Affordable Coastal Protection in the Pacific Islands: Testing and Design of Alternative Protection Options for Low-Energy Coastlines

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Abstract

Management of coastal erosion caused by both natural and anthropogenic drivers is an ongoing challenge for many island nations of the Pacific. While conventional coastal protection techniques have included rock or concrete revetments and seawalls, non-conventional or 'non-engineered' protection methods have also been trialled with varying levels of success. Typically these alternative protection methods have looked to overcome obstacles to traditional forms of coastal protection such as a lack of suitable construction materials or high costs to import materials.

The Pacific Region Infrastructure Facility is undertaking a study on affordable coastal protection options in the Pacific Islands. The first of three project stages developed a desktop analysis to catalogue and critically evaluate the range of coastal protection methods used throughout the Pacific Islands, and identified several more affordable alternative coastal protection methods with potential for use on low energy coastlines. These alternative methods included the use of smaller hand-placed sand-filled geotextile containers, as well as the use of concrete masonry "besser" construction blocks, both placed on a sloping revetment. These innovative protection options have the benefit of being either widely available or cheaper to import to Pacific Islands, and they can be placed without the need for heavy construction equipment. The second stage of the project comprised a physical modelling study to investigate the performance of these alternative coastal protection methods, and to develop a design guidance report. The results will be piloted in stage three to verify and monitor these alternative coastal protection measures in Pacific Islands over time.

This paper presents results from the physical modelling stage of the project. The modelling program considered the stability and runup/overtopping characteristics of both 40kg sand-filled geotextile containers as well as concrete masonry blocks, placed on a 1V:1.5H revetment slope. A range of placement configurations and wave conditions were investigated for both armouring options to determine the threshold of unit stability. The results indicated that the geotextile containers could be used in wave conditions with significant wave height up to approximately 0.5 m, while the concrete masonry blocks were stable in waves with significant wave height up to 1 m.

Keywords: Coastal, erosion, protection, alternative, Pacific Islands

1. Introduction

1.1 Background

Management of coastal erosion and recession is an ongoing challenge for many Pacific Island Countries, caused by a range of both natural and anthropogenic drivers [6; 7; 8]. While conventional coastal protection has included rock or concrete revetments and seawalls, non-conventional or non-engineered coastal protection methods have also been trialled with varying levels of success. Typically these alternative protection methods have looked to overcome obstacles to traditional forms of coastal protection such as a lack of suitable construction materials, limited construction plant availability or high costs to import materials.

A desktop review was undertaken by the Pacific Region Infrastructure Facility (PRIF) to catalogue and critically evaluate the range of coastal protection methods used throughout the Pacific Islands, and identified several more affordable alternative coastal protection methods that have potential for use on low energy coastlines [8; 9]. These alternative methods included smaller hand-placed and sand-filled geotextile containers (GSCs) and concrete masonry "besser" construction blocks (CMBs), both placed on a sloping revetment. These innovative protection options have the benefit of being either widely available, have existing established supply chains, are cheaper to import, and/or they can be placed without the need for heavy construction equipment. However, without previous application or testing there is little to no engineering design guidance available.

1.2 Overview of Investigation

A physical modelling study was undertaken to investigate the performance of these alternative coastal protection methods, and to develop initial design guidance [2]. The modelling program considered the stability and runup/overtopping characteristics of both 40 kg sand-filled geotextile containers (Table 1, Figure 1) and concrete masonry blocks (Table 1, Figure 2), when placed on a 1V:1.5H revetment slope. A range of placement configurations and wave conditions were investigated for both armouring options to determine the threshold of unit stability as well as wave runup characteristics.

A key characteristic of the GSCs is that they were intended to be hand-placed. As such, it was considered that a GSC with mass of 40 kg was a reasonable upper limit to be hand-placed by two people. This mass was used as a basis for the container design. The measurements of the characteristics of in-situ GSCs from [1] were used to develop suitable design characteristics (shape, aspect ratio etc.) for the 40 kg GSCs in this investigation.

Table 1 40 kg geotextile bag and concrete masonry block specifications

	40 kg Geotextile Bag Details	Concrete Masonry Block Details
Average Mass[1]	40 kg	15-17 kg
Typical Volume	0.029 m^3	0.0076 m^3
Typical Length, L	570 mm	390 mm
Typical Width, W	474 mm	190 mm
Typical Depth, D	133 mm	190 mm
T1	N/A	36 mm
T2	N/A	32 mm

Figure 1 Geotextile bag dimensions (Source: [5]).

