increase in reflection values. The results prove this, as each of these 3 models has higher reflection values at lower water depth, however, at higher water depth they perform well as slopes are less steep and the water depth is slightly higher to be affected by the transition points and steeper first slopes.

However, the impact of the transition point and first slopes can be viewed in figure 47, as to therefore even at 0.8m water depth, the model 1E (1:4 slope) performs better compared to models 1B (1:2 & 1:5 slope), 1C (1:2.5 and 1:5 slope) and 1D (1:2 and 1:6 slope).

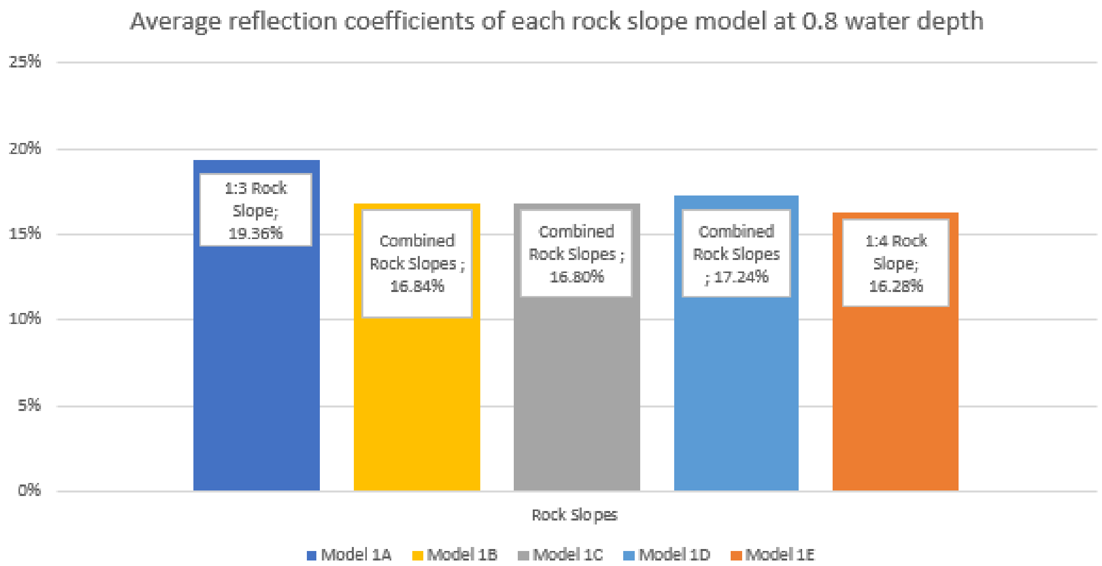

Figure 47: Average reflection coefficient values of different models of variant 1 at 0.8 water depth

Considering the overall average reflection coefficient values, figure 48 shows and indicates that model 1E outperforms each model and has the least overall average reflection value within all the models from variant 1. Therefore, model 1E is selected from variant 1 for comparison in the evaluation matrix with other variants best performing models.

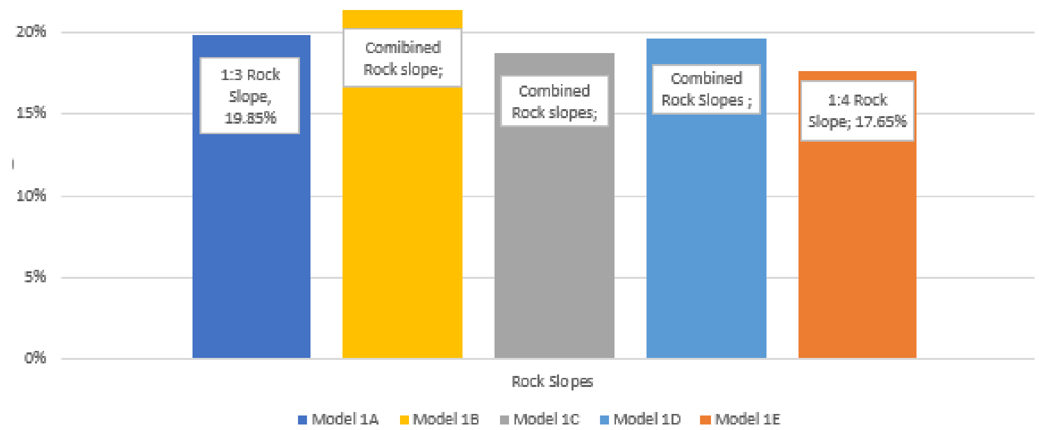

Figure 48: Average reflection coefficient values of different models of variant 1

