Innovative Ecological Engineering: Two-Dimensional Physical Modelling of Oyster Shell Filled Bags for Coastal Protection

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Abstract
Historically, naturally occurring oysters reefs were widely distributed around Australia. However, since the 1880s, these reefs have largely disappeared due to a combination of over-exploitation, pollution, increased estuarine siltation and the introduction of a parasitic mudworm. A new technique has been proposed to encourage restoration of these oyster reefs and reduce intertidal riverbank erosion from wind waves and boat waves. This involves the use of seeded oyster shells in coir (coconut fibre) bags. Utilising organic materials, this method is being trialled at a number of relatively protected tidal sites in NSW.

Prior to initiation of the field trials, the Water Research Laboratory (WRL) designed and undertook preliminary two-dimensional (2D) physical modelling of generic oyster shell filled bags to better understand their expected behaviour when exposed to wave attack. The modelling objectives were to assess the stability and wave attenuation of this type of coastal protection structure under a variety of water level and wave attack scenarios. The test program was conducted in two distinct phases:

1. The bags were not anchored to the bed or secured together.
2. The bags were both anchored to the bed and tethered to each other.

The threshold wave heights for initiation of bag rocking were recorded for each water depth, wave period, and bag arrangement combination. Recommendations were given as to the cross-shore position of the oyster shell filled bags on the inter-tidal profile. Existing wave-driven foreshore erosion processes are expected to be attenuated immediately landward of an oyster shell filled bag structure.

Keywords: oyster reef restoration, riverbank erosion, emerging coastal protection.

1. Introduction

Prior to European settlement, naturally occurring oysters reefs were widely distributed around Australia. However, since the 1880s, these reefs have largely disappeared due to a combination of over-exploitation, pollution, increased estuarine siltation and the introduction of a parasitic mudworm. A new technique has been proposed to encourage restoration of these oyster reefs and reduce intertidal riverbank erosion from wind waves and boat waves. This involves the use of seeded oyster shells in coir (coconut fibre) bags. Deliberately utilising only organic materials, the method is being trialled at a number of waterway sites in NSW as a potential alternative to traditional coastal protection structures by promoting the restoration of living oyster reefs.

In their natural state, oysters filter suspended particles, excess nutrients and phytoplankton from the water column, maintaining good water quality. Each individual oyster shell, and the wider oyster reef, provide habitat for snails, crabs and algae which in turn attract fish, birds and other larger marine species. Naturally occurring oyster reefs also provide shoreline stabilisation and protection.

A limited amount of full scale hydraulic modelling has been undertaken previously [1] to examine wave transmission through long, thin netted bags filled with oyster shells under wave attack. However, an understanding of the dynamic behaviour (stability) of these more flexible-type (deformable) structures composed of all natural materials was not readily available.

Preceding the initiation of the field trials, the Water Research Laboratory (WRL) designed and undertook preliminary two-dimensional (2D) physical modelling of generic oyster shell filled bags to better understand their expected behaviour when exposed to wave attack.

This conference paper discusses the full scale laboratory tests on oyster shell filled bag structures conducted in a wave flume at WRL.

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.

2. Environmental Design Conditions

As the study was not site specific, other than only considering relatively protected (locations not exposed to ocean swell) tidal sites in NSW, test situations were developed based on broad estimates of the typical wave and water level conditions that the oyster shell filled bags may be exposed to. These were considered to include:

- Short period wind generated waves; and
- Boat waves (ex high speed catamaran ferries).

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 a potential site 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. Tides in NSW are classified as semi-diurnal, microtidal with a mean spring range of 1.25 m (± approximately 0.1 m) [5].

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, based on field sampling at Port Stephens (NSW), the optimal zone for growth of Sydney Rock and Pacific oysters is 0.3 – 1.2 m above Indian Spring Low Water [2] (approximately 0.7 m below Mean Sea Level (MSL) to 0.2 m above MSL) [5]. That is, for potential installation sites within NSW, the optimal elevation of the toe is 0.7 m below MSL to maximise promotion of new oyster growth on the oyster shell filled bags. Since the flume bathymetry was not purpose-built (see Section 3.3.1); the maximum depth of water tested at the model structures was only 0.40 m.

The combination of variables adopted for testing in the physical model is summarised in Table 1. 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. Wave periods of 1, 2 and 3 s were considered to be representative of most wind and boat waves expected at potential sites. 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 1 Summary of adopted wave and water level conditions

Test 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

3. Physical Model Design and Operation

3.1 Testing Facilities

The physical modelling for the oyster shell filled bags was undertaken in WRL's 2D, three metre wave flume. The flume measures approximately 32.5 m in length, 3.0 m in width, and 1.3 m in depth. 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.

3.2 Model Scaling

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

3.3 Model Construction

3.3.1 Bathymetry (Foreshore Slope)

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.

