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Preliminary Testing of Oyster Shell Filled Bags

WRL Technical Report 2015/20
January 2016

By I R Coghlan, D Howe and W C Glamore

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University of New South Wales
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1. Introduction

OceanWatch Australia Ltd (hereafter "OceanWatch") commissioned the Water Research Laboratory (WRL) of the School of Civil and Environmental Engineering at UNSW Australia to undertake preliminary two-dimensional (2D) physical modelling of generic oyster shell filled bags to better understand their expected behaviour when exposed to wave attack.

Prior to undertaking the physical modelling tests, detailed discussions were held between WRL and OceanWatch regarding:

- Bag design;
- Bag shape (geometry);
- Bag material;
- Oyster shell packing density;
- Arrangement of bags;
- Expected behaviour under wave attack; and
- Longevity.

2. Background

A new technique has been proposed to install seeded oyster shells in coir (coconut fibre) bags, using natural materials wherever possible, at a number of sites fronting relatively protected waterways within Sydney Harbour and Botany Bay. This is a pilot project with the primary purpose of reducing foreshore erosion from wind waves and boat waves. Their secondary purpose is to create habitat where new oyster growth might occur. These units may be considered temporary coastal protection structures with a desired working life of approximately 1-3 years.

Figure 2-1: Example Proposed Field Site Experiencing Bank Erosion for Oyster Shell Bag Structure Sugarloaf Point (Lane Cove River National Park), East Ryde

3. Preliminary Wave and Water Level Design Conditions

3.1 Preamble

While the design life, design event and accepted risk of design event exceedance for the oyster shell bags remains unspecified by OceanWatch, WRL made some broad estimates of the typical wave and water level conditions that the proposed oyster shell bags may be exposed to.

3.2 Preliminary Wave Conditions

3.2.1 Long Period Ocean Swell Waves

Large ocean swells do penetrate into Sydney Harbour and Botany Bay. Swell wave heights reduce with distance into both embayments, and are mainly affected by wave refraction, diffraction and shoaling. WRL expects that the oyster shell bags are not suitable for use in locations exposed to ocean swell.

Swell waves would generally be sufficiently attenuated so that oyster shell bags may be able to be used in locations west of the following landmarks:

• Middle Harbour:	the Spit Bridge;
• Sydney Harbour:	a line extending from Bradleys Head to Point Piper (Watson and Lord, 2008); and
• Botany Bay/Georges River:	the Captain Cook Bridge.

3.2.2 Short Period Wind Generated Waves

Wind waves are generated when the wind blows across a body of water. The size (height) and period of these waves depends on the wind speed, the distance and duration over which the wind blows and the water depth.

It is outside the scope of works to develop detailed wind wave climates, including wave hindcasting and refraction modelling, at each of the trial sites within Sydney. However, 10, 20 and 50 year average recurrence interval (ARI) wave heights are presented in the *Sydney Metropolitan Area Fore-and-Aft Mooring Study* (MSB NSW, 1987) for a range of locations. While design wave climate locations in that study are not co-incident with the sites being considered for oyster shell bag deployment, several locations in adjacent bays indicated 10 year ARI significant wave heights (H_S) of up to 0.8 m. The study indicates that wave periods associated with such wave heights would be between 2 and 4 seconds for fetch lengths up to 4 km (MSB NSW, 1987). More frequent wind wave events (i.e. 1 year ARI) would be expected to have smaller wave heights and slightly shorter corresponding wave periods.

More detailed wind wave modelling may be able to be accessed from relevant Sydney Councils who have prepared coastal hazard studies and/or coastal zone management plans with study areas encompassing the prospective oyster shell bag sites. It is also readily calculable by a coastal engineer, but is beyond the scope of this study.

3.2.3 Boat Waves

As a boat travels through the water, it generates a series of waves. The height and period of these waves vary depending on boat speed and type.

Wakeboarding and Waterski Vessels

WRL completed full scale field testing of several wakeboarding and waterski vessels in 2005 on Manly Dam (Glamore and Hudson, 2005) and in 2014 on the Clarence River (Glamore et al., 2014) to determine the characteristic waves generated by a range of different recreational boats. Maximum wave heights (and periods) were observed to be produced at a speed of approximately 8 knots. The maximum wave heights ($H_{\max}$) and their associated wave period (T_{PEAK}) during field testing of the boats were measured 22 m from the sailing line and are reproduced in Table 3-1.

Table 3-1: Maximum Wave Heights for Waterski and Wakeboard Boats (Source: Glamore and Hudson, 2005)

Boat	Velocity (knots)	H_{max} (m)	T_{peak} (s)
Waterski	8	0.35	1.73
Wakeboard	8	0.33	1.86

At their operating conditions when towing a rider (30 knots for a waterski boat, 19 knots for wakeboarding boats and 10 knots for wakeboarding boats undertaking wakesurfing), the boat waves generated are smaller in magnitude (Table 3-2) than when travelling at 8 knots.

Table 3-2: Wave Heights for Waterski, Wakeboard and Wakesurf Activities under Operating Conditions (Source: Glamore and Hudson, 2005 and Glamore, et al., 2014)

Boat	Velocity (knots)	H_{max} (m)	T_{peak} (s)
Waterski	30	0.12	1.50
Wakeboard	19	0.25	1.57
Wakesurf	10	0.36	2.03

High Speed Catamaran Ferries

Blumberg et al. (2003) recognised that high speed catamaran ferries generate a relatively long bow wave. Blumberg et al. (2003) considered it to have a period of between 4.0 and 6.5 seconds.

WRL has previously undertaken three campaigns of field wave measurements at Darling Harbour (Miller 2004, 2005 and 2006) which consistently included measurements of waves generated by high speed catamaran ferries. Measurements were collected on five (5) days over an 18 month period as shown in Table 3-3, on the outside of the Australian National Maritime Museum (ANMM) Quay. Measurements were only taken mid-week (i.e. not on weekends) and were carried out during winter, spring and summer.

Table 3-3: WRL Field Wave Measurements at Darling Harbour

Dates	Season	Day(s) of the Week	Duration (days)
18 June 2004	Winter	Friday	1
5-6 October 2005	Spring	Wednesday-Thursday	2
12-13 January 2006	Summer	Thursday-Friday	2

Key summary tables from the first two field campaigns are reproduced in the following discourse. Table 3-4 shows the distribution of wave heights measured at Darling Harbour on 18th June 2004.

Table 3-4: Distribution of Wave Heights, 18th June 2004 (Miller, 2004)

Wave Height (m)	% of Waves	No. of Waves
0.00 – 0.04	12.46	1,129
0.04 – 0.08	28.67	2,598
0.08 – 0.12	25.96	2,353
0.12 – 0.16	14.98	1,358
0.16 – 0.20	8.31	753
0.20 – 0.30	7.37	668
0.30 – 0.40	1.69	153
0.40 – 0.50	0.42	38
0.50 – 0.60	0.10	9
0.60 - 0.80	0.04	4
Total	100	9,063

Table 3-5 shows a summary of the results as wave periods and the corresponding average recurrence in waves per hour on the outside of the ANMM Quay.

Table 3-5: Average Recurrence Interval of Longer Period Waves, 5th – 6th October 2005 (Miller, 2005)

Wave Period (s)	Average Recurrence (waves per hour)
4-5	25.2
5-6	2.1
6-7	1.0
>7	0.6

Table 3-6 presents the period and height of all waves with period greater than 5 s for the same data.

Table 3-6: Occurrence of Waves Greater than 5 Second Period 5th – 6th October 2005 (Miller, 2005)

Wave Period (s)	Wave Height (m)
5.02	0.11
5.06	0.08
5.16	0.20
5.22	0.28
5.24	0.20
5.24	0.11
5.26	0.09
5.28	0.10
5.28	0.09
5.32	0.09
5.32	0.41
5.42	0.26
5.60	0.15
5.64	0.24
5.66	0.18
5.72	0.24
5.74	0.17
5.80	0.20
5.90	0.20
5.94	0.24
6.22	0.22
6.28	0.12
6.32	0.20
6.36	0.18
6.40	0.28
6.44	0.24
6.54	0.26
6.56	0.22
6.64	0.10
7.22	0.21
7.32	0.15
7.58	0.28
7.90	0.21
9.02	0.24
9.38	0.14

On the basis of all raw data collected during the three (3) wave measurement campaigns outside the ANMM Quay, WRL conservatively recommends that the wave period of bow waves from high speed catamaran ferries is assumed to be 7.0 s with a wave height of 0.30 m (Coghlan et al., 2007). However, sensitivity testing should be conducted at 9.0 s, as wave periods of up to 9.4 s have previously been observed. Such wave periods are comparable to ocean swell.

If oyster shell bags are to be installed at proposed sites in Greenwich and Gladesville (Sydney Harbour), consideration should be given to the exposure of boat waves from passing high speed catamaran ferries (Sydney RiverCats).

Other Vessels

Typical boat wave height and period measurements for a range of other vessels are presented in the *Sydney Metropolitan Area Fore-and-Aft Mooring Study* (MSB NSW, 1987) in Table 3-7 and by Gary Blumberg & Associates (Blumberg et al., 2003) in Table 3-8.

