OPTIMAL OYSTER REEF DESIGN FOR SHORELINE PROTECTION USING COMBINATIONS OF OYSTER SHELL FILLED BAGS AND SANDBAGS

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by

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Originality Statement

'I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, or substantial proportions of material which have been accepted for the award of any other degree or diploma at UNSW or any other educational institution, except where due acknowledgement is made in the thesis. Any contribution made to the research by others, with whom I have worked at UNSW or elsewhere, is explicitly acknowledged in the thesis. I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation and linguistic expression is acknowledged.'

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Abstract

The increasing popularity of eco-engineering and living shorelines has seen the development of an oyster reef suggested as a natural solution to erosion in low to moderate energy estuarine environments. With a focus on reducing the ecological footprint of artificial shoreline protection systems, this solution aims to not only minimise erosion, but facilitate the growth of surrounding marine life. Substantial research has revealed the positive impact of oysters on the natural ecosystem, while limited studies have demonstrated wave transmission characteristics comparable to traditional rubble mound breakwaters. However, wave attack consistent with small boat wakes has seen these reefs displace, and as a result, sandbags have been combined with oyster bags to enhance the stability of the reefs. This paper compares measurements of wave transmission, wave reflection, and dissipated energy, to evaluate combined oyster bag/sandbag designs.

A variety of configurations involving both oyster bags and sandbags were modelled under multiple wave conditions and flow depths. Results from the physical modelling demonstrated that for all tiers of structures, configurations that consisted of sandbags landward of the oyster bags, and at the crest of the structure, prevented structural displacement. However, the addition of sandbags enhanced wave transmission and wave reflection, with greater reflection particularly evident for sandbags at the seaward face of the structure. Therefore, optimal designs incorporated sandbags landward of the oyster bag reef. This setup is consistent with the results for dissipated energy, as designs with oyster bags closest to wave attack offered the highest values.

The configurations that best optimised wave attenuation and provided stability to the oyster reef, were determined for each tier of structures. These outcomes have led to the design of an artificial oyster reef that can be implemented as shoreline protection in estuarine environments where wave climates reflect the wakes generated by small boats.

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Notation

$H_{max} = Maximum\ Wave\ Height$

$T_{peak} = Peak\ Wave\ Period$

$h_c = Crest\ Height$

$B = Crest\ Width$

$d = Water\ Depth$

$T = Wave\ Period$

$H_i = Incident\ Wave\ Height$

$H_t = Transmitted\ Wave\ Height$

$H_r = Reflected\ Wave\ Height$

$K_t = Wave\ Transmission\ Coefficient$

$K_r = Wave\ Reflection\ Coefficient$

$H_m = Maximum\ Wave\ Height$

$T_m = Maximum\ Wave\ Period$

$E_i = Incident\ Wave\ Energy$

$E_r = Reflected\ Wave\ Energy$

$E_t = Transmitted\ Wave\ Energy$

$E_d = Dissipated\ Wave\ Energy$

1 Introduction

The erosion of coastlines and waterways has become more and more apparent through the persistent impact of waves and rapid currents. Increasing rates of climate change have led to rising tides and storm surges, that have enhanced the forces that act upon the land, resulting in further land degradation due to the heightened impact of waves (Zhang et al. 2004). Estuarine environments are also susceptible to the forces imposed by boat wakes that result from recreational aquaculture activities and transport routes, while streams and rivers are exposed to high velocity currents and hydrodynamic forces. As a result, wetlands have been eliminated and intertidal habitats destroyed. Anthropogenic influences such as coastal development and dredging, have exacerbated these processes, and with the human population expected to increase dramatically (10 billion in 2100, Raftery et al. 2014), many countries are becoming incentivised to reclaim more land from the sea as a solution to shoreline erosion (Han et al. 2013).

Figure 1.1 - Shoreline erosion of Manly Lagoon, NSW, Australia

Other solutions however, have been implemented for a number of decades through the use of man-made materials in the form of sea walls, coastal breakwaters, gabions, groynes and revetments. Although these methods of coastal protection are able to alleviate the effects of strong river currents and high energy waves, they are often relied on too heavily, resulting in increased development closer to the shoreline (Freitas & Dias 2016). Moreover, large amounts of concrete and other artificial material are used to produce these structures, and although their purpose to reduce erosion and increase shoreward sediment transport has been fulfilled, the marine environment has suffered as a result of their development. More recently, the concept of eco-engineering (ecological engineering) has been investigated with a view to not only mitigate shoreline loss and reduce erosion, but to promote the growth of the natural ecosystem (Borsje et al. 2010; Piazza et al. 2005). One increasingly popular solution is with the use of oyster reefs.

Figure 1.2 - Oyster Reefs formed using bags of shells along the shoreline at MacDill Air Force Base, Florida, USA (Pontee et al. 2016)

Artificial oyster reefs have the potential to provide a sustainable solution to erosion in waterways, with notable wave attenuating properties (Borsje et al. 2010), and the ability to become a self-sustaining three-dimensional reef (Walles et al. 2016). Additionally, these reefs are able to facilitate the growth of other economically important species (Scyphers et al. 2011), enhance the producer and consumer surplus associated with the affected fisheries (Kroeger 2012), and filter phytoplankton and other sediment from the water column (Sisson et al. 2011). Carbon sequestration is another important role of oysters in maintaining the quality of the estuarine environments in which they live, storing carbon and subsequently deferring the marine accumulation of fossil fuels (Dehon 2010). Consequently, utilising oysters as a natural barrier to the forces imposed on shorelines by strong currents and waves provides a cleaner and more diverse ecosystem.

Figure 1.3 – Marine growth on bagged oyster shells six months after deployment in Manly Lagoon, NSW, Australia (Photo courtesy of OceanWatch Australia)

Although the implementation of artificial oyster reefs has been limited, certain hydrodynamic and wave parameters have been measured to quantify the usefulness of oysters in reducing erosion. Flume experiments have been performed to identify the wave attenuating properties of oysters (Allen 2013;

Borsje et al. 2010; Manis et al. 2014; Coghlan et al. 2016), as well as the effects on shoreline retreat (Piazza et al. 2005; Scyphers et al. 2011; Walles 2014), with some tests utilising oysters within caged designs such as ReefBLKs (Allen 2013). The results have demonstrated that although oyster reefs provide adequate engineering properties for erosion control in coastal zones, survival rates tend to be lower due to the high energy environment of coastlines (Piazza et al. 2005). Therefore, to maximise the design life of this natural solution, other estuarine environments such as lakes and lagoons would provide greater suitability for survival. Hydrodynamic testing of existing oyster reefs has outlined the capacity for oysters to provide resistance to turbulent river flows and high velocities (Styles 2015), permitting the possibility for implementation of oyster reefs within rivers and other tributaries.

While the engineering properties of existing and artificial oyster reefs have been studied, there has been little investigation into the structural design for these reefs. Biologically engineered concrete has been tested as a means to attract oyster growth, modifying existing breakwater technologies to utilise the ecological properties of oysters (Ortego 2006), while oyster bags and ReefBLKs have been tested for their ability to attenuate waves with varying characteristics (Allen 2013). Therefore, there is an opportunity for future research to demonstrate how oyster reefs can be incorporated into existing erosion control structures to mitigate the effects of erosion and dissipate the energy imposed by waves and currents.

2 Literature Review

2.1 Conditions for Oyster Reef Growth and the Environmental Benefits

2.1.1 Environmental Conditions for Oyster Growth

In order for oysters to settle and grow within estuaries, specific environmental conditions are required. The initial settlement of oyster larvae requires precise conditions that can be influenced by the addition of chemicals and modified structural aggregates, while the rate of vertical reef accretion fluctuates depending on a variety of ecological parameters such as salinity and aerial exposure. Studies of sediment dynamics also provide the information required to determine the long term suitability of the environment for the development of oyster reefs.

The initial settlement of oyster larvae on the shells of artificial reefs or on the substrate of existing shoreline protection structures can be difficult given the environmental conditions. Chemical additives have often been used to attract oyster larvae to the structure, while the growth of oysters on different substrates has been tested to determine which materials are best suited for oyster growth. With hydrodynamic conditions approaching those of natural benthic environments, chemical cues have been tested to demonstrate their usefulness in mediating larval settlement (Turner et al. 1994). Turbulent flows move larvae further from the beds on which they settle, and thus waterborne cues are used to greatly enhance the vertical movement towards the beds, improving the subsequent settlement of the larvae. These flume tests have demonstrated the tendency for oyster larvae to react to the waterborne peptide in both still water and flowing water, as the larvae have been shown to swim downwards at higher speeds to reach the bed. The significance of these tests is that the tested peptides of dopamine and glycyl-glycyl-L-arginie (GGR) are metabolites that are produced by oysters (Turner et al. 1994), highlighting the importance of settling oyster larvae on existing oyster reef structures. Another experiment tested flows of 2.8, 6.2 and 10.4cm/s within a small racetrack flume, with computer assisted video motion detecting the behaviour of oyster larvae in response to adult oyster conditioned seawater, as well as a synthetic peptide analogue (Tamburri et al. 1996). The testing produced similarly identical results to that of still water, where the larvae travelled downwards in the water column before attaching to the bottom of the flume.

The use of chemicals to encourage larval settlement can also be likened to the effects of various substrates. One study compared growth rates for the Eastern Oyster (Crassostrea Virginica) on unconsolidated oyster shell, oyster shell embedded in concrete, and on concrete oyster castles (Theuerkauf et al. 2015). Results showed that juvenile oyster recruitment was greatest on the oyster castles, which are made from limestone gravel, concrete and crushed oyster shell, achieving higher biomass and oyster density. Unconsolidated oyster shell was also favoured over the embedded oyster shell, in both mesocosm and field experiments. Substrate aggregates with more rugosity and porosity have demonstrated higher rates of settlement and survival, with the cementation of oyster shells increasing the flexural strength of the structure (Risinger 2012). Therefore, through the use of substrates that incorporate crushed or unconsolidated oyster shell, restoration methods are able to employ cost effective solutions to maximise oyster recruitment.

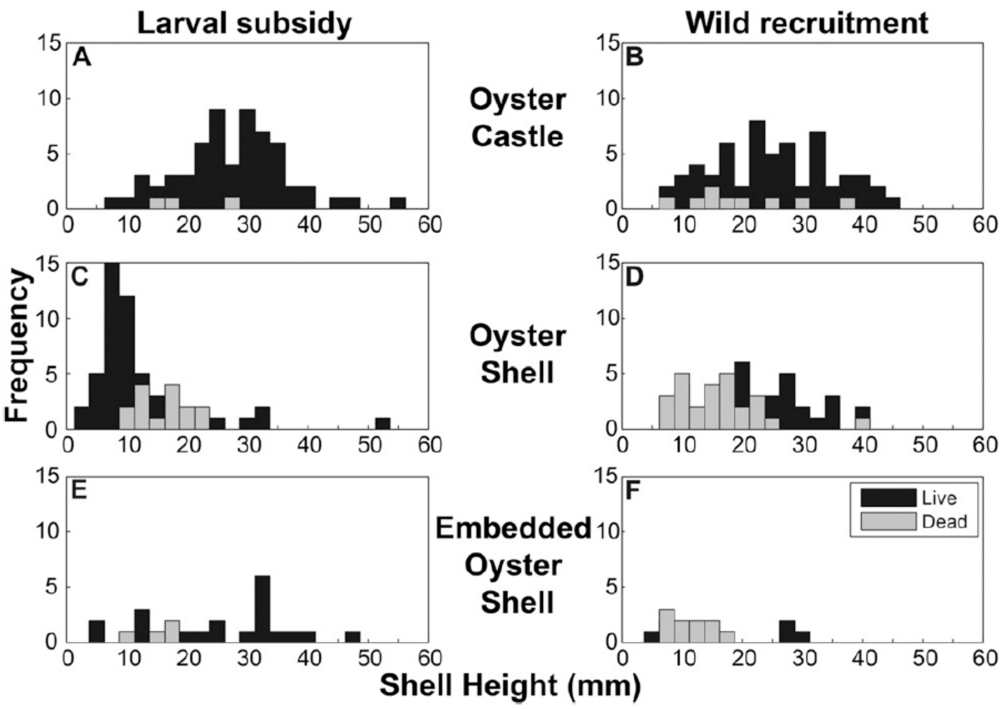


Figure 2.1 - Size frequency histogram illustrating the proportions of live and dead oysters on Oyster Castles (A and B), oyster shell (C and D), and embedded shell (E and F) (Theuerkauf et al. 2015)

As a saltwater bivalve, the salinity of the environment is detrimental to the survival of oyster reefs. Measurements of salinity within brackish waters have been compared to oyster growth to determine the optimal range and levels that are suitable for accretion. High salinity environments (30-35psu) may improve the accretion rates of oysters, but are also likely to attract predators (Ridge et al. 2015) such as the dermo inducing pathogen Perkinsus Marinus (Laakkonen 2014; Tolley et al. 2005), and the Southern Oyster Drill (Thais Haemastoma), whereas fluctuations in salinity appear to limit the activity of these predators (Garton & Stickle 1980; Wells 1961). Mesohaline (5-18psu) and polyhaline (18-30psu) environments are hence more conducive to oyster reef development, although these settings may expose the reef to low oxygen events (Ridge et al. 2015). As a result, an optimal range of salinity levels is required to ensure the continual growth of oyster reefs, with this range measured to be around 14-28ppt (Laakkonen 2014). Oyster cover and density has shown to be proportional to salinity within lower intertidal regions, with negative relationships in higher intertidal areas due to higher distributions of predators (Bergquist et al. 2006). Studies across seven estuaries in Florida revealed the dependence on salinity for oyster survival, with initial measurements of oyster recruitment exceptionally low due to the influx of freshwater as a result of flood control releases and storms (Parker et al. 2013). Sites within this study at Mosquito Lagoon and Tampa Bay were free from excessive anthropogenic freshwater inflows, and consequently retained the highest values of salinity across the estuaries. With the only considerable freshwater input from localised rain, the salinity remained near oceanic conditions and rates of oyster recruitment exceeded 2 spat/shell/month. Although Mosquito Lagoon contained high salinity values, other variables such as temperature and dissolved oxygen levels likely contributed to the oyster growth rates, as these values were lower than the measurements at Tampa Bay, which experienced similar salinity levels.