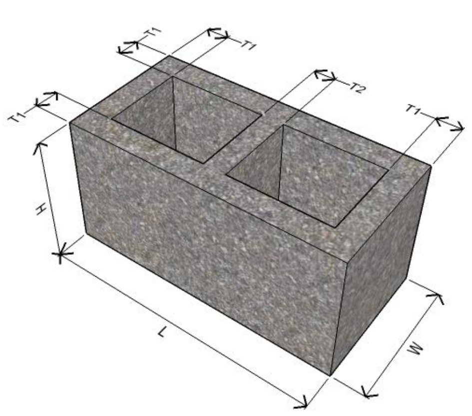

Figure 2 Concrete masonry block dimensions (Source: [2]).

2. Modelling Program Details

2.1 Model Scaling and Test Facility

A two-dimensional (2D) wave flume physical model with a length scale of 1:7.5 was used for the investigation. Testing was undertaken at the Water Research Laboratory using a 1.2 m wide by 44 m long wave flume.

A nearshore bathymetric profile was constructed in the flume, having a flat “reef” section extending ~70 m seaward of the test revetments, before dropping steeply into deeper water. This profile was indicative of typical profiles found on sheltered “lagoon-side” coastlines of Pacific Island atolls for example, and provided wave conditions that were generally representative for more sheltered reef-mediated coastlines.

The methodology presented in [3] was used to scale the model GSCs, and included considerations of a range of parameters including:

- Target in-situ shape and dimensions;
- Geotextile fabric thickness, stiffness and permeability;
- Fill sand permeability; and
- Filled GSC mass.

Model concrete masonry blocks were injection moulded for the investigation, with the units having the correctly scaled dimensions, wall thickness and density (corrected for fresh water used in the model, as opposed to sea water at real world locations).

2.2 Test Conditions

The overall objective of the testing program was to investigate the stability of both the GSC and CMB revetments under a range of wave conditions experienced on low-energy coastlines of Pacific Islands, so as to determine the upper limit of wave conditions where these revetment types could be reasonably applied.

A range of wave conditions were investigated, with three different spectral peak wave periods (3 s, 5 s and 10 s) and wave heights ranging up to either:

- The wave height that resulted in significant damage or failure of the revetment;
- The physical steepness or depth limit of waves at which higher waves would break prior to reaching the test structure; or
- The limit of the wave machine.

All tests were undertaken with a water depth of 2.3 m at the revetment toe, which was considered a suitable depth to achieve the target range of potential wave conditions and was also considered realistic for the potential application locations.

3. Results: Concrete Masonry Blocks

3.1 CMB Revetment Designs Tested

Five different CMB revetment designs were tested in the flume modelling program. The designs included four non-overtopped revetments used to investigate stability of CMBs in various placement patterns on the revetment slope (Figure 3), as well as one overtopped revetment used to investigate the stability of CMBs on the revetment crest under overtopping flows (Figure 4).