Table 3-7: Typical Boat Wash Characteristics – Measured Close to Vessel Tracks (MSB NSW, 1987)

Vessel Type	**H_{MAX} (m)**	**T (s)**
Hydrofoil (1 of 2)*	0.76	2.3
Hydrofoil (2 of 2)*	0.87	2.4
Ferries	0.40	2.2
Water Taxis	0.48	2.2
15 m Motor Cruiser	0.80	3.6
13 m Tug	0.76	1.4
Power Boat	0.40	2.0

*Note: WRL understands that these vessels no longer operate in Port Jackson.

Table 3-8: Typical Vessel Wash Characteristics in Unrestricted Waters (Blumberg et al., 2003)

Vessel Type	**H_{MAX} (m)**	**T (s)**
Power Boat	0.35	3.0
First Fleet Ferry	0.62	3.0
Contractor’s Workboat	0.55	2.5
Commercial Fishing Boat	0.40	2.5
Harbour Charter Boat	0.35	2.7
Small Police Boat	0.30	1.8
Large Police Boat	0.72	2.5
New-Generation “Lower-Wash” Police Launch	0.51	4.1

Finally, large container and cruise ships, which operate at low speeds (typically 5-6 knots), generate low boat wave heights (typically less than 0.30 m) with short wave periods (less than 3.0 s) in typical navigation channels (Sorensen, 1967).

3.3 Preliminary Water Level Conditions

Elevated water levels consist of (predictable) tides, which are forced by the sun, moon and planets (astronomical tides), a tidal anomaly and other local processes. Astronomical tidal planes for Sydney are shown in Table 3-9, based on values from MHL (2013). While the mean high water mark is approximately 0.5 m above mean sea level (0 m Australian Height Datum AHD), some tides will reach up to approximately 1.0 m above mean sea level without any additional anomaly.

Table 3-9: Average Annual (1990-2010) Tidal Planes for Sydney, Port Jackson (HMAS Penguin) (MHL, 2013)

Tide	Level	
	(m Zero Camp Cove)	(m AHD)
High High Water Solstice Springs (HHWSS)	1.920	0.995
Mean High Water Springs (MHWS)	1.572	0.647
Mean High Water (MHW)	1.449	0.524
Mean High Water Neaps (MHWN)	1.326	0.401
Mean Sea Level (MSL)	0.945	0.020
Mean Low Water Neaps (MLWN)	0.564	-0.361
Mean Low Water (MLW)	0.441	-0.484
Mean Low Water Springs (MLWS)	0.318	-0.607
Indian Spring Low Water (ISLW)	0.069	-0.856

Tidal anomalies primarily result from factors such as regional wind setup (or setdown) and barometric effects, which are often combined as "storm surge". Additional anomalies occur due to "trapped" long waves propagating along the coast. Design storm surge levels (astronomical tide + anomaly) are recommended in *the Coastal Risk Management Guide* (NSW DECCW, 2010) based on data from the Fort Denison tide gauge in Sydney and reproduced in Table 3-10 – these values exclude wave setup and runup effects which can be significant where waves break on shorelines.

Table 3-10 Design Water Levels Tide + Storm Surge
Newcastle – Sydney – Wollongong (source NSW DECCW, 2010)

Average Recurrence Interval (ARI) (year)	**Water Level Excl. Wave Setup and Runup** (m AHD)
0.02	0.97
0.05	1.05
0.10	1.10
1	1.24
2	1.28
5	1.32
10	1.35
20	1.38
50	1.41
100	1.44
200	1.46

Water levels at any specific shoreline location are also subject to wave setup and wave runup. Site specific coastal engineering assessments could be completed to assess these processes as well as the influence of local wind setup and coincident local freshwater flooding.

It is considered appropriate to exclude sea level rise from the preliminary water level assessment due to the modest desired working life of the oyster shell bags.

3.4 Adopted Wave and Water Level Conditions for Preliminary Physical Modelling

The water depth at the toe of the oyster shell bags determines the maximum depth limited breaking wave height that can reach the structure. That is, even if wind or boat waves in deeper water offshore of each of the trial field sites exceed the adopted wave heights tested in the physical model, the wave height at the oyster shell bags may be less than this due to wave breaking. The design wave and water level conditions at the structure affect the hydraulic performance (wave runup and overtopping) and stability of the bags.

To establish a site specific, depth limited wave height at the oyster shell filled bags a number of parameters should be considered:

- cross-shore location of the oyster shell bags;
- exposure to wind and boat waves;
- water level variability; and
- expected beach scour level (sand/mud level) at the toe.

The cross-shore positioning of the oyster shell bags is yet to be confirmed by OceanWatch. It is obvious that the oyster shell filled bags will have the greatest stability (smallest wave exposure) when located towards the back of the active beach. However, this may not be the optimal cross-shore positioning to also promote new oyster growth on the oyster shell filled bags. WRL has assumed that the toe of the oyster shell filled bags will be placed above mean sea level (~ 0 m AHD) within the intertidal zone but that the structure height will not exceed 0.4 m. At this height, it is likely that large spring tides will exceed the crest elevation of the oyster shell filled bags when the cross-shore position is finalised.

In considering the preliminary wave and water level conditions outlined in Sections 3.2 and 3.3 and the physical limitations of the flume geometry and wave paddle capabilities, the combination of variables adopted for testing in the physical model is summarised in Table 3-11. Three (3) water levels were selected corresponding to the top of each tier of oyster shell filled bags in a three-tier high pyramid arrangement. Note that a "tier" is considered equivalent terminology to a "course" (e.g. a horizontal brickwork row) more commonly used in the engineering and construction industries. Wave periods of 1, 2 and 3 s are considered to be representative of most wind and boat waves expected at the proposed sites. Note that boat waves from high speed catamaran ferries (typical wave period 7.0 s) have not been considered. For each water level and wave period combination, the wave height was incrementally increased until depth limited or wave steepness limited conditions were achieved.

Table 3-11 Summary of Adopted Wave and Water Level Conditions

Condition	Condition Values
Depth of Water at Structure	0.16 m, 0.32 m, 0.40 m
Wave Period	1 s, 2 s, 3 s
Wave Height at Structure	0.05 m to 0.30 m

4. Process Not Considered

Consideration of the influence of the following processes on the stability of the oysters shell filled bags was outside the scope of works:

- tidal currents;
- flood velocities;
- vessel thruster currents;
- expected beach scour level (sand/mud level) at the toe and vertical settlement of the bags;
- longevity and durability of the bag material (i.e. lifetime fatigue, biological decay and vandal resistance); and
- strength (bearing capacity and skin friction) of anchoring stakes in a mobile bed.

5. Preliminary Physical Modelling

5.1 Objectives

The objectives of the preliminary 2D physical modelling study were to assess the stability and wave attenuation of the oyster shell filled bags under a variety of water level and wave attack scenarios.

As a type of coastal structure, oyster shell filled bags will be exposed to a large number of permutations of possible incident water level and wave conditions combined with varying structure and site geometries. Physical modelling was required to assess some of these complex permutations.

5.2 Model Testing Facility

2D testing was undertaken in the three metre wave flume at WRL. This flume measures approximately 32.5 m in length, 3 m in width and 1.3 m in depth. The flume walls are constructed of rendered brick. The permanent, horizontal floor of the flume is constructed of concrete. 2D testing was undertaken using the centre of 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.

The wave generator in this flume is a paddle type and is powered by a 55 kW hydraulic piston system. The system is capable of generating both monochromatic and irregular wave spectra. The input signal is generated and fed to the wave paddle using a PC and the National Instruments LabVIEW software package.

5.3 Model Scaling

All tests were undertaken at full scale (i.e. an undistorted length scale of 1:1).

5.4 Model Construction

5.4.1 Bathymetry

The oyster shell filled bags were located on an existing impermeable false floor in the wave flume constructed from blue metal fill overlain with concrete capping and had 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.

Note that no effort was made to match the bathymetric profiles offshore of each of the prospective sites in Sydney with the existing 1V:55H false floor.

There was a 7.2 m length of the 1V:55H bathymetric profile seaward of the oyster shell filled bag model. At the highest water level tested (0.4 m depth at the toe), this length corresponds to 5 wavelengths with 1 s wave period, 2 wavelengths with 2 s wave period or 1.2 wavelengths with 3 s wave period. The tests for 2 and 3 s wave periods are not in accordance with the minimum recommended value of 3-5 wavelengths recommended by Hydralab (2007) for physical modelling for coastal structures. However, given the preliminary nature of these tests, the shortened bathymetric profile length seaward of the model oyster shell filled bags is considered reasonable and allowed for the possible water depths and wave heights at the structure to be maximised on the existing false floor.

5.4.2 Oyster Shells

Oyster shells to fill the bags were supplied by OceanWatch. These were a mix of Sydney rock oyster (Saccostrea glomerata) and Pacific oyster (Crassostrea gigas) shells obtained from oyster farmers in Port Stephens. (Figure 5-1). These empty shells were free of oyster tissue and subject to biosecurity treatment prior to transport from Port Stephens. While WRL did not measure the grain density of the oysters shells provided, samples of the Pacific oyster grown under natural field conditions in France had a reported density of 1810 kg/m^3 (His and Robert, 1987). A published shell grain density value for the Sydney rock oyster was not found in the literature.

