Optimising Ecological and Engineering Values in Coastal Protection via Combined Oyster Shell and Sand Bag Designs

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Abstract
The increasing popularity of eco-engineering and living shorelines has seen oyster reefs suggested as a natural solution to erosion in low to moderate energy estuarine environments. With a focus on reducing the ecological footprint of artificial shoreline protection systems, an ecological solution with artificially created oyster reefs could be used to not only minimise erosion, but facilitate the growth of surrounding marine life. Substantial research has revealed the positive impact of oysters on the natural ecosystem. However, there is limited information on the stability and other design parameters such as wave transmission, reflection and energy dissipation for oyster reefs.

The present research studied various oyster shell filled bag configurations and their combination with sandbags to enhance the stability of the oyster reef design. A prototype scale coastal protection setup comprising various configurations of oyster bags and sandbags was established. The experiments consisted of tests with different levels of bags, creating one, two and three tier structures. For all configurations, the transmission, reflection, and dissipated energy of waves were evaluated.

Experimental results demonstrated that configurations consisting of sandbags landward of the oyster bags, and at the crest of the structure, prevented structural displacement. However, the addition of sandbags enhanced wave transmission and reflection, with greater reflection particularly evident for sandbags at the seaward face of the structure. The configurations that best optimised wave attenuation and provided stability to the oyster reef, were determined for each tier of structures. Designs with larger crest widths and freeboard were recommended for greater wave attenuation. Field implementation of these designs is expected to yield a reduction in shoreline erosion, with the addition of sandbags increasing the stability of the combined oyster shell and sandbag structure.

Keywords: design optimisation, ecological coastal protection, oyster reef restoration, physical modelling, riverbank erosion.

1. Introduction

The erosion of coastlines and waterways has become apparent through the persistent impact of waves and rapid currents (Figure 1). Climate change has led to rising tides and storm surges, which have enhanced the forces that act upon the land, resulting in further land degradation [15]. Estuarine environments are also susceptible to the forces imposed by wind waves and boat wakes that result from recreational activities and transport routes, while streams and rivers are exposed to high velocity currents and hydrodynamic forces. As a result, wetlands and intertidal habitats have been impacted. Figure 1 illustrates typical shoreline erosion within Manly Lagoon (NSW). Anthropogenic influences such as coastal development and dredging, have exacerbated these processes, and with the human population expected to increase to 10 billion in 2100 [11], many countries are becoming incentivised to reclaim more land from the sea as a solution to shoreline erosion [6]. Other shoreline protection solutions have been implemented using a range of natural and man-made materials in the form of seawalls, breakwaters, gabions and groynes.

Figure 1 Shoreline erosion of Manly Lagoon, NSW, Australia (Photograph taken 26th June 2016).

Concrete and more naturally available materials such as rocks are commonly used in these structures. Although their purpose to reduce erosion and increase shoreward sediment transport has been fulfilled, the marine environment may suffer. The concept of ecological engineering has been investigated with a view to not only mitigate shoreline loss and reduce erosion, but to promote the growth of the natural ecosystem [3, 12]. One solution is the use of artificial oyster reefs (Figure 2).

Figure 2 Marine growth on bagged oyster shells six months after deployment in Manly Lagoon, NSW, Australia (Photo courtesy of OceanWatch Australia).

Oysters are able to facilitate the growth of other species [12], enhance the producer and consumer surplus associated with the affected fisheries [8], and filter phytoplankton and other sediment from the water column [13]. Additionally, artificial oyster reefs have the potential to provide a sustainable solution to erosion in waterways, with notable wave attenuating properties [1, 3, 4, 9], and the ability to become a self-sustaining three-dimensional reef [14]. Previous laboratory experiments with waves representative of shallow intertidal flats and small boat wakes highlighted the usefulness of oyster reefs within these wave climates [3, 4]. The wave attenuating properties of oyster reefs enable their use as a shoreline protection measure while simultaneously providing a cleaner and more diverse ecosystem.