Like the salinity of the surrounding region, the exposure of the submerged oyster reef to the atmosphere plays a pivotal role in the development of the oysters, with reef growth hampered by increasing tidal emersion (Walles et al. 2016). Studies of both natural and constructed oyster reefs with varying ages, have demonstrated ideal ranges of aerial exposure between 10% and 55% for decade old reefs, with these values representing zero growth boundaries (Ridge et al. 2015). Above 55%, oysters have been known to sporadically survive, however not at densities resulting in oyster reefs (Walles 2014). For these reefs, the highest mean growth occurred at 20-40% exposure (Ridge et al. 2015), with this range of exposure referred to as the optimal growth zone. Three year old reefs exhibited similar properties to the decade old reefs, however rapid growth was experienced at 45% exposure for the shallowest reef. Accretion rates for reefs below the 10% zero growth boundary have been attributed to sediment build up, which plays a significant role in the capacity of oysters to grow.

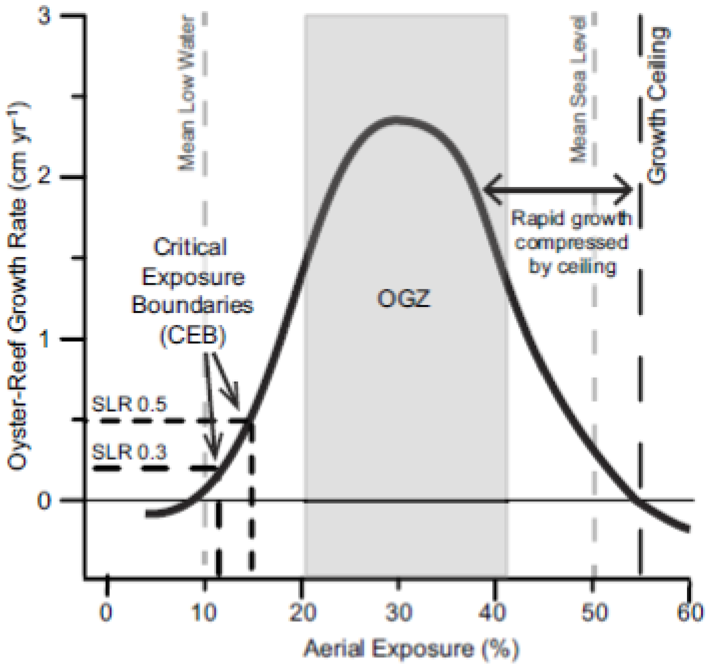


Figure 2.2 – Optimal growth zone (OGZ) and critical exposure boundaries (CEB) for oyster reef growth (Ridge et al. 2015)

As oysters begin to grow in size, sediment build up may exceed the rate of growth, burying the reef and reducing the rate of survival. Recent modelling has revealed three different outcomes for oyster reefs with respect to sediment dynamics (Housego & Rosman 2016). These results refer to reef growth outpacing sedimentation such that the reef achieves maximum height, deposition outpacing reef growth with shear stress not exceeding critical shear stress, such that the reef becomes buried, and deposition outpacing growth but shear stress exceeding critical shear stress, such that erosion occurs and a steady state height is reached. This study has shown that for initially large reef heights, oyster reef development can occur for higher velocities, as faster velocities are required for sediment to be distributed higher in the water column to cover the reef. In this regime, larger currents result in greater erosion as well as a thicker layer of live oysters at the top of the structure. Food supply to the oyster reef is also replenished in waters with high velocities. Housego and Rosman (2015) reveal that for large initial reef heights, a critical grain size of 0.08-0.13mm exists for which the reef is able to grow with grains beyond this size. For these grain sizes, the deposition of sediment is small enough on the top of the reef such that reef growth is able to outpace sediment accumulation. As a result, it is recommended that sites for oyster reef deployment contain large grain sizes and relatively high water velocities. Therefore, the study of sediment accretion at the reef itself is beneficial to determining the long term development of the oyster reef, based on the height of the initial reef that is deployed, as well as the sediment grain size and velocity of the waterway.

2.1.2 Ecological Benefits of Developed Oyster Reefs

Developed oyster reefs are able to enhance the surrounding environment by providing higher quality water that is free of sediment and chemicals, as well as promote the growth of other economically important species such as seagrass, whelks, fish and crabs. These filter feeders not only clean the water, but store chemicals such as carbon and nitrogen within their shells, consequently creating an improved habitat for other marine life.

Filtration is a significant advantage that accompanies the use of oysters within engineering structures, as waterways are cleaned and biodiversity is promoted. Suspended sediment such as effluent from shrimp farms can be removed via oyster filtration. Varying densities of the Sydney rock oyster (Saccostrea Commercialis) were tested in different tanks of shrimp pond effluent to determine the quality of the water after filtration (Jones & Preston 1999). The tank containing the highest density of oysters was able to reduce total suspended solids to 49% of the initial level, the bacterial numbers to 58%, total nitrogen to 80% and total phosphorous to 67%. The concentration of Chlorophyll a was also reduced to 8% of the initial effluent value through the combined effects of settlement and oyster filtration.

The removal of suspended sediment from estuarine environments is combined with bio-sequestration, with oysters naturally storing carbon and nitrogen within their shells. Artificial reef construction in the Louisiana Gulf Coast has shown that oysters were able to capture 12% of the initial structures’ weight in excess carbon over a period of thirty months (Dehon 2010). Water quality improvement standards can be met through the restoration and construction of oyster reefs, as a study of oyster reefs in Lynnhaven River demonstrates that oysters are able to sequester nitrogen in the tissues and shells, and convert organic nitrogen to gas that is removed from the water via diffusion (Sisson et al. 2011). From these studies it is evident that growing oyster populations have the potential to remove quantities of suspended sediment and chemicals from the water column.

The abundance of marine life within the vicinity of natural and artificial oyster reefs has been attributed to the removal of chemicals and sediment from the water. Various species of fish and crab have appeared with increasing numbers, while the rate of population growth for whelks has also increased. Two stretches of eroding shoreline in Alabama hosted construction of breakwater reefs made from loose oyster shells, with the effects on the surrounding marine life quantified (Scyphers et al. 2011). Control plots without reefs were compared to the constructed sites, with the corridor between the intertidal marshes and oyster reef breakwaters supporting higher abundances and different communities of fish. Several economically beneficial species were enhanced through the development of these reefs, with blue crabs (Callinectes sapidus) benefiting the most (+297%), while red drum (Sciaenops ocellatus) (+108%), spotted seatrout (Cynoscion nebulosus) (+88%) and flounder (Paralichthys sp.) (+79%) also dramatically increased in number. The growth of marine life surrounding a low lying oyster reef within the Grand Bay Natural Estuarine Research Reserve was also documented, and compared to that of a non-vegetated site (Shervette & Gelwick 2008). Results have shown that oysters are able to provide a highly spatial and diverse nekton community, with an abundance of marine life including mud crabs (P. obesus, P. simpsoni, E. depressus) and snapping shrimp (Alpheus sp.). Additionally, hooked mussel and mud crab are two species that have been drawn to the habitat provided by the Eastern Oyster (Bergquist et al. 2006). Other marine life such as whelks (Morula Marinalba) are similarly attracted to structures containing oysters, as one study with the Sydney rock oyster (Saccostrea Glomerata) has shown (Jackson et al. 2008). On seawalls with many oysters, whelks were more abundant than on seawalls with few oysters, while densities of whelks were found to be similar to the densities of oysters on seawalls and rocky shores that contained oysters. The size of the whelks was also larger where oysters lived. As a result of these studies, the implementation of oyster reefs demonstrates ecological justification for future, shoreline protection projects.

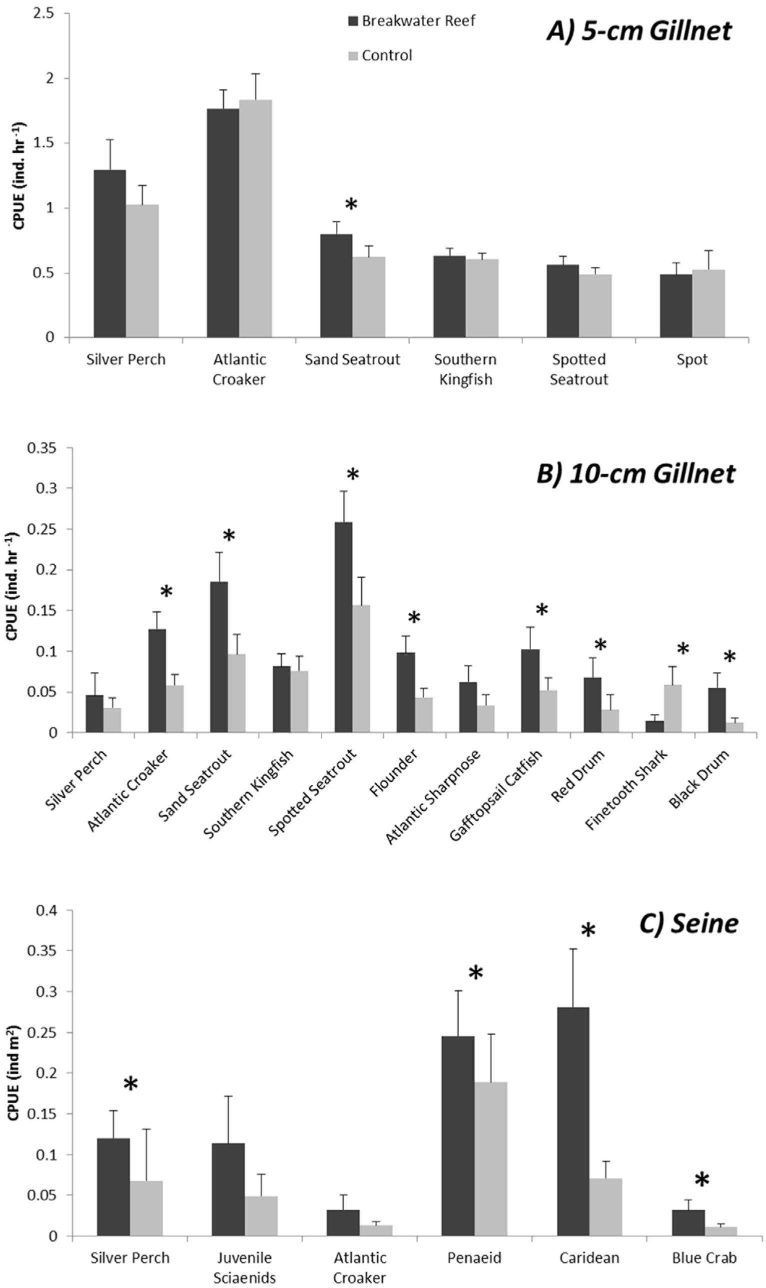


Figure 2.3 - Relative abundance of dominant demersal fish and decapod taxa due to the presence of a breakwater oyster reef (Scyphers et al. 2011)

2.1.3 Key Target Conditions

To utilise oysters as an ecological engineering solution to shoreline retreat, the ideal environmental conditions for oyster survival and growth must be ensured.

Therefore, key target conditions that aim to promote the survival and long term growth of the oysters, have been identified from these field studies.

The ideal implementation of oyster reefs involves larval settlement on material with high rugosity and porosity (Risinger 2012), such as unconsolidated oyster shell or crushed oyster shell within a concrete matrix (Theuerkauf et al. 2015). To improve the rates of settlement, waterborne peptides such as oyster produced metabolites including dopamine and glycyl-glycyl-L-arginine (GGR), may be introduced to the surrounding environment (Turner et al. 1994).

This environment will be best suited to oyster reef development if salinity levels of 14-28ppt persist (Laakkonen 2014), with aerial exposure between 10% and 55% (Ridge et al. 2015). If timed well, 20-40% exposure can offer significant growth rates (Ridge et al. 2015). Following early growth of the oyster reefs, long term survival will depend on an understanding of the regional sediment dynamics. Larger initial reef heights are suggested to combat sediment deposition at the top of the reef, with ideal sites containing higher velocities and larger grain sizes (Housego & Rosman 2016). If these factors can be guaranteed, the ecological consequences of the oyster reefs are significant, with enhanced water quality and an increase in the growth of local marine communities.

Growth Factor	Optimal Conditions
Larval Settlement	Unconsolidated or crushed oyster shell substrate
Salinity	14-28ppt
Aerial Exposure	10-55% (Higher growth rates at 20-40%)
Sediment Deposition	Large grain size

Table 2.1 – Key target conditions for oyster growth

2.2 Engineering Aspects of Oyster Reefs

Riparian zones and estuarine shorelines are often affected by waves, strong currents and turbulent flows, with gabions used as the main stabilisation treatment against erosion. Although the effectiveness of gabions in reducing erosion for riverbanks and other estuarine environments is well documented (Lee et al. 2014; Pagliara et al. 2010; Srineash & Murali 2015; Yoon 2005), the study of living shorelines such as oyster reefs, to mitigate the impacts of waves and high velocity flows, is limited. There are however, parameters such as wave transmission coefficients that are frequently measured to quantify the suitability of erosion control structures for the given environment.

2.2.1 Coastal Engineering

Coastal and estuarine erosion control measures are designed to dissipate the energy of waves and reduce shoreline retreat. Therefore, to quantify the effectiveness of using oyster shells as coastal protection, properties of wave attenuation and changes to bathymetric profiles are measured. These measurements result from tests performed within flumes, on existing reefs and on artificial reefs. Prior to field implementation, the properties of oysters have been measured in wave flumes, using instruments that mimic the physical attributes of waves. These waves vary in period and height, and often replicate the wave climate of intertidal zones, or regions that are liable to intermittent boat wakes (Manis et al. 2014).

