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DOI 10.3390/w12092471
ISSN 2073-4441

Publisher: MDPI

water

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Protecting Coastlines from Flooding in a Changing Climate: A Preliminary Experimental Study to Investigate a Sustainable Approach

Matteo Rubinato [1,2,*], Jacob Heyworth [1] and James Hart [1,2]

[1] School of Energy, Construction and Environment, Coventry University, Coventry CV1 5FB, UK; heywort2@cucollege.coventry.ac.uk (J.H.); ac5950@coventry.ac.uk (J.H.)
[2] Centre for Agroecology, Water and Resilience, Coventry University, Ryton Gardens, Wolston Lane, Coventry CV8 3LG, UK
* Correspondence: matteo.rubinato@coventry.ac.uk; Tel.: +44-(0)-24-7765-0887

Received: 20 July 2020; Accepted: 28 August 2020; Published: 3 September 2020

Abstract: Rising sea levels are causing more frequent flooding events in coastal areas and generate many issues for coastal communities such as loss of property or damages to infrastructures. To address this issue, this paper reviews measures currently in place and identifies possible control measures that can be implemented to aid preservation of coastlines in the future. Breakwaters present a unique opportunity to proactively address the impact of coastal flooding. However, there is currently a lack of research into combined hard and soft engineering techniques. To address the global need for developing sustainable solutions, three specific breakwater configurations were designed and experimentally compared in the hydraulic laboratory at Coventry University to assess their performance in reducing overtopping and the impact of waves, quantifying the effectiveness of each. The investigation confirmed that stepped configurations work effectively in high amplitudes waves, especially with the presence of a slope angle to aid wave reflection. These results provide a very valuable preliminary investigation into novel sustainable solutions incorporating both artificial and natural based strategies that could be considered by local and national authorities for the planning of future mitigation strategies to defend coastal areas from flooding and erosion.

Keywords: climate change; coastal protection; coastal flooding; sea defence; experimental modelling; sustainability

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1. Introduction

In the last 140 years, scientific research has established that average sea levels have significantly increased [1–3], and this phenomenon is accelerating. This is a critical issue as even small increases can have devastating effects on coastal habitats [4–7]. Rising sea levels have been identified as a major cause of flooding events across the world [8,9]. Flooding poses a threat to property, safety, and the economic wellbeing of coastal communities [10]. In fact, considering that coastal areas provide a great amount of economic and leisure activities, they contribute significantly to the local and national economy. Thus, more people are continuously attracted to coastal zones contributing to an intense urbanization of these areas. To aggravate this situation, the ecosystems are also threatened by the impact of human activities in coastal areas as well as by the increase of natural extreme weather events (e.g., intensity and duration of storms, floods) generated by climate change, which interfere with local wave climate and changes in morphological beach characteristics [11]. More frequently, high tides reach values that cause costal recession and high sediment transport deficit, and hence, it is necessary to protect these areas with various coastal structures to reduce or at least to mitigate coastal erosion problems. As a result, impacts of climatic variations are usually the greatest along the coast [12–14]. However, many of the current coastal protections (e.g., groins, seawalls, and emerged breakwaters) were built with the single purpose of protecting the coast, without environmental or economic concerns, maintenance costs, or the negative consequences that such structures could cause up to considerable distances along the coast. Coastal regions and their managers consequently face ever-increasing challenges to accommodate safely both the growth of these areas and their development [15].

Traditionally, bulkheads, seawalls, and revetments have been the most commonly used type of shoreline infrastructure implemented as a primary response to coastal hazard. Other applications such as shoreline armouring have also been adopted to protect coastal property from hazards like erosion and flooding [16]. However, there has been a growing interest during the last decade in developing sustainable approaches to guarantee solutions that could deal with the daily and emergency issues in parallel with promoting downtown living [17–19]. For example, in Hong Kong, the land policy emphasizes ecological protection [20–23] and reclamation, enhancing the innovative value in sustainable coastal land use management.

In line with these new approaches, recent studies conducted by scientists and practitioners have demonstrated the benefits of nature-based strategies for restoring degraded coastal ecosystems and mitigating risks including natural defences and “living shorelines” [24,25]. Without any human interaction, shorelines are mainly comprised of biogenic habitats (e.g., saltmarshes, mangroves, oyster and coral reefs) in their natural conditions. These natural coastal habitats secure the provision of essential habitat for marine life, promotion of favourable water quality, and reduction of shoreline erosion and flooding by attenuating waves, stabilizing sediments, and dampening surge [24,26,27]. As such, they are widely valued for their environmental benefits. By adopting alternative sustainable approaches, it is possible to enhance the quality of natural environments along the coasts that can help reduce the impact of coastal hazards [28–32].

It is clear that a crucial goal is to identify nature-based structures that can protect coastal areas and provide a low-cost option to effectively reduce the damaging effects of extreme meteorological events on coastal populations by absorbing storm energy [33], thus enhancing the quality of lives of people living in the surrounding areas. These green areas (including vegetation such as coral reefs or aquatic plants) typical of nature-based solutions could aid the production of sediments (sea grass beds and coral reefs) or could store and hold the sand together (mangroves and coastal dunes) [34]. For example, the benefits provided by coastal herbaceous wetlands in helping to reduce economic damages generated by hurricanes and their impacts have already been demonstrated [34,35].

One type of solution that has not been considered is the mix of artificial and green solutions. Human design structures can guarantee resistance to strong wave impacts and reduce the amount of flooding in coastal areas. However, if mixed with natural ecosystems/green solutions that can still help to reduce wave energy, coastal erosion, and flood hazards [36–41], it could also be possible to recover the natural functioning of the entire coastal area and target future conservation and restoration processes [35–37]. In brief, this option promotes coastal protection through the recovery of the natural functioning of natural ecosystems by means of conservation and restoration actions [38,42]. The trade-offs between socioeconomic development and conservation can be integrated [43–45], which will help with improving coastal development and promoting a sustainable coastal development.

This study provides a comprehensive review of existing hard and soft solutions adopted for coastal protection. Furthermore, it will experimentally investigate and compare preliminary sustainable approaches that could deliver both protection from coastal flooding and the added benefit of conserving, sustaining, and restoring valuable ecosystem functions and services to local communities [46–51].

Hard and Soft Engineering Solutions for Coastal Protection

To identify structural designs that assess new sustainable approaches for coastal protection and to highlight the advantages and disadvantages of existing hard and soft engineering solutions adopted to protect coastal lines, a review was conducted on the techniques available to date. Table 1 summarises the results obtained.

Table 1. A review of existing coastal protection measures with advantages and disadvantages identified for each solution.

Engineering Method	Hard (H) or Soft (S)	Brief Description	Advantages	Disadvantages
Sea wall [52–54]	H	Wall built by the coastline (usually built along the front of cliffs to protect settlements and often curved to reflect wave energy).	• Effectively dissipates wave energy from high impact waves • Long life span and re-assures local communities	• Prevents the movement of beach material along the coast and beach may be lost without replenishment • Maintenance high and expensive to construct
Breakwater [55–57]	H	When waves hit the breakwaters, the power of the wave is dissipated on the breakwater structure so the erosion impact on the cliffs is much less.	• Effectively dissipates wave energy • Easy to maintain	• Prevents the movement of beach material along the coast and beach may be lost without replenishment
Tetrapods [58,59]	H	Multi angular concrete shaped that are preformed and tipped onto the beach to form interlocking components.	• Effectively dissipate energy • Easy installation	• Only applicable at low water level and usually used offshore
Gabions [60–62]	H	Wire cage with pebbles stones and rocks inside. Protect the coastline by reducing the energy of the wave before it directly hits the cliffs	• Allow the build-up of a beach • Easy installation • Relatively cheap to construct • Dissipated wave energy	• Regular maintenance required as faces constant high impact waves • Looks unnatural and not robust
Revetments [62–66]	H	Sloping structures on banks or cliffs built in such a way to absorb some of the energy from the incoming water.	• Effective way of dissipating energy by utilising beach like slope method. • Cheaper and less intrusive than sea walls	• Still allows for erosion to take place • Unsuitable where wave energy is high and difficult to maintain