Research on the design of oyster reefs as shoreline erosion control structures is limited, with available studies measuring wave transmission for oyster shells in a variety of designs [1, 4]. These studies demonstrated that oyster reefs may be comparable to traditional rubble mound breakwaters in low wave environments, inferring the potential use of oysters as preventative measures for shoreline erosion. While previous research by the Water Research Laboratory (WRL) suggested adequate wave attenuating capabilities, artificially created oyster reefs with oyster shells in coconut fibre bags were displaced under wave attack of small boat wakes [4]. Herein the present study explored the possibility to combine oyster bags with sandbags, to form a more stable composite structure. A variation of design combinations was tested to determine the optimal design for the oyster reef. The assessment comprised the stability of the structure as the most important parameter as well as several parameters describing the effectiveness of the structure to protect the shoreline, including wave transmission, wave reflection, and energy dissipation.

2. Methodology

2.1 Experimental Facility and Instrumentation

A physical model that combined oyster bags and sandbags to form an erosion control structure was established in WRL's two-dimensional, three metre wave flume. The flume measures approximately 32.5 m in length, 3.0 m in width, and 1.3 m in depth (Figure 3). 2D Testing was undertaken using three × 1 m wide mini flumes built internally within the wider 3 m flume, restricting the model oyster shell filled bag crest length to 1 m.

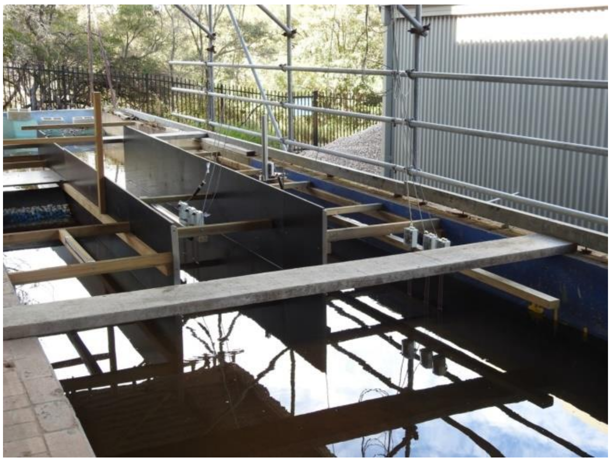


Figure 3 The experimental setup reveals the division of the 3 m wave flume into three small 1 m flumes, with wave probes in arrays of three used to separate incident and reflected wave heights.

The oyster shell filled bags were located on an impermeable false floor in the wave flume constructed from blue metal fill overlain with concrete capping with the following characteristics:

- 1V:55H slope (where the mini flume and oyster shell bags were located); and
- Seaward of this main slope, the false floor sloped at 1V:5H until it intersected the permanent flume floor.

Testing was undertaken for a range of bag configurations using packets of 10 monochromatic waves. The flow depths and wave conditions were consistent with the conditions used in previous research by WRL [4], with wave heights representative of small boat wakes that the oyster bags are expected to experience in the field. These tests were performed for flow depths of d = 0.16 m, 0.32 m and 0.40 m, which corresponded to the heights of the 1, 2 and 3 tier oyster bag structures respectively. The wave conditions consisted of wave heights between 0.05 m and 0.30 m, with wave periods of 1 s, 2 s and 3 s. During the experiments, qualitative observations of displacement and movement were noted for each structure. In order to determine the incident, transmitted and reflected wave heights, seven single capacitance wave probes were used to collect water level data within the flume (Figure 3). Two arrays, each containing three wave probes, were established adjacent to, and in front of the structure. Each wave probe array recorded the water level during the experiments, from which the incident and reflected wave heights were determined. Additionally, a single wave probe was set up landward of the structure to measure transmitted wave heights.