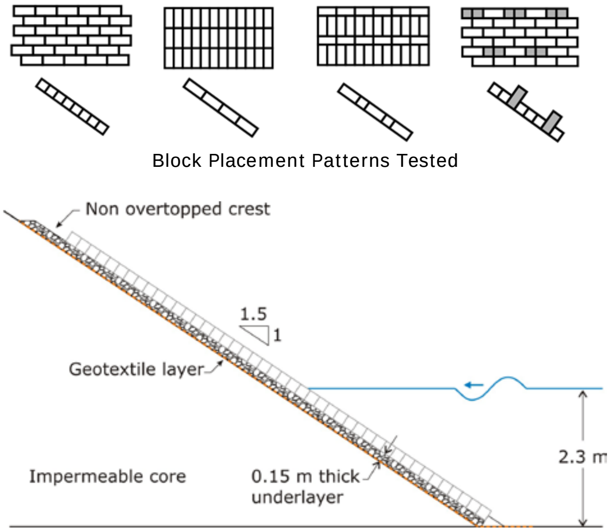

Figure 3 Non-overtopped CMB revetment designs tested in modelling program

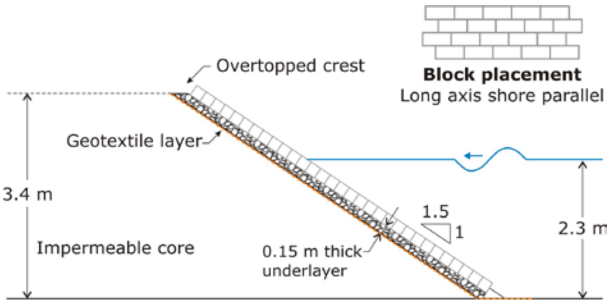

Figure 4 Overtopped CMB revetment design tested in modelling program

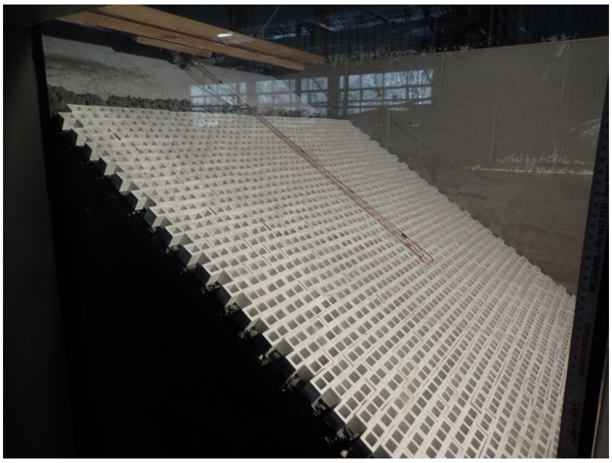

Figure 5 Photo of model CMB revetment in flume

3.2 CMB Revetment Stability Results

For all three wave periods investigated (T_p = 3, 5, 10 s), test sequences with significant wave heights ranging up to the steepness or depth limitation were investigated in the model. Under all tested conditions for all four block placement configurations, the concrete masonry blocks on the non-overtopped revetment slope were observed to be completely stable with no block displacement or movement. There was also no displacement of the underlayer rock (D_{n50} = 70 mm) through the holes in the CMBs. These stability results are summarised in Figure 6.

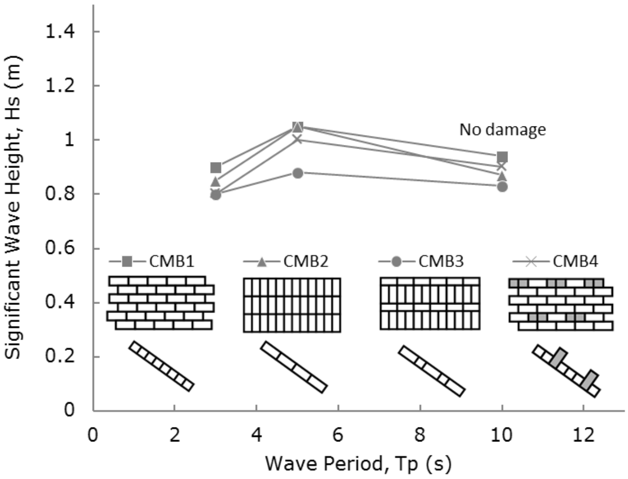

Figure 6 Summary of CMB revetment stability results for non-overtopped revetments

3.3 Influence of Overtopping on CMB Revetment Stability

For most low-energy coastlines where a CMB revetment may be applicable, it is likely that a revetment would be relatively low crested and that some degree of wave overtopping would occur during storms. As such, the stability of CMBs placed at the crest of a revetment slope would likely differ when exposed to overtopping waves, compared with CMBs placed on the slope of a non-overtopped revetment.

A series of tests were also undertaken with a lower crested revetment structure for waves with 5 second spectral peak period, to identify the upper limit of wave overtopping flows before the crest blocks became destabilised. The results are summarised in Figure 7. For average overtopping flow rates of up to 0.2 L/s/m, it was found that there was minimal damage sustained to the revetment crest. However, a slight increase in overtopping flow rate to 1.3 L/s/m resulted in significant displacement of crest blocks, with all blocks in the top course and several blocks in the second course completely displaced. It is likely that this test underestimated the observed damage, as in reality the displacement of crest blocks would coincide with erosion of the revetment substrate at the crest, which would exacerbate destabilisation of blocks. This process was, however, not simulated in the model due to the presence of the fixed revetment core.