6.2.2 Variant 2

For variant 2, two models are examined and analysed based on their reflection values. In figure 49, the graph has reflection values indicated along the y-axis and the respective tests are indicated on the x-axis. The black line represents model 2A and the orange indicates 2B. There is a large difference between the lines representing the models in figure 49 and this is due to the difference in reflection values which is even larger at higher water depth (0.8m). This is because at higher water depth model 2A performs very well. The reason for this is that its height is adjusted according to the water depth. This shows that if the pulley is used to adjust the slope according to the testing water depth, the wave reflection can be minimized. The shape helps in creating a steep slope at the start and a mild slope in the zone of wave breaking, with even a slightly higher point in the centre of the shape. However, keeping it static at the height of 1m, which is the case in Model 2B, will not give the ideal conditions for minimizing reflections. This is mainly because the steep slope becomes too steep for dissipating energy and the end part of the damper slope does not even come into use.

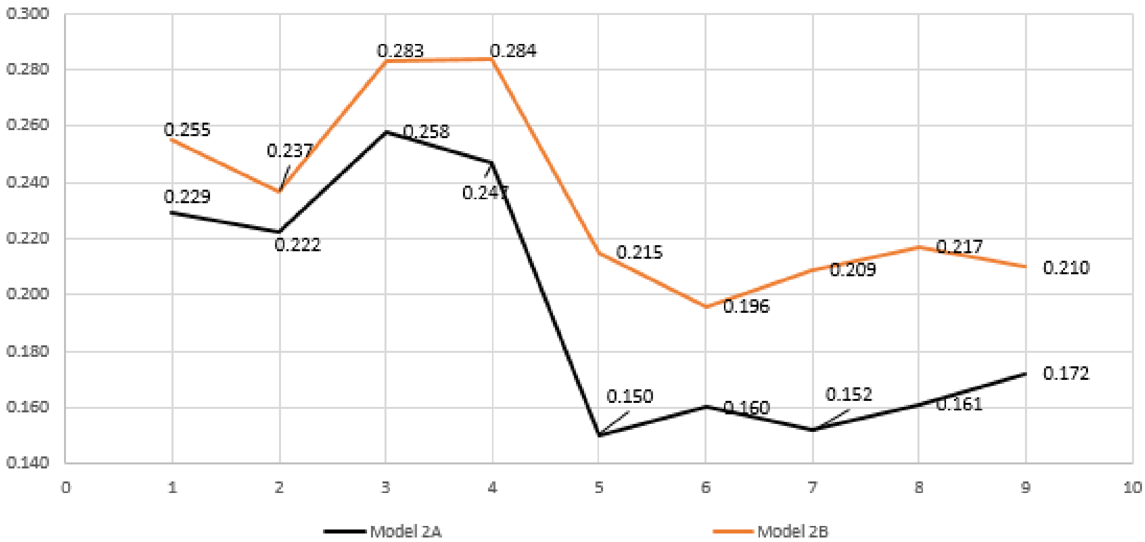

Figure 49: Reflection coefficient values of model 2A and 2B

Model 2A, drops to even 15% of reflection for certain hydrodynamic conditions when adjusted according to the testing water depth. Due to time and space limitations, model 2A could not be adjusted for 0.6m water level at 0.6m height. However, at 0.8m water depth it shows that if the pulley is raised to different water depths that are being tested, it can cause fewer reflections based on its adjustments as it acts as a lesser steep slope and uses the parabolic shape to minimize reflections. As model 2A shows better overall results, also indicated in figure 50 hence it will be used to represent variant 2 in the evaluation matrix.