Confirming oyster reefs as the ideal natural solution to shoreline erosion, Borsje et al. (2010) compared the effectiveness of oyster beds and mussel beds in dissipating wave energy along the flume, measuring the wave height at particular distances seaward of the structure. As a meso-scale study that reproduced waves to reflect the climate of intertidal flats, wave heights were only tested to 3.34cm. With a constant bed length of 3.1m, and constant physical forces applied, oyster beds demonstrated a reduction in relative wave height of more than 50% around 3m downstream of the structure, while mussel beds only provided a reduction of over 20% at the same location. These results, although simplistic, offer an early insight into the wave attenuating characteristics of oyster beds, and demonstrate their superiority over alternative natural structures such as mussel beds.

To better understand how oyster reefs can protect estuarine shorelines, studies have measured the attenuating properties of reefs for waves reflective of small boat wakes. Recreational and commercial boating has become increasingly common in recent years, with jet skis, fishing boats and speedboats utilising waterways, and contributing to shoreline erosion (Parnell & Kofoed-Hansen 2001; Stevens & Ekermo 2003; Schoellhamer 1996). As a result, boat wakes are created in the otherwise stable wave climates of estuaries. Due to the consequent erosion, wave attenuating structures need to be designed to combat these irregularities and consider the impact of future boat wakes. The effect of boat wakes on the wave attenuating properties of oyster shells within coir bags was tested within a 3m wave flume at the UNSW Water Research Laboratory. For these tests, oyster bags were configured in one, two and three tier pyramid arrangements (Coghlan et al. 2016). The heights and periods of the waves that were tested, reflected those of small boat wakes and wind waves that were expected at the proposed sites of Sydney Harbour. Wave transmission coefficients were used to quantify wave transmission for the oyster bag structures. For the single tiered oyster bag, wave transmission was recorded to be relatively high, attenuating only 20-60% of the wave height when the water elevation was equivalent to the height of the structure, whereas 50-95% of the wave height was attenuated for the two-tiered arrangement. Monochromatic and irregular waves were also tested on the oyster bag structures, with displacement as well as both landward and seaward oscillation evident for the entire structure. While this study has exhibited the wave attenuating characteristics of oyster bags when exposed to wave climates that reflect small boat wakes, further long-term research is required to measure the durability of the coir, as well as methods to improve the stability of the overall oyster bag structure.

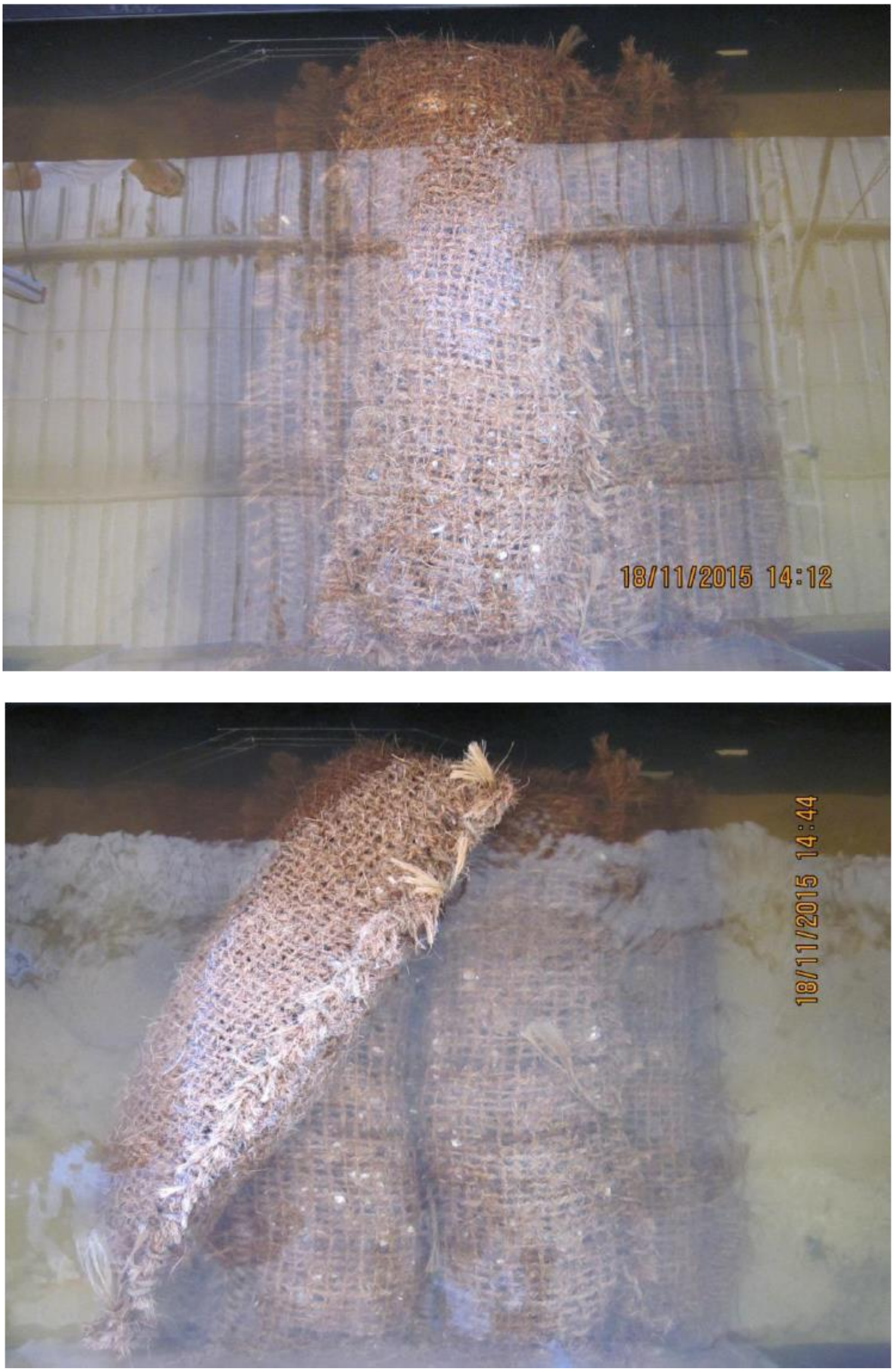


Figure 2.4 - Before and after photos illustrating complete displacement of the crest oyster bag during wave testing (Coghlan et al. 2016)

Reflecting the boat wakes that occur in Mosquito Lagoon, Florida, waves were produced in a flume to measure the attenuating properties of Crassostrea Virginica (Eastern Oyster) and Spartina Alterniflora (smooth cordgrass) at varying stages of growth, newly deployed and one year old (Manis et al. 2014). The impact that this shoreline stabilisation treatment has on wave attenuation is compared with the results for bare sediment. Oysters were attached vertically to mats to replicate natural intertidal oyster reef formation, and placed in the flume on sediment at depths where natural larval recruitment was expected to occur, 0.26m to 0.22m below the SWL. Capacitance wave gauges were set up to measure the free-surface displacements at the locations of a well-developed wave, before treatment and after treatment. These displacements were then converted to wave heights using the statistical zero-crossing method. Wake surveys conducted within the lagoon, determined the average wave height that was to be replicated in the flume. It was found that individual boat wave trains consisted of 10 waves, with an average wave height of 12.7cm and a period of 1.8s. Newly deployed stabilisation treatments reduced wave heights substantially less than the one year old established treatments. The combination of established oysters and cordgrass achieved the largest mean reduction in wave height, equating to an energy reduction of 67.3%, with established oyster achieving the second highest reduction of wave energy of 44.7%. These results illustrate the usefulness of combining natural erosion control measures in attenuating wave energy, while further validating the idea of oysters as a more than capable solution of dissipating boat wakes alone. As the most effective solution involved the use of established one year old oyster reefs, wave energy reduction can be expected to continue as the reef grows.

By installing oysters within artificial reefs, the vertical height of the reef can be controlled. The non-dimensional height of the reefs was the overarching factor in the design of oyster bag reefs and ReefBLKs for testing in the wave basin of the University of South Alabama (Allen 2013). Wave attenuation was measured for each of these designs through the calculation of wave transmission coefficients, while the influence of the designs on the wave period was also evaluated. The first composite breakwater structure consisted of oyster bags that were placed within PVC piping for stability. A splitter wall was also installed within the basin to minimise the effects of diffraction around the oyster bags. The oyster bags were then arranged into a trapezoidal structure, with a water depth of 0.30m, before 36 small wave and 7 large wave experiments were conducted. Triangular ReefBLKs were set up in an alternating point row, utilising the entire width of the wave basin, with three wave gauges located leeward of the structure to record wave heights. Oyster shells filled polyethylene netting before being placed within the frames of the ReefBLKs. The wave transmission coefficient for the oyster bags was determined for varying crest widths and structure heights. For the ReefBLKs, the results revealed a relationship between the transmission coefficient and the non-dimensional length and height of the structure. These results exhibited the wave attenuating characteristics of the oyster bags and ReefBLKs, likening their use to that of rubble mound breakwaters. Wave attenuation was shown to be greatest when the reef height was equal to the water depth, while increasing reef height for fully submerged structures improved wave attenuating properties. However, once the reef height reaches the water depth, large increases in structure height are required to achieve greater wave attenuation. As the non-dimensional length increases, the wave attenuating capacity increases for both these structures, although the rate of change only shifts once the non-dimensional length is greater than 0.45. From these results, it is evident that wave attenuation is dependent on the reef dimensions for the oyster bag designs.

Figure 2.5 – ReefBLKs filled with oyster shells, installed at Coffee Island, Alabama, USA (Allen 2013)

2.2.2 Bathymetry

In addition to monitoring the effects that oyster reefs have on dissipating wave energy, many tests have been undertaken to directly determine the effects of this energy on shoreline retreat. Bathymetric profiles have been constructed from field tests to evaluate the effect that stabilisation treatments such as oyster reefs, have on tidal flat morphology (Piazza et al. 2005; Risinger 2012; Scyphers et al. 2011; Stricklin et al. 2009).

Shoreline and bathymetric change were quantified for subtidal oyster reefs at rapidly eroding shorelines in Port aux Pins and Alabama Port (Scyphers et al. 2011). Unaltered reference areas were established as controls and compared to the oyster reefs, which comprised of trapezoidal sections of loose oyster on geo-textile fabric. Bathymetric surveys were conducted using a depth sounder system during preliminary site selection, and yearly, following construction of the reefs. Constructed sites all recorded decreasing water depths and gained more sediment than the reference areas. Although one altered site mitigated 40% of shoreline retreat, erosion rates were still high across all sites, indicating the lack of suitability for oyster reefs in high energy environments. This may however be due to the lack of cohesion with which the reefs were built, with the mesh covering not rigid enough to withstand the force of the waves, resulting in the reefs flattening and expanding outwards over time. However, despite this shortcoming, the results of the bathymetric profiles validate the claim that oyster reefs are able to reduce shoreline erosion.

The suitability of oyster reefs to provide sufficient erosion control in high energy environments has also been questioned following a study in Louisiana (Piazza et al. 2005). Three-dimensional Eastern Oyster (Crassostrea Virginica) reefs were created to protect eroding marsh shorelines and compared to non-cultched sites. Reefs were located within 5m from the shore, with three cultched and three non-cultched sites in both high and low energy environments, making a total of twelve sites. Shoreline retreat, defined as the waterward extent of the wetland macrophytes, was recorded highest for cultched sites in low energy locations, compared to the non-cultched sites in these locations. However, the magnitude of shoreline retreat was relatively indistinguishable between cultched and non-cultched sites in the high energy environment. These results highlight the capacity of oysters to protect eroding shorelines in low energy environments, rather than settings with stronger wave dynamics.

While these studies have shown that oyster reefs have the capacity to affect the erosion of the shoreline, it has also been demonstrated that the reefs have an influence on an area wider than the length of the reef. Three different tidal flats within the Oosterschelde estuary of the Netherlands, contain natural existing reefs of the Pacific Oyster (Crassostrea Gigas), and were studied to determine the area influenced by oysters (Walles 2014). Elevations were measured on the lee side of the reefs, with three-dimensional surface maps displaying the changes in morphology. Curved fitting tools on MATLAB were used to linearly interpolate between data to obtain these plots. As a result, the dimensions of the reefs, in particular, the length, were strong determinants in analysing the shoreward areas that were affected by the oysters. However, it is likely that the affected areas beyond the reefs were also influenced by wave dissipation and wave diffraction.

The ability of artificial oyster reefs to mitigate shoreline loss has also been compared to the capacity of natural oyster reefs. One comparison took place in the Grand Bay National Estuarine Research Reserve (NERR) in Jackson County, Mississippi whereby the extent of marsh edge erosion was measured for oyster bags and for natural oyster reefs (Stricklin et al. 2009). Overall, the average marsh edge retreat was 0.728m for natural reefs and 0.043m for constructed reefs, highlighting the importance of the designed reef for future management of erosion processes in estuarine ecosystems like the Grand Bay NERR.

Historical data from multiple projects in Louisiana has also shown that fringing oyster reefs can effectively reduce marsh erosion, although these outcomes are less significant in regions of low exposure rates (La Peyre et al. 2015). However in order to become fully effective, other factors that influence habitat suitability such as exposure rates, will need to be considered prior to the commencement of future reef development projects.

2.2.3 Hydrodynamics

Wave attenuation and morphological changes to the shoreline have been measured for oyster reefs within estuarine settings. However, the impact of this natural solution on river and creek hydrodynamics has not been investigated heavily. One study evaluates a series of hydrodynamic parameters around an oyster bank, within a salt marsh creek (Styles 2015).

Measurements of velocity, turbulence and Reynold stresses, were taken in the vicinity of an Easter Oyster (Crassostrea Virginica) bank within an intertidal salt marsh channel (Styles 2015). The reef, located in the North Inlet of the Winyah Bay National Estuary Research Reserve, was compared to the opposite side of the channel without oyster cover. Results were recorded using two Sontek Acoustic Doppler Velocimeters (ADVs) that were deployed over four semidiurnal tidal cycles on opposite sides of the intertidal channel.