The oyster bags used in the testing were the same as those used in previous research by WRL [4], and were provided by OceanWatch Australia. A mixture of Sydney rock oyster (Saccostrea glomerata) and Pacific oyster (Crassostrea gigas) filled bags of coconut fibre woven into netting with 12 mm x 12 mm aperture and sewn at the seams with Manila rope. This material was used for the single, double and triple oyster bags, and assembled by OceanWatch Australia [4]. The oyster bags were 0.93 m in length, and measured 0.16 m in height. The widths of the single, double and triple bags were 0.33 m, 0.60 m, and 0.92 m respectively. With the density of the Sydney rock oyster unable to be found in the literature, and the density of the Pacific oyster in natural field conditions determined to be 1810 kg/m^3 [7], small scale density tests were undertaken to determine an average density for the oyster shell mixture. This was calculated as 2108 kg/m^3 by measuring the weight and volume of a random selection of 10 oyster shells from the mixture.

For the sandbags, Maccaferri SMP 200/50 geotextile fabric was used to form 6 bags, with average dimensions 92 mm x 37 mm to closely follow the shape and size of the oyster bags. Further sandbags were made of ELCOMAX 600R geotextile with the same dimensions to test the effect of bag material upon the sandbag performances.

2.2 Model Configurations

In the present study, a series of oyster and sandbag configurations was tested (Table 1). These composite structures of oyster and sandbags were compared to the base cases of oyster bags and sandbags respectively. Each configuration was categorised into 1, 2 and 3 tier structures. Alternative design options evaluated the effects of increasing crest width and rotating the longitudinal axes of the bags by 90 degrees parallel to the wave attack. Further tests comprised different sandbag materials comparing Maccaferri geotextile sandbags with ELCOMAX 600R sandbags. Further details about the flow configurations and the experimental setup can be found in [5].

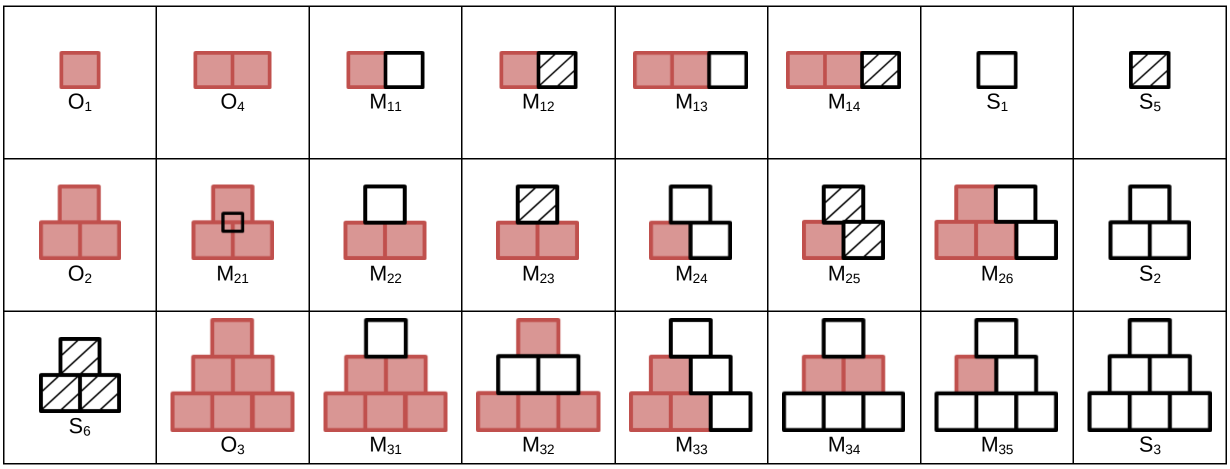
2.3 Design Parameters

For each test, detailed observations of the flow patterns were conducted and any bag movement was recorded including the initiation of the rocking of the crest bag and the initiation of displacement of the whole bag structure. The incident wave heights that resulted in the initiation of rocking and displacement for each configuration were recorded to quantify the stability of each design.