Groynes [52,67,68]	H	Wooden barrier built at right angles to the beach to retain material and prevent longshore drift.	• Prevents the movement of beach material along the coast (beach encourages tourism) • Relatively cheap to construct	• Unattractive structure • Trapping sediment can prevent the replenishment of sediment further down the coastline increasing erosion elsewhere
Boulder Barrier [69,70]	H	Large boulders piled up on the beach.	• Prevent the effects of coastal erosion effectively • Help to prevent coastal flooding	• Boulders can become easily dislodged with the force of the sea. As a result, they may cause more damage during transportation • Requires regular maintenance
Mangrove Planting [71–74]	S	Mangroves planted along coastline to dissipate wave energy, trap sediment, and control water levels	• Can help to prevent coastal flooding • Can trap pollutants from coming back to land Effective at trapping sediment • Benefits to marine life	• Not effective against high waves. Struggle to adapt to certain climates
Offshore Reefs [75,76]	S	Artificial sand/gravel offshore deposits designed to intercept wave action and dissipate energy.	• Effectively dissipates wave energy • Benefits marine life	• Impact is comparatively a lot less than many hard engineering techniques • Deposits require replacing
Seagrasses [77,78]	S	Submerged aquatic vegetation ecosystem with thick stems.	• Effectively dissipates wave energy • Sustainable solution • Benefits marine life • No maintenance	• Not effective against large storm waves • Seagrasses may be damaged as not protected
Sills [79,80]	S	Shingle or sand beach that is often submerged.	• Effectively dissipates wave energy	• Deposits can often require replacing
Beach nourishment [52,81–83]	S	Replacing beach or cliff material that has been removed by erosion.	• Beaches dissipate wave energy effectively • Easy to monitor impact of longshore drift	• Not sustainable as problem will continue and more material will require replacing • Material

Managed retreat [52,84–86]	S	Allocated areas of the coast that can erode and flood naturally (low value areas)	• Low costs in protection measures	• Loss of land over prolonged period may mean protection measures are required down the line
Beach Dewatering [75]	S	The artificial lowering of the water table within beaches by a system of drains and pumps	• Alternative to more traditional methods of shoreline stabilization • Stabilization of sediments on the surface of the beach • Fast recovery of the beach after storms • Build-up of a sand stock serving as a “buffer-stock” for the following storms	• Expensive • Maintenance • Can contaminate bodies of water

To date, as previously mentioned, natural solutions have been adopted to preserve and/or restore coastal areas. For example, the presence of wetlands has demonstrated to retard waves and the mass flux of water with the presence of vegetation [87]. Despite a few studies on the effect of these vegetated surface, there are not specific guidelines available to determine the optimal shape of the vegetation to consider, the density to be selected, or the height of the vegetation to make it fully under water or emergent. Therefore, to seek this information, this preliminary experimental study was conducted to propose an approach that could combine hard and soft engineering characteristics; thus, it can be the base for a sustainable solution to be adopted. Despite initially using non-real vegetation due to the limitations explained below, hard and soft engineering techniques should be combined in a more ecological way (e.g., facilitating the growth of aquatic plants next to artificial structures), to achieve a less invasive structure on the environment and mitigate the negative influence of hard engineering on ecosystems [49]. In order to identify a feasible "softer" hard sustainable engineered solution, the paper experimentally compared three solutions tested in a wave tank with a physical model, which are presented in Section 2, on the foreshore of the beach and thus did not impede the wave energy or prevented land to sea interaction. The main purpose of the submerged breakwater systems identified is wave attenuation, with the idea of creating splashing and hydraulic conditions that can support sediment capture, helping at the same time in the mitigation of storm surge [30].

2. Materials and Methods

The experimental work presented in this paper was conducted using a wave flume at the Sir John Laing Building, Coventry University (Figure 1). The flume is 18 m long, 1 m deep, and 0.6 m wide. A wave generator is located at the upstream end of the flume while a beach is located at the downstream end to dissipate the energy induced by the waves reproduced.

2.1. Experimental Configurations

To identify sustainable breakwater solutions previously mentioned in Section 1 and investigate their benefits against the use of hard and soft breakwater strategies, three different configurations of sustainable breakwaters (A, B, and C; Figure 2) have been designed and tested within the flume for their effect on overtopping volume and wave attenuation. These sustainable breakwater solutions were tested under a variety of hydraulic wave conditions characterized by dissimilar frequencies and amplitudes.

Figure 1. Wave flume apparatus. Example of wave generation along the flume (**left**), wave generator at the upstream section of the flume (**centre**), and dissipation beach at the downstream section of the flume (**right**).

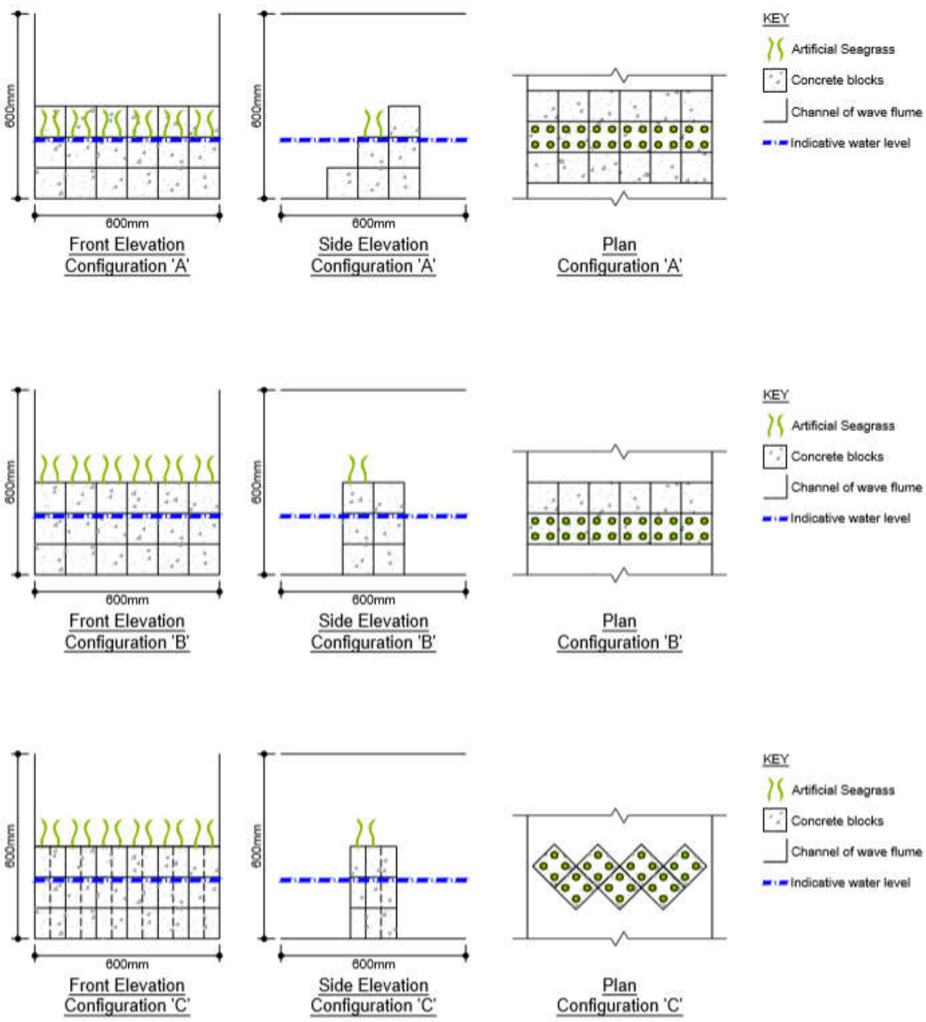

Figure 2. Sustainable coastal protections. Configurations A–C identified in this study.

Configuration A consists of a partly submerged breakwater wall with three steps and artificial vegetation located on the second step of the structure to simulate thick stem vegetation, as displayed in Figure 2. Studies into the wave overtopping of stepped revetments [64] pinpointed that their effectiveness is due to the introduction of slope roughness. Furthermore, it was highlighted that stepped structures, constituting of a slope with uniform roughness, can reduce overtopping volumes of breaking waves up to 60% compared to a smooth slope [64]. This configuration was therefore designed with uniform steps to gradually take the energy out of the wave as the flow could be channelled up the face of the structure. By utilising this approach, the wave collision could be less direct, and water may pass over the structure with less energy rather than generating intense splashing. Vegetation installed on the second step aims to assist with creating increased friction and dissipate wave energy prior to the overtopping. When thinking about reflected waves, the aim is that the sloped shape of the structure could aid destructive interference once the reflected wave meets the incoming waves that they will be out of phase, resulting in the two waves cancelling each other out and giving a reduced wave impact thereafter.