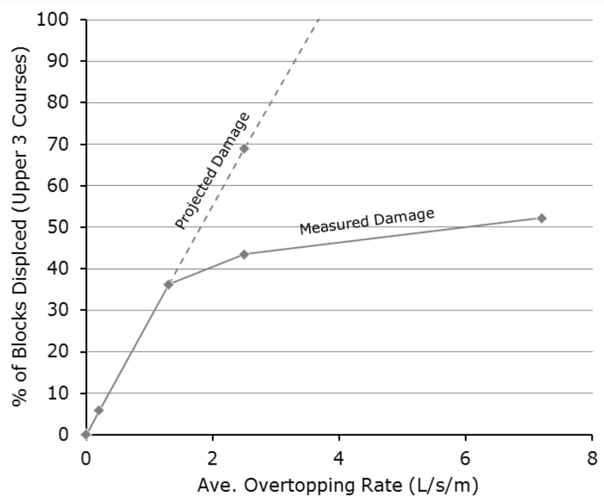

Figure 7 Summary of CMB revetment crest armour stability for overtopped revetment

3.4 CMB Revetment Wave Runup Results

Wave runup measurements were undertaken to allow for analysis of runup characteristics for each CMB placement pattern, consistent with typical coastal engineering design methods such as [4]. Figure 8 provides a summary of measured relative runup values for each CMB placement pattern tested (for the largest wave heights tested). Relative runup values for a smooth slope under the same wave conditions were also measured for comparative reference.

The results indicated that there is very little difference in wave runup levels that occur with the various “in-plane” CMB placement patterns tested. However, by placing a small number of CMBs within the armour layer on their end as per the fourth placement pattern shown in Figure 3 (long axis of block protruding outwards from armour layer), up to 20% reduction in wave runup levels were achieved for all three wave periods tested, when compared with a standard running bond placement pattern.

3.5 Discussion of Results for CMB Revetments

The results recorded in the physical model testing suggest that purely from a stability perspective, concrete masonry blocks do have potential for application as coastal protection in low energy wave conditions when placed on sloping revetment structures. When applied in locations exposed to locally generated wind waves and relatively shallow foreshore depths (sheltered lagoon coastlines for example), sloping revetments armoured with CMBs have been shown to be stable in wave conditions up to approximately 1 m significant wave height, if overtopping of the revetment crest is controlled (overtopping rates less than ~2 L/s/m), and the toe of the revetment is well supported.

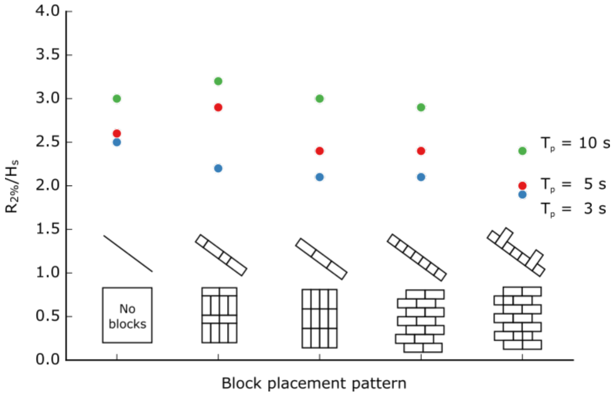

Figure 8 Summary of wave runup characteristics for CMB revetments

While not directly investigated to date, it should be recognised that the integrity and durability of the masonry blocks may be a limitation for their application as long term coastal protection works, or when applied in wave conditions as high as was tested in the physical modelling. This is an area of additional research to be undertaken. However, within the current physical modelling program, a number of tests were undertaken to investigate the influence of block breakage on the stability/integrity of the overall CMB armour layer.

Initially a revetment was constructed with ~5% of blocks artificially damaged or removed from the armour layer (within 8 block courses above and below the water level). The damaged/removed blocks were either individual units or occasionally a pair of adjacent units. This revetment was tested with waves having a spectral peak wave period of 5 seconds and wave heights ranging up to the depth limited significant wave height (H_S~1.1 m). In spite of the artificial “damage” to 5% of the blocks in the layer, no additional displacement of blocks was observed as a result of wave attack, even blocks adjacent to “damaged” units. There was also no removal of secondary armour rock through the small gaps that were created in the armour layer by the “damaged” units. Pre and post-test photographs from this test are shown in Figure 9.