Figure 2.6 – Intertidal channel oyster bank with ADV probe positioned on the lower bank (Styles 2015)

Velocity variance was separated into three components, along-channel, cross-channel and vertical. All components were significantly higher over the oyster bank, revealing the capacity for oyster reefs to inhibit the erosive nature of the channel flow. A similar hindrance was exhibited by the oyster columns in the form of eddy generation, as the presence of oysters contributed to the flow separation between patches of oysters and around columns. This increased turbulence demonstrates how oyster reefs can be utilised to dissipate the energy of the flow in channels. Additional parameters were also measured to signify the usefulness of oyster banks in resisting high energy currents within channels. Hydraulic roughness and drag coefficients were calculated for both sides of the channel, and were found to be an order of magnitude higher over the oyster bank, while Reynolds stresses were also higher for the oysters, characterising oysters as substantial erosion control measures for intertidal salt marsh creeks. These parameters extend to the use of oyster reefs within structures of varying environments, including other estuarine and coastal settings.

Therefore, Styles (2015) has demonstrated the potential for the use of oyster reefs in riverine environments. With limited research on the hydrodynamics that surround oyster reefs in these settings, further studies that measure the effects of oyster reef designs in establishing eddies and breaking up flows are possible.

2.3 Environments for Oyster Reef Application

The implementation of oysters has a number of significant applications, due to their ability to disrupt the wave climate and currents of the surrounding environment (Allen 2013; Coghlan et al. 2016; Styles 2015). With artificial oyster reefs performing better in moderate energy environments that are free from the powerful wave climates of oceans (Scyphers et al. 2011), the use of oysters appears to be best suited to mitigating erosion and reducing the effects of waves within low energy estuaries.

The erosion of marshes is of particular concern in areas of high boat traffic (Castillo et al. 2000) and prominent wind waves (Leonardi et al. 2016). These factors are coincident with the wave conditions tested on oyster bags by Coghlan et al. (2016), suggesting the potential for oyster reef use in areas of marsh erosion. More specifically, significant erosion scarp has been noted due to waves undercutting marshes and causing root-mat overhang (Schwimmer 2001). Therefore, without fragile root systems, oyster reefs could provide adequate protection for these marshes.

Figure 2.7 – Erosional scarp and root-mat overhang due to excessive undercutting at Horse Island, Rehoboth Bay, Delaware, USA (Schwimmer 2001)

In addition to preventing the collapse of marshes, oyster reefs may be useful replacements for existing natural protection such as the cordgrass Spartina anglica (Sheehan & Ellison 2015). This cordgrass has been identified as a threat to native species, however the removal of Spartina in the Tamar Estuary of Tasmania, has revealed significant rates of marsh erosion compared to sites where removal did not take place (Sheehan & Ellison 2015). As a result, replacing cordgrass with oyster reefs may prevent the loss of sediment that accompanies large scale denudation, and create a healthier environment for local species.

The application of oyster reefs to prevent marsh erosion can be directly transferrable to rivers, as similar erosive processes occur in both waterways. Riverbank erosion can lead to significant slope instability, resulting in landslides and the subsequent loss of infrastructure over time. This has stimulated substantial interest in understanding the stability of rivers that experience persistent erosive forces (Tamrakar et al. 2014), with eco-engineering measures such as the implementation of oyster reefs becoming a viable solution to the geotechnical instability of the surrounding region. Erosion induced instability has been attributed to seepage (Aziz 2003), as well as flooding (Nazneen 2013), and has proven to be more disastrous than flooding in terms of non-recoverable damage, especially in countries where climate change has notable effects (Rahman et al. 2015). In addition to high velocities from rapid flows, a significant cause of riverbank erosion is likely to be the waves generated from passing boat traffic, with these forces having a greater impact than high discharge flows during events such as the spring freshet (Cameron & Bauer 2014). This recent study examined the effects of boundary shear stresses and drawdown effects, providing potential parameters for future testing on oyster reefs within this field. As a result, the potential for oyster reefs to break up currents and attenuate wave energy within rivers is evident.

Additionally, oyster reefs can be utilised for the protection of existing structures such as river dykes, with vegetated foreshores employed across areas of the Netherlands to avoid costly solutions such as raising the levels of dykes (de Vriend et al. 2014). This suggests that the implementation of wave-attenuating shallow foreshores, such as oyster reefs, may improve dyke stabilisation, as well as reduce seepage and encourage the growth of shoreward nature reserves.

2.4 Structural Design of Oyster Reefs

The ability of oyster reefs to reduce shoreline erosion through wave attenuation has revealed the usefulness of oysters as effective erosion control measures in the correct environment. However, there are limited studies that focus on the structural configuration and design of oyster reefs as erosion control structures, with further research suggested to show how oysters can be adapted for use within existing and proposed control measures.

2.4.1 Previous Oyster Reef Designs

Previous design testing has measured parameters such as the wave transmission coefficient, found to be strongly affected by the dimensions of the structure. Oysters were placed in bags to form a trapezoidal structure, as well as utilised within ReefBLKs to provide an alternative control measure (Allen 2013). Although brief, this study focused on the non-dimensional lengths and heights of these solutions, analysing the effects of these parameters on the energy dissipated by the structure. A multi-tiered pyramid arrangement of oyster bags was also tested to determine the stability and wave attenuating characteristics of oysters by measuring the wave transmission coefficient (Coghlan et al. 2016). Although the experimental setup differs, a comparative study of these structures, in addition to the concrete pyramid testing (Allen 2013), provides an overview of how oysters compare to other structures in their ability to reduce wave height.

The Water Research Laboratory study suggested the need to further investigate the stability of the structure, recommending hardwood stakes and manila rope to tie the oyster bags together (Coghlan et al. 2016). Other studies failed to prioritise the design of the oyster reefs, placing loose oysters on geotextile fabric, which led to the flattening and outward expansion of the reef over time (Manis et al. 2014; Scyphers et al. 2011). Field tests and laboratory studies that have replicated the effects of boat wakes on single and clusters of oysters, have shown that small wave heights of 2cm are able to move clusters of oysters (Campbell 2015), prompting research into the structural design of artificial reefs. Further studies were limited to investigations surrounding natural oyster reefs and consequently contained no design elements. To fully utilise the engineering properties of oysters, stable structures are required, and thus their adaptation for use within current methods of erosion control may be possible. Existing structures that prevent shoreline retreat and limit the impact of hydrodynamic forces include gabions, ripraps, revetments, and sandbags, which can all utilise the engineering and ecological properties of oysters to varying degrees.

2.4.2 Gabions

Gabion structures are often used as effective counter measures against scour within estuarine and riverine environments, even providing useful protection for bridge piers (Pagliara et al. 2010; Yoon 2005). As the stability of artificial reefs has been questioned (Campbell 2015; Coghlan et al. 2016; Scyphers et al. 2011), the use of gabions for this purpose has recently been proposed, with studies evaluating the pressure and stability of gabion boxes in reef applications (Srineash & Murali 2015) to demonstrate the ability of gabions to distort the wave field past the structure, lessening the dynamic pressure. The wave attenuating properties of gabion stone used to line channels, have also been measured with reference to the wave transmission coefficient (Bishop 1987), while numerical modelling has seen gabions control rip currents, reducing velocities by 38% (Lee et al. 2014). This rip current study at Haeundae Beach in South Korea also records submerged breakwaters as reducing 90% of current velocities, leading to the possibility of combining gabions with oyster reefs as submerged breakwaters for enhanced effects. In addition to reducing velocities, gabions have been shown to prevent sediment transportation into reservoirs and dams at sub-catchment areas in Ethiopia, with an efficacy of trapping sediment of 74% (Mekonnen et al. 2015). Oyster reefs require salinity to survive and although this study displays preventative measures for sediment transport into freshwater catchments, oyster reefs may still be effective for implementation within saltwater estuaries that are prone to the movement of sediment. While oyster shells provide a capable filling for gabions and other structures through their ability to resist wave impact and hydrodynamic forces, they must also satisfy the criteria of a gabion structure, with optimisation techniques such as the Taguchi Method revealing that safety factors for toppling and sliding are to be accounted for in design (Uray & Tan 2015). Assuming the structural properties of gabions are maintained, oyster shells may be utilised within these structures as an ecologically friendly tool to prevent shoreline damage and reduce the impact of hydrodynamic forces.

2.4.3 Ripraps and Hybrid Revetments

Riverbank protection is also attained by way of riprap installation, which can acquire significant stabilisation via compression of rock layers (Jafarnejad et al. 2014). While the rocks used within riprap structures are often too large to simply be replaced with oyster shells, the use of granite and concrete riprap as a substrate for oysters has been shown to support healthy oyster populations (Burke 2010), which may then be used as a broodstock reef for nearby artificial oyster reefs. Concrete may also be used for ripraps, with biological additives such as cottonseed, enhancing oyster growth (Ortego 2006). Analogous to the use of oysters within riprap structures, hybrid revetments that incorporate plant collocation with gabion structures or ecological bags have also been proposed (Tian et al. 2016). This discussion for restoration of the riparian zone of the Xianghe segment of China's Grand Canal, reveals the opportunity for implementing oyster reefs together with artificial structures. From these studies of riverbank protection, it can be seen that oysters have the potential to grow on riprap structures, as well as act as part of hybrid revetments in conjunction with gabion structures. As a result, further research into the combination of oyster bags with other erosion control measures may provide enhanced protection to shorelines.

2.4.4 Sandbags

Sandbags are simple control measures that are often used for flood mitigation, although little research has been published regarding the effectiveness of sandbags to retain floodwaters and protect shorelines from wave attack. However, the use of sandbags as a stable flood retention mechanism has recently been evaluated, with a number of studies analysing sandbag dykes as protection for local communities (Krahn 2005; Offman 2009).

Of the studies available, most papers analysed the performance of sandbags to retain rising floodwaters. Krahn (2005) noted that densification of sandbags during flood retention resulted in significant compaction and a consequent reduction in the height of the dyke. As a result, target construction heights should be increased to account for the compaction of the sandbags. With structure heights lower than the recommended design heights, floodwaters may easily pass over the sandbag dykes, limiting their success. However, the stability of sandbag structures was revealed to decrease as the height of the structure increased (Krahn 2005), with the number of rows of sandbags within the structure as well as the duration of the flood, shown to have direct impacts on the stability of the structure (Reeve et al. 2003). Kobayashi and Jacobs (1998) revealed instability for small sandbags (8.9cm x 12.7cm) subject to wave conditions of incident wave heights less than 19cm, and wave periods between 1 and 2.2 seconds. Woven slit film polypropylene (WSFPP) sandbag dykes were found to experience displacement at the front face of the structure for incident wave heights above 0.41m, while overall displacement was revealed to be far greater under wave attack than static water levels (Offman 2009). Offman (2009) also recommended future research involving the use of non-woven material for sandbag coverings, and the use of interlocking devices to help support the overall structure. Moreover, shear strength measurements of the geotextile material used as the covering for sandbags have revealed that the interface shear strength of sandbags in contact with other sandbags is far greater than the shear strength of sandbags in contact with material such as polyethylene sheeting (PES) (Krahn et al. 2007).

With the front face of sandbag dykes failing under wave heights greater than 0.41m (Offman 2009), but surviving wave attack of lesser heights as well as static water levels, it is evident that sandbags may be used together with oyster reefs to reduce shoreline erosion in waterways that experience low wave heights. As the research into the performance of sandbags to resist wave attack is limited, further testing is recommended to confirm the usefulness of sandbags to protect shorelines.

Figure 2.8 - Front face of sandbag dike using woven slit film polypropylene (WSFPP) (Offman 2009)

2.5 Review of Rubble Mound Breakwater Structures

A comprehensive study of shoreline protection systems in riverine and estuarine environments has revealed a number of differences and similarities that exist across these control measures. Comparisons between oyster bags and other erosion control structures such as concrete pyramids, gabions and sandbags, have led to an understanding of the usefulness of oysters in coastal protection. The wave transmission coefficient has been used to quantify and compare the ability of a range of structures to reduce the height of transmitted waves and consequently mitigate shoreline erosion.

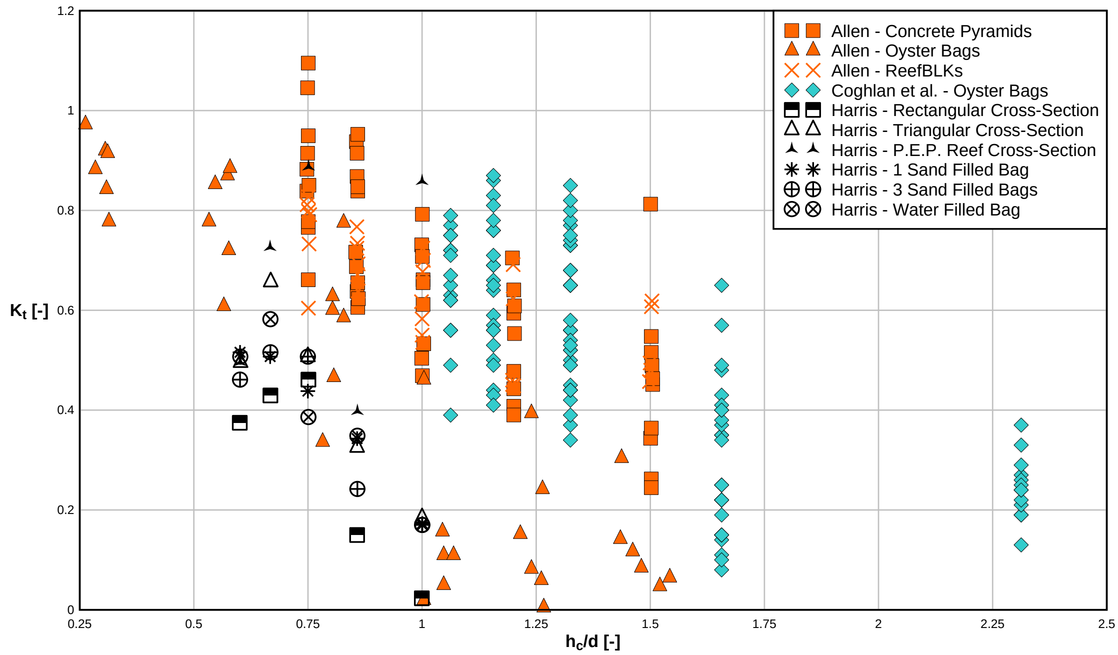


Figure 2.9 - Wave transmission coefficients for rubble mound breakwater structures

The wave transmission coefficients for the oyster bag tests of Allen (2013) and Coghlan et al. (2016) were dependent on a number of parameters that differed across both studies. For non-dimensional heights from 1 to 1.25, the oyster bag structure examined by Allen demonstrated lower transmission coefficients. This outcome was likely to be the result of discrepancies in the structures' crest widths, with crest widths reaching 1.96m (Allen 2013), considerably greater than the 0.32m crest widths measured by Coghlan et al. (2016). Artificial structures such as concrete pyramids produced similar transmission coefficients to both oyster bag designs, indicating the potential to replace existing synthetic structures with oyster bags.