Figure 5-1: Sample Oyster Shells

5.4.3 *Bags*

The bag material used was coconut coir netting with 12 mm × 12 mm aperture with seams sewn with Manila rope. For Phase 2 Testing, the bags were fastened together using Sisal rope. Two single bags (Figure 5-2), one double bag and one triple bag (Figure 5-3) were assembled by OceanWatch.

Figure 5-2: Example Single Oyster Shell Filled Bag

Figure 5-3: Example Triple Oyster Shell Filled Bag

Each bag was measured and weighed (dry) by WRL prior to testing. Key measurements are summarised in Table 5-1. While the length of each bag was relatively consistent, their height and width were varied. Treating the bags as elliptical cylinders, bulk volumes were estimated for each bag. Dry bulk densities were inferred from these calculations with a range between approximately 330 and 450 kg/m^3. Assuming an oyster shell grain density of 1810 kg/m^3, the porosity of the oyster shell bags was approximately 75-80%.

Table 5-1 Summary of Oyster Shell Filled Bag Dimensions

Bag #	Bag Type	Mass (kg)	Length (m)	Height (m)	Width (m)	Bulk Volume (m^3)	Dry Bulk Density (kg/m^3)	Porosity (%)
1	Single	12.84	0.92	0.17	0.32	0.039	327	0.82
2*	Single	14.91	0.94	0.18	0.32	0.041	361	0.80
3	Double	30.25	0.91	0.20	0.27	0.070	430	0.76
			0.91	0.19	0.24			
4	Triple	34.48	0.92	0.17	0.25	0.078	444	0.75
			0.92	0.13	0.21			
			0.90	0.18	0.22			

* Bag 2 was measured and weighed but never tested in the wave flume.

5.4.4 Stakes

For Phase 2 Testing, the bottom tier of oyster shell filled bags was tied (on the seaward side) to two hot dipped galvanised steel brackets (40 mm wide × 150 mm high) using Sisal rope. The centre-to-centre spacing between these brackets was 450 mm (that is, the brackets were located 275 mm inside the mini flume walls). The brackets were fastened into the concrete false floor using screws.

As mentioned in Section 4, the anchoring stakes (steel brackets) used in the model were not expected to fail (i.e. pull out) during model testing. WRL understands that OceanWatch is considering using an alternative method to that tested in the wave flume to secure the oyster shell filled bags into the sand (or mud) during field trials. This will likely involve hardwood stakes on the seaward and landward side of the oyster shell filled bags in conjunction with Manila rope. This arrangement was not tested by WRL in the wave flume.

5.4.5 Modelled Oyster Bag Arrangements

The preliminary physical modelling for the oyster shell filled bags was conducted in two phases over two days.

Phase 1 tests were undertaken on 18 November 2015 using 5 to 10 wave "packets" of monochromatic waves only. For this phase, the oyster shell bags were not anchored to the bed and were not secured together so as to identify their behaviour and identify threshold wave heights for bag movement. Wave transmission through/over the structure was also measured to infer the likely reduction in foreshore erosion with the oyster shell bags in place. Table 5-2 summarises oyster shell filled bag arrangements and corresponding water levels tested. The bags were arranged in a pyramid fashion and tested with water levels corresponding to the top of each tier of oyster shell filled bags (where available). Photos of one tier and two tier oyster shell filled bag arrangements are shown in Figure 5-4 and Figure 5-5, respectively.

Table 5-2 Summary of Oyster Shell Filled Bag Arrangements (Phase 1 Tests)

No. of Tiers	Oyster Shell Filled Bag Arrangement	Water Depths Tested
1	Single Bag Only	0.16 m
2	Single Bag on Crest, Double Bag at Toe	0.16 m, 0.32 m
3	Single Bag on Crest, Double Bag in Middle, Triple Bag at Toe	0.16 m, 0.32 m, 0.40 m

Figure 5-4: 1 Tier Oyster Shell Filled Bag Arrangement - Unsecured (Phase 1 Tests)

Figure 5-5: 2 Tier Oyster Shell Filled Bag Arrangement - Unsecured (Phase 1 Tests)

Phase 2 tests were undertaken on 23 November 2015 using 10 wave "packets" of monochromatic waves and irregular (random) wave spectrums of 26 minutes duration (~ 1,000 waves). For this phase, the oyster shell filled bags were anchored to the bed and secured together. Their movement while tethered together was monitored but wave transmission was not recorded. Table 5-3 summarises oyster shell filled bag arrangements and corresponding water levels tested. A photo of the anchored three tier oyster shell filled bag arrangement is shown in Figure 5-6.

Table 5-3 Summary of Oyster Shell Filled Bag Arrangements (Phase 2 Tests)

No. of Tiers	Oyster Shell Filled Bag Arrangement	Water Depths Tested
2	Single Bag on Crest, Double Bag at Toe	0.16 m, 0.32 m,
3	Single Bag on Crest, Double Bag in Middle, Triple Bag at Toe	0.16 m, 0.32 m, 0.40 m

Figure 5-6: 3 Tier Oyster Shell Filled Bag Arrangement - Secured (Phase 2 Tests)

All tests were undertaken with the long axis of the oyster shell filled bags perpendicular to the direction wave attack (i.e. long axis parallel to wave crest).

The oyster shell filled bags were slightly (~ 80 mm) narrower than the width of the mini flume allowing some minor wave energy to pass on either side of the structure. As a result, wave transmission measurements are considered to be conservative.

5.5 Data Collection and Analysis

5.5.1 Wave Data

For Phase 1 tests, water level data was collected by a single capacitance wave probe in-line with the seaward toe of the oyster shell filled bag structure using one of the outer 1 m wide mini flumes to avoid wave reflections from the model structure. A second, single capacitance wave probe was located landward (leeward) of the oyster shell filled bag structure in the centre mini flume to measure transmitted waves. Data from the wave probes was recorded on a PC using the National Instruments LabVIEW software package. As all tests were conducted with monochromatic wave "packets", the wave height at the structure and the transmitted wave height for each test was determined by manually selecting a typical wave height from the first two or three waves to pass each probe, before wave reflections from the far end of the wave flume affected the recorded signal.

For Phase 2 tests with irregular (random) wave spectrums, an array of three capacitance wave probes, located in-line with the seaward toe of the oyster shell filled bag structure in one of the outer mini flumes, were used to record wave data in the flume during these tests, with the data then processed using the least squares method described by Mansard and Funke (1980) to separate and interpret incident and reflected waves. Based upon the time series of water level data recorded, wave statistics for each location were then able to be calculated using WRL's in-house wave processing software package, WARDAN. The significant wave height, H_S, was derived by statistical techniques using a zero-crossing analysis (average height of the waves which comprise the highest 1/3 of waves in a test). Zero up-crossing and zero down-crossing analysis was undertaken and the average significant wave height of the two techniques recorded for the test (the difference between the two was negligible). The maximum wave height, H_{MAX}, was the single greatest wave height measured during the test using the greater of the up-crossing and down-crossing assessments. The peak wave period, T_P, was derived by spectral analysis and corresponded to the peak spectral frequency, f_P; the frequency bin with the greatest amount of wave energy.

5.5.2 Oyster Bag Stability Assessment

An oblique, overhead video camera, set-up on a timber access-way across the top of the three metre wave flume, filmed each test so that post-test analysis of the stability and movement of oyster shell bags could be completed.

Plan view still photographs were also taken of each oyster shell bag arrangement following tests where significant movement occurred.

5.6 Phase 1 Test Results

5.6.1 Overview

The results from each of the 112 monochromatic wave tests conducted in Phase 1 are presented in Table 5-4. Note that when the whole oyster shell filled bag structure was displaced by sliding along the concrete false floor of the wave flume during a test, its position was reset prior to the commencement of the next test.

Table 5-4 Summary of Phase 1 Tests

Test #	No. of Tiers	No. of Bags	Water Depth at Structure (m)	Wave Period (s)	Wave Height at Structure (m)	Transmitted Wave Height (m)	C_t (transmission coefficient)	Wave Overtopping?	Observations
1	1	1	0.16	1	0.054	0.042	0.77	Y	Bag rocking, no displacement
2					0.089	0.035	0.39	Y	Bag rocking and displaced by ~100 mm
3					0.078	0.044	0.56	Y	Bag rocking and displaced by ~100 mm
4					0.064	0.036	0.56	Y	Bag rocking and displaced by ~100 mm
5					0.080	0.039	0.49	Y	Bag rocking and displaced by ~100 mm
6				2	0.064	0.041	0.63	Y	Bag rocking and displaced by ~80 mm
7					0.099	0.075	0.75	Y	Bag rocking and displaced by ~400 mm
8					0.107	0.077	0.72	Y	Bag rocking and displaced by ~500 mm
9					0.101	0.079	0.79	Y	Bag rocking and displaced by ~500 mm
10					0.132	0.081	0.62	Y	Bag rocking and displaced by ~700 mm
11				3	0.015	0.011	0.72	Y	No bag movement
12					0.042	0.032	0.75	Y	Bag rocking, no displacement
13					0.090	0.064	0.71	Y	Bag rocking and displaced by ~120 mm
14					0.123	0.079	0.65	Y	Bag rocking and displaced by ~450 mm
15					0.113	0.075	0.67	Y	Bag rocking and displaced by ~450 mm
16					0.136	0.085	0.62	Y	Bag rocking and displaced by ~470 mm
17	2	3	0.16	1	0.069	0.013	0.19	N	No bag movement
18					0.086	0.011	0.13	N	Bag rocking, no displacement
19					0.064	0.012	0.19	N	Bag rocking , no displacement
20				2	0.062	0.013	0.21	N	No bag movement

Table 5.4 Summary of Phase 1 Tests (Cont.)