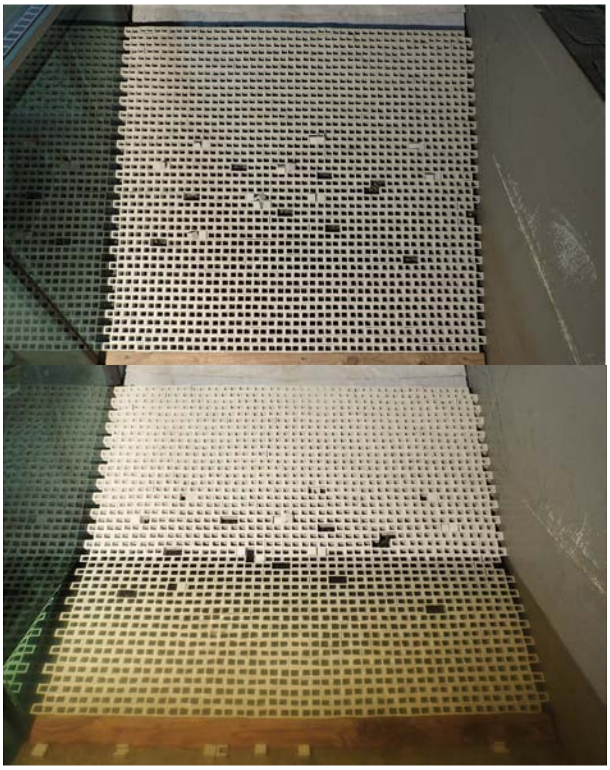

Figure 9 Pre and post-test photos of revetment structure with 5% artificial block “damage”

A second series of tests were undertaken with ~10% of blocks artificially damaged or removed. With larger holes in the armour layer, waves with significant wave height as small as ~0.7 m were able to dislodge a small number of adjacent CMBs from the armour layer, as well as displacing significant quantities of secondary armour. More severe wave conditions with significant wave height of ~1.1 m resulted in additional ongoing displacement of blocks adjacent to holes in the armour layer, removal of large quantities of secondary armour rock, and general fracturing/settlement of the CMB armour layer. Pre and post-test photographs from this test are shown in Figure 10.

These test results suggest that CMB armoured revetment slopes can likely tolerate damage or removal of a small percentage of units (<5 %) without having a significant impact on the integrity of the overall armour layer. However, damage to a larger number of blocks would result in premature and irreparable failure of the revetment armouring.

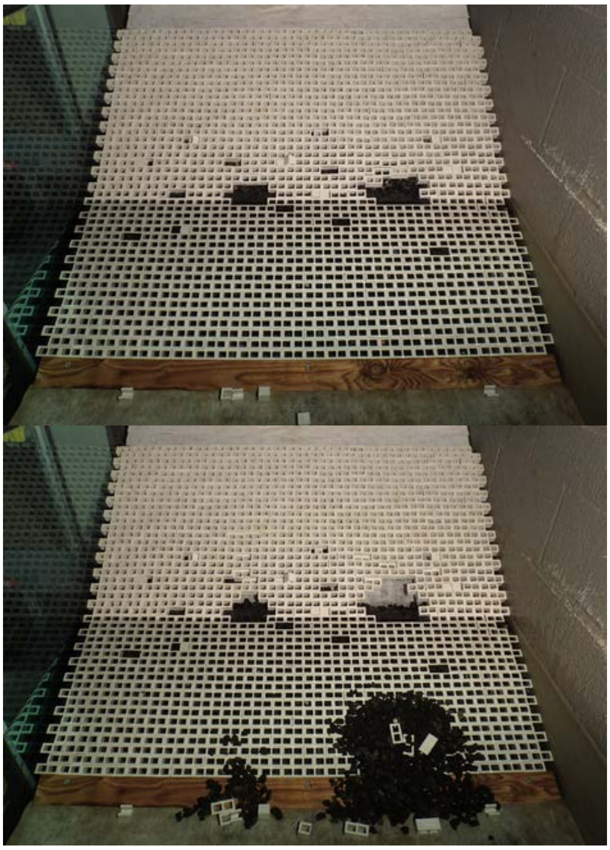

Figure 10 Pre and post-test photos of revetment structure with 10% artificial block “damage”

4. Results: 40 kg Geotextile Sand-Filled Containers

4.1 GSC Revetment Designs Tested

Non-overtopped revetments constructed with two different GSC placement patterns were each tested for spectral peak wave periods of 3, 5 and 10 seconds (Figure 11, Figure 12). The revetments were exposed to wave conditions with significant wave height increasing until complete failure of the GSC layer was achieved, in order to identify the upper limit stability threshold of the GSCs on the revetment slope.