Other designs that have been modelled as rubble mound breakwaters include sandbags and bags filled with water, while modifications to cross-sectional design have also been tested (Harris 1996). Results for these experiments yielded transmission coefficients in the vicinity of the data for the oyster bag structures proposed by Allen (2013). This comparison further highlights the capability of oyster bag reefs to match the wave attenuating proficiency of sandbags and other breakwater structures.

However, the evidence for oyster reefs to reduce wave transmission is limited, and therefore to further evaluate oysters as a viable solution to shoreline erosion, additional testing of significant parameters is required. Wave reflection and energy dissipation have been examined as supplementary measures for quantifying the effectiveness of rubble mound breakwaters (Harris 1996; Sollit & Cross 1972), and an analysis of these parameters for oyster reefs would lead to a greater understanding of how oysters can be used to protect shorelines from wave attack. In addition to measurements that quantify wave attenuation, assessing the structural stability of oyster reefs would also prove significant to the design life of oysters as a natural solution. Complementing the previous study by the UNSW Water Research Laboratory (Coghlan et al. 2016), the use of sandbags in conjunction with oyster bags would aim to improve the stability of the oyster reef. Sandbags may also prove useful for the application of oyster bags in the field, with additional height and stability aiding the growth of oysters in environments that are subject to strong currents (Housego & Rosman 2016).

2.6 Summary

The concept of eco-engineering has gathered significant momentum in recent years, and as a result, ecologically friendly alternatives to man-made structures are being proposed. The benefits of oysters to the surrounding environment, as well as the ideal environmental conditions for survival, have been well documented. However, fewer studies have been published that outline the effects of using oyster reefs to attenuate waves and other hydrodynamic forces, as well as reduce shoreline retreat. With limited research into the design elements of the reefs, and the types of structures used, further literature surrounding existing erosion control structures has been reviewed, to provide suggestions for the future use of oysters within waterways.

Oyster growth is highly dependent on the conditions for which the reef is to develop, with dead oyster shells used within concrete aggregates to help larvae settle (Theuerkauf et al. 2015), while chemical additives have been shown to expedite this process (Turner et al. 1994). An optimal salinity range of around 14-28ppt salinity for the surrounding environment is recommended for oyster growth (Laakkonen 2014), and to prevent predation of species that only live at high levels of salinity (Bergquist et al. 2006). Aerial exposure is also necessary for reef accretion, as developed reefs experience 10-55% exposure with optimal growth occurring at 20-40% (Ridge et al. 2015). As oysters grow, sediment is constantly deposited onto the reef, and consequently, oyster reefs develop a critical grain size for which growth is able to outpace sedimentation (Housego & Rosman 2016). Once fully developed, oyster reefs have the potential to store considerable amounts of carbon and nitrogen within their shells, and remove suspended sediment from the water column (Dehon 2010). This improved water quality creates improved habitats for other nekton communities, enhancing the populations of different crab, whelk and fish species (Scyphers et al. 2011).

Research papers regarding the suitability of oyster reefs and their ecological consequences far outnumber the studies of the engineering properties of these reefs. Many tests have been performed on existing natural reefs to determine their usefulness in reducing shoreline retreat by measuring the surface elevation leeward of the structure. Results indicate that oyster reefs are more useful in low to moderate energy environments as opposed to settings with strong wave dynamics (Piazza et al. 2005; Scyphers et al. 2011). Wave heights were also measured before and after oyster reefs in laboratory experiments, to determine the wave attenuating capacity of the structures. Experiments produced waves that reflect those of shallow intertidal flats as well as small boat wakes, indicating the usefulness of oyster reefs within these environments (Borsje et al. 2010; Coghlan et al. 2016). Other hydrodynamic forces such as velocity and turbulence were recorded in the vicinity of an existing oyster reef on one side of an intertidal salt marsh channel (Styles 2015). Results of this test demonstrated the ability for oyster reefs to break up the flow in the vicinity, inducing turbulence and developing stresses along the reef. This was significant when compared to the opposite side of the channel, which only contained bare sediment. With oyster reefs demonstrating significant wave attenuating properties and the ability to disrupt river flows, further research into the potential for oyster reefs to provide services within a number of other applications, is suggested. Applications for the use of oysters as future topics for study include reducing the effects of riverbank erosion by providing slope stability, alleviating the effects of floods, restoring wetlands and protecting existing structures such as river dykes.

With gaps in the current knowledge surrounding the design of oyster reef structures, studies relating to the use of gabions, ripraps, hybrid revetments, and sandbags as erosion protection, suggest that the engineering properties of oysters may be of use within such applications. Therefore, the implementation of oyster reefs as an eco-engineering solution to erosion problems has strong potential for future research.

2.7 Objectives of Research

Research on the design of oyster reefs as erosion control structures is limited, with available studies measuring wave transmission for oyster shells in a variety of structures (Allen 2013; Coghlan et al. 2016). These papers have demonstrated results for oyster reefs that are comparable to traditional rubble mound breakwaters, inferring the potential use of oysters as preventative measures for shoreline erosion. While this research suggests adequate wave attenuating capabilities, oyster reefs constructed using oyster shells in coconut fibre bags have been noted to displace under wave attack reflective of small boat wakes (Coghlan et al. 2016). As a result, sandbags, which are mostly used for flood mitigation, have been identified as an element that could be combined with oyster bags to form a more stable composite structure.

This structural combination forms the basis of this research, whereby a range of configurations consisting of both oyster bags and sandbags are constructed to determine the optimal design for the oyster reef. Wave conditions are set up to reflect small boat wakes, which are expected to occur in low energy estuarine environments. The aim is to analyse and compare each design according to a series of parameters. Assessing the stability of the structure is the highest priority, with sandbags introduced to ensure displacement is reduced. Parameters that evaluate the effectiveness of the structure in protecting the shoreline are also analysed. Wave transmission and wave reflection coefficients are calculated together with the amount of energy that is dissipated. Designs are then compared to determine the ideal configuration for each tier of structures that satisfies the optimal requirements of each parameter.

3 Methodology and Experimental Setup

3.1 Introduction

A physical model that combines oyster bags and sandbags to form an erosion control structure was established in a three metre wave flume at the UNSW Water Research Laboratory, Manly Vale. The aim of this full scale model was to improve the stability of an oyster bag reef by creating composite structures that utilise sandbags, while maintaining the ideal dissipative characteristics of typical rubble mound breakwaters. Two-dimensional testing was undertaken for each configuration of the model, with each structure experiencing packets of 10 monochromatic waves. The wave conditions reflected small boat wakes, for which the oyster reef is expected to experience in the field. These tests were performed for flow depths of 0.16m, 0.32m and 0.40m, which correspond to the heights of the 1, 2 and 3 tier oyster bag structures respectively. During the experiments, qualitative observations of displacement and movement were noted for each structure, while data was processed following the tests to determine the results of wave transmission, reflection and energy dissipation.

3.2 Physical Setup and Experimental Procedure

3.2.1 Model Testing Facility

All physical modelling was completed in the 3m wave flume at the UNSW Water Research Laboratory, Manly Vale. This flume was noted by Coghlan et al. (2016) to be approximately 32.5m in length, 3m in width and 1.3m in depth, with walls constructed of rendered brick and a permanent horizontal floor constructed of concrete. The two-dimensional testing in the flume was restricted to the right of three 1m wide smaller flumes that had been built internally within the 3m flume. Due to the setup of another project within the inside 1m smaller flume, as well as wooden beams along the floor in the centre of the smaller flumes, the outside mini flume was used for the experiments.

Testing was undertaken at full scale for the experiments (i.e. an undistorted length scale of 1:1) on an impermeable false floor that consisted of concrete capping overlaying blue metal fill (Coghlan et al. 2016). The slope of this floor was 1V:55H where the mini flumes and structures were located, before sloping towards the wave paddle at 1V:5H until it intersected the permanent horizontal floor (Coghlan et al. 2016).

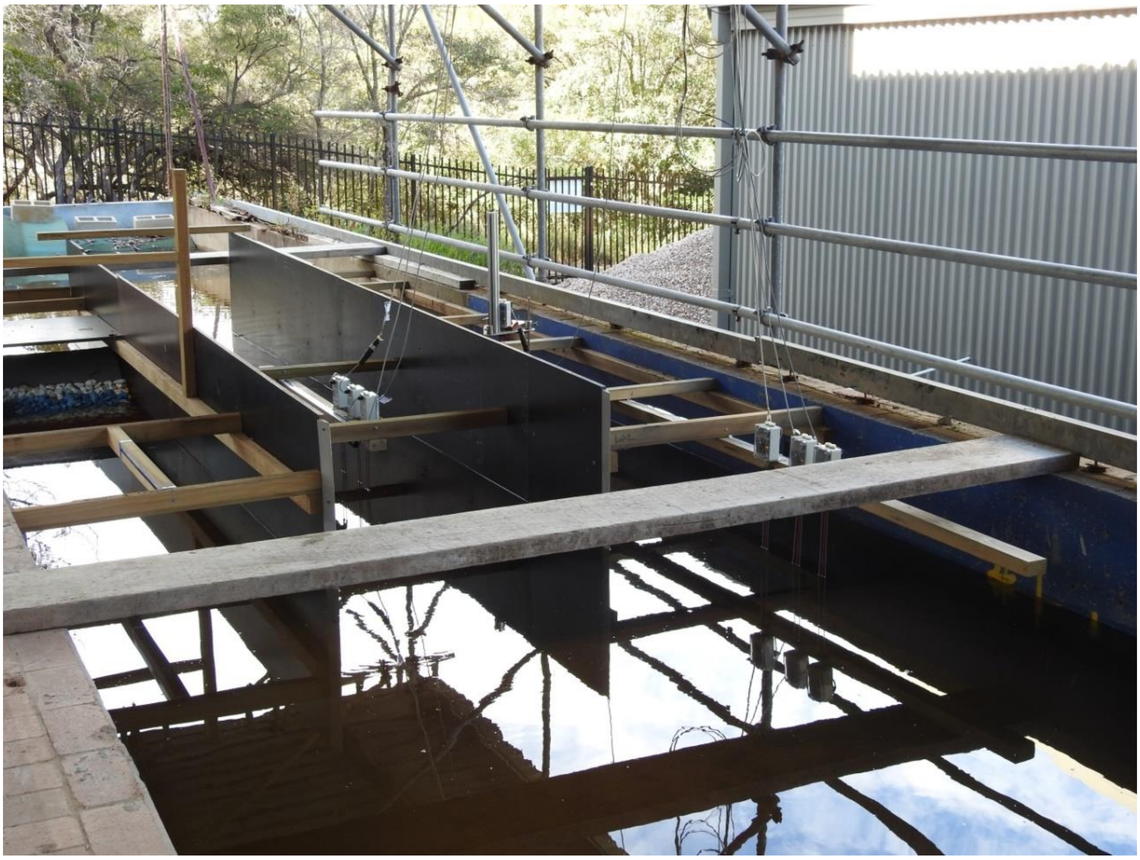


Figure 3.1 - Division of 3m wave flume into three 1m mini flumes

Monochromatic wave trains were generated in the flume using a wave paddle that is powered by a 55kW hydraulic piston system. An input signal is generated using the National Instruments LabVIEW software package on a nearby computer and fed through to the wave paddle.

Figure 3.2 - 3m Wave flume at the UNSW Water Research Laboratory, Manly Vale

Figure 3.3 - Wave paddle for the 3m wave flume

3.2.2 Wave Probe Setup

In order to determine the incident, transmitted and reflected wave heights, seven single capacitance wave probes were used to collect water level data at specific locations within the flume. Each probe was calibrated to ensure that the correct water levels were being recorded during testing. This calibration was conducted by connecting each probe to the nearby computer and adjusting the submerged depths of the probe elements.

Offshore probes 0, 1 and 2 were used as a comparison to ensure data was being collected correctly for the other probes. However, these probes were not used to collect water level data that was used in wave height calculations. The three probe array, consisting of probes 3, 4 and 5 was used to determine the reflected wave heights immediately seaward of the structure. A second three probe array, consisting of probes 6, 7 and 8, was used to determine the incident wave heights. These probes were located in the centre of the three 1m mini flumes, such that waves propagated through this mini flume undisturbed. Probe 6 was aligned directly adjacent to the toe of the structure. Finally, probe 9 was clamped to a stand landward of the structure to measure the transmitted wave heights. This probe was made easily movable to avoid damage in the event of structural displacement. The schematic for the probe setup is shown in Figure 3.4.

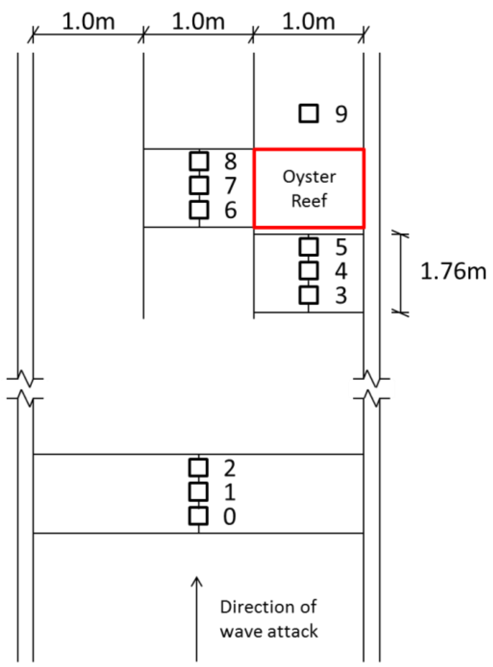


Figure 3.4 - Wave probe setup

Each three probe array was used to collect water level data that could generate the required transmitted and reflected wave heights as described by the least squares method proposed by Mansard and Funke (1980). The positions of the probes in these arrays were dependent on the water depth at the structure, as well as the wave period. Therefore, the positions of the probes were changed for each set of wave conditions and water levels. Each wave probe was screwed into wooden beams, with ruler tape marking the positions for each set of tests. Probe distances for each set of experimental conditions are summarised in Table 3.1.