Configuration B is a flat facing and partly submerged breakwater wall with artificial vegetation located on top of the structure (to simulate thick stem vegetation) as shown in Figure 2. This configuration was used to optimize existing hard infrastructures (sea walls) where it would be possible to notice nature adapting to the existing conditions and growing on surfaces not ideal (concrete). Furthermore, this configuration could also replicate the forces interaction between artificial and natural solution where the last layer of the hard structure (seawall) is an ideal environment for coral reefs and porous structures to develop and grow under control. This configuration has been mainly considered to observe which kind of effects could have vegetation on top of existing structures for the simplest case of seawall.

Configuration C is a partly submerged breakwater wall with angled blocks and artificial vegetation located on the top of the structure (to simulate thick stem vegetation), as shown in Figure 2. A study conducted on breakwaters by Ahmadian, 2016 [88], detected several features influencing the effect of the incident wave impact on structures. This work informed that wave breaking, or turbulent losses, can be increased with geometrical alterations, structural characteristics, and the water to structure depth ratio [88]. By incorporating angled blocks, it provided a streamlined method of cutting through incident waves. In turn, this caused waves to become more turbulent, and energy depleted gradually prior to hitting the main body of the wall, rather than causing an instant impact. This configuration allowed comparison of results against the wall shown in Figure 2, to recognise if geometrical alterations, such as streamlining the concrete blocks, assist in dissipating wave energy, in contrast to the high impact stopping force that the flat facing angular wall can offer. Vegetation on the top was intended to dissipate the energy of any overtopping waves.

For each of the three structural configurations displayed in Figure 3, experiments were conducted both with and without a testing platform. The beach in the flume has a gradient of 4.5%. Existing studies expressed [89–91] the importance of a recurved wall profile for high wave return walls, since they define the trajectory of the returned water jet. Shallow angles proved the most effective in attenuating and reflecting waves. Therefore, all the configurations were tested with and without the platform, so that the datasets obtained could have been compared to assess the effectiveness of a slope angle that aims to reflect wave energy.

Figure 3. Overall geometrical configurations.

All the three coastal protection structures tested in this research where built with different configurations of concrete cubes (Figure 3). These had been manufactured from a normal mix with a strength of 20N/mm^2 (fck) and proportions 1:2:3:0.5, Portland cement, fine aggregate, 10mm coarse aggregate and water. A total of 36 (100 × 100 × 100 mm) cubes were cast and left to cure for 28 days to achieve full strength.

To measure overtopping volumes, a vertical overtopping collection board was manufactured from plywood (600 × 300 × 10 mm), with small arcs at the base, allowing the water to pass freely between either side of the structure. This allowed a detachable metal collection tray (600 × 200 × 100 mm) to be hooked on the plywood wall as demonstrated in Figure 4. The wall was located on the foreshore slope in the flume (14 m) and determined the point at which overtopping was being collected. A ruler (accuracy ±1 mm) was used to measure the height of water in the tray prior to testing and after simulation to allow the change in volume collected to be calculated. From this collection method, a volume was provided in litres for resultant graphs by utilising the following calculation:

$$V_c = (W_w \times L_w \times H_w)/1000 \quad (1)$$

where V_c is the volume collected = overtopping (litres), W_w is the measuring device width (20 cm), L_w is the measuring device length (60 cm), H_w is the measuring device depth measured (cm), and 1000 is the conversion factor used to transform from cubic metres to litres.

As the collection device had a maximum capacity of 12 litres, a measuring jug was used to empty water back into the flume on the side of the incoming wave to ensure the water levels either side of the wall remained constant. The testing platform (600 × 300 mm) for assessing structures with and without a slope angle can also be noticed in Figure 4. This had a varying thickness across its length to account for the sloping foreshore (1 in 20 gradient).

Figure 4. Overtopping collection device. The red box highlights the testing platform.

2.2. Hydraulic Testing Conditions

Two different wave spectrums were used in this study in order to simulate the way different oceans act. This research uses the following wave spectrums within its testing:

- Sine waves simulated regular waves that occur in bodies of water. This aimed to investigate the different structural configurations performed with a regular and repeating low-energy wave. During the tests, frequency and amplitude were varied. To investigate the effect of changing frequency, the frequency ranged from 0.2 Hz up to 0.5 Hz, with overtopping measured at intervals of 20 seconds. The amplitude was the control variable at 0.05 m. The overall duration of each test was 60 seconds. The reason for changing the frequency was to assess how each design can influence the reflection of incoming waves to create destructive interference and review its effect on overtopping volumes collected. The experiments then assessed changing amplitudes, where values of amplitude tested ranged from 0.05 m to 0.09 m, in intervals of 0.01 m. As a control measure, the frequency remained at 0.02 Hz throughout (this was the maximum possible due to limitations with the calibration of the equipment tested). Again, the overall testing duration was 60 seconds. This comprised of a 10 second run time for each experiment, 20 seconds to allow for the observation of the water, and a further 30 seconds allowing the water to rest prior to additional testing. The reason for testing change in amplitude was to find patterns to help assess each designs' effectiveness in attenuating and reflecting wave energy under increasing wave height.
- JONSWAP waves to simulate varying waves patterns found in ocean waters, where there are intermittent waves at different frequencies and irregular amplitudes are of a higher energy. This aimed to mimic realistic water effects of varying wave forms on a structure.

By using an off-the-self computer program associated with the control software for the wave tank piston, irregular patterns in waves could be produced in a synthesis to simulate a JONSWAP wave.

Table 2, shown below, displays the characteristics of these waves.

Table 2. JONSWAP simulation parameters.

Gamma (γ)	Height of Waves	Amplitude	Period of Waves (Tp)	Max Frequency	Min Frequency
6.6	0.6 m	0.3 m	0.9s	2 Hz	0.2 Hz

The figures for the JONSWAP synthesis above were chosen to simulate a higher wave energy, compared to that tested in the sine wave experiments. The chosen JONSWAP wave synthesis had a frequency between 0.2 Hz to 2 Hz (compared to 0.2 Hz to 0.5Hz tested in sine waves) and an amplitude of up to 0.3 m (which is significantly higher than the amplitudes of 0.05–0.09 m tested in the sine waves testing). The purpose of testing in these more extreme conditions was because a JONSWAP simulation relates to irregular wave patterns, where there would likely be a potential storm situation. Table 3 summarises the conditions for all the experimental tests conducted.

Due to the impracticability of growing real seagrasses, a physical model has been made to reproduce submerged vegetation by using straws and plastic sheets to mimic the thick stem structure and broad narrow leaves as shown in Figure 5. Translucent 100 mm straws were used and cut to replicate the 'V' shape for the plastic sheets to slot in. The plastic sheets were fairly stiff and had a course surface providing increased roughness and stood at about 100 mm high making the overall vegetation height 100–150 mm. This was then held together with tape and stuck to the holed board with glue. This kind of flexible setup aimed at representing the binding between interlocking structures that together can create a more sustainable barrier needed to combat the wave energy towards the beach to be protected, as well as miming the behaviours of reefs and submerged vegetation. However, it is also essential to consider the limitations associated with the choice of not using actual seagrass. By using similar structures next to each other, realistic and complex plant morphologies such as flexing elements with varying cross-sectional area over depth could not be replicated, leading to dissimilar flow patterns generated by a variety of stems, branches, roots, and leaves. Even if the height of the stems or the length of the roots can interfere with erosion, deposition patterns, transport of pollutants, stability of the plant, and exchange of nutrients between one type of vegetation to another, this was not the main focus of the study presented in this paper.

The choice of this artificial solution was made to isolate specific responses within the laboratory experiment under controlled conditions and to inform future work with real vegetation. Ideally, future studies will also incorporate the testing of specific patches and geometries which could generate a variety of drag coefficients C_D and Reynolds numbers *Re*.

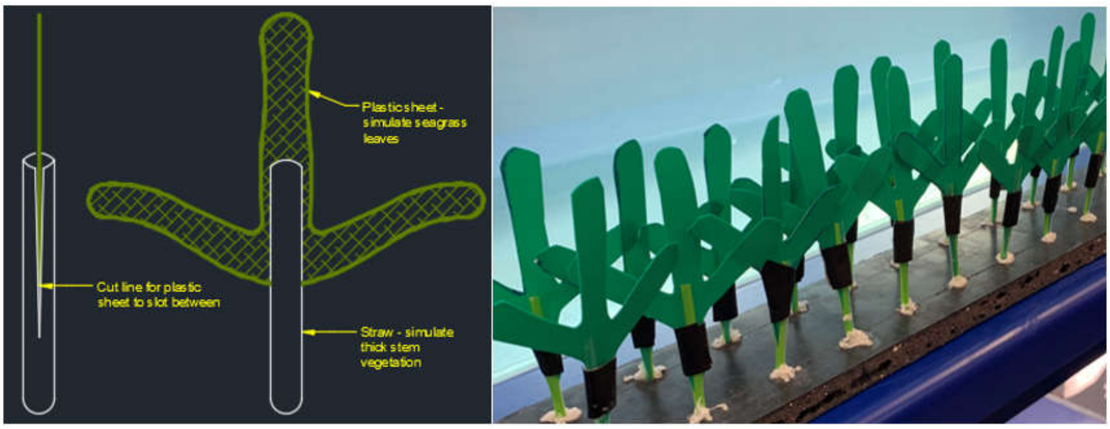

Figure 5. Artificial sea grass reproduced.