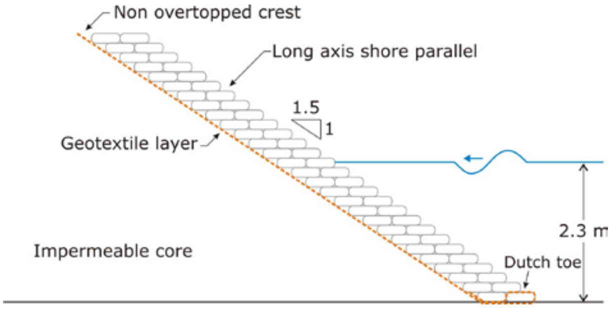

Figure 11 Non-overtopped double layer GSC revetment design tested in modelling program

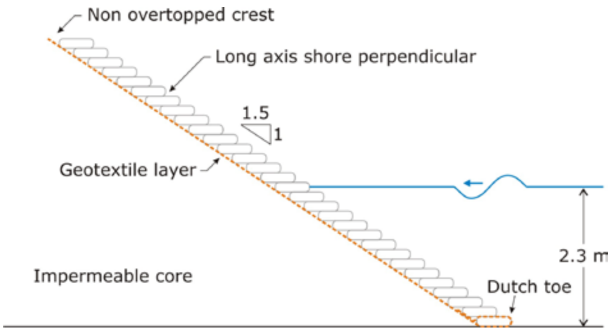

Figure 12 Non-overtopped single layer GSC revetment design tested in modelling program

4.2 GSC Revetment Stability Results

Figure 13 shows the recorded stability results for the test revetment with double layer GSC armouring. For this revetment it was identified that the GSCs could withstand waves with significant wave height up to 0.3-0.4 m without any bag displacement. Once the significant wave height was increased beyond 0.4 m the outer GSC layer on the revetment progressively failed with ongoing wave exposure. It was noted that the shorter period 3 second waves resulted in lower GSC stability, as the larger wave heights at this short period were actually breaking on the structure slope, as opposed to surging up the slope as was experienced for the longer period waves.

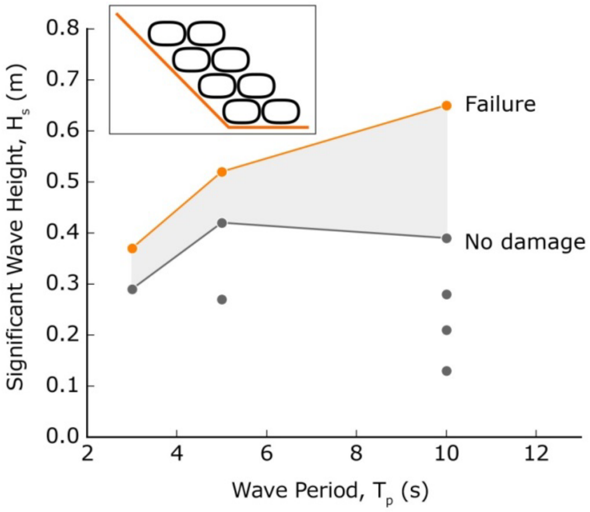

Figure 13 GSC revetment stability results for double layer shore-parallel container placement

Figure 14 shows the recorded stability results for the test revetment with single layer GSC armouring. For this revetment it was identified that the GSCs could withstand waves with significant wave height up to ~0.5 m with only minor bag displacement. Once the significant wave height was increased to 0.6 m and beyond, the outer GSC layer on the revetment progressively failed with ongoing wave exposure. It was again noted that the shorter period 3 second waves resulted in slightly lower GSC stability compared with the longer period waves, due to the wave breaking intensity on the structure. It was also noted that this bag placement pattern with long axis running shore-perpendicular resulted in slightly higher stability, presumably due to the larger interface friction area between bags. However, with a single layer of GSCs there is very little redundancy in the armour layer to cope with displaced bags compared with a double layer design.