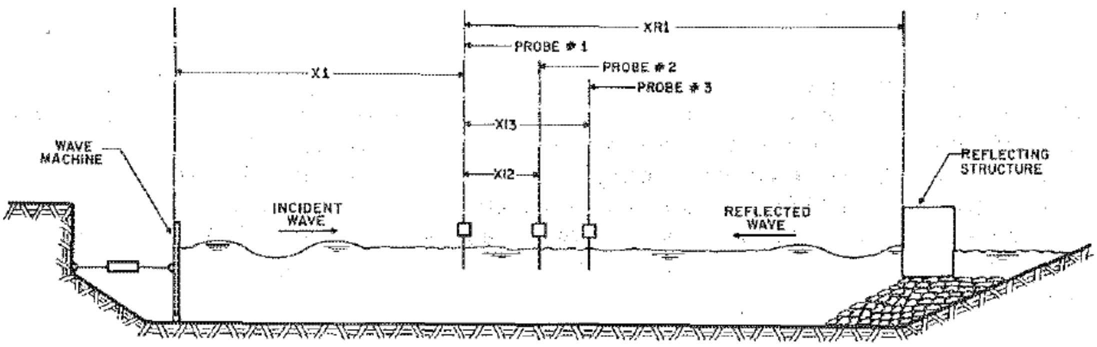


Figure 3.5 - Three probe array setup for wave reflection measurement (Mansard & Funke 1980)

Water Depth (m)	**Wave Period (s)**	**X_{12} (m)**	**X_{13} (m)**
0.16	1	0.112	0.280
	2	0.244	0.610
	3	0.372	0.929
0.32	1	0.140	0.349
	2	0.335	0.839
	3	0.519	1.298
0.40	1	0.146	0.366
	2	0.370	0.924
	3	0.577	1.442

Table 3.1 - Three probe array distances X_{12} and X_{13}

The probe of each array that was most seaward remained in the same position for all tests. For the reflected probe array, the distance of this probe from the structure was recommended to be 1 wavelength from the structure. However, due to physical constraints within the flume, the furthest distance that this probe could be moved back without being exposed to turbulence and reflected waves outside the structure's mini flume, was 1.76m. This value does not comply with wavelengths for 3 second waves, although changes in the results were expected to be minor. The three probe array adjacent to the structure, that was used to measure the incident wave heights, incurred a number of probe malfunctions throughout the testing. As a result, only probe 6 in line with the toe of the structure was used to collect water level data in the centre flume. In the least squares method developed by Mansard and Funke (1980), three wave probes are required to separate and interpret incident and reflected waves. Therefore, a single probe is not sufficient for this separation. The reflected waves from the back of the flume however, are negligible in comparison to the incident waves in the centre flume, and thus the results are largely unaffected for incident wave calculation.

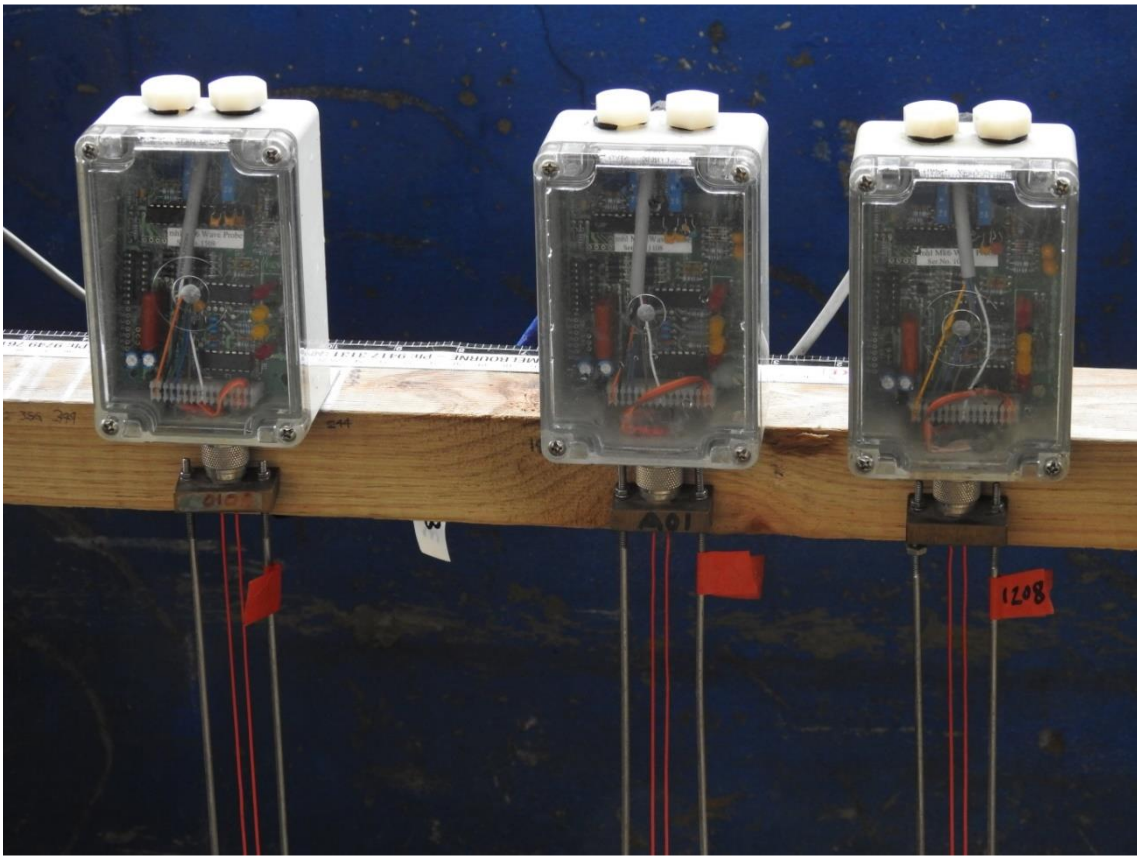


Figure 3.6 - Three probe array used to separate incident and reflected waves

3.2.3 Experimental Procedure

All the bags that were required for the test structure were moved into the rear of the 3m wave flume and dragged into the outside channel. The configuration was assembled in the outside mini flume, lining the toe of the structure up with a marked line.

For the corresponding test conditions, the water level was adjusted accordingly, and the correct wave period and calibration factor were selected on the National Instruments LabVIEW software package on the computer. A folder was set up with the date, and set as the acquisition path for the data collected by the selected wave probes. The paddle driver software was then used to send a signal to the wave paddle, initiating the generation of a packet of 10 monochromatic waves. During each test, any movement of the structure was noted. If significant displacement occurred, photos of the structure were taken after each test. The structure was then reassembled, with the toe moved back into position before the next test.

3.3 Components of the Physical Model

3.3.1 Oyster Bags

The oyster bags used in the testing were the same as those used in report by Coghlan et al. (2016), and were provided by OceanWatch Australia. A mixture of Sydney rock oyster (Saccostrea glomerata) and Pacific oyster (Crassostrea gigas) filled the bags, and were acquired from oyster farmers in Port Stephens (Coghlan et al. 2016). Free from oyster tissue, the empty oyster shells underwent biosecurity treatment prior to delivery from Port Stephens.

With the density of the Sydney rock oyster unable to be found in the literature, and the density of the Pacific oyster in natural field conditions determined to be 1810 kg/m^3 (His and Robert, 1987), small scale density tests were undertaken to determine an average density for the oyster shell mixture. This was calculated by measuring the weight and volume of a random selection of 10 oyster shells from the mixture.

Oyster Shell	Density (kg/m^3)
Sydney rock oyster	-
Pacific oyster	1810
Oyster mixture	2107.63

Table 3.2 - Oyster shell density

Figure 3.7 - Sample of oyster shell mixture

Coir (coconut fibre) was woven into netting with 12mm x 12mm aperture and sewn at the seams with Manila rope. This material was used for the single, double and triple oyster bags, and assembled by OceanWatch Australia.

Figure 3.8 - Single oyster bag provided by OceanWatch Australia

Figure 3.9 - Double oyster bag provided by OceanWatch Australia

Figure 3.10 - Triple oyster bag provided by OceanWatch Australia

3.3.2 Sandbags

Maccaferri geotextile fabric was used to form 6 bags, with net dimensions 90mm x 75mm to closely follow the shape and size of the oyster bags. Each bag was folded along the 90mm edge and stapled on two sides, allowing for the bags to be filled from one end. Brookvale sand was then used to fill each bag. The dimensions of the sandbags slightly vary from the oyster bags as additional geotextile fabric was used at the edges to ensure adequate stapling. These bags were assembled at WRL and labelled A-F. Sandbag A is shown in Figure 3.11 prior to labelling.

Figure 3.11 - Single Maccaferri geotextile sandbag

ELCOMAX 600R geotextile was also tested for the sandbags. The sandbags using this material were formed in the same manner as the initial sandbags, and were also filled with Brookvale sand. Only three bags were assembled with this material, labelled A-C (Figure 3.12).

Figure 3.12 - ELCOMAX geotextile sandbags, labelled A-C

3.3.3 Dimensions of Oyster Bags and Sandbags

Key measurements for the bags are summarised in Table 3.3, with the lengths and widths varying marginally across all bags. The heights of the sandbags however, were lower than those of the oyster bags.

Bag Type	Bag ID	Length (m)	Width (m)	Height at centre (m)	Volume (m^3)
Oyster Bags	Single	0.93	0.33	0.16	0.007
	Double	0.93	0.6	0.16	0.014
	Triple	0.93	0.92	0.15	0.016
Maccaferri Sandbags	A	0.95	0.36	0.12	0.023
	B	0.94	0.37	0.12	0.023
	C	0.93	0.38	0.12	0.027
	D	0.88	0.37	0.12	0.028
	E	0.9	0.36	0.12	0.027
	F	0.91	0.37	0.12	0.024
ELCOMAX Sandbags	A	0.95	0.37	0.12	0.024
	B	0.95	0.37	0.13	0.024
	C	0.95	0.37	0.13	0.026
Small Sandbags*	55	0.18	0.17	0.045	0.004
	158	0.17	0.155	0.04	
	56	0.165	0.165	0.04	
	827	0.18	0.17	0.035	
	1051	0.17	0.165	0.04	
	445	0.17	0.16	0.045	

* Small sandbags from a previous WRL experiment were combined with the oyster bag structure for an alternative design

Table 3.3 - Key measurements for all oyster bags and sandbags

3.3.4 Model Configurations

To evaluate the effects of incorporating sandbags into the oyster bag structure, a series of configurations were developed. These composite structures were compared to the base cases of oyster bags alone and sandbags alone. Each configuration is categorised into 1, 2 or 3 tiered structures. Alternative design options were tested to evaluate the effects of increasing crest width and rotating the longitudinal axes of the bags 90 degrees, parallel to wave attack.

The cross-sectional diagram for each configuration is illustrated below, with each design denoted by a unique reference ID. For these cross-sections, the direction of wave propagation is from left to right.

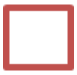
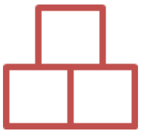
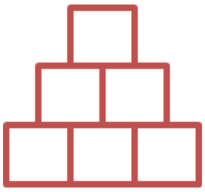
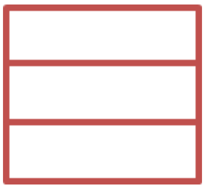
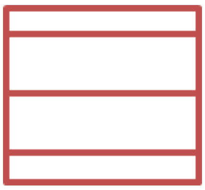
Structure ID	Cross-Section	Description
O_1		1 Tier Structure 1 x Oyster Bag
O_2		2 Tier Structure 3 x Oyster Bag
O_3		3 Tier Structure 6 x Oyster Bag
O_4		1 Tier Structure 2 x Oyster Bag
O_5	 Top View	1 Tier Structure 3 x Oyster Bag Parallel to Wave Attack
O_6	 Top View	2 Tier Structure 5 x Oyster Bag Parallel To Wave Attack

Figure 3.13 - Oyster bag configurations

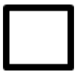
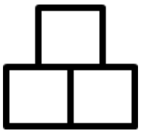
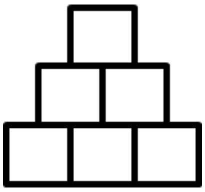
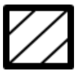
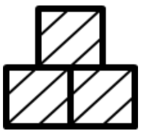
Structure ID	Cross-Section	Description
S_1		1 Tier Structure 1 x Maccaferri Sandbag
S_2		2 Tier Structure 3 x Maccaferri Sandbag
S_3		3 Tier Structure 6 x Maccaferri Sandbag
S_4	 Top View	1 Tier Structure 3 x Maccaferri Sandbag Parallel to Wave Attack
S_5		1 Tier Structure 1 x ELCOMAX Sandbag
S_6		2 Tier Structure 3 x ELCOMAX Sandbag

Figure 3.14 - Sandbag configurations

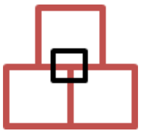
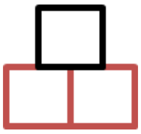
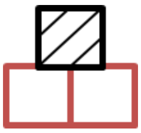
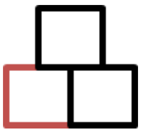
Structure ID	Cross-Section	Description
M11		1 Tier Structure 1 x Oyster Bag 1 x Maccaferri Sandbag
M12		1 Tier Structure 1 x Oyster Bag 1 x ELCOMAX Sandbag
M13		1 Tier Structure 2 x Oyster Bag 1 x Maccaferri Sandbag
M14		1 Tier Structure 2 x Oyster Bag 1 x ELCOMAX Sandbag
M21		2 Tier Structure 3 x Oyster Bag 5 x Small Sandbags
M22		2 Tier Structure 2 x Oyster Bag 1 x Maccaferri Sandbag
M23		2 Tier Structure 2 x Oyster Bag 1 x ELCOMAX Sandbag
M24		2 Tier Structure 1 x Oyster Bag 2 x Maccaferri Sandbag
M25		2 Tier Structure 1 x Oyster Bag 2 x ELCOMAX Sandbag