While the 1V:55H false floor was not purpose-built for the oyster bag modelling, it was used opportunistically and considered broadly representative of foreshore profiles at possible deployment locations in relatively protected waterways in NSW.

3.3.2 Oyster Shells

The oyster shells used to fill the bags were a mix of Sydney rock oyster (Saccostrea glomerata) and Pacific oyster (Crassostrea gigas) shells (Figure 1). These empty shells were free of oyster tissue and subjected to biosecurity treatment. The average grain density of the mixed Sydney Rock and Pacific oyster shells was 2108 kg/m^3 [4].

Figure 1 Sample oyster shells

3.3.3 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, one double bag and one triple bag (Figure 2) were assembled.

Each bag was measured and weighed (dry) prior to testing. Key measurements are summarised in Table 2. 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. Based on an average oyster shell grain density of 2108 kg/m^3, the porosity of the oyster shell bags was approximately 80-85%.

Figure 2 Example triple oyster shell filled bag

Table 2 Summary of oyster shell filled bag dimensions

Bag #	Bag Type	Mass (kg)	Length (m)	Height (m)	Width (m)	Bulk Density (m^3)	Dry Bulk Density (kg/m^3)	Porosity (%)
1	Single	12.84	0.92	0.17	0.32	0.039	327	84
2	Single	14.91	0.94	0.18	0.32	0.041	361	83
3	Double	30.25	0.91	0.20	0.27	0.070	430	80
			0.91	0.19	0.24			
4	Triple	34.48	0.92	0.17	0.25	0.078	444	79
			0.92	0.13	0.21			
			0.90	0.18	0.22			

3.3.4 Supports

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 and were not expected to fail (i.e. pull out) during model testing. Note that steel brackets are not proposed to be used during field trials; resistance to sliding, slipping and toe scour is proposed to be assessed on a site specific basis.

3.3.5 Bag Arrangements and Test Program

The preliminary physical modelling for the oyster shell filled bags was conducted in two phases. Table 3 summarises the oyster shell filled bag arrangements and corresponding water levels tested for both test phases.

Table 3 Summary of oyster shell filled bag arrangements

No. of Tiers	Bag Arrangement	Water Depths (m)	Test Phases
1	Single Bag Only	0.16	1 only
2	Single Bag on Crest, Double Bag at Toe	0.16 0.32	1 and 2
3	Single Bag on Crest, Double Bag in Middle, Triple Bag at Toe	0.16 0.32 0.40	1 and 2

Phase 1 tests were undertaken with 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. 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 Figures 3 and 4, respectively.

Figure 3 1 Tier oyster shell filled bag arrangement - unsecured (Phase 1 Tests)

Figure 4 2 Tier oyster shell filled bag arrangement - unsecured (Phase 1 tests)

Phase 2 tests were undertaken with 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. A photo of the anchored three tier oyster shell filled bag arrangement is shown in Figure 5.

Figure 5 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.

3.4 Data Collection and Analysis

3.4.1 Wave Data

For all Phase 1 tests and Phase 2 tests with monochromatic waves, 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. For tests 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 [6] to separate and interpret incident and reflected waves.

3.4.2 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 for the Phase 1 tests using Equation 1.

$$K_t = \frac{H_t}{H_i} \tag{1}$$

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.

3.4.3 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.

4. Results

4.1 Phase 1 (Bags not anchored or tethered)

4.1.1 Oyster Shell Filled Bag Stability

A summary of the 112 monochromatic wave tests conducted in Phase 1 is presented in Table 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 oyster shells within each bag under wave attack was also observed. For water depths of 0.32 and 0.40 m, the wave height initiating shell bag movement generally decreased with increasing wave period. For a water depth of 0.16 m, the wave height initiating shell bag movement was largely independent of wave period.

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 6); and
- Complete displacement of the crest bag (see example in Figure 7).

Table 4 Summary of wave heights initiating oyster shell filled bag movement (Phase 1 tests)

No. of Tiers	No. of Bags	Water Depth (m)	Wave Period (s)	Wave Height (m) at Structure Initiating …		
				Rocking	Whole Structure Displacement	Crest Bag Displacement
1	1	0.16	1	0.05	0.09	N/A
			2	0.06	0.06	N/A
			3	0.04	0.09	N/A
2	3	0.16	1	0.09	-	-
			2	0.08	-	-
			3	0.09	0.09	-
		0.32	1	0.04	-	-
			2	0.09	0.11	-
			3	0.05	0.08	0.18
3	6	0.16	1,2,3		-	-
		0.32	1	0.07	-	-
			2	0.10	0.15	0.19
			3	0.07	0.11	0.18
		0.40	1	0.10	-	-
			2	0.08	0.18	0.18
			3	0.08	0.13	0.18