The wave probes were sampled simultaneously for each test case. The raw wave data was post-processed with the least squares method [10] to separate and interpret transmitted and reflected waves. The coefficient of wave transmission K_t was calculated according to Equation 1.

$$K_t = \frac{H_t}{H_i} \quad (1)$$

Table 1 Mixed configurations using combinations of oyster bags and sandbags. All cross-sections are sketched indicatively, as the actual bags are rounded, and vary in dimensions. Red filled squares = oyster bags; Black hollow squares = Maccaferri sandbags; Black hatched squares = ELCOMAX sandbags; Wave direction from left to right.



where K_t = transmission coefficient; H_i = incident wave height on the seaward toe of the structure; and H_t = transmitted wave height on the landward side of the structure. Wave transmission provided a measure of the reduction in wave height, i.e. a transmission coefficient smaller than 1 indicated a reduction in wave height and a reduced erosion potential.

For each test, wave reflection coefficients K_r were determined according to Equation 2.

$$K_r = \frac{H_r}{H_i} \quad (2)$$

where K_r = reflection coefficient; H_i = incident wave height on the seaward toe of the structure; and H_r = reflected wave height seaward of the structure. Reflection coefficients provided information about the size of the reflected waves which should be minimised to avoid impacting adjacent, unprotected shorelines.

The ability to dissipate wave energy is also of concern in the design of shoreline protection structures. Energy dissipation represents the amount of energy that is lost when waves break on the structure. For each experimental test in the present study, the energy dissipation E_d was calculated according to Equation 3.

$$E_d = E_i - E_t - E_r \quad (3)$$

where E_d = dissipated wave energy; E_t = transmitted wave energy, E_r = reflected wave energy; and E_i = incident wave energy. E_t, E_r and E_i were estimated using Equation 4 [2].

$$E = 1962 H_m^2 T_m^2 \quad (4)$$

where E = wave energy; H_m = maximum wave height; and T_m = maximum wave period. Representative incident, transmitted and reflected wave heights were used to determine the corresponding maximum wave energy values.

3. Results

The aim of combining sandbags with oyster bags was to enhance the stability of oyster bag shoreline protection and determine the optimal configuration that minimised wave transmission and wave reflection and maximised energy dissipation. The mixed configurations were analysed to identify the ideal solution that acted as the best erosion control structure while maintaining a sizeable oyster reef. The presentation of results in this conference paper focuses mostly on 3-tier structures while the results of the full tests can be found in [5].

3.1 Stability Assessment

In order to quantify the stability of each structure, the incident wave heights that initiated bag movement were recorded. Specifically, bag movement was separated into two categories, rocking of the structure (typically the crest bag rocked first), and displacement of the whole structure. Higher incident wave heights indicated a greater resistance to wave attack. The incident wave heights that induced bag movement were directly comparable for the same wave conditions across all configurations. Table 2 presents some example results of the stability assessment for the 3-tier structures comprising oyster bags only, sandbags only and combinations of sand and oyster bags. The results showed that all oyster bag structures were the least stable while all sandbag structures were the most stable. The combined oyster bag and sandbag structures had stability performance between these extremes (Table 2).

Table 2 Incident wave heights that induced movement for selected 3-tier structures; d = 0.32 m.

Structure ID	Wave Period (s)	Incident Wave Height (m)	
		Crest Bag/Structure Rocking	Displacement of Structure
O_3	1	-	-
O_3	2	0.13	0.15
O_3	3	0.10	0.11
S_3	1	-	-
S_3	2	-	-
S_3	3	-	-
M_{31}	1	-	-
M_{31}	2	-	-
M_{31}	3	-	0.11
M_{33}	1	-	-
M_{33}	2	0.16	-
M_{33}	3	0.07	-
M_{34}	1	-	-
M_{34}	2	-	-
M_{34}	3	0.13	-