Test #	No. of Tiers	No. of Bags	Water Depth at Structure (m)	Wave Period (s)	Wave Height at Structure (m)	Transmitted Wave Height (m)	C_t (transmission coefficient)	Wave Overtopping?	Observations
21	2	3	0.16	2	0.079	0.017	0.22	N	Crest bag rocking, no displacement
22					0.118	0.028	0.24	N	Crest bag rocking, no displacement
23					0.115	0.031	0.27	N	Crest bag rocking, no displacement
24					0.103	0.026	0.26	N	Crest bag rocking, no displacement
25				3	0.045	0.015	0.33	N	No bag movement
26					0.088	0.022	0.25	N	No bag movement
27					0.118	0.028	0.24	N	Crest bag rocking, no displacement
28					0.087	0.033	0.37	N	Crest bag rocking, no displacement
29					0.091	0.027	0.29	N	Crest bag rocking, whole structure displaced by ~30 mm
30	2	3	0.32	1	0.039	0.020	0.50	Y	Crest bag rocking, no displacement
31					0.075	0.033	0.44	Y	Crest bag rocking, no displacement
32					0.107	0.047	0.43	Y	Crest bag rocking, no displacement
33					0.111	0.066	0.59	Y	Crest bag rocking, no displacement
34					0.146	0.060	0.41	Y	Crest bag rocking, no displacement
35					0.135	0.066	0.49	Y	Crest bag rocking, no displacement
36					0.138	0.074	0.53	Y	Crest bag rocking, no displacement
37				2	0.091	0.062	0.69	Y	Crest bag rocking, no displacement
38					0.114	0.078	0.69	Y	Crest bag rocking, whole structure displaced by ~150 mm
39					0.143	0.091	0.64	Y	Crest bag rocking, whole structure displaced by ~300 mm
40					0.177	0.101	0.57	Y	Crest bag rocking, whole structure displaced by ~300 mm
41					0.193	0.127	0.66	Y	Crest bag completely displaced, whole structure displaced by ~450 mm

Table 5.4 Summary of Phase 1 Tests (Cont.)

Test #	No. of Tiers	No. of Bags	Water Depth at Structure (m)	Wave Period (s)	Wave Height at Structure (m)	Transmitted Wave Height (m)	C_t (transmission coefficient)	Wave Overtopping?	Observations
42	2	3	0.32	2	0.204	0.114	0.56	Y	Crest bag slightly displaced, whole structure displaced by ~300 mm
43					0.180	0.138	0.76	Y	Crest bag slightly displaced, whole structure displaced by ~200 mm
44				3	0.084	0.065	0.76	Y	Crest bag rocking, whole structure displaced by ~50 mm
45					0.064	0.054	0.83	Y	Crest bag rocking, no displacement
46					0.045	0.038	0.86	Y	Crest bag rocking, no displacement
47					0.031	0.027	0.87	Y	No bag movement
48					0.111	0.090	0.81	Y	Crest bag rocking, whole structure displaced by ~150 mm
49					0.152	0.109	0.71	Y	Crest bag rocking, whole structure displaced by ~300 mm
50					0.188	0.123	0.65	Y	Crest bag rocking, whole structure displaced by ~350 mm
51					0.183	0.142	0.78	Y	Crest bag rocking, whole structure displaced by ~400 mm
52					0.202	0.113	0.56	Y	Crest bag rocking, whole structure displaced by ~400 mm
53	3	6	0.16	3	Wave data not recorded			N	No bag movement
54	3	6	0.32	1	0.065	0.005	0.08	N	Crest bag rocking, no displacement
55					0.089	0.012	0.14	N	Crest bag rocking, no displacement
56					0.106	0.012	0.11	N	Crest bag rocking, no displacement
57					0.095	0.014	0.15	N	Top 2 bag tiers rocking, no displacement
58					0.098	0.010	0.10	N	Top 2 bag tiers rocking, no displacement
59					0.123	0.018	0.15	N	Top 2 bag tiers rocking, no displacement
60					0.127	0.024	0.19	N	Top 2 bag tiers rocking, no displacement
61					0.108	0.016	0.15	N	Top 2 bag tiers rocking, no displacement
62				2	0.099	0.022	0.22	N	Crest bag rocking, no displacement

Table 5.4 Summary of Phase 1 Tests (Cont.)

Test #	No. of Tiers	No. of Bags	Water Depth at Structure (m)	Wave Period (s)	Wave Height at Structure (m)	Transmitted Wave Height (m)	C_t (transmission coefficient)	Wave Overtopping?	Observations
63	3	6	0.32	2	0.128	0.028	0.22	N	Crest bag rocking, no displacement
64					0.154	0.038	0.25	N	Top 2 bag tiers rocking, whole structure displaced by ~100 mm
65					0.185	0.046	0.25	Y	Top 2 bag tiers rocking, whole structure displaced by ~200 mm
66					0.236	0.052	0.22	Y	Top 2 bag tiers rocking, whole structure displaced by ~300 mm
67					0.225	0.078	0.35	Y	Top 2 bag tiers rocking, whole structure displaced by ~450 mm
68					0.194	0.067	0.35	Y	Crest bag completely displaced, whole structure displaced by ~150 mm
69					0.185	0.068	0.37	Y	Crest bag completely displaced, whole structure displaced by ~150 mm
70					0.193	0.073	0.38	Y	Crest bag completely displaced, whole structure displaced by ~150 mm
71				3	0.033	0.021	0.65	N	No bag movement
72					0.068	0.027	0.40	N	Crest bag rocking, no displacement
73					0.070	0.034	0.48	N	Crest bag rocking, no displacement
74					0.093	0.040	0.43	N	Crest bag rocking, no displacement
75					0.114	0.047	0.41	Y	Crest bag rocking, whole structure displaced by ~50 mm
76					0.139	0.048	0.34	Y	Crest bag rocking, whole structure displaced by ~350 mm
77					0.179	0.072	0.40	Y	Crest bag completely displaced, whole structure displaced by ~400 mm
78					0.201	0.099	0.49	Y	Crest bag completely displaced, whole structure displaced by ~400 mm
79					0.226	0.130	0.57	Y	Crest bag completely displaced, whole structure displaced by ~400 mm
80	3	6	0.40	1	0.089	0.037	0.42	Y	No bag movement
81					0.098	0.036	0.37	Y	Crest bag rocking, no displacement
82					0.123	0.054	0.44	Y	Crest bag rocking, no displacement
83					0.144	0.066	0.45	Y	Crest bag rocking, no displacement

Table 5.4 Summary of Phase 1 Tests (Cont.)

Test #	No. of Tiers	No. of Bags	Water Depth at Structure (m)	Wave Period (s)	Wave Height at Structure (m)	Transmitted Wave Height (m)	C_t (transmission coefficient)	Wave Overtopping?	Observations
84	3	6	0.40	1	0.158	0.061	0.39	Y	Crest bag rocking, no displacement
85					0.159	0.054	0.34	Y	Crest bag rocking, no displacement
86					0.139	0.062	0.44	Y	Crest bag rocking, no displacement
87					0.166	0.081	0.49	Y	Crest bag rocking, no displacement
88					0.174	0.077	0.44	Y	Crest bag rocking, no displacement
89				2	0.101	0.050	0.50	Y	Crest bag rocking, no displacement
90					0.075	0.049	0.65	Y	Crest bag rocking, no displacement
91					0.056	0.029	0.52	Y	No bag movement
92					0.026	0.015	0.56	Y	No bag movement
93					0.125	0.070	0.56	Y	Crest bag rocking and slightly displaced, rest of structure not displaced
94					0.150	0.084	0.56	Y	Crest bag rocking and moderately displaced, rest of structure not displaced
95					0.181	0.105	0.58	Y	Crest bag completely displaced, whole structure displaced by ~100 mm
96					0.207	0.101	0.49	Y	Crest bag completely displaced, whole structure displaced by ~200 mm
97					0.233	0.121	0.52	Y	Crest bag completely displaced, whole structure displaced by ~400 mm
98					0.268	0.144	0.54	Y	Crest bag completely displaced, whole structure displaced by ~600 mm
99					0.273	0.146	0.53	Y	Crest bag completely displaced, whole structure displaced by ~800 mm
100				3	0.018	0.013	0.73	Y	No bag movement
101					0.037	0.024	0.65	Y	No bag movement
102					0.047	0.040	0.85	Y	No bag movement
103					0.078	0.054	0.68	Y	Crest bag rocking, no displacement
104					0.087	0.067	0.77	Y	Crest bag rocking, no displacement

Table 5.4 Summary of Phase 1 Tests (Cont.)