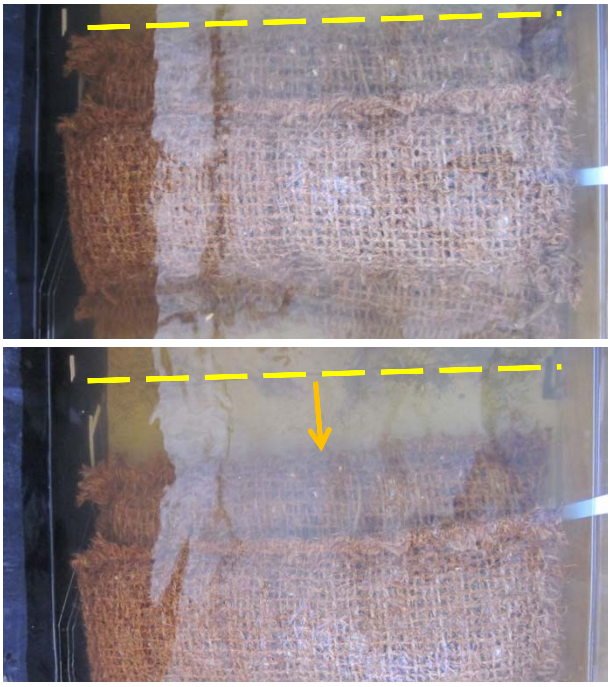

Figure 6 Before (top) & after (bottom) displacement of whole structure (2 tiers, WL=0.32 m, T=2 s, H=0.11 m). Note – waves were travelling from top to bottom.

Figure 7 After complete displacement of crest bag (3 tiers, WL = 0.40 m, T = 2 s, H = 0.18 m). Note – waves were travelling from right to left.

4.1.2 Wave Transmission

For each bag arrangement, the wave transmission coefficient generally increased with increasing wave period. Refer to [3] for all test results.

When the water level was equivalent in elevation to the crest of the oyster shell filled bag structure, wave transmission was 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 was equivalent in elevation to the top of the second tier of oyster shell filled bags (i.e. 1 bag of freeboard), wave transmission was 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.

4.2 Phase 2 (Bags anchored and tethered

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 20 monochromatic wave tests in Phase 2, only the depth limited (worst case) condition for each water depth and wave period combination (established in Phase 1) was evaluated.

Two (2) irregular wave tests (JONSWAP spectrum) were also conducted during Phase 2 with a significant wave height (H_S).at the structure of 0.11 m and peak wave period (T_P) of 2.0 s. These tests were undertaken on the two (2) and three (3) tier arrangements with water levels corresponding to the respective crests (i.e. 0.32 m and 0.40 m water depth). Example photographs of the oyster shell filled bags under wave attack during testing Phase 2 are presented in Figure 8.

Figure 8 Wave attack on oyster shell filled bags during Phase 2 (3 tiers, WL = 0.40 m, T_P = 3 s, H_S = 0.28 m). Note – waves were travelling from right to left.

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 oscillated 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.

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.

5. Discussion

In terms of cross-shore position of the oyster shell bags on the inter-tidal profile, WRL recommends that the toe of the 2 tier (3 bag) and 3 tier (6 bag) arrangements be located no lower than 0.33 m and 0.25 m above MSL, respectively, to replicate conditions experienced in the wave flume. With this cross-shore position at NSW 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 above MSL [5]) coincident with wind or boat waves exceeding 0.3 m in height. However, it is acknowledged that this is above the optimal zone for promoting new oyster growth on the oyster shell filled bags (0.7 m below to 0.2 m above MSL). Unless it can be demonstrated that the local wave climate at potential sites does not exceed that tested in the wave flume, oyster shell filled bag structures should not be deployed in deeper water depths without additional physical modelling.

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.

While failure of the oyster shell bags did not occur during Phase 2 of the preliminary physical modelling program, two (2) key stress types were identified for future monitoring during field trials. These include the support points 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 also recommends anchoring the bottom tier of oyster shell filled bags on the landward side so that displacement in the seaward direction via sliding (which was observed to occur coincident with wave troughs) is resisted.

6. Conclusions

WRL has undertaken a preliminary research program into the stability and wave attenuating properties of oyster shell filled bag structures under wave attack. The full scale wave flume investigation yielded threshold wave heights for initiation of bag rocking and displacement were recorded for each water depth, wave period, and bag arrangement combination. Recommendations were given as to the cross-shore position of the oyster shell filled bags on the inter-tidal profile to remain within conditions experienced in the laboratory. As a result of wave energy dissipation (which will vary throughout the tidal cycle), wave-driven foreshore erosion processes are expected to be attenuated immediately landward of oyster shell filled bag structures.

Future research should focus on the long-term durability of the bag material to resist degradation from abrasion, vandalism and ultra-violet light. Additional physical modelling with deeper water depths corresponding to the optimal zone for new oyster growth is recommended. The EurOtop roughness factor for estimating wave runup and overtopping on the oyster shell filled bags should also be assessed in a physical model.

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8. References

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