Figure 3.15 – Mixed 1 and 2 tier configurations

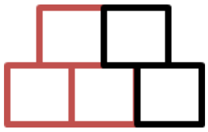
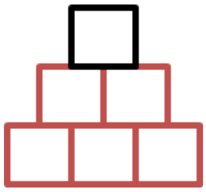
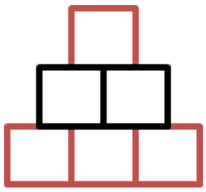
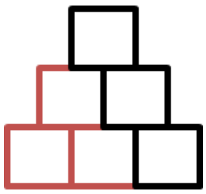
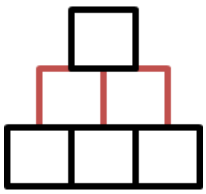
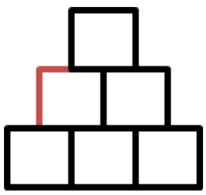
Structure ID	Cross-Section	Description
M26		2 Tier Structure 3 x Oyster Bag 2 x Maccaferri Sandbag
M31		3 Tier Structure 5 x Oyster Bag 1 x Maccaferri Sandbag
M32		3 Tier Structure 4 x Oyster Bag 2 x Maccaferri Sandbag
M33		3 Tier Structure 3 x Oyster Bag 3 x Maccaferri Sandbag
M34		3 Tier Structure 2 x Oyster Bag 4 x Maccaferri Sandbag
M35		3 Tier Structure 1 x Oyster Bag 5 x Maccaferri Sandbag

Figure 3.16 – Mixed 2 and 3 tier configurations

3.4 Wave and Water Level Design Conditions

3.4.1 Preamble

In order to directly compare the results of the experiments with the previous oyster bag testing conducted by the Water Research Laboratory (Coghlan et al. 2016), similar experimental conditions were established. The flow depths and wave conditions were consistent with the conditions proposed by Coghlan et al. (2016), and are reflective of small boat wakes that the oyster bags are expected to experience in the field.

Adopted wave and water level conditions:

- Wind waves and boat wakes
- Flow depths, reflective of tides

Prior to the study undertaken at WRL by Coghlan et al. (2016), the flow depths and wave conditions were determined for the proposed sites of Sydney Harbour and Botany Bay. In these locations, the most common types of waves that are anticipated to reach the oyster bags are wind waves and small boat wakes.

3.4.2 Wave Conditions

Data from the Sydney Metropolitan Area Fore-and-Aft Mooring Study (MSB NSW 1987) indicates that for 10 year ARI significant wave heights (H_s) of 0.8m in bays adjacent to Sydney Harbour and Botany Bay, wave periods of 2-4 seconds can be expected for fetch lengths up to 4km.

Wind waves were largely outside the scope of works for the 2016 WRL report, with the main focus on boat generated waves. Several full scale field studies of recreational boating activities (Glamore & Hudson 2005), have shown that wakeboarding and waterski vessels produce maximum wave periods of between approximately 1 and 2 seconds for velocities of 8 knots (Table 3.4). Wave heights that are smaller in magnitude were generated for operating conditions when towing a rider (Glamore et al. 2014), and are summarised in Table 3.5.

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

Table 3.4 – Maximum wave heights for waterski and wakeboard boats (Glamore & Hudson 2005)

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

Table 3.5 – Wave heights for waterski, wakeboard and wakesurf activities under operating conditions (Glamore & Hudson 2005; Glamore et al. 2014)

The waves generated from high speed catamaran ferries demonstrate periods of 4 to 6.5 seconds (Blumberg et al. 2003), and were not adopted for the testing in the WRL report by Coghlan et al (2016). These conditions were assumed to be comparable to ocean swell and were thus not expected to impact the oyster bags at the proposed field sites. A range of wave heights and periods for other vessels presented by the Sydney Metropolitan Area Fore-and-Aft Mooring Study (MSB 1987), and Gary Blumberg and Associates (Blumberg et al. 2003), were also considered, with these wash characteristics revealing wave periods mostly between 1 and 3 seconds.

3.4.3 Water Level Conditions

The design life for the oyster bags was not specified in the report by Coghlan et al. (2016), and as such, it was assumed that the impact of sea level rise was negligible for the range of flow depths being considered. Effects of wave setup, wave runup and storm surge may also influence the proposed flow depths, but were not part of the experimental setup for the oyster bags. With the cross-shore position of the oyster bags not specified, it was assumed that the bags would be placed at around 0m AHD, with maximum water depth of 0.40m. This corresponds to the crest level of the three tiered oyster bag structure, arranged in a pyramid configuration. Each tier refers to each row of bags that are arranged in the configuration. The water levels were therefore determined to be the depths that corresponded to the crest levels for each tier of oyster bags, as these depths represented the worst case scenarios for non-submerged structures.

3.5 Adopted Wave and Water Level Conditions

The wave conditions and water levels that have been adopted are reproduced below, and are similarly adopted for the experimental setup of oyster bags and sandbags.

Condition	Values
Water Depth at Structure	0.16m, 0.32m, 0.40m
Wave Periods	1s, 2s, 3s
Wave Height at Structure	0.05m – 0.30m

Table 3.6 - Tested water levels and wave conditions (Coghlan et al. 2016)

The wave heights at the structure were assumed to be 0.05m to 0.30m, reflecting the expected waves generated from boats. Packets of 10 monochromatic waves were generated in the 3m wave flume, with wave attack perpendicular to each structure. However, due to wave breaking on the 1V:55H slope of the flume, wave heights less than 0.05m were produced for some wave cases.

Before each test, a calibration factor was increased with increments of 0.1 to change the generated wave heights. The choice of these calibration factors was dictated by wave breaking. Once wave heights were increased to a limit such that the waves broke near the structure, one further test was run with the calibration factor increased to ensure that wave breaking occurred seaward of the structure, and that testing of the largest waves had been captured. All of these tests were conducted for the oyster bag structures, before the number of tests for each set of wave conditions was reduced. Lower calibration factors were also chosen to observe bag movement at a range of wave heights. Table 3.7 outlines the calibration factors that were chosen for each water depth and wave period.

Water Depth (m)	Wave Period (s)	Calibration Factor
0.16	1	0.5, 0.6, 0.7
	2	0.2, 0.4, 0.5
	3	0.3, 0.5, 0.6, 0.7
0.32	1	0.6, 0.8, 0.9
	2	0.7, 0.8, 0.9, 1
	3	0.6, 0.8, 0.9, 1
0.40	1	0.7, 0.8, 0.9, 1
	2	0.4, 0.6, 0.9, 1
	3	0.3, 0.7, 0.8

Table 3.7 - Reduced experimental conditions including calibration factors

3.6 Measured Design Parameters

3.6.1 Stability Assessment

The addition of sandbags into the design of the artificial oyster reef was intended to provide additional stability to the structure. Qualitative notes were taken for each test to describe whether the wave attack resulted in any bag movement, particularly rocking of the crest bag and displacement of the structure. For significant displacement, photos were also taken. The incident wave heights that resulted in the inception of rocking and displacement for each configuration, were then determined, providing a comparison for the stability of each design.

3.6.2 Wave Transmission

Reducing wave transmission is another important component of design for erosion control structures. Therefore, to quantify the reduction in wave height for each structure, transmission coefficients were calculated. The coefficient value is dependent on both the incident wave height and the transmitted wave height, as shown below.

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

Where: K_t = transmission coefficient

H_t = transmitted wave height landward of the structure

H_i = incident wave height at the toe of the structure

3.6.3 Wave Reflection

The reflection of waves is similarly researched for traditional rubble mound breakwaters, and is pivotal to ensuring erosion control structures do not generate large standing waves. For each test, wave reflection coefficients were determined for the structure, calculated as the ratio of the reflected wave height to the incident wave height as represented below.

$$K_r = \frac{H_r}{H_i}$$

Where: K_r = reflection coefficient

H_r = reflected wave height seaward of the structure

H_i = incident wave height at the toe of the structure

3.6.4 Energy Dissipation

The ability to dissipate wave energy is of major concern in the design of structures used for coastal defence. Energy dissipation represents the amount of energy that is lost when waves break on the structure, and was calculated for each test. An equation for the wave energy of vessel wash in Noosa River and Brisbane River is given by the Australian Maritime College (2003).

$$E = 1962{H_m}^2{T_m}^2$$

Where: E = wave energy (J/m)

H_m = maximum wave height (m)

T_m = maximum wave period (s)

To determine the wave energy that is dissipated by each structure, the incident wave energy is written as a function of the transmitted, reflected and dissipated energy.

$$E_i = E_t + E_r + E_d$$

Where: E_i = incident wave energy

E_t = transmitted wave energy

E_r = reflected wave energy

E_d = dissipated wave energy

Therefore, the dissipated wave energy can be represented as follows.

$$E_d = E_i - E_t - E_r$$

3.6.5 Data Processing

Data from the single capacitance wave probes was output to two variables, time and voltage. A MATLAB code developed for the oyster bag testing was similarly used to convert the data to a time series of water depth using the method proposed by Mansard and Funke (1980). As per the Mansard and Funke method, input variables of water depth and the spacing of three probe arrays were required. This information was linked to the MATLAB code for each set of wave conditions.

From the generated time series of water depth, the wave heights at each probe position were determined for each test. Wave heights were selected manually from time series plots using an additional MATLAB code. Representative wave heights were chosen from the first three waves in the packet of 10 waves, as succeeding waves were exposed to varying levels of turbulence and reflection from the back of the flume. These wave heights were recorded and used for the calculation of transmission and reflection coefficients as well as the energy that was dissipated during each test. A few wave probes incurred faults throughout the testing period and consequently some of the test data could not be processed.

3.7 Summary

Oyster bag testing with sandbags was conducted in the 3m wave flume at the UNSW Water Research Laboratory. The adopted wave conditions and water depths for the testing match the conditions of the oyster bag testing conducted by Coghlan et al. (2016) (Table 3.6), with calibration factors for each set of tests selected to provide a clearer comparison of data (Table 3.7). A mixture of Pacific oysters and Sydney rock oysters covered in woven coconut fibre were used as oyster bags and were provided by OceanWatch Australia. The sandbags were constructed from Maccaferri and ELCOMAX geotextile, and filled with Brookvale sand. Configurations comprising oyster bags, Maccaferri sandbags and ELCOMAX sandbags, were developed to determine the optimal oyster reef structure. A series of wave probes were used in locations adjacent to, behind, and in front of the structure to collect water level data at these locations within the flume. During the testing, notes regarding the movement of the structures as well as photos of significant displacement were taken. The least squares method developed by Mansard and Funke (1980) was consulted to convert the water level data into wave heights. This method is dependent on the spacing between the probes in the three probe array as well as the water depth of the seaward most probe in order to separate the reflected and incident wave heights. The wave heights were determined using MATLAB codes that were developed during the modelling and prior to the testing conducted by Coghlan et al. (2016). From this data, coefficients for wave transmission and reflection as well as energy dissipation were determined. An analysis of the stability of each structure was also developed using the notes, photos and videos taken during the testing.

4 Results

4.1 Introduction

The aim of combining sandbags with oyster bags was to enhance the stability of the oyster bag reef and determine the optimal configuration that improves wave transmission, wave reflection and energy dissipation. Extreme values for each of the measured parameters were determined using the base case scenarios that consisted solely of oyster bags and solely of sandbags. The mixed configurations were then analysed to identify the ideal solution that acted as the best erosion control structure while maintaining a sizeable oyster reef.

For each parameter that was measured, the analysis is separated according to the number of tiers in each design. Alternative design options that were developed to either test the effects of utilising larger crest widths or employing bags that have their longitudinal axes parallel to wave attack, are examined separately but are still compared to the regular designs. All relevant data is provided in each chapter, with the complete results given in the appropriate appendices.

4.2 Stability Assessment

In order to quantify the stability of each structure, the incident wave heights that initiated bag movement were noted. Specifically, bag movement was separated into two categories, rocking of the structure (or crest bag), and displacement of the structure. Higher incident wave heights indicate a greater resistance to wave attack. The data was only obtained for the calibration factors that were tested, and as a result, the exact incident wave height that may induce rocking or displacement was not determined. Therefore, wave heights slightly less than those calculated here may yet result in rocking and displacement. The incident wave heights that induce bag movement are directly comparable for the same wave conditions across all configurations, but may not provide accurate comparisons for different water depths and wave periods. The smallest incident wave heights that had resulted in either rocking or displacement were noted.

4.2.1 Stability Assessment of 1 Tier Structures

All configurations of 1 tier structures were tested at water depths of 0.16m. The base case designs for the 1 tier structures were the single oyster bag and the single sandbag. Both Maccaferri and ELCOMAX geotextile sandbags were included in the stability analysis. To improve the stability of the single oyster bag, the double oyster bag was used instead, and compared to the configuration of the single oyster bag in front of the single sandbag. These configurations were repeated with both geotextile materials. For the 1 tier configurations, rocking was noted when either the entire structure or the front bag rocked. Both configurations containing single sandbags did not exhibit any movement, and therefore the following table only gives the incident wave heights for the oyster bags and mixed designs.

Structure ID	Wave Period (s)	Incident Wave Height (m)	
		Crest Bag/Structure Rocking	Displacement of Structure
O_1	1	0.072	-
O_1	2	0.049	0.086
O_1	3	0.037	0.068
O_4	1	-	-
O_4	2	-	0.092
O_4	3	-	0.092
M_{11}	1	-	-
M_{11}	2	0.092	-
M_{11}	3	0.074	-
M_{12}	1	-	-
M_{12}	2	0.069	-
M_{12}	3	0.071	-

Table 4.1 - Incident wave heights that induced movement for 1 tier structures; d=0.16m

For the single oyster bag structure, rocking was observed for all wave conditions, while displacement occurred for wave periods of 2 and 3 seconds. The incident wave heights that cause rocking and displacement for the single oyster bag arrangement decrease as the wave period increases. This trend is largely maintained across all structures for all wave conditions and water depths.