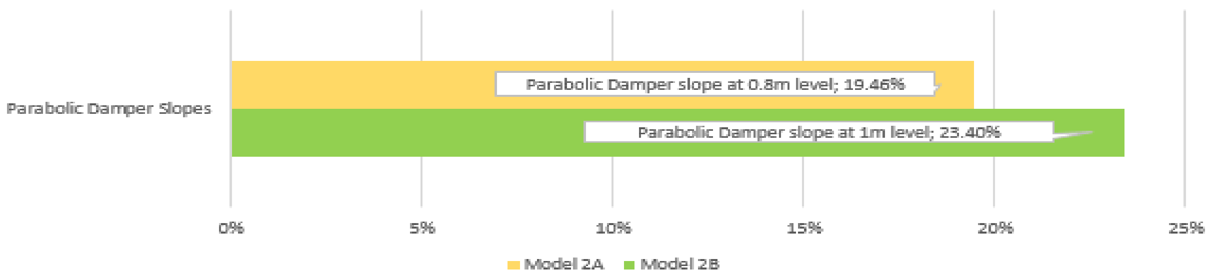

Figure 50: Graph indicating average reflection coefficient values of models 2A and 2B

6.2.3 Variant 3

Variant 3 had four different models being tested, the first three had similar configurations, just the layer of permeable mattresses was made of different materials and had different weights. This, of course, affected the permeability and stiffness of the material. The results show us the best performing material among the three materials with A=400g/m2, B=700g/m2 and C=260g/m2. For testing, the thickness of the layer of mattresses was decided after performing tests with a 10cm and 20cm layer of material A placed on a 1:4 rock slope. The results table below shows that the 10cm layer performed better. For the shorter wave test, the difference is insignificant. This is because, for shorter waves, the mattresses did not make a larger difference in wave energy dissipation. They even performed worse than a consistent 1:4 rock slope. The 1:4 rock slope has a reflection value for a similar test (6H13T19) of 17.8% and the mattress model had 18.4% and 18.7%. All three materials performed worse for shorter waves irrespective when compared with the rock slope. The mattresses are not effective on shorter waves.

Test results for thickness comparison for permeable mattresses							
Thickness 10cm (Model A)				Thickness 20cm (Model A)			
Results				Results			
Test name	**H_{m0}**	**T_p**	**Reflection**	**Test name**	**H_{m0}**	**T_p**	**Reflection**
J6H13T19	0.114	1.98	0.187	I6H13T19	0.114	1.980	0.184
J6H19T23	0.172	2.46	0.210	I6H19T23	0.173	2.457	0.228

Hence from the second test, it was evident that the layer of 10cm, is ideal to be used for analysing the performances of these mattresses. The difference between reflection values was almost 2%. Therefore, a layer of 10cm for all three materials was chosen, irrespective of the type and weight to keep the conditions constant.

Model 3A, 3B and 3C, when examined based on the processed results, it shows that the model 3A which used the material with 400g/m2 weight performs the best once placed with a thickness of 10cm above a single 1:4 rock slope. This is mainly because of the permeability and stiffness of the material. Model 3B and 3C, with materials B and C, respectively were able to absorb less wave energy and minimize reflections. For model 3B the material used was also less flexible, therefore it even performed less than model 3C which used material C, which was similar in the flexibility of model 3A material. It is an assumption that flexibility allows the material to break waves and be able to absorb energy such that the impact on reflections is less. The material properties were outside the project scope and hence were not analysed in detail.

Model 3D, based on the mangrove forest concept was also performed, however, the results indicate that it doesn’t work efficiently in terms of reflection. However, during the visual analysis of the test, it was observed that the energy dissipation after the waves passed through the vertical structure was impressive. This was mainly as the permeable material acted as a damper of energy, just how mangroves act in the coastal areas. In figure 51, the graph shows the reflection values of each model of variant 3. This clearly shows that model 3A performs the best.