Testing was repeated three times for each hydraulic condition and corresponding structural configuration simulated. Simulations were also recorded using a camera to allow further analysis of the hydraulic behaviours (e.g., wave impact on the protective structures).

Table 3. Experimental testing conditions.

Analysis	Hydraulic Conditions	Structural Configuration	Testing Platform Used
Frequency Vs Overtopping	Sine Spectrum	A	Yes
Frequency Vs Overtopping	Sine Spectrum	B	Yes
Frequency Vs Overtopping	Sine Spectrum	C	Yes
Frequency Vs Overtopping	Sine Spectrum	A	No
Frequency Vs Overtopping	Sine Spectrum	B	No
Frequency Vs Overtopping	Sine Spectrum	C	No
Amplitude Vs Overtopping	Sine Spectrum	A	Yes
Amplitude Vs Overtopping	Sine Spectrum	B	Yes
Amplitude Vs Overtopping	Sine Spectrum	C	Yes
Amplitude Vs Overtopping	Sine Spectrum	A	No
Amplitude Vs Overtopping	Sine Spectrum	B	No
Amplitude Vs Overtopping	Sine Spectrum	C	No
Overtopping Vs Time	JONSWAP Spectrum	A	Yes
Overtopping Vs Time	JONSWAP Spectrum	B	Yes
Overtopping Vs Time	JONSWAP Spectrum	C	Yes
Overtopping Vs Time	JONSWAP Spectrum	A	No
Overtopping Vs Time	JONSWAP Spectrum	B	No
Overtopping Vs Time	JONSWAP Spectrum	C	No

3. Results

This section presents a description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

3.1. Sine wave Conditions—Frequency Analysis

Resultant data from the testing of overtopping against change in frequency are displayed in Figures 6 (no slope angle) and 7 (with slope angle) below.

To identify a process which could directly provide a comparison between the performances of each structure tested, for each set of frequencies run within the experimental facility, these values have been normalized by using the maximum frequency used, which corresponds to 0.5 Hz. The same procedure was conducted for the overtopping values, which were normalized by using the maximum overtopping amount recorded within the entire set of tests under each configuration. Table 4 displays the experimental datasets collected for these hydraulic conditions.

From the data presented in and Figures 6 and 7, it can be seen that all data sets show an initial increase in overtopping with wave frequency, which obtains a peak value and then decreases with wave frequency. A polynomial second order trend line has been fitted to the data to demonstrate this trend. For tests with no slope angle, Configuration A first obtains the peak value, followed by C and then B. For tests with a slope angle, the peak of Configuration C shifts notably, meaning that now Configuration C is the first to hit peak value, followed by A and then B.

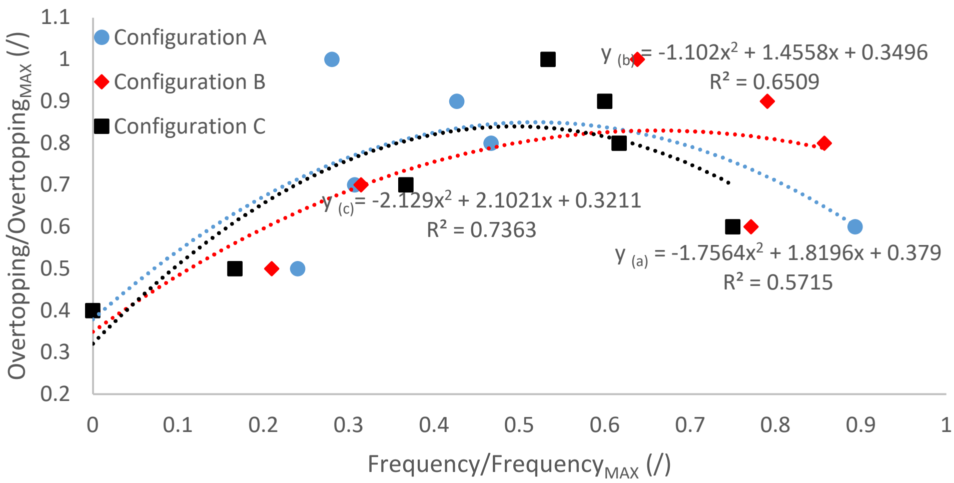

Figure 6. Sine wave hydraulic conditions; relationship between wave crest amplitude A and overtopping volume Q (averaged results); no slope angle adopted within the experimental facility.

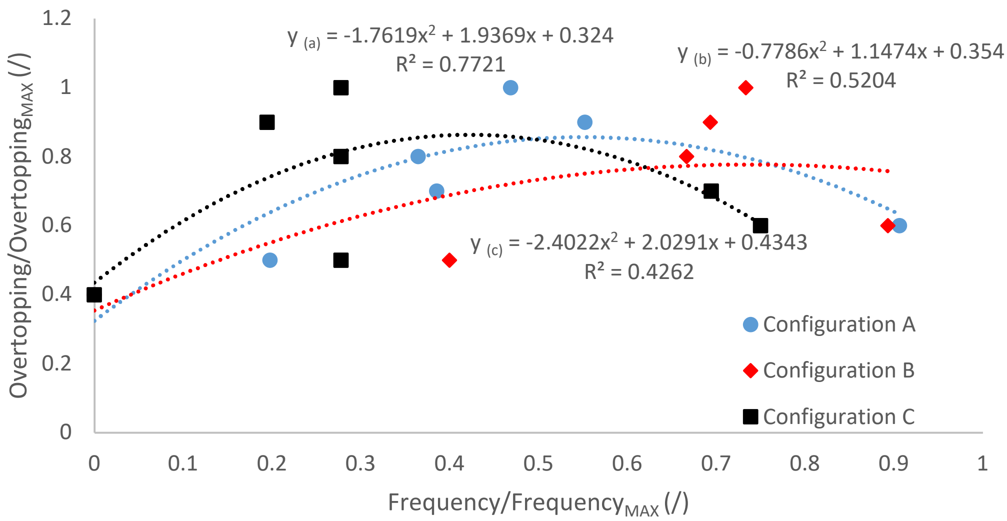

Figure 7. Sine wave hydraulic conditions; relationship between wave crest amplitude A and overtopping volume Q (averaged results); slope angle adopted within the experimental facility.

Table 4. Experimental testing parameters collected for sine wave (F = frequency) with and without slope angle.

F	Conf. A	Conf. B	Conf. C	Conf. A	Conf. B	Conf. C
(Hz)	Overtopping Volume (L)	Overtopping Volume (L)	Overtopping Volume (L)	Overtopping Volume (L)	Overtopping Volume (L)	Overtopping Volume (L)
	No slope angle			With slope angle		
0.2	0	0	0	0	0	0
0.2	0	0	0	0	0	0
0.2	0	0	0	0	0	0
0.25	0.6	0.6	0.36	0.6	1.2	0.24
0.25	0.6	1.2	0.24	0.96	1.44	0.6
0.25	0.96	0.84	0.6	0.72	0.96	0.36
0.3	3	3	1.8	3	2.4	0.6
0.3	2.4	3.6	1.2	3.6	3	1.2
0.3	2.64	3.12	2.4	3.84	2.64	1.44

0.35	0.6	1.2	0.6	1.2	1.8	0.6
0.35	1.2	1.56	1.2	1.44	2.4	1.2
0.35	0.96	1.2	0.84	1.8	2.04	1.2
0.4	1.2	3.6	1.2	1.2	1.8	0.24
0.4	1.2	4.2	1.8	1.8	2.4	0.6
0.4	1.8	3	1.44	1.2	1.8	0.36
0.45	1.2	3.6	1.2	2.4	2.4	0.24
0.45	1.2	3	1.44	1.8	1.8	0.36
0.45	1.44	3.36	1.68	2.16	2.04	0.24
0.5	0.6	2.4	1.2	1.8	1.8	0.36
0.5	1.2	3	1.44	1.56	2.4	0.24
0.5	0.72	2.64	1.2	2.04	2.4	0.6

3.2. Sine Wave Conditions—Amplitude Analysis

As shown in Figures 8 and 9 (results summarised in Table 5), Configuration C was the most effective at attenuating wave energy and has the least overtopping volume, closely followed by Configuration B.