Test #	No. of Tiers	No. of Bags	Water Depth at Structure (m)	Wave Period (s)	Wave Height at Structure (m)	Transmitted Wave Height (m)	C_t (transmission coefficient)	Wave Overtopping?	Observations
105	3	6	0.40	3	0.122	0.089	0.73	Y	Crest bag rocking, no displacement
106					0.131	0.102	0.78	Y	Crest bag rocking, whole structure displaced by ~50 mm
107					0.175	0.140	0.80	Y	Crest bag completely displaced, whole structure displaced by ~300 mm
108					0.230	0.149	0.65	Y	Crest bag completely displaced, whole structure displaced by ~600 mm
109					0.249	0.185	0.74	Y	Crest bag completely displaced, whole structure displaced by ~300 mm
110					0.236	0.177	0.75	Y	Crest bag completely displaced, whole structure displaced by ~300 mm
111					0.270	0.221	0.82	Y	Crest bag completely displaced, whole structure displaced by ~300 mm
112					0.281	0.190	0.68	Y	Crest bag completely displaced, whole structure displaced by ~300 mm

5.6.2 Oyster Shell Filled Bag Stability

In general, as the wave height was increased at the seaward toe of the oyster shell bag structure, the following behaviour was incrementally noted:

- No bag movement;
- Rocking back and forth of the crest bag;
- Rocking back and forth of the bags in the 2nd tier;
- Displacement of the whole structure via sliding (see example in Figure 5-7); and
- Complete displacement of the crest bag (see example in Figure 5-8).

Table 5-5 consolidates the results presented in Table 5-4, documenting the threshold wave height at which rocking, displacement of the whole structure and displacement of the crest bag was initiated for each bag arrangement, water depth and wave period combination. Internal movement of oysters shells within each bag under wave attack was also observed. Generally the wave height initiating shell bag movement decreases with increasing wave period.

Table 5-5 Wave Heights Initiating Oyster Shell Filled Bag Movement (Phase 1 Tests)

No. of Tiers	No. of Bags	Water Depth at Structure (m)	Wave Period (s)	Wave Height at Structure (m)		
				Initiating Rocking	Initiating Displacement of the Whole Structure	Initiating Complete Displacement of Crest Bag
1	1	0.16	1	0.054	0.089	N/A
			2	0.064	0.064	N/A
			3	0.042	0.090	N/A
2	3	0.16	1	0.086	-	-
			2	0.079	-	-
			3	0.087	0.091	-
		0.32	1	0.039	-	-
			2	0.091	0.114	-
			3	0.045	0.084	0.180
3	6	0.16	1, 2, 3	-	-	-
		0.32	1	0.065	-	-
			2	0.099	0.154	0.185
			3	0.068	0.114	0.179
		0.40	1	0.098	-	-
			2	0.075	0.181	0.181
			3	0.078	0.131	0.175

The crest bag would begin rocking back and forth for wave heights between 0.05 and 0.10 m. At these wave heights, any rope stitching between the crest bag and the second tier of oyster shell bags would be under tension. The crest bag was displaced when wave heights at the structure reached 0.18 m. Rope stitching would be under considerable strain to resist these motions at this wave height. At a wave height of approximately 0.10 m (range 0.06 to 0.18 m), the whole oyster shell bag structure was displaced. The Phase 2 system anchoring the oyster shell bags (rope and stake) into the concrete false floor would be expected to take up load at this wave height.

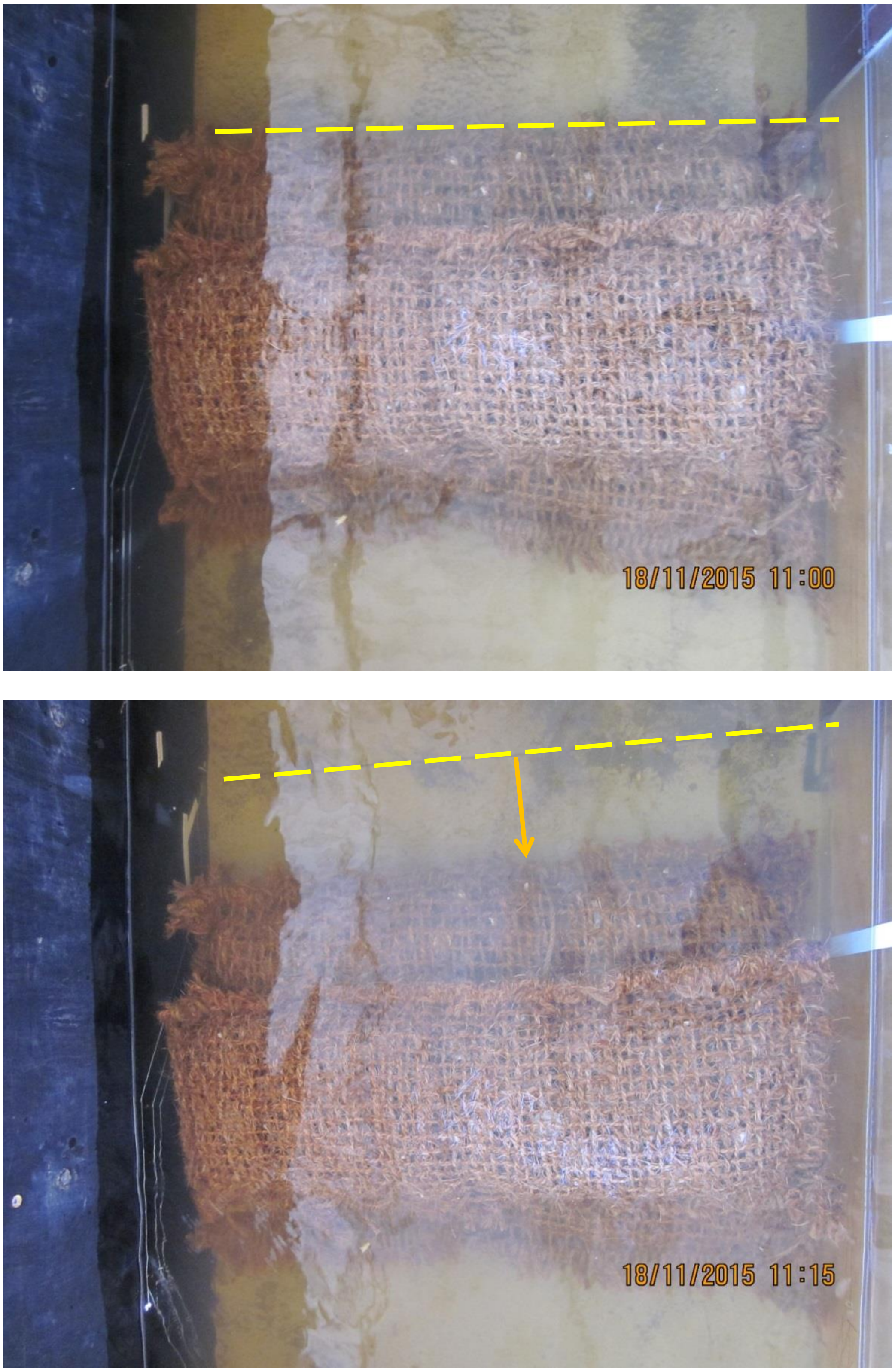

Figure 5-7: Before (Top) and After (Bottom) Photos Illustrating Displacement of Whole Structure (2 Tier High Structure) Note – Waves are Travelling from Top to Bottom