Detailed stability assessments were also observed for all sand bag and oyster bag configurations (Table 1) confirming the results for the 3-tier structures. The results are not presented herein but can be found in [5]. Overall the incorporation of sandbags into the oyster bag design had the desired effect of reducing the tendency for rocking and displacement. For the 1-tier structures, the design of a single oyster bag followed by a sandbag (M_{11}) offered the greatest stability. Displacement was prevented for all wave conditions, with rocking occurring for 2 and 3 second waves at incident wave heights of 0.09 m and 0.07 m respectively. The 2-tier structures behaved similarly for all water depths, with a single oyster bag combined with two sandbags (M_{24}) offering the greatest resistance to displacement. Rocking of the oyster bag was limited to 3 second waves, requiring an incident wave height of at least 0.15 m. Multiple 3-tier configurations provided adequate support to the oyster reef. The symmetrical configuration, M_{34}, proved most stable, while a larger reef with 3 oyster bags in configuration M_{33} was quite stable, despite rocking occurring for 2 and 3 second wave periods (Table 2).

Experimentation with alternative 1- and 2-tier designs revealed that larger crest widths were able to reduce bag movements for water depths of 0.16 m, requiring larger incident wave heights at wave periods of 2 s to induce rocking. Increasing the crest width of the designs but retaining all oyster bags in the front face of the 2-tier structure (M_{26}) offered little improvement to the all oyster bag base case (O_2). Designs that were oriented parallel to wave attack marginally improved resistance to displacement, but offered greater support against rocking [5]. This was largely attributed to the connectivity of the double and triple oyster bags.

3.2 Wave Transmission Analysis

For each test the wave transmission coefficient was calculated with Equation (1) to quantify wave attenuation for the oyster bag/sandbag combinations. Lower transmission coefficients indicated less wave transmission through/over the structure providing better protection of the shoreline. The overall performance ranking of the structures is shown in Table 3.

1- and 2-tier designs with the largest crest widths (M_{13}, M_{14}, and M_{26}) had the lowest wave transmission coefficients, ranging from 0.2 to 0.5 and ranking higher than the other modelled configurations. The 3-tier all oyster bag structure (O_3) offered the least wave transmission across all wave conditions (Figure 4). These results revealed that structures with a seaward face of oyster bags provided the greatest reduction in wave transmission. For 1-tier structures, the single sandbag had similar wave transmission coefficients as the single oyster bag base case. The combination of oyster bags and sandbags improved results due to the increased crest width. Consistent with the findings for 1-tier structures, the larger crest width of configuration M_{26} provided the lowest wave transmission of all the 2-tier structures. At a water depth of 0.16 m, the all oyster bag structure (O_2) offered the least wave transmission, while at a water depth of 0.32 m, all designs with the same crest width achieved similar results. The all oyster bag structure, O_3, demonstrated a reduction in transmitted wave height compared to the other 3-tier structure configurations, particularly for wave periods of 1 and 3 seconds.

Observations of the combined sandbag and oyster bag structures revealed similar transmission coefficients for 2 second waves across all configurations, while all oyster bag structures reduced the transmitted wave height considerably (Figure 4). Differences in crest height also impacted the results, with smaller crest heights allowing more wave overtopping, and consequently higher transmitted waves. Figure 4 shows typical results for various 3-tier structures indicating the smallest transmission coefficients for oyster bags and close agreement between mixed bag structures and all sandbag configurations.

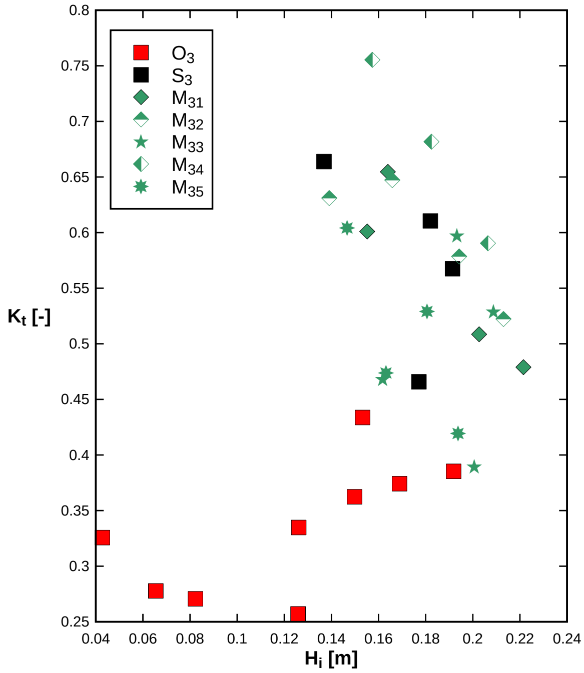


Figure 4 Wave transmission coefficients for 3-tier structures; d = 0.32 m, T = 2 s.