Configuration A was the least effective at attenuating wave energy, as the overtopping volumes measured greatly exceeded that of the other configurations, often with the overtopping device reaching full capacity in large amplitude waves.

All configurations showed a linear increese in overtopping with wave amplitude.

Regression analyses presented in Figures 8 and 9 all show correlation values of $R^2 > 0.93$. There is only a slight change in results when a slope angle is present that becomes increasingly evident under large amplitudes exceeding 0.07 m. This indicates that when the structures are subject to high amplitude waves, the effect of a slope angle is more important as the resultant wave shape can be reflected back away from the structure rather than in a vertical profile.

High amplitude waves also have increased energy, so the importance of reflecting this wave energy is emphasised.

Table 5. Experimental testing parameters collected for sine wave (A = amplitude) with and without slope angle.

A	Conf. A	Conf. B	Conf. C	Conf. A	Conf. B	Conf. C
(m)	Overtopping Volume (L)	Overtopping Volume (L)	Overtopping Volume (L)	Overtopping Volume (L)	Overtopping Volume (L)	Overtopping Volume (L)
	No slope angle			With slope angle		
0.05	0	0	0	0	0	0
0.05	0	0	0	0	0	0
0.05	0	0	0	0	0	0
0.06	0.6	1.2	0.36	0.6	1.2	0.24
0.06	0.84	1.44	0.36	0.6	1.56	0.6
0.06	0.6	0.84	0.6	0.84	0.96	0.36
0.07	4.2	2.4	1.2	3.6	3	1.2
0.07	4.8	3	1.44	4.2	3.24	1.56
0.07	4.2	2.64	1.2	4.56	3.6	1.56
0.08	7.2	3.6	1.8	7.2	3.6	1.8
0.08	7.8	3.84	2.4	6.6	3.84	2.4
0.08	8.4	4.2	2.4	7.56	4.2	1.8
0.09	12	4.2	3	12	4.2	2.4
0.09	12	4.8	2.4	10.8	4.8	3
0.09	12	4.56	3	9.6	4.8	2.88

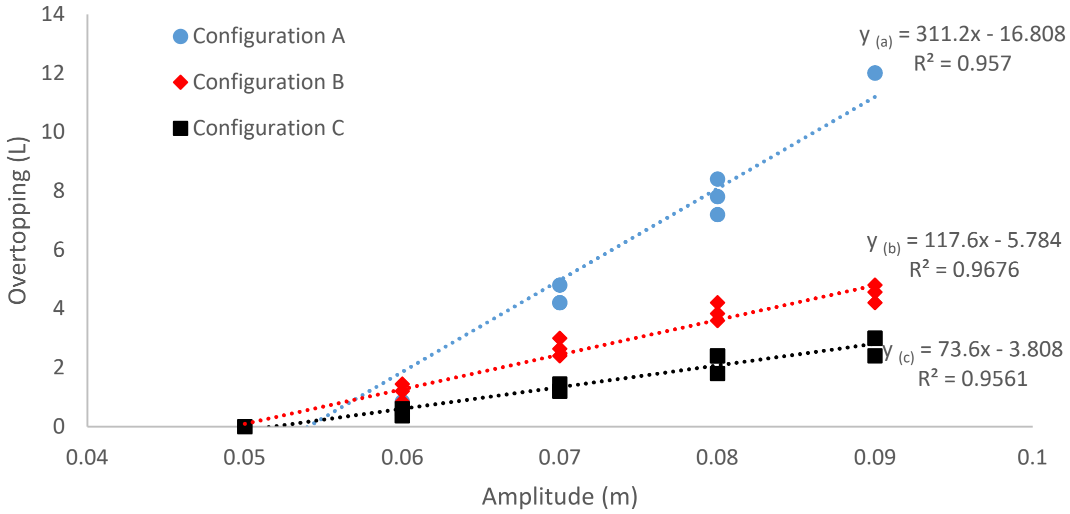

Figure 8. Sine wave hydraulic conditions; overtopping measure vs amplitude; no slope angle adopted within the experimental facility.

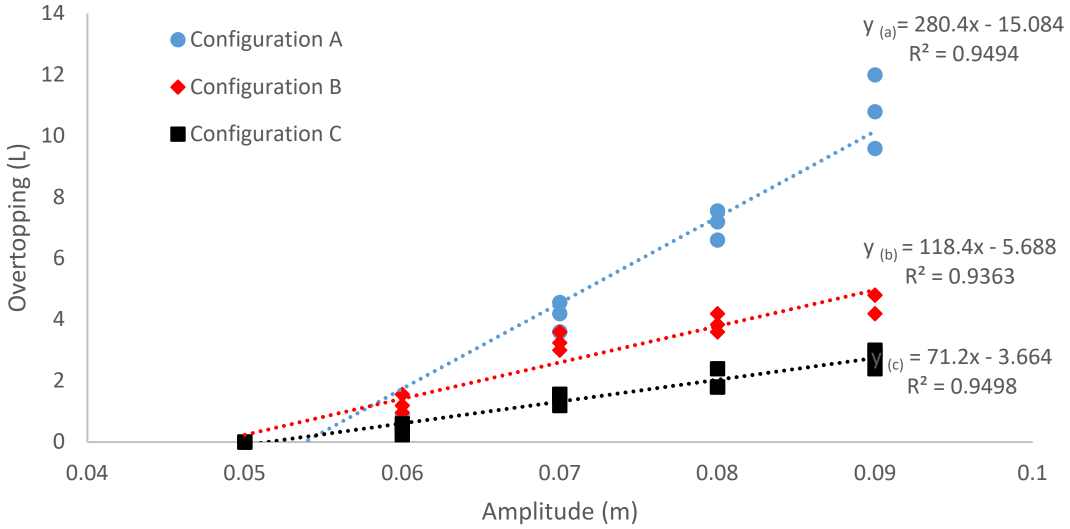

Figure 9. Sine wave hydraulic conditions; overtopping measure vs amplitude; slope angle adopted within the experimental facility.

3.3. JONSWAP Wave Conditions

Figures 10 and 11 display the comparison of experimental datasets collected under JONSWAP hydraulic conditions without and with a slope angle present (measurements are summarised in Table 6).

Results show that Configuration A was the most effective at attenuating wave energy and had the least overtopping volume collected, closely followed by configuration C. Configuration B was the least effective as overtopping measured greatly exceeded that of the other configurations, with it being unable to complete the full simulation without a slope angle present due to the overtopping device being at full capacity at three minutes (180 seconds) in. It is interesting to note that configurations B and C effectively switch places between tests with the sine wave and JONSWAP wave.

A reduction in overtopping volumes of configurations B and C is noticed when a slope angle is present. Configuration A shows a slight increse in overtopping volume when the slope angle is present.

A linear trendline had been used for graphical data to show a direct correlation between the increase in time and overtopping, and R^2 values obtained exceed 0.91 and are a strong indicator of direct proportionality, despite varying wave heights and frequencies.

The resultant graphs for the JONSWAP simulation against Configurations A, B, and C reinforce the findings from testing in frequency and amplitude. Configuration A and C did not benefit from having a slope angle present, but Configuration B did, as the nature of its shape allowed the reflected wave to be directed away from the face of the structure. This is also noticeable in Figure 10 where it is clear that Configuration B without any slope angle could not complete the full final simulation. Results recorded after the collection tray had reached full capacity have been omitted from the graphical data to give a more accurate trendline as the data was clearly outlying in Figure 11.

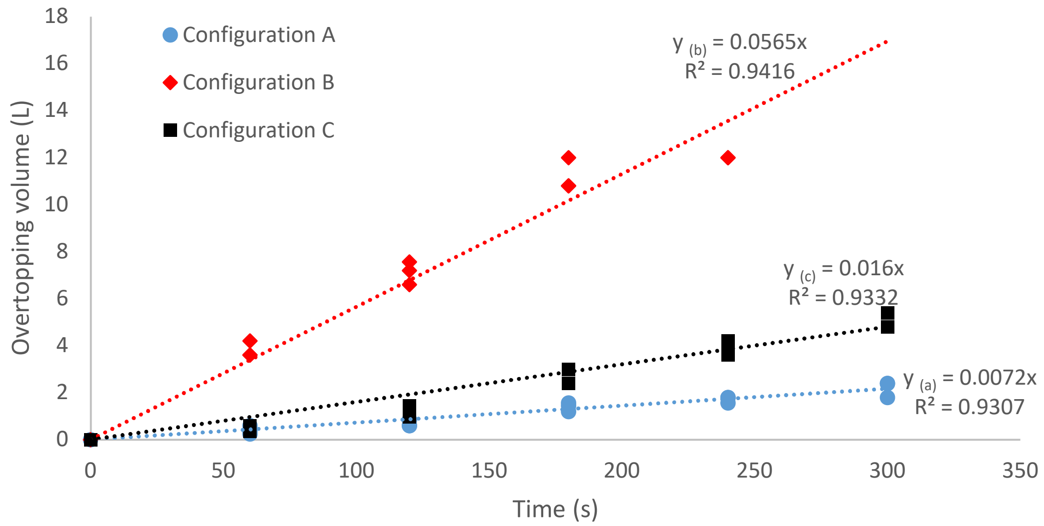

Figure 10. JONSWAP hydraulic conditions, overtopping measure; no slope angle adopted within the experimental facility.