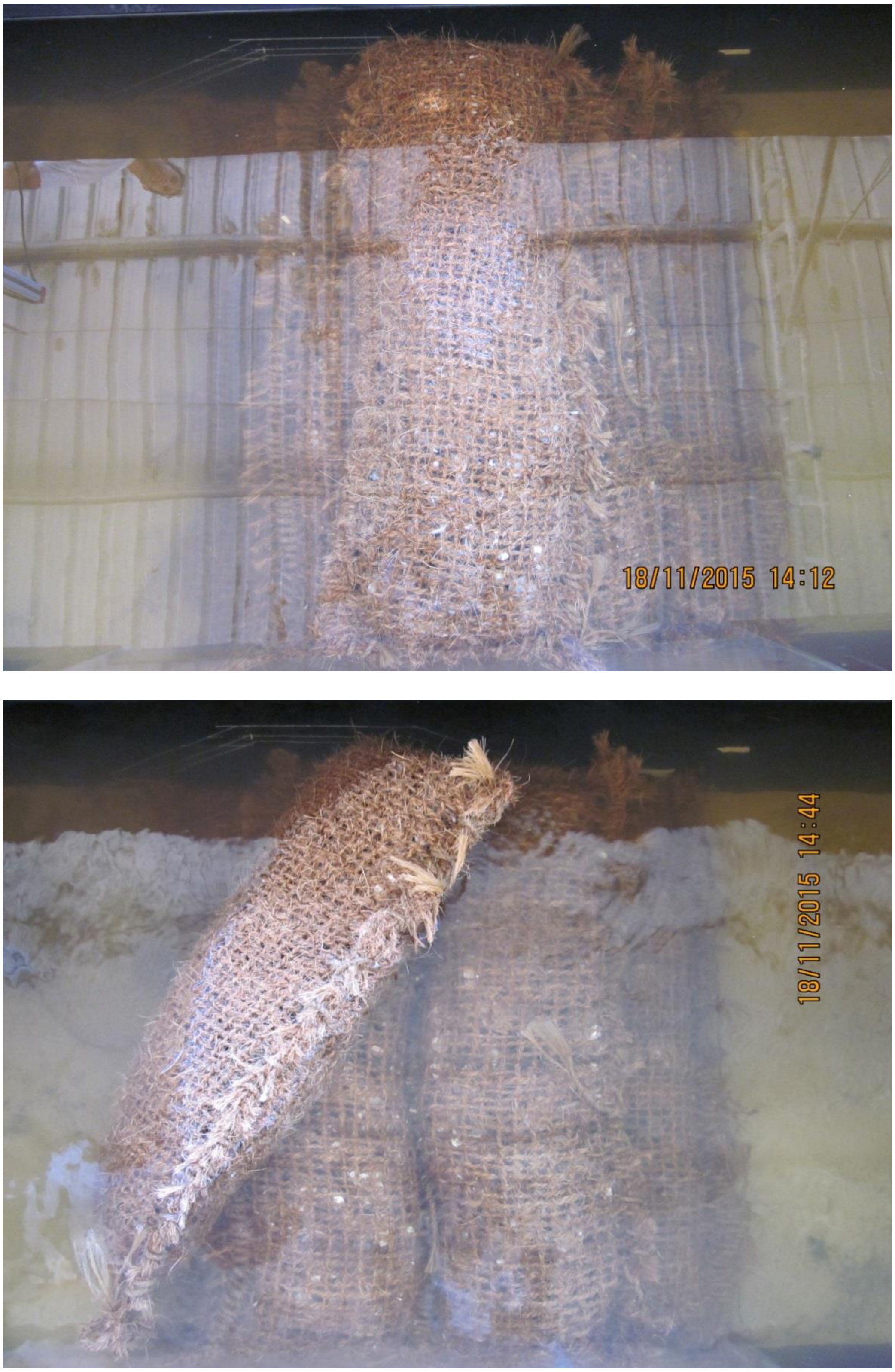

Figure 5-8: Before (Top) and After (Bottom) Photos Illustrating Complete Displacement of Crest Bag (3 Tier High Structure) Note – Waves are Travelling from Right to Left

5.6.3 Wave Transmission

To quantify the reduction in wave height (attenuation) as a direct result of the presence of the oyster shell filled bags, wave transmission through/over the bags was evaluated. Wave transmission is commonly defined in Equation 5.1:

$$C_t = \frac{H_t}{H_i} \qquad (5.1)$$

where: C_t = transmission coefficient
H_i = the incident wave height on the seaward toe of the structure
H_t = the transmitted wave height on the landward side of the structure

From this definition, it can be observed that $C_t \leq 1.0$ and the smaller the value, the lower the transmitted wave energy.

The wave transmission coefficients for each bag arrangement and wave period combination are plotted in Figure 5-9 through Figure 5-13. Generally the wave transmission coefficient increases with increasing wave period.

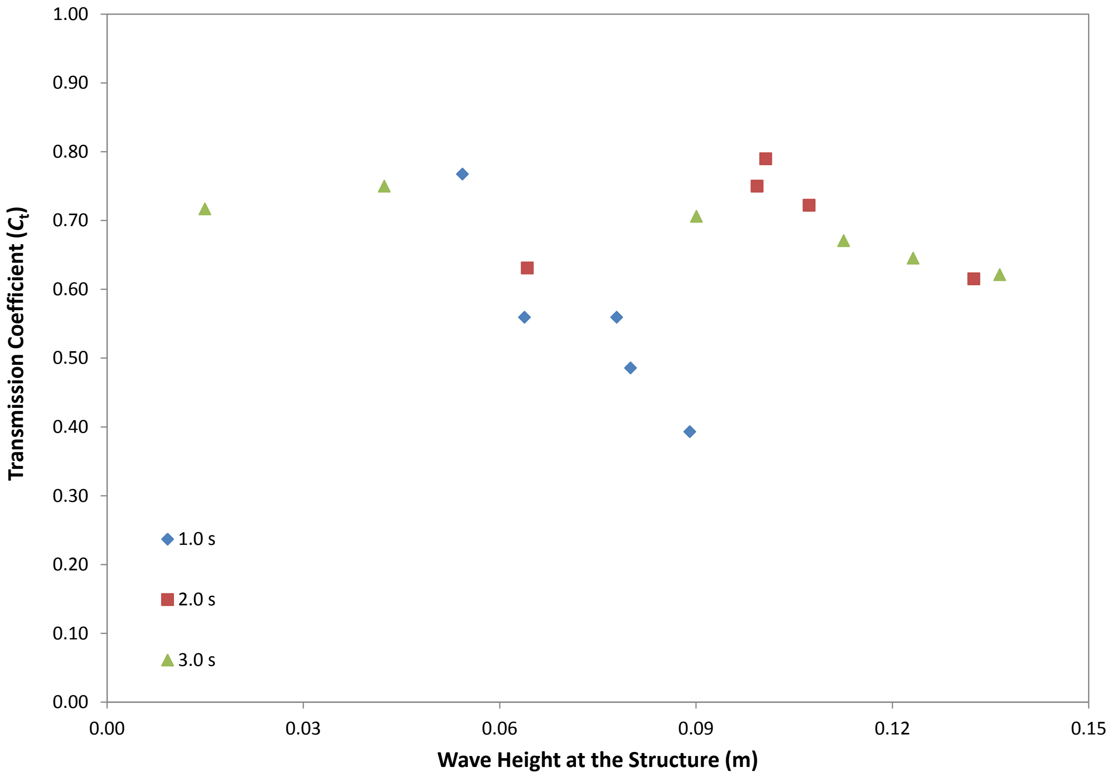

Figure 5-9: Transmission Coefficients for 1 Tier Bag Arrangement (0.16 m Water Depth)

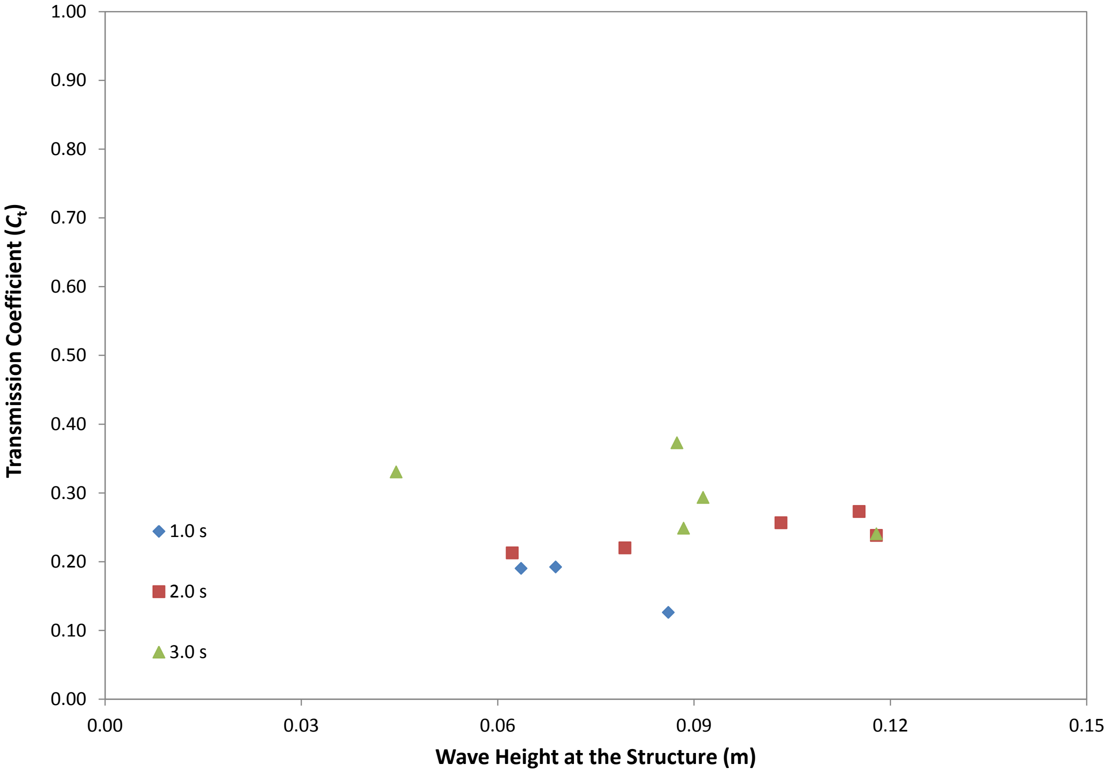

Figure 5-10: Transmission Coefficients for 2 Tier Bag Arrangement (0.16 m Water Depth)