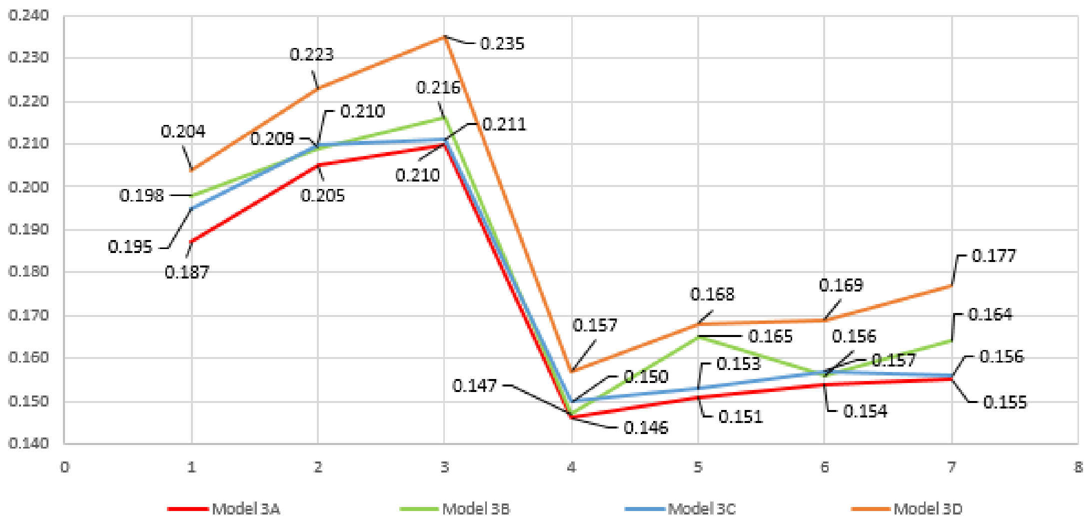

Figure 51: Reflection coefficient values for each model of variant 3.

The average reflection values of all four models are presented in figure 52, the differences between models 3A, 3B and 3C, are very small. Hence, material properties can even be neglected when looking at these values. For model 3D, the average reflection coefficient value is the highest when compared with 3A, 3B and 3C. This can be seen in the graph in figure 52. Therefore, model 3A is selected to represent variant 3 for comparison with other variants in the evaluation matrix.

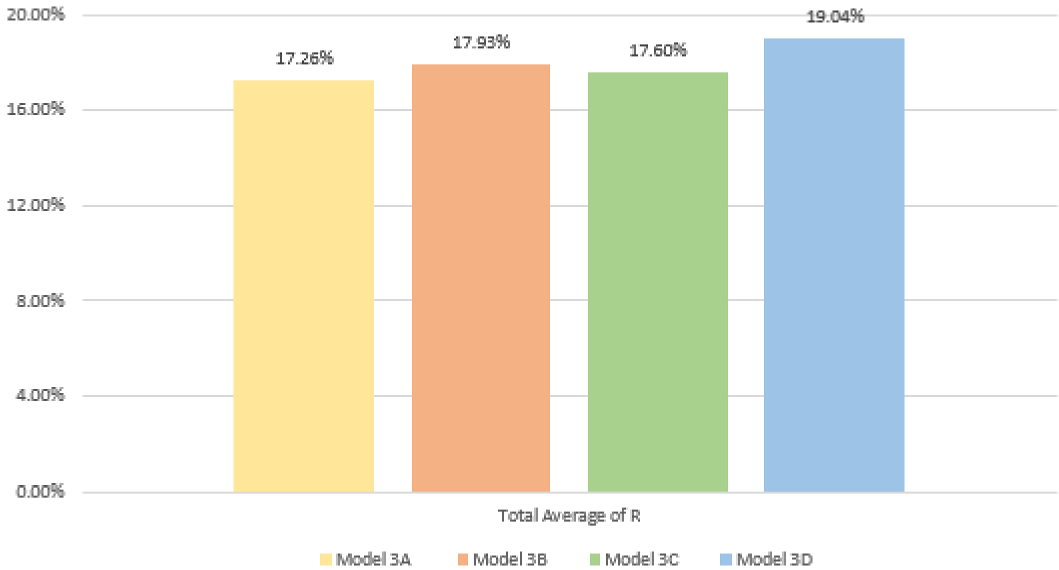

Figure 52: Average reflection coefficient values for each model of variant 3.

6.3 Performance comparison for variants

As performance is one of the main trade-offs for a recommendation of an optimized passive method for minimizing wave reflections, hence the best performing models of each variant are compared with each other based on their performance, which will be analysed on the model's average reflection coefficient value. For this purpose, the graph in figure 53, shows each variant's best-performing model's reflection values. After examining the graph, it is evident that models 1E and 3A, are very close and their values clearly show that. This is because both models have a similar configuration, however, model 3A has a 10cm layer of the permeable mattress on the top. The layer influences the reflection values and therefore, model 3A performs better than model 1E, which is a 1:4 normal rock slope. According to the results, the performance of the models is the following: 3A > 1E > 2A. However, at, a lower water depth, a tough competition between 3A and 1E occurs, and 1E performs better. As explained earlier, this is because for shorter waves the mattresses have less impact and are not very efficient in absorbing the wave energy from them. This is evident from the first two tests (6H13T19 and 6H16T21) of 0.6m water depth but in the third test (6H19T23), the waves are larger and in this case model 3A performs better with 21% reflection, compared to a rock slope with reflection value of 21.3%.