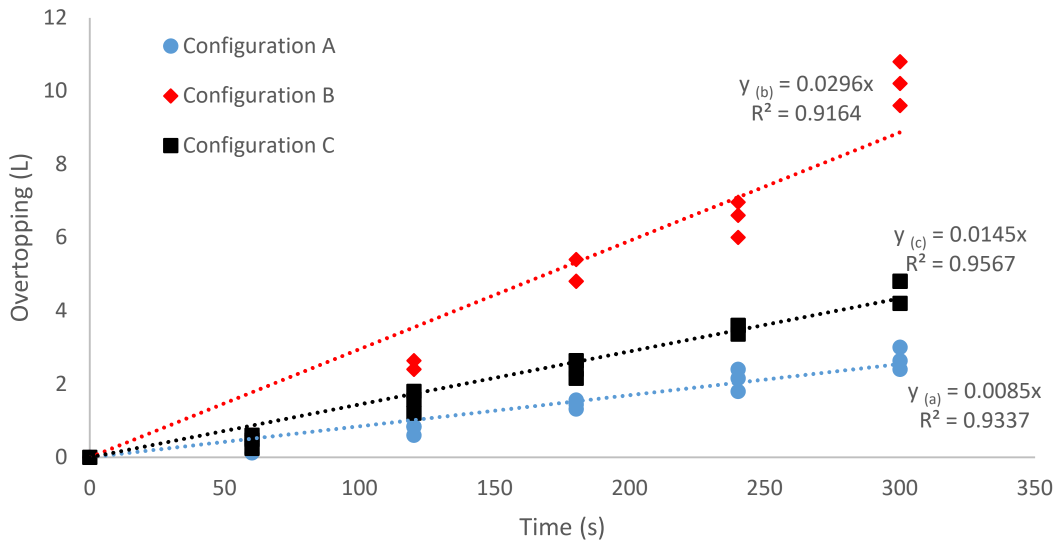

Figure 11. JONSWAP hydraulic conditions; overtopping measure; slope angle adopted within the experimental facility.

All these aspects can be clearly noticed in Figures 12–14 where the performace of each configuration is compared with and without slope angle.

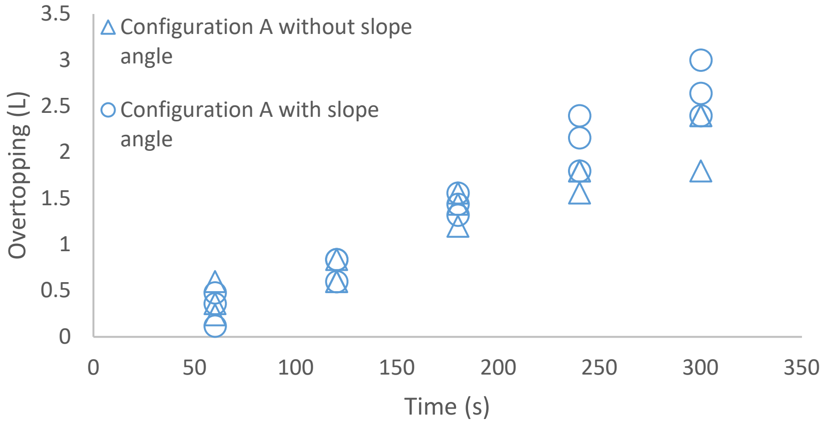

Figure 12. Performance of Configuration A with and without slope angle for JONSWAP hydraulic conditions.

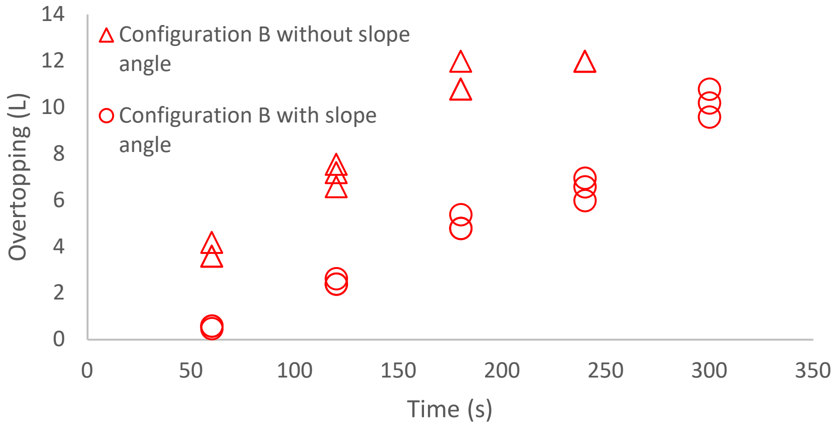

Figure 13. Performance of Configuration B with and without slope angle for JONSWAP hydraulic conditions.

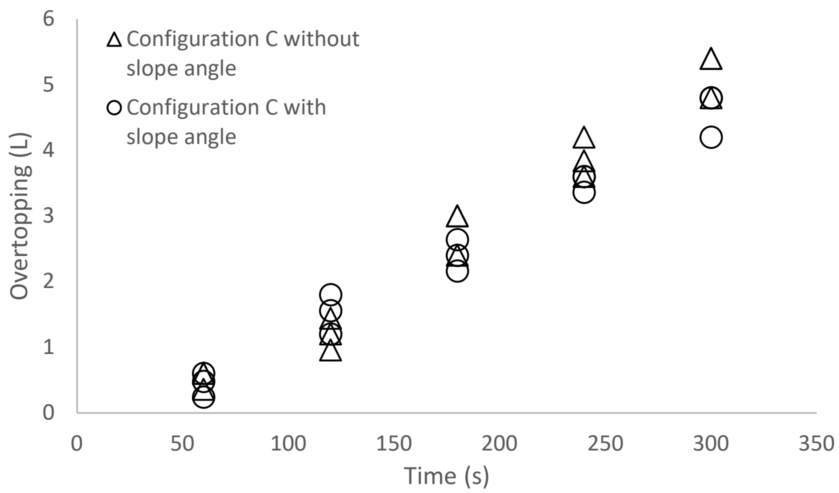

Figure 14. Performance of Configuration C with and without slope angle for JONSWAP hydraulic conditions.

Table 6. Experimental testing parameters collected for JONSWAP waves with and without slope angle.

Time (s)	Conf. A Overtopping Volume (L)	Conf. B Overtopping Volume (L)	Conf. C Overtopping Volume (L)	Conf. A Overtopping Volume (L)	Conf. B Overtopping Volume (L)	Conf. C Overtopping Volume (L)
	No slope angle			With slope angle		
60	0.24	3.6	0.6	0.12	0.48	0.48
60	0.6	4.2	0.6	0.36	0.6	0.6
60	0.36	3.6	0.36	0.48	0.6	0.24
120	0.6	7.2	1.2	0.6	2.4	1.56
120	0.84	6.6	0.96	0.84	2.4	1.2
120	0.6	7.56	1.44	0.84	2.64	1.8
180	1.2	10.8	2.4	1.32	4.8	2.4
180	1.56	12	3	1.44	5.4	2.16
180	1.44	10.8	3	1.56	4.8	2.64
240	1.56	12	3.6	1.8	6	3.6
240	1.8	/	3.84	2.16	6.6	3.36
240	1.8	12	4.2	2.4	6.96	3.6
300	1.8	/	4.8	2.4	9.6	4.2
300	2.4	/	5.4	2.64	10.8	4.8
300	2.4	/	5.4	3	10.2	4.8

4. Discussion

4.1. Wave Attenuation Mechanisms Observed

Figure 15 displays images taken from lab recordings of high amplitude waves observed during testing. By observing the wave interaction with the structure, it can help us understand why different shaped structures work better in dissipating wave energy and re-directing the incoming water.