3.3 Wave Reflection Analysis

To best understand how each design reflected incident waves, reflection coefficients were determined for each test. In this manuscript only the basic findings are presented and details can be found in [5]. The overall performance ranking of the structures is shown in Table 3. Smaller wave reflection coefficients are preferred to avoid impacts on adjacent, unprotected shorelines. Reflected wave heights did not vary between the 1-tier structures, and thus no single optimal design was established for this tier in terms of wave reflection. For the 2-tier structures, configurations with a seaward face of oyster bags had the least reflections, with the structure M_{22} performing the best across all tested wave conditions. The oyster bag structure, O_3, had the fewest reflections of the 3-tier structures.

The results for all experiments indicated that oyster bag structures as well as mixed structures, yielded similar reflection coefficients across the range of wave conditions and water levels tested. Sandbags that used the thicker ELCOMAX geotextile fabric generally produced greater reflections than those composed of the thinner

Maccaferri fabric. Reflections were lowest when oyster bags were used at the seaward face of the structure. The combined bag configurations had reduced reflections for an increased crest width combined with a front face of oyster bags.

3.4 Energy Dissipation Analysis

Ideally, energy dissipation values should be as high as possible for shoreline protection structures, ensuring that a large proportion of incident wave energy is not transmitted or reflected. In this manuscript only the basic findings are presented and details can be found in [5]. The overall performance ranking of the structures is shown in Table 3. As the incident wave height was increased, energy dissipation was also found to increase. For 1-tier structures, an increased crest width with seaward oyster bags (M_{13}), demonstrated the greatest energy dissipation. This trend was consistent across all tiers, with a seaward face of oyster bags in designs M_{26} and O_3 dissipating the most energy. The thicker ELCOMAX geotextile material contrastingly demonstrated low levels of dissipated energy, coinciding with the previously discussed high reflection coefficients that the ELCOMAX sandbags produced.

4. Discussion

To determine the optimal design for each tier of structures, all designs were ranked according to the ideal characteristics of an erosion control structure [5]. A rank of 1 was given to the designs that performed best in each of the four design criteria (Table 3). The optimal observations for each analysis included no displacement or rocking during the stability assessment, low wave transmission and reflection coefficients, and high values of dissipated energy. A stable oyster reef structure is pivotal to the survival and growth of the reef, as well as ensuring long term shoreline protection. Therefore, a weighting of 2 was given to the stability rankings. The alternative designs were also included in the ranking system for all tiers of structures. Table 3 presents the final rankings of each structure for the tested design criteria. Configurations which incorporated an increased crest width yielded the optimal designs for the 1- and 2-tier structures. The ideal arrangement of sandbags within the oyster reef structure was consistent across the range of tiers.

The analysis of the 1-tier structures at a water depth of 0.16 m, suggested that a stable and effective artificial oyster reef can be designed using two oyster bags that are supported by a geotextile sandbag in the lee of the structure (M_{13}). Similarly, 2-tier configurations that contained sandbags leeward of the oyster bags (M_{24}, M_{26}) offered a greater level of stability than the oyster bag structure (O_2) and a larger reduction of both transmitted and reflected waves. It was found that at least one sandbag on the lower tier behind the oyster reef as well as one sandbag on the upper tier was required to provide support against displacement and rocking. For the 3-tier structures, the symmetrical design consisting of a double oyster bag wedged between two layers of sandbags (M_{34}) was most optimal overall. However, environmental concerns regarding the setup of the structure may see greater preference in the configuration that uses three oyster bags at the seaward face of the structure, M_{33}. The all oyster bag base case structure, O_3, experienced considerable displacement during testing, and despite the increased weighting of the stability assessment, was ranked second in the ranking system. This observation highlighted the strong dissipative characteristics of the porous oyster bags. However, with stability of greater concern than transmission, reflection and energy dissipation to the survival of the oyster reef, this design is not seen to be as reliable as configurations that employed sandbags leeward of the oyster bags. Further, an increased crest width demonstrated improvements in all the measured parameters, indicating greater shoreline protection. The physical modelling of oyster bag and sandbag design structures has revealed the potential for successful oyster reef deployment in estuaries where wave climates are similar to the laboratory conditions.