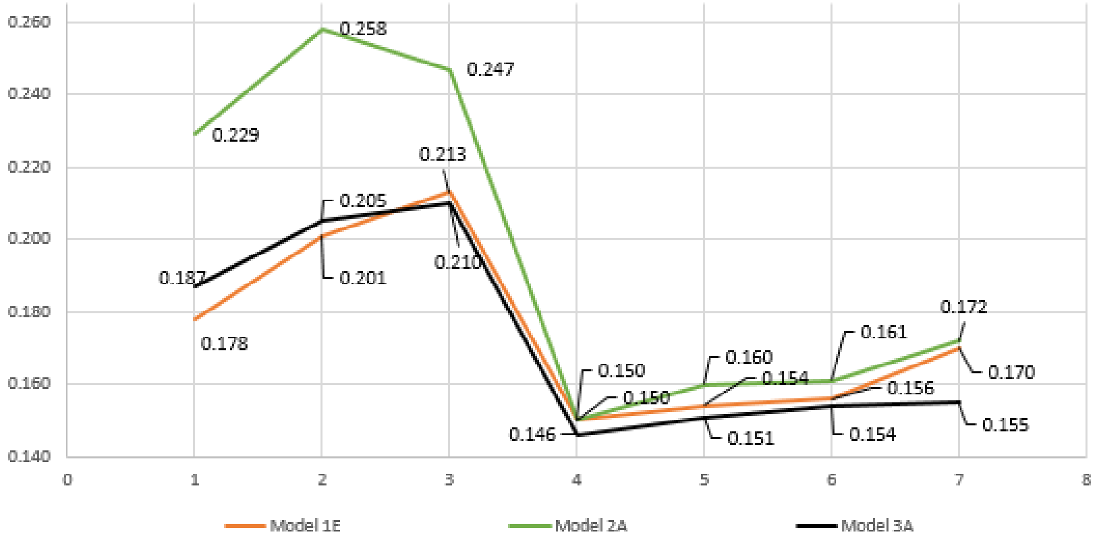

Figure 53: Reflection coefficient values for each wining model of all three variants.

As is visible from figure 54, the average reflection coefficient values show that model 3A has the best performance for minimizing wave reflections, the difference between the reflection coefficient of model 1E and 3A is 0.2%, which is very low.