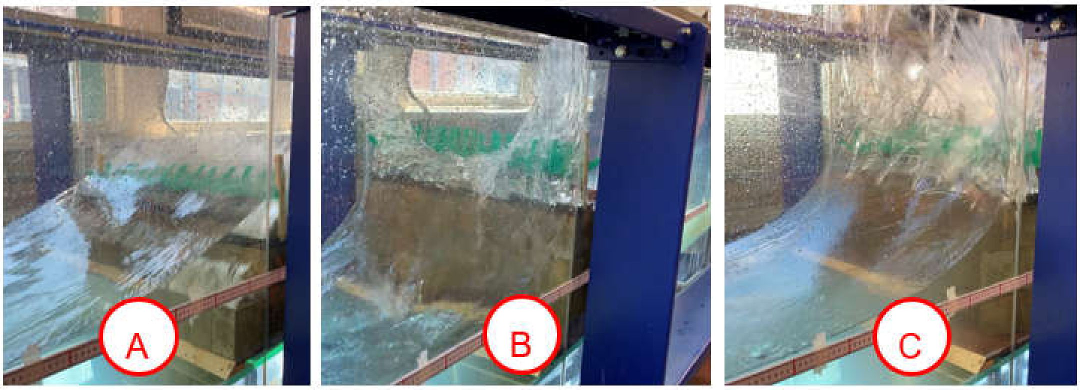

Figure 15. Resultant wave shapes for Configurations A–C.

The behaviours of these waves can be described as follows:

Configuration A—Wave impact was low and flat, resulting in wave energy being dissipated on the breakwater structure. The stepped approach acted as a ramp channelling the water over the top of the structure. However air voids between steps helped to increase turbulence and reduce wave energy. The photographs demonstrate that the artificial vegetation reduces the energy of waves as the stems and broad leaves could be seen to bent back in. This supported Kerpen's claims [64] that stepped structures, constitutive of a slope with uniform roughness, reduce overtopping volumes [64]. Waves were not observed at a great height over the structure and never neared the top of the flume walls.

Configuration B—Wave impact on this structure was sudden and as a result caused the waves to ride up the surface of the flat faced wall. This meant that reflected waves often passed over the structure or collapsed on top in a large wave wall without the presence of a slope angle to direct flow away. The wave height observed was far greater than the other configurations in particular with the configuration tested with 0.8 m amplitude.

Configuration C—The impact of waves was sudden and often had a clapping noise as it impacted the angled block wall and water filled the air voids. The incident wave ran up the surface of the structure and fell in streaks due to the "V" channels created by streamlining the blocks. The wave height observed for a 0.8 m amplitude wave was high, splashing above the flume walls (0.6 m).

Effect of Slope Angles

Having a slope angle was key to real life schemes as often sea defence structures are built on the foreshore and the topographical levels on the ground have varying gradients. At some point in the construction process there will be a decision made whether a platform (structural foundation) is required due to ground conditions and the most suitable angle to aid the protection of the coast and provide stability. From lab testing the key benefits of the shallow slope angle can be summarised as follows.

Surface runoff is directed back out to sea. Potential water that would have overtopped the structure due to surface runoff was directed back towards the incoming waves. Although ultimately this did not make a significant difference to the volume collected within this study, this is important when considering a scaled-up model. Over a longer duration, a large amount of water has the potential to be accumulated, giving an increased importance to last resort defence features, such as sea walls.

Wave reflection is aided and splash is directed back to sea. Rather than the wave splash being at 90° to the water surface and a horizontal splash profile that causes much of the wave to collapse back onto the structure, the introduction of a slope angle means that the resulting splash will be at an acute angle to the water's surface. The wave energy therefore will be directed back out towards incoming waves. The effect of this can be appreciated in the results from the JONSWAP synthesis analysis that with a slope angle Configuration B performed far better, completing a full five-minute simulation that it was not previously able to.

4.2. Effectiveness in Reducing the Overtopping

In order to evaluate the overall effectiveness of structures and assess how they performed in wave attenuation across the various testing spectra, Table 7 was created. It displays a point scoring system based on the overtopping volume collected in resultant graphs, with structures collecting the least water volume being 1st (3 points), 2nd (2 points) and the structure overtopping the most receiving 3rd (1 point).

The total effectiveness in this study concludes that Configuration C performed the best across the three testing scenarios but does not necessarily mean that it is the most practical to use in every coastal scenario. This is due to effectiveness being dependant on multiple conditions including the type of waves the structures are subject to, the location of the protection measure, and subsequent impacts to the ecosystem from its construction.

Table 7. Effectiveness scoring.

Configuration	Frequency Testing		Amplitude Testing		JONSWAP Testing		Points Total	Total
	Slope Angle	No Slope Angle	Slope Angle	No Slope Angle	Slope Angle	No Slope Angle	(/)	%
A	2	1	1	1	3	3	11	30.56
B	1	2	2	2	1	1	9	25.00
C	3	3	3	3	2	2	16	44.44

After considering the results from the sine testing (changing amplitude and frequency), it would have been reasonable to predict that Configuration C would have also been the most effective in a JONSWAP testing scenario. However, this was not the case in JONSWAP testing where Configuration A outperformed all structures when subject to high energy wave conditions at irregular amplitudes and frequencies. This was mainly because the sine testing was more influenced by friction and gravity (than wave reflection) as the lower energy of the waves had a smaller impact in this respect. In contrast to this, JONSWAP waves simulated high energy waves, which created more interference with each other over the duration. Although friction factors and gravity losses still played a significant part in the JONSWAP simulation, the way the structures reflected wave energy and the resultant wave interception were more important when analysing the performance of configurations tested.

When reviewing the footage of the experiments, interference caused by the reflected wave played a big part in its effectiveness as it created wave interference when two waves from opposite directions meet. When considering Configuration A, the most effective in JONSWAP testing, it could be seen that reflected waves caused destructive interference. The crest of the reflected wave lined up with the trough of the incoming wave, resulting in them cancelling out as they were out of phase and thus creating a reduced wave. On camera footage, the sloped shape of this configuration allowed some overtopping but also allowed some of the incident wave energy to run back down the structure. As a result, this created a rocking motion within the water and aiding the waves sinusoidal wave movement. Another observation during JONSWAP testing is how the reflected wave location moved position in the tank. At the start of testing, the location of reflected waves meeting incoming waves was near to the structure, and as the frequent waves continued, the reflected wave moved back throughout the flume. This indicates that by using structures that are effective at creating destructive interference (Configuration A), the impact on the coastal structure will be lessened and over time overtopping will be greatly reduced as a result of this.

This contrasted to Configuration's B and C, which were not as effective in this process. Due to the nature of their shape creating a high impact force for waves, the wave reflection was more aggressive, unlike the stepped shape breaking down energy and creating turbulence, as the water energy is re-directed up in the air and crashes down. This would often cause constructive interference, making irregular larger waves as a result of the crests of reflected waves and incoming waves lining up. This would help to explain why wall-like structures (such as Configurations B and C) are more effective as a last resort defence on the shoreline, rather than a breakwater on the foreshore. In amplitude testing, R^2 values were taken very close to 1 (direct proportionality). This indicated a very good positive correlation in results, indicating that with increased amplitudes, the wave speed and energy increases, causing a higher overtopping. Configurations with a large impact stopping force, such as B and C, performed far better in these scenarios as they reflected wave energy effectively.

4.3. Real Life Implications

When comparing configuration A to existing structures identified by the literature review, it is possible to see similarities to a coastal revetment. The stepped nature of the structure made it act like a ramp, aiding in dissipating some of the wave energy and proving a direction for the water to travel, so the water runs up its surface, rather than producing a direct impact, by utilising a sloped approach method. Similarities can also be drawn with the tetrapod's strategy as the nature of waves breaking against the structure aiding its wave attenuation can be drawn, and both structures seem most applicable at low water levels, as the stepped structure did not perform well under high amplitude waves.

On the other hand, Configuration B, if compared to existing structures identified by the literature review, has multiple similarities to a seawall structure. It proved effective against high amplitude waves as it provided a direct stopping force for the energy. For real life implications, seawalls are usually curved at the top as the large wave wall produced can then be directed back out to sea. Instead, artificial seagrass located on top of the wall aimed to re-direct water back away from the structure. This method was effective under low wave amplitudes; however, as the wave energy increased, the water was overpowering and often bypassed the seagrass completely due to the reflected water trajectory. It was noticed that the nature of a seawall is not effective in creating destructive interference as when reflected waves met incoming waves; this often led to the creation of larger waves, with higher wave energy and the potential to cause more erosion.