Table 3 Optimal design rankings for the tested configurations (Note: weighting of 2 applied to stability)

Tier	Configuration	Ranking				Total	Final Ranking
		Stability	Wave Transmission	Wave Reflection	Energy Dissipation		
1	O_1	8	6	1	4	27	7
	O_4	7	4	1	2	21	4
	S_1	1	7	1	5	15	3
	S_5	1	8	6	7	23	5
	M_{11}	4	3	1	2	14	2
	M_{12}	5	5	7	8	25	6
	M_{13}	3	1	1	1	9	1
	M_{14}	6	1	8	6	27	7
2	O_2	8	3	4	4	27	5
	S_2	1	9	9	8	28	7
	S_6	1	8	8	9	27	5
	M_{21}	8	3	7	7	33	9
	M_{22}	6	2	1	1	16	3
	M_{23}	7	6	6	6	32	8
	M_{24}	3	3	3	3	15	2
	M_{25}	4	7	5	5	25	4
	M_{26}	5	1	2	1	14	1
3	O_3	6	1	1	1	15	2
	S_3	1	7	5	6	19	5
	M_{31}	5	5	5	4	24	6
	M_{32}	6	6	5	7	30	7
	M_{33}	4	3	2	2	15	2
	M_{34}	2	2	3	3	12	1
	M_{35}	3	3	3	4	16	4

To provide a heightened understanding of the suitability of these structures to a range of environments, further analysis of oyster bag performance under a variety of conditions is required. Additional testing of the oyster bag and sandbag structures under oblique and irregular wave attack could establish a more comprehensive coastal engineering design for the oyster reef. If the oyster reef designs are implemented in the field, the performance and durability of the coconut fibre bags should be assessed by increasing the duration of wave attack and testing the bags under high velocity currents.

5. Conclusion

In the present study, sandbags were tested together with oyster bags to reduce the movement under wave attack, and to determine the optimal oyster reef design for use as an erosion control structure. A range of configurations were tested against wave attack, and analysed according to a variety of parameters. The addition of sandbags behind the oyster bag reef prevented landward displacement, while further sandbags on top of the oyster reef prevented all movement for the scenarios modelled. As a result, all optimal design solutions utilised oyster bags at the seaward face with sandbags leeward of the oysters. Oyster bags were also shown to generate the highest values of dissipated energy, coincident with the lower wave transmission and reflection that these bags offered. For all wave conditions tested, structures with greater freeboard gave lower wave transmission and reflection coefficients and higher values of energy dissipation, while designs that increased crest width gave the most favourable results.

The optimal design for the 1-tier structures, M_{13}, utilised a larger crest width to achieve a significant reduction in wave transmission and wave reflection, while increasing energy dissipation. Similarly, M_{26} achieved the most favourable results for the 2-tier structures by making use of an enhanced crest width, incorporating a seaward face of oyster bags with sandbags for support. The 3-tier sandbag and composite structures did not perform as well as the oyster bag base case in terms of wave attenuation, but with stability prioritised, configuration M_{34} ranked the highest overall for shoreline protection.

This study highlighted the possibility of optimising artificially designed oyster bags for shoreline protection by combining them with stabilising sandbags. The present findings provide important design optimisation for implementation in real-world environments to contribute to the robustness and longevity of ecological engineering shoreline protection structures.

6. Acknowledgements

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