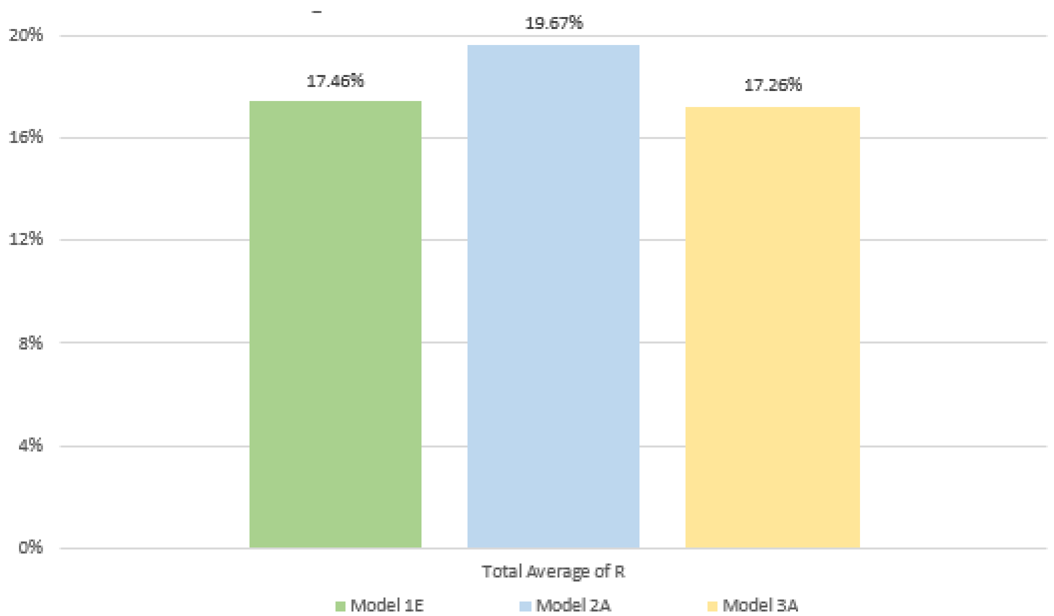

Figure 54: Average reflection coefficient values for each wining model of all three variants.

6.4 Evaluation Matrix

The first table below defines the criteria and their grading definitions. The second table shows the results of the evaluation of the variants based on the criteria from the first table. Based on the assessment, why the winning variant is selected is briefly explained as well.

Three different variants are assessed, and a multi-criteria evaluation matrix is conducted for the assessment. The score of a criterion can be 1, 2, or 3. 1 means that the variant scores low for this criterion and 2 means that the variant has a moderate score on the criterion. 3 indicates that the variant scores very good and is ideal under this criterion.

Criteria	Performance	Budgetary Impact	Feasibility
Scoring Definitions	1. Poor performance: Minimizing low wave reflections 2. Moderate performance: Minimizing moderate wave reflections. 3. Most favourable performance: Minimizing most wave reflection	1. Less Favourable: High costs to implement 2. Favourable: Moderate costs to implement. 3. Most favourable: Low costs to implement.	1. Low: No/small likelihood of being enacted. 2. Medium: Moderate likelihood of being enacted. 3. High: High likelihood of being enacted

	Scores			
	Performance	Budgetary Impact	Feasibility	**Total points**
Variant 1	2	3	2	**7**
Variant 2	1	1	1	**3**
Variant 3	3	2	3	**8**

From the evaluation matrix, it is evident that variant 3, is an ideal recommendation based on the trade-off – Performance, feasibility, and economic viability. The winning variant performs the finest for minimizing reflection and is not very expensive to implement and install. The cost of mattresses is not very high and it’s a promising solution, therefore, it is feasible and has a high chance of being implemented.

7 Discussions

7.1 Limitations of the research

The research was conducted within practical and professional standards, however as all researches have certain limitations, a few important limitations for this research are in this sub-section.

7.1.1 Space limitations

There must be a minimum defined distance between the models and wave height meters to capture and produce precise data that can be used for accurate analysis. The length of the flume is 7m, and therefore a minimum distance of 3m was decided to keep between the WHMs and models. The WHMs could not be placed outside the flume as that would bring other reflections and distortions from side walls and back walls of the Pacific basin into account. They were to be minimized and hence on the advice of a specialist the WHMs were placed inside the flume. Due to this distance limitation, a single slope of 1:5, could not be constructed and tested as well. 1:5 slope results were gathered using a combination of slopes where a 1:2 slope was constructed as the first slope and then a 1:5 slope as explained in sub-section 5.1 with detailed figures. Hence, for a better understanding and results of a consistent 1:5 rock slope, future space limitations can be investigated.

7.1.2 Rock sizes

From the experiences of hydraulic specialists at Deltares and considering the permeability factor uniform rock size of 32-50mm diameter was sought to be ideal for use and hence was chosen for performing the tests. As the experiments were conducted in a limited time frame, testing several different models with different rock sizes was practically not feasible due to time and labour limitations. Therefore, the rock sizes for all the models were kept constant and that resulted in the optimization of the construction process. However, due to this, the effect of different rock sizes and their permeability could not be investigated.

7.2 Maintenance of the permeable mattresses

The permeable mattresses are durable and strong to be installed in various industries and areas. However, they are not very commonly used as a wave dampening beach yet. In China, they are being used in a facility, therefore the maintenance matters and their costs were not in the scope of the project. Hence, they were not investigated. The wave energy sometimes may be too much for the mattresses over a long period, it may cause the stiffness and permeability of the material to be affected. This was not investigated as it was beyond the scope of the project.