Finally, when comparing configuration C to existing structures identified by the literature review, you can see similarities to a seawall and a breakwater. It could effectively manage high amplitude waves as it could take the high impact of the waves and channel the water up the wall like a seawall. As with Configuration B, the artificial seagrasses located on top appeared to be most effective under low wave energy, where splash height was low and overtopping less aggressive. It also acted in a similar way to breakwater, as the concrete blocks in breakwater are often in random arrangements causing the water to interact with the edges of blocks causing a streamlined effect and channelling the water round them rather than a direct impact with their flat face. This causes the wave energy to disperse rather than a direct impact.

When investigating the sustainability of all the configurations tested, they can be deliberately considered to manipulate the shoreline to satisfy human need [92] and so are still largely seen as hard from an engineering perspective. However, they can all be considered ideal for the development of coral reefs and natural ecosystems that could replace the "green areas" simulated on this study, in line with the theory of incorporating natural habitats into hard solutions by permitting space for coastal adjustments. By implementing sea life and habitat restoration on the foreshore of beaches to combine with engineering options, a combined solution can be found where the ecosystem and engineering methods can act together to provide effective wave attenuation [93,94].

4.4. Limitations

4.4.1. Importance of Slope Factors

The slope of the coast is a key factor that could largely influence the inundation during a flooding event (permanent or sporadic) generated by sea level rise. Additionally, the angle of the beaches could actually control the velocity with which the sea withdraw in case of inland water running for flooding due to other types (e.g., river or urban). This is a crucial factor that was not considered in this study but that will require an extensive experimental campain to produce map of slopes and the consequent hydraulics conditions associated for varius flow rates and velocities to be used to calibrate and validate numerical models and to identify solutions, which could reduce the vulnerability of lower slopes (in the case of flooding from the sea) or higher slopes (in the case of inland flooding) [95,96]. Furthermore, to accurately quantify wave energy and other crucial parameters, more sophisticated equipment is needed. For example, for quantifying the wave energy, an instrument more accurate than a ruler would be necessary to estimate the significant wave height. Low-cost techniques recently published and applied to other fields [97–100] will provide a support in improving the accuracy of the measurement within this study. For example, by using low cost cameras (GoPro), it will be possible to implementing Particle Image Velocimetry and Planar Concentration Analysis techniques to better quantify velocity field and pollutant maps to assess the performance of coastal structures in terms of wave attenuation and pollutant transport.

4.4.2. Importance of Permeability Factors

Studies conducted to date have confirmed that tsunamis and storms have generated washover deposits across beaches or dunes in the last decade [101]. The deposition of sediments therefore continues to alter the morphology of coastal areas after each storm event [102–108], penetrating into existing material and causing various levels of stratification which vary the permeability of the site. This is another aspect that was beyond the scope of this study but would require the characterization of sedimentary characteristics of varius type of washover successions for multiple coastal tophography configurations, including the beach ridge elevation and backshore tophography. The presence of specific permeable material within the first layers of the stratification could in face, if characterized, be used as a sustainable solution for storing part of the water that inundates communities living in coastal areas.

4.4.3. Importance of Marine Currents and Bathymeric Factors

Wind waves, storm surges and ocean circumation play a significan contribution to to risk of flooding in coastal areas [109]. All these aspects can alter the mechanical force of the storm surge [110–113], generating different erosion effects and flooding conditions [114,115]. Despite being typical and dissimilar for each site conditions, concurrence of astronomical high tides and energetic waves can influence the likelihood of overtopping and consequent inundation, posing a hugh threat for coastal population and urbanisation. This aspect requires the quantification of velocity vector maps, quantification of tide rise and the characterization of waves induces by strong winds, and this was not possible to replicate within the experimental facility adopted in this study. However, it is also vital to estimate the interaction between these natural and environmental conditions and the frequency and magnitude of flooding events to target specific schemes that could better perform and are less sensitive to the natural processes involved and their interaction [116].

4.4.4. Importance of Real Vegetation Studies

As previously written, due to the impracticability of growing real seagrasses, a physical model has been made to reproduce submerged vegetation by using straws and plastic sheets to mimic the thick stem structure and broad narrow leaves. The choice of this artificial solution was made to isolate specific responses within the laboratory experiment under controlled conditions and to inform future work with real vegetation. Ideally, future studies will also incorporate the testing of specific patches and geometries, which could generate a variety of drag coefficients C_D and Reynolds numbers Re.

5. Conclusions

The purpose of the research was to assess the viability of a combined hard and soft engineered breakwater solution for coastline protection. A comprehensive literature review was conducted to identify existing structures to aid the protection of coastlines and innovative solutions being investigated worldwide. Advantages and disadvantages for each solution were discussed and combined into three newly designed configurations. Experimental tests were then conducted testing these three different configurations for overtopping performance against a range of varying wave simulations that were designed to replicate different real-life conditions.

The tests were performed at the same testing location, with overtopping measured at the end of each wave simulation to judge the amount of wave attenuation of each structural configuration. The results showed that configurations with a high impact stopping force (such as Configurations B and C) outperformed a stepped structure (Configuration A) in lower energy sine waves that simulate shallower water. During the JONSWAP simulation, however (with higher energy waves, such as would be found in conditions in the North Sea), a stepped configuration outperformed the walled configurations as it attenuated the waves further and hence allowed less overtopping. It was identified that the contributing factor influencing the increased effectiveness was the structure's ability to reflect waves in a nature that causes destructive interference of the reflected wave and the incident wave. This resulted in reduced waves as they cancelled each other out.

In addition to measuring overtopping volumes, a video camera was used to observe the hydraulic behaviours for each structural configuration. These could best be seen under the high amplitude (0.09 m) sine spectrum waves tested, where the increased wave height resulted in increased wave energy. Images provided demonstrate the resultant wave shape of the stepped configuration was low and flat, making it suitable as a breakwater; however, wave impact on a flat faced wall was sudden and caused the waves to ride up the surface. To build further on this, the experiments also explored the performance of each structural configuration with and without using a testing platform. This modification was incorporated to create an angle to the structure in the water, to match that of the sloping foreshore. It was found that the presence matching the sloping foreshore

(4.5% gradient) aided structural protection measures with a high impact stopping force (Configurations B and C), with key benefits to the reflected wave trajectory and surface runoff. The findings of this work helped provide recommendations for future research needed to achieve sustainable approaches in coastal defence design.

Future research could explore the performance of the breakwater structures in the remaining ranges of the JONSWAP wave that were not covered in the initial sine testing (by testing frequencies between 0.5–2 Hz and amplitudes from 0.1–0.3 m), in order to better understand and predict the exact frequency and amplitude values, at which the stepped breakwater began to outperform the wall-like structures. Furthermore, in order to further understand sustainable design of submerged breakwaters, future research should focus on the following criteria to be analysed:

- The use of different materials to identify how material roughness influences overtopping and if a sustainable material can be utilized for practical implications.
- The use of real vegetation to investigate effects of flexible coral reefs and underwater vegetation for the wave attenuation and the spread of pollutants in the proximity of coastal areas.
- The testing of structural configurations with different vegetation appropriate for saltwater to assess their effectiveness in reducing overtopping, decreasing wave energy and the structure's effect on their longevity.
- Further experimentation with slope angles to determine a best shape/angle to reflect wave energy with each breakwater design.
- Investigation into sediment movements by testing structures with a hit and miss concrete base.

By allowing these open channels within the structure, the flow of water will work with the natural movement of sands and waves to allow sand deposition further along the coast. This way, the sea defence will not prevent the beach from replenishing its supply of sand as a natural defence to dissipate wave energy. This method will also allow the possibility to investigate longshore drift and the effect of the structure on the movement of beach sediment.

Author Contributions: Conceptualization, M.R.; methodology, M.R. and J.H. (Jacob Heyworth); validation, M.R., J.H. (Jacob Heyworth), and J.H. (James Hart); formal analysis, J.H. (Jacob Heyworth) and M.R.; investigation, J.H. (Jacob Heyworth) and M.R.; resources, M.R.; data curation, M.R., J.H. (Jacob Heyworth), and J.H. (James Hart); writing—original draft preparation, M.R., J.H. (Jacob Heyworth), and J.H. (James Hart); writing—review and editing, M.R., J.H. (Jacob Heyworth), and J.H. (James Hart); visualization, J.H. (Jacob Heyworth); supervision, M.R.; project administration, M.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors would like to thank Ian Breakwell and Craig Harrison for technical support with this project.

Conflicts of Interest: The authors declare no conflicts of interest.

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