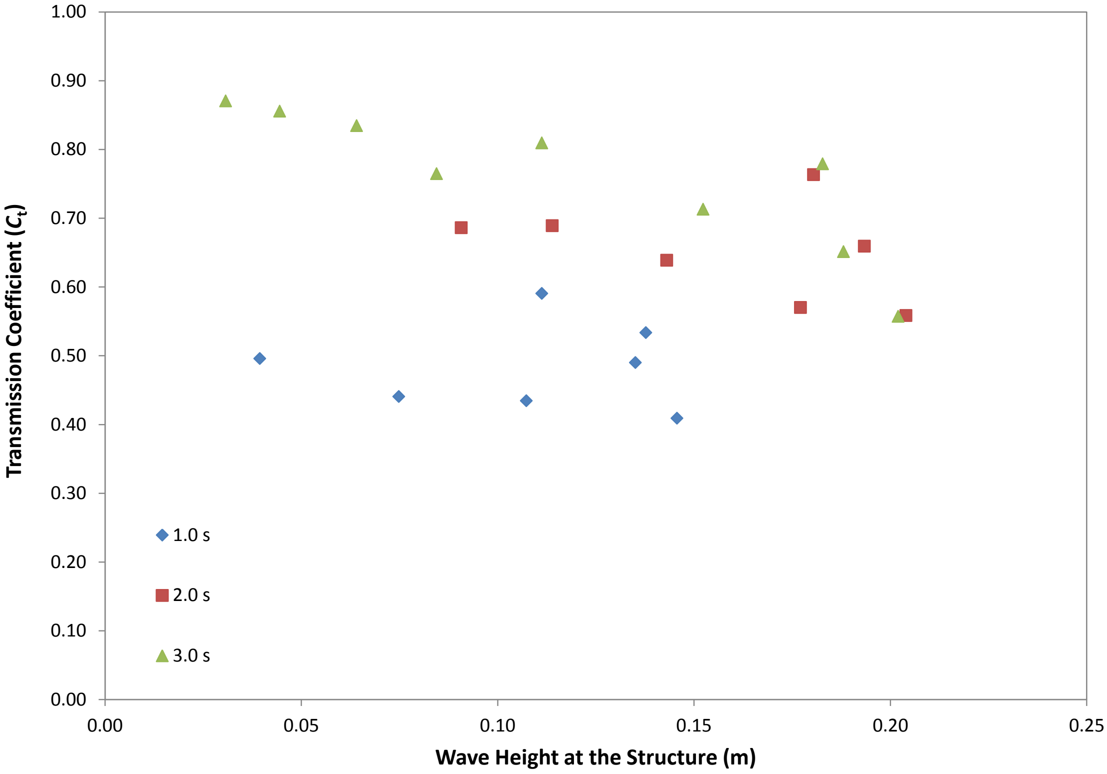

Figure 5-11: Transmission Coefficients for 2 Tier Bag Arrangement (0.32 m Water Depth)

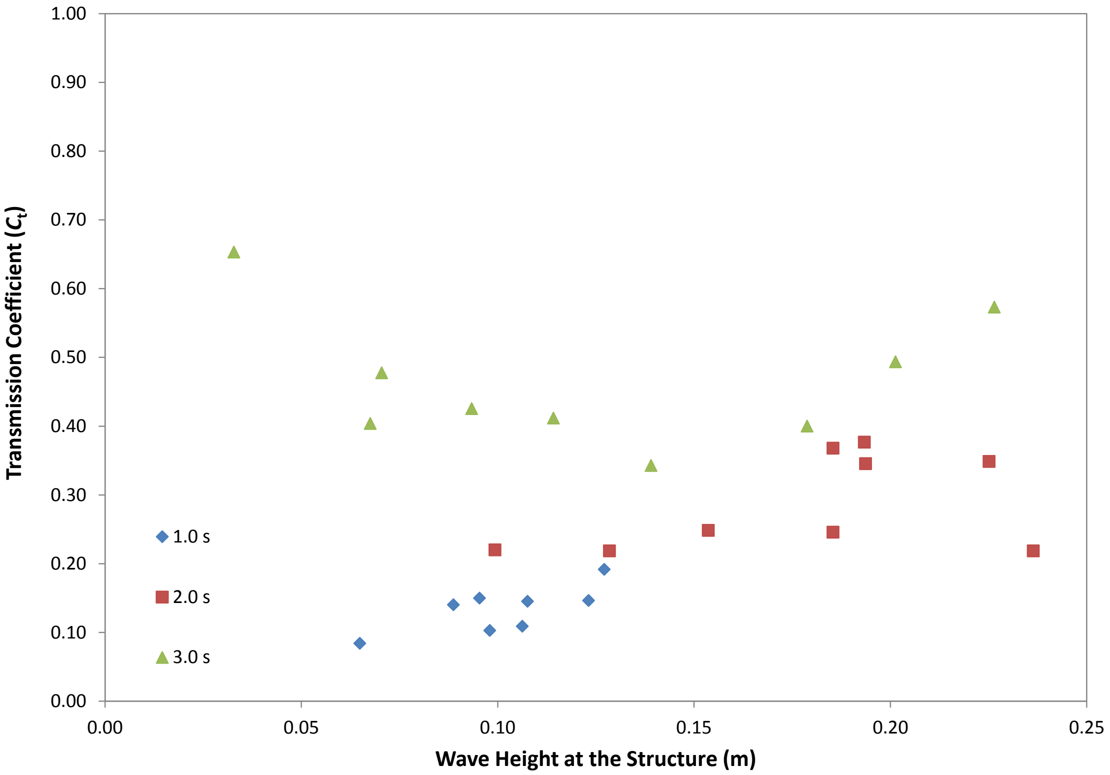

Figure 5-12: Transmission Coefficients for 3 Tier Bag Arrangement (0.32 m Water Depth)

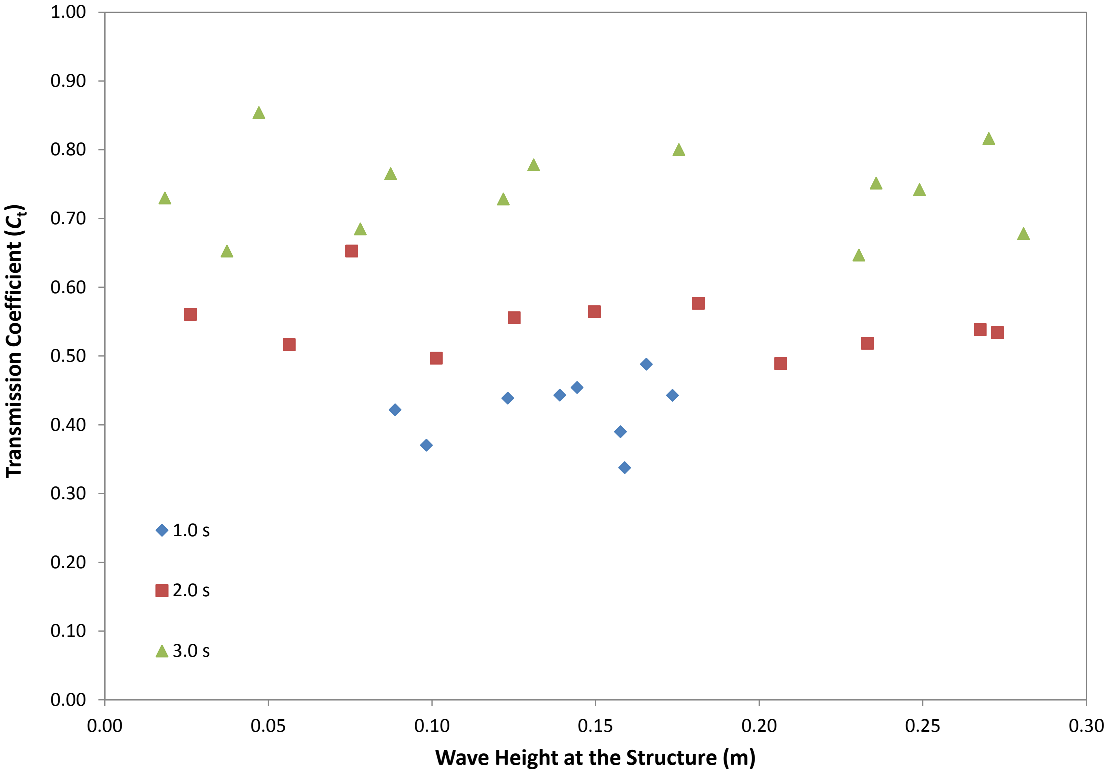

Figure 5-13: Transmission Coefficients for 3 Tier Bag Arrangement (0.40 m Water Depth)

When the water level is equivalent in elevation to the crest of the oyster shell filled bag structure, wave transmission is quite high, with coefficients generally between 0.40 and 0.80. This corresponds to a 20-60% reduction in wave height as a result of the presence of the oyster shell filled bag structure. Since wave energy is proportional to the square of wave height, this corresponds to a 5-35% reduction in wave energy impacting the shoreline leeward of the structure at this water level.