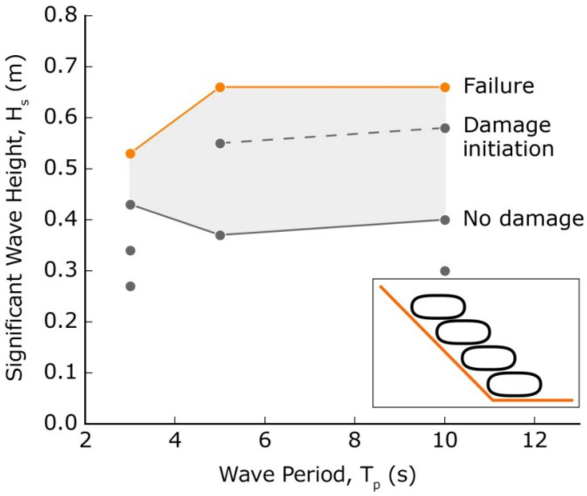

Figure 14 GSC revetment stability results for single layer shore-perpendicular container placement

4.3 Influence of Overtopping on GSC Revetment Stability

Again recognising that most revetment structures in real world applications would experience some degree of wave overtopping, the stability of GSCs placed at the crest of an overtopped revetment was also tested. A series of tests were undertaken with a lower crested revetment structure for 5 second period waves, to identify the upper limit of wave overtopping flows before the crest bags became destabilised. A range of wave conditions with significant wave height up to 0.9 m and average overtopping rates up to 4 L/s/m were tested, and the GSCs at the crest of the revetment remained stable throughout all tests.

During these tests the slope of the revetment was mostly protected from wave attack to prevent the slope from failing at lower wave heights than the crest. Nevertheless during the final test, the upper slope area of the revetment failed prior to crest bags being displaced from overtopping. Given the stability measurements for the non-overtopped GSC revetments (Figure 13), these results indicate that it is likely that the GSC revetments would initially fail from slope armour instability rather than crest armour instability, unlike the CMB revetments.

4.4 GSC Revetment Wave Runup Results

Wave runup measurements were undertaken to allow for analysis of runup characteristics for both the single and double layer GSC placement patterns, consistent with typical coastal engineering design methods. Figure 15 provides a summary of measured runup values.

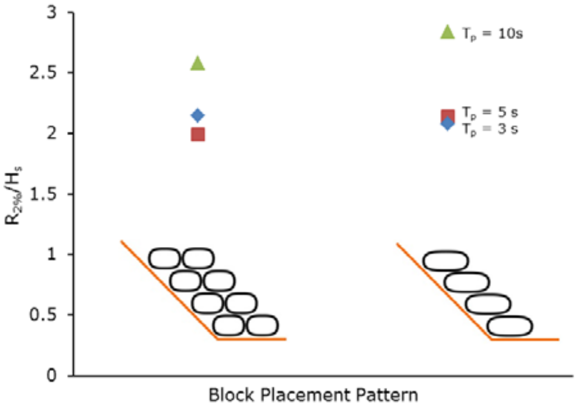

Figure 15 Summary of wave runup characteristics for GSC revetments

5. Discussion of Results for GSC Revetments

The results of the physical modelling indicate that the small hand-placed GSCs have a relatively low stability, and applications would need to be restricted to locations having a significant wave height of less than ~0.4 m. While the single layer revetment design had slightly higher GSC stability, damage to the structure rapidly progressed to complete failure. A double layer revetment design therefore offers a higher level of redundancy.

A re-scaling of the stability results for GSCs was undertaken, for comparison with results from [3]. The results compared very well, with design curves for initiation of armour damage from both investigations being largely consistent.

6. Summary

The stability of concrete masonry blocks in four alternative placement configurations was tested, and for all wave periods modelled (3 – 10 sec), the blocks were found to be stable in waves up to almost 1 m significant wave height. This was considered the physical limit of wave height due to depth or steepness limitations on waves. It was only when the crest of the revetment was overtopped by waves that the upper courses of blocks became unstable. The threshold of block stability on the crest was investigated for a range of wave overtopping rates. Due to the potential that some blocks would be damaged during a storm, the impact of this damage on the stability of the overall armour layer integrity was also investigated in the modelling.

The stability of small geotextile containers in two alternative placement configurations was tested, and for all wave periods modelled (3 – 10 sec), the containers were found to have a stability limit of approximately 0.4 m significant wave height. Waves in excess of this height resulted in rapid displacement of the containers from the revetment face slope. The stability limit of geotextile containers placed on the crest of a revetment was also investigated for a range of overtopping flows, and unlike the concrete masonry blocks, the geotextile containers were stable in relatively high overtopping flows (up to 4 L/s/m was tested).

7. References

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8. Acknowledgements

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