7.3 Validity of the research

This research was based on practical experiments that were conducted with accurate data from the database, a legitimate and strong research framework, and inputs from Deltares specialists. For each variant consisting of several different models, a test series was performed with a combination of different hydrodynamic conditions. Based on the results of the model experiments that were conducted in the Pacific basin, an evaluation matrix was used to assess the models and provide recommendations for an ideal solution that is based on a trade-off between performance, feasibility, and cost-efficiency. Hence the results of this research can be validated and used as a basis for future research.

8 Conclusions

This research aims to minimize wave reflections and optimize the wave energy dissipation in the energy dissipation zone of the ‘Atlantic basin’. This is done by using a passive wave energy absorption method, that aims to achieve low reflection rates, and high energy dissipation rates in the wave energy dissipation zone. It is preferred that a passive absorption method is used, which is a trade-off between performance, cost efficiency and feasibility. The report mentions how these variants are effective against the wave reflection and the result completes the objective of the research. Furthermore, the report demonstrates a comparison of the different variants that are tested and gives a brief overview of the factors that affect the reflections and wave energy dissipation. The main research question was therefore formulated as follows:

What optimizations can be made in the wave dissipation zone to enhance wave absorption and minimize wave reflection in the Atlantic Basin?

For this purpose, practical experiments with a series of different hydrodynamic conditions were concluded in the Pacific basin. The experiment analysed three main variants consisting of several models with different configurations.

- Variant 1: 1:4 rock slope consisting of smaller and uniform rock size
- Variant 2: Parabolic damper slope
- Variant 3: Permeable mattress layer above a 1:4 rock slope with small and uniform rock size

Generally, all three selected variants for wave reflections performed well, however, the permeable mattresses outperformed other variants in terms of performance with an average reflection coefficient value of 17.26%. In the current situation, the reflection values lie between 16-29%, with an average value of 22%. For variants 2 and 3, the average reflection values are 19.67% and 17.46% respectively which lie below 22% as well, which shows that all three variants performed well as alternatives.

These results agree with the expectations, as slopes with smaller and uniform rock sizes or permeable materials have higher porosities and therefore cause fewer reflections. It also shows that the steepness has a significant effect on wave reflections, therefore considering space, the less steep the slope is constructed the ideal are conditions for minimizing wave reflections. Technically variant 3, uses the concept of variant 1 and improves its overall efficiency due to the permeable mattress. With the help of the set criterion in the evaluation matrix, it is concluded that under given boundary conditions and limitations, variant 3 is an effective solution for optimizing the wave energy dissipation zone by enhancing wave absorption and minimizing wave reflection in the Atlantic Basin.

The only limitation of variant 3 is that as it’s an innovative variant, therefore not a lot of information on the material’s long-term interaction with wave energy and its required maintenance is present.

8.1 Recommendations

For further improvements in the efficiency and design of the variants, the following recommendations are made for further research.

- The rock size that was being used previously was too large which affected the existing slopes' porosity. As permeability is affecting energy dissipation, the effect of different rock sizes can be investigated in future.

- Due to space limitations, the consistent rock slopes with steepness lower than 1:4 were not investigated, for future research, these can be considered.

- The permeable mattresses were used as vertical layers in front of a rock slope, however, for minimizing reflections from the side and back of the basin, thick layers of mattresses and their effect on reflection can also be further investigated.

- To keep these rocks stable as can be seen in the figures, a steel mesh was used. Even though by visual observation, the rocks were not rolled by the given wave conditions however for the design implementation in the Atlantic basin it is suggested to use a steel mesh throughout to keep the rocks intact and more stable, or a better alternative can be investigated for future.

- Similarly, to keep the mattresses attached to the rock slope, different alternatives that keep the mattresses stable and don't affect their primary goal, can be examined in future.

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10 Appendices

10.1 Appendix A

An excel file is used for the input data and complete results of the experiments conducted. This file can be found in the ZIP file for the Graduation thesis, Rawfaeh Abbasi (76136) – Appendices – Experiment data and results.

10.2 Appendix B

An excel file is used for selecting the hydrodynamic conditions for the test experiments, the excel file consists of data of all previous tests executed in the Atlantic basin.
This file can be found in the ZIP file for the Graduation thesis, Rawfaeh Abbasi (76136) – Appendices – Database Atlantic Basin.

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