When the water level is equivalent in elevation to the top of the second tier of oyster shell filled bags (i.e. 1 bag of freeboard), wave transmission is lower, with coefficients generally between 0.05 and 0.45. This corresponds to a 55-95% reduction in wave height (30-90% reduction in wave energy) at this lower water level as a result of the presence of the oyster shell filled bag structure.

The reduction in wave energy impacting the shoreline leeward of the structure varies throughout the tidal cycle and is dependent on its final cross-shore position on the intertidal beach. However, as a direct result of the presence of an oyster shell filled bag structure, some existing wave-driven foreshore erosion processes are expected to be attenuated immediately landward of the structure. This attenuation may not occur during very high tides.

5.7 Phase 2 Test Results

The results from each of the 20 monochromatic wave tests and two (2) irregular wave tests conducted in Phase 2 are presented in Table 5-6. The two (2) JONSWAP spectrum irregular wave tests, had a peak wave period (T_P) of 2.0 s. For these two tests in Table 5-6. "Wave Period" is equivalent to T_P and "Wave Height at Structure" is equivalent to the significant wave height (H_S).

Oyster bag stability, within the constraints of tier-to-tier fastening and anchoring to the bed, was the primary observation for these tests. For each of the monochromatic wave tests in Phase 2, only the depth limited (worst case) condition for each water depth and wave period combination was evaluated.

Similar results to the equivalent Phase 1 tests were observed except that displacement of the whole structure was limited to the length of slack in the anchor ropes and complete displacement of the crest bag was prevented by the tier-to-tier fastening rope. To the limits of slack available in the anchor and tier-to-tier fastening ropes, each tier of bags shifted as landward as possible during these tests. This resulted in the oyster shell filled bag cross-section appearing similar in profile to a scalene triangle (with a landward bias/weight) rather than an isosceles triangle after the conclusion of the tests. For 2 s and 3 s period waves with a 0.40 m water level at the three (3) tier structure, the whole structure would oscillate back (landward) and forth (seaward) with the arrival of wave peaks and troughs, respectively. In this mode, the fastened oyster shell filled bag arrangement operated as one unit, analogous to the behaviour of swaying seagrass. Example photographs of the oyster shell filled bags under wave attack during testing Phase 2 are presented in Figure 5-14.

None of the Manila rope seams on the individual oyster shell filled bags broke during the preliminary physical modelling program, however, the limited duration of model tests is not a true indicator of long term durability.

Table 5-6 Summary of Phase 2 Tests

Test #	No. of Tiers	No. of Bags	Water Depth at Structure (m)	Wave Type	Wave Period (s)	Wave Height at Structure (m)	Maximum Wave Height at Structure (m)	Observations
113	3	6	0.32	Mono.	1	0.135	N/A	Crest bag rocking, no displacement
114					1			(repeat – 10 × 10 wave "packets")
115					2	0.204		Top 2 bag tiers rocking, displacement of whole structure (tension in anchors)
116					2			(repeat)
117					2			(repeat – 10 × 10 wave "packets")
118					3	0.202		Top 2 bag tiers rocking, crest bag shifted landward, whole structure sliding ± 50 mm
119					3			(repeat – 10 × 10 wave "packets")
120			0.40		1	0.166		Crest bag rocking, no displacement
121					1			(repeat – 10 × 10 wave "packets")
122					2	0.273		Top 2 bag tiers rocking and shifted landward, whole structure sliding ± 50 mm
123					2			(repeat)
124					3	0.281		Bags rolling back and forth at tier interfaces, whole structure sliding ± 50 mm
125					3			(repeat)
126				Irreg.	2	0.106	0.187	Crest bag rocking, displacement of whole structure (tension in anchors)
127	2	3	0.32	Mono.	1	0.135	N/A	Crest bag rocking, no displacement
128					2	0.204		Both bag tiers rocking, whole structure sliding ± 50 mm
129					3	0.202		Bags rolling back and forth at tier interface, whole structure sliding ± 50 mm
130				Irreg.	2	0.105	0.183	Crest bag rocking, displacement of whole structure (tension in anchors)
131			0.16	Mono.	1	0.078	N/A	Crest bag rocking slightly, no displacement
132					2	0.132		Crest bag rocking, displacement of whole structure (tension in anchors)
133					3	0.113		Crest bag rocking, displacement of whole structure (tension in anchors)
134					3			(repeat)

Figure 5-14: Example Photographs of Wave Attack on Oyster Shell Filled Bags During Phase 2 (Test 124) Note – Waves are Travelling from Right to Left

6. Discussion

In terms of cross-shore position of the oyster shell bags on the inter-tidal profile, WRL recommends that the toe of the 3 tier (6 bag) arrangement be located no lower than 0.25 m AHD (approximately 0.25 m above mean sea level) to replicate conditions experienced in the three metre wave flume. With this cross-shore position at sites with incident waves of no longer than 3.0 s period, depth limited waves exceeding that tested in the flume could only occur for water levels exceeding the Mean High Water Springs level (~0.65 m AHD or 1.6 m on NSW tide charts) coincident with wind or boat waves exceeding 0.3 m in height. In the absence of tidal anomalies, this water level is exceeded approximately 6% of the time (550 hours annually) via approximately 240 separate high tides (typical exceedance duration of 2.5 hours) not all of which will coincide with waves exceeding 0.3 m. Note that this recommendation has no allowance for beach scour at the toe or vertical settlement of the oyster shell filled bags down into the underlying sand/mud.

Similarly, the 2 tier (3 bag) arrangement is recommended to be located no lower than 0.33 m AHD (slightly below Mean High Water Neaps level) to replicate conditions experienced in the three metre wave flume.

While failure of the oyster shell bags did not occur during Phase 2 of the preliminary physical modelling program, two (2) key stress types have been identified for monitoring over its life. These include the hardwood timber stakes and Manila rope which will anchor the oyster shell bags to the beach and the Manila rope which fastens each oyster shell filled bag tier together. If the combined wave and water depth conditions experienced in WRL's wave flume are not exceeded during the life of an oyster shell filled bag structure; biological decay and/or fatigue failure at these stress locations is likely at some point. This was not tested in the wave flume.

WRL recommends anchoring the bottom tier of oyster shell filled bags on the landward side too so that displacement in the seaward direction via sliding (which was observed to occur coincident with wave troughs) is resisted. As indicated earlier, OceanWatch has advised that the method of securing bags in the field will likely differ to the method employed in the wave flume.

7. Future Research Opportunities

The preliminary physical modelling test results describe the behaviour of the oyster shell filled bags under wave attack for several different bag arrangements. WRL understands that they will now be installed at one or more sites within protected waterways within Sydney as field trials. If OceanWatch intends to increase the present level of understanding of coastal engineering aspects of these bags, a series of opportunities for future research are outlined below. Note that an undergraduate UNSW student will examine some of these opportunities during 2016.

It would be worthwhile to collect laboratory grain density measurements from samples of both Sydney rock and Pacific oyster shells used in the testing.

If further physical modelling is undertaken with a comprehensive physical modelling program for the purposes of detailed coastal engineering design, generic design guidelines for coastal engineers implementing oyster shell filled bag structures could be developed. Such a comprehensive program could include testing other oyster shell filled bag geometrical arrangements, similar to that conducted with sand filled geotextile containers (Coghlan et al., 2009), such as:

- Four or more oyster shell filled bag tiers high (10 bags);
- Evaluating a longer test section with “stretcher bond”;
- Having two or more bags wide at the crest (a wider structure to further reduce wave transmission);
- With the long axis of the oyster shell filled bags parallel to the direction of wave attack;
- Installing the oyster shells as a “groyne” rather than a “seawall” to reduce updrift erosion;
- Testing the oyster shell filled bags under a greater variety of irregular wave conditions;
- Testing the oyster shell filled bags under a greater variety of offshore bathymetric profiles;
- Placing load cells in-line with the Manila rope anchoring the oyster shell filled bags to the beach to record peak tensile forces under wave attack;
- Under oblique wave attack (quasi three-dimensional tests); and
- Under velocities typical of a flood in a flume in “flow through” mode.

A detailed coastal engineering case study could be prepared for one of the sites within Sydney, (including wave hindcasting and refraction modelling) which would consider the preliminary 2D physical modelling results, to further optimise the recommended cross-shore position of the structure on a site-specific basis.

If further physical modelling is undertaken with a comprehensive physical modelling program for the purposes of detailed coastal engineering design, generic design guidelines for coastal engineers implementing oyster shell filled bag structures could be developed.

If a pilot field trial is undertaken at one of the sites within Sydney, cross-sectional monitoring surveys should be undertaken seaward and landward of the oyster shell filled bag structure and at another control location nearby with similar wave exposure and sediment composition. The deployment of a wave gauge, which is able to accurately measure waves with relatively small heights and periods, located just offshore of the oyster shell filled bags would also assist in performance monitoring.

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