A suitable solution to the oyster bag displacement was observed to be sandbags, with both sandbag base cases failing to show any movement across all tests. The double oyster bag as well as composite structures comprised of both oysters and sand revealed intermediate results.

Rocking was not observed for the double oyster bag, although displacement did occur for wave periods of 2 and 3 seconds, similar to the single oyster bag. Displacement resulted from incident wave heights of approximately 91mm, larger than the wave heights required for movement of the single oyster bag. The mixed configurations consisted of one sandbag placed behind the single oyster bag, differing only by geotextile fabric. These structures exhibited rocking but no displacement throughout the testing. The Maccaferri geotextile sandbag required a larger incident wave height for the 2 second waves to cause rocking, compared to the ELCOMAX geotextile sandbag.

As a result of the testing, it can be seen that the oyster reef stability is drastically improved with the addition of a single sandbag for the 1 tier structures. The oyster bag did however continue to rock despite the added support from the sandbag, and thus further testing involving the use of stakes or screws to anchor the oyster bag, may prevent bag movement entirely.

For the tested wave conditions, configuration M_{11} offered the greatest resistance to displacement and rocking, for a water depth of 0.16m.

4.2.2 Stability Assessment of 2 Tier Structures

The single oyster bag was placed in the centre, on top of the double oyster bag to form the base case oyster reef for the 2 tier structure. This pyramid configuration was replicated for the sandbag base cases as well as the mixed assemblies. The results that follow have been separated into 0.16m and 0.32m water depths for direct comparison.

i. 0.16m Water Depth

Incident wave heights ranging from 90-110mm resulted in crest bag rocking for the oyster bag structure, with no displacement evident across all tests with a water depth of 0.16m. The sandbag configurations as well as the mixed designs containing either 1 or 2 sandbags, did not exhibit any movement. However, configuration M_{21}, which used small sandbags beneath the oyster crest bag, was observed to rock. The addition of smaller sandbags provided greater resistance to wave attack, as the height of the incident waves that induced rocking was lower than those recorded for the oyster bag structure. As a result, Table 4.2 compares the incident wave heights recorded for the oyster bag structure and the mixed design with small sand bags. The complete results are provided in Appendix A.

Structure ID	**Wave Period (s)**	**Incident Wave Height (m)**	
		Crest Bag/Structure Rocking	**Displacement of Structure**
O_2	1	-	-
O_2	2	0.113	-
O_2	3	0.093	-
M_{21}	1	-	-
M_{21}	2	0.072	-
M_{21}	3	0.065	-

Table 4.2 - Incident wave heights that induced movement for 2 tier structures; d=0.16m

ii. 0.32m Water Depth

Both sandbag base cases did not exhibit any movement at a water depth of 0.32m, while both rocking and displacement were evident for the oyster bag structure. Similarly to the 1 tier oyster bag structure at a water depth equal to the crest height, displacement was only observed for wave periods of 2 and 3 seconds.

Structure ID	Wave Period (s)	Incident Wave Height (m)	
		Crest Bag/Structure Rocking	Displacement of Structure
O_2	1	0.105	-
O_2	2	0.089	0.137
O_2	3	0.047	0.102
M_{21}	1	0.079	-
M_{21}	2	-	0.143
M_{21}	3	-	0.077
M_{22}	1	-	-
M_{22}	2	-	0.153
M_{22}	3	-	0.144
M_{23}	1	-	-
M_{23}	2	-	0.146
M_{23}	3	-	0.080
M_{24}	1	-	-
M_{24}	2	-	-
M_{24}	3	0.152	-
M_{25}	1	-	-
M_{25}	2	-	-
M_{25}	3	0.139	-

Table 4.3 - Incident wave heights that induced movement for 2 tier structures; d=0.32m

Configuration M_{21} that uses the small sandbags, displayed rocking at wave periods of 1 second, which did not occur for the other mixed structures. Double oyster bags with a single sandbag on top still demonstrated displacement at both 2 and 3 second wave periods, while displacement was not observed for the structures with a single oyster bag at the front of the base.

A larger incident wave height was required to move Maccaferri sandbag structures, compared to designs that used the ELCOMAX sandbags, although this difference was minor.

For the 2 tier structures, the artificial oyster reef greatly benefited from having a single sandbag behind the single oyster bag at the base, with another sandbag on top. This design (configurations M_{24} and M_{25}) prevented displacement across all wave conditions, with rocking only occurring at depths of 0.32m and wave periods of 2-3 seconds.

4.2.3 Stability Assessment of 3 Tier Structures

Three water depths, 0.16m, 0.32m and 0.40m were tested for the 3 tier structures. Each configuration was pyramidal in shape, with three bags at the first tier, two bags at the second and a single crest bag as the third tier. The oyster bag base case used the triple, double and single oyster bags, while only the Maccaferri geotextile fabric was used for the sandbags. Five composite structures were tested and compared to these base cases.

i. 0.16m Water Depth

For the oyster bag case, no data was recorded for a water depth of 0.16m. However, the January 2016 WRL report reveals that for the same wave conditions, no oyster bag movement was observed (Coghlan et al. 2016). All other 3 tier configurations similarly showed no signs of rocking or displacement. As a result, the incident wave heights that would result in movement were non-existent for the range of wave conditions tested.

ii. 0.32m Water Depth

The oyster bag structure demonstrated rocking and displacement for both 2 and 3 second waves at a water depth of 0.32m. Contrastingly, the sandbag structure did not demonstrate any movement for the same conditions.

Mixed designs M_{31} and M_{32} were both displaced for 3 second waves, while M_{32} experienced significant rocking and crest bag displacement for 2 second waves. With an increasing number of sandbags, designs M_{33}, M_{34} and M_{35} did not displace for the tested wave conditions at a water depth of 0.32m. However, rocking did occur for these structures, with the most symmetrical design, M_{34}, only observed to rock for 3 second waves. Despite using 5 sandbags in the design of M_{35}, the asymmetrical arrangement of the configuration may have led to increased rocking, which occurred for 2 and 3 second waves.

A larger oyster reef can be achieved by using configuration M_{33}, as three oyster bags make up the arrangement. However, rocking is reduced with a smaller oyster reef size in configurations M_{34} and M_{35}.

Structure ID	**Wave Period (s)**	**Incident Wave Height (m)**	
		Crest Bag/Structure Rocking	**Displacement of Structure**
O_3	1	-	-
O_3	2	0.126	0.153
O_3	3	0.097	0.108
S_3	1	-	-
S_3	2	-	-
S_3	3	-	-
M_{31}	1	-	-
M_{31}	2	-	-
M_{31}	3	-	0.106
M_{32}	1	0.075	-
M_{32}	2	0.139*	-
M_{32}	3	0.068*	0.149
M_{33}	1	-	-
M_{33}	2	0.162	-
M_{33}	3	0.069	-
M_{34}	1	-	-
M_{34}	2	-	-
M_{34}	3	0.129	-
M_{35}	1	-	-
M_{35}	2	0.181	-
M_{35}	3	0.129	-

*This wave height induced both rocking as well as crest bag displacement.

Table 4.4 - Incident wave heights that induced movement for 3 tier structures; d=0.32m

iii. 0.40m Water Depth

With the heights of the sandbags lower than the heights of the oyster bags, and further densification of the sandbags occurring throughout testing, the overall height of the designs that contained sandbags was reduced. As a result, the sandbag base case and the mixed arrangements acted as marginally submerged structures for the 0.40m water depth. This likely reduced the incident wave heights that resulted in rocking and displacement.

The results for d=0.40m are consistent with those presented for d=0.32m, and are displayed in Appendix A. However at this water depth, lower incident wave heights are able to initiate structural movement compared to those examined at 0.32m. Displacement and rocking were also evident at lower wave periods for the oyster bag structure as well as designs M_{31} and M_{32}.

4.2.4 Stability Assessment of Alternative Designs

i. 1 Tier Structures

Increasing the crest width for 1 tier structures resulted in configurations that were three times the width of a single bag. These designs consisted of a double oyster bag followed by a single sand bag. This arrangement was repeated for both geotextile fabrics, and compared to the arrangements for a single oyster bag followed by a single sandbag. Moreover, the triple oyster bag was rotated 90 degrees, such that the long edges of the bags were parallel to the direction of the waves. This set up was also repeated for the Maccaferri geotextile bags.

The arrangements that increased the crest width, displayed rocking for wave periods of 2 and 3 seconds with no displacement for all wave conditions, similar to the designs consisting of a single oyster bag followed by a single sandbag. The alternative designs that contained Maccaferri sandbags were proven to exhibit greater resistance to wave attack than the ELCOMAX sandbags, with higher incident wave heights required to induce rocking. The ELCOMAX material was more rigid and did not allow for the sand to mould as easily with the combined oyster bags, allowing oyster bags to move more readily at smaller wave heights. Designs that were rotated parallel to wave attack, prevented both rocking and displacement. This was consistent with previous observations of sandbags, while a significant improvement was noted for the oyster bags in this orientation. The 1 tier oyster bag base case experienced displacement at wave periods of 2 and 3 seconds, as well as rocking for all wave periods. Orienting the triple oyster bag showed an improvement in both rocking and displacement, and can be attributed to the increased crest width, as well as waves directly impacting the smaller side of each bag rather than the long side. The triple oyster bag maintained a stronger connection than individual bag combinations, with this collective weight more difficult for waves to shift.

Overall, these alternative design options show that an increase in crest width by around 50% reduced the wave heights that induce rocking and displacement, while orientation parallel to wave attack vastly improved the stability of the oyster bags. A comparison of the stability assessment of the alternative designs with the regular structures is provided in Appendix A.

ii. 2 Tier Structures

Two alternative designs were developed for the 2 tier structures. The incident wave heights that result in rocking and displacement are compared to the previous 2 tier structures for both d=0.16m and d=0.32m. This data is summarised in Appendix A.

At a water depth of 0.16m, the alternative configurations, M_{26} and O_6, did not display any movement across the range of tests. These results are consistent with the mixed structures outlined in the original 2 tier structure tests.

For d=0.32m, configuration M_{26} revealed rocking for all wave periods, and displacement for 3 second waves, with the initiating incident wave heights similar to those of the oyster bag base case. This reveals the limitations of having the seaward face of the structure made up entirely of oysters. The sandbags behind the oysters limit the displacement to the 3 second waves, although this is still inferior to configurations M_{24} and M_{25} that use sandbags behind and on top of the single oyster bag. As a result, the direct effect of the crest width to impact the stability of the structure cannot be determined from these comparisons, with an all oyster bag seaward face likely negating any positive results.

All rocking was reduced for configuration O_6, which arranged the triple and double oyster bags parallel to wave attack. Without sandbags however, this design experienced displacement for 2 and 3 second wave periods. These observations reflect the 1 tier test results, to reveal that connected bags within the structure minimise the chance of crest bag rocking, but do not greatly affect displacement.

4.2.5 Discussion of Stability Assessment

The incorporation of sandbags into the oyster reef design had the intended effect of reducing the tendency for the structure to rock and displace. For the 1 tier structures, the design of a single oyster bag followed by a sandbag, offered the greatest stability with little difference between the Maccaferri and ELCOMAX geotextile designs. Displacement was prevented for all wave conditions, with rocking occurring for 2 and 3 second waves.

The 2 tier structures experienced similar results, with a single oyster bag combined with two sandbags offering the greatest resistance to displacement, and limiting the rocking of the oyster bag to 3 second waves. Multiple designs provided adequate support to the oyster reef for the 3 tier structures. The symmetry of configuration M_{34} proved most successful, while a larger reef with 3 oyster bags in configuration M_{33} is also recommended, despite rocking occurring at 2 and 3 second wave periods. Designs for each tier that prevented displacement and reduced rocking are summarised in Table 4.5.

Tier	Water Depth (m)	Optimal Design Configuration
1	0.16	M_{11} (M_{12}*)
2	0.16	M_{22} (M_{23}*), M_{24} (M_{25}*)
	0.32	M_{24} (M_{25}*)
	Overall	M_{24} (M_{25}*)
3	0.16	All
	0.32	M_{34} (M_{33} for larger reef)
	0.40	M_{34} (M_{33} for larger reef)
	Overall	M_{34} (M_{33} for larger reef)

*Both geotextile materials produced similar results

Table 4.5 - Optimal oyster reef designs based on the stability assessment

Experimentation with alternative designs revealed that larger crest widths were able to reduce movement for water depths of 0.16m across 1 and 2 tier structures. Increasing the crest width of the designs but retaining all oyster bags for the front face of the 2 tier structure, offered little improvement to the oyster bag base case. Designs that were oriented parallel to wave attack marginally improved resistance to displacement from wave attack, but offered greater support against rocking. This was largely attributed to the connectivity of the double and triple oyster bags.

4.3 Wave Transmission Analysis

In order to quantify wave attenuation for the oyster bag/sandbag combinations, a wave transmission coefficient was calculated for each test. Recall that the equation for the transmission coefficient is as follows.

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

Where: K_t = transmission coefficient

H_t = transmitted wave height landward of the structure

H_i = incident wave height at the toe of the structure

Lower transmission coefficients infer less wave transmission through/over the structure. This suggests that oyster bag and sandbag arrangements with lower transmission coefficients are better suited to protecting the shoreline.

4.3.1 Wave Transmission of 1 Tier Structures

A comparison of wave transmission coefficients for the base cases of oyster bags and sandbags reveals little difference between each erosion control measure, particularly for 1 second wave periods. Although sandbags had revealed similar transmission coefficients to oyster bags, consolidation of sand inside the bags during testing, meant that reasonable overtopping occurred, resulting in increased wave transmission. This is highlighted in Figure 4.1, which compares the base cases of a single oyster bag and a single sandbag at a water depth of 0.16m for a wave period of 3 seconds. From this comparison, it is evident that single sandbags alone do not provide a significant reduction in wave transmission compared to the single oyster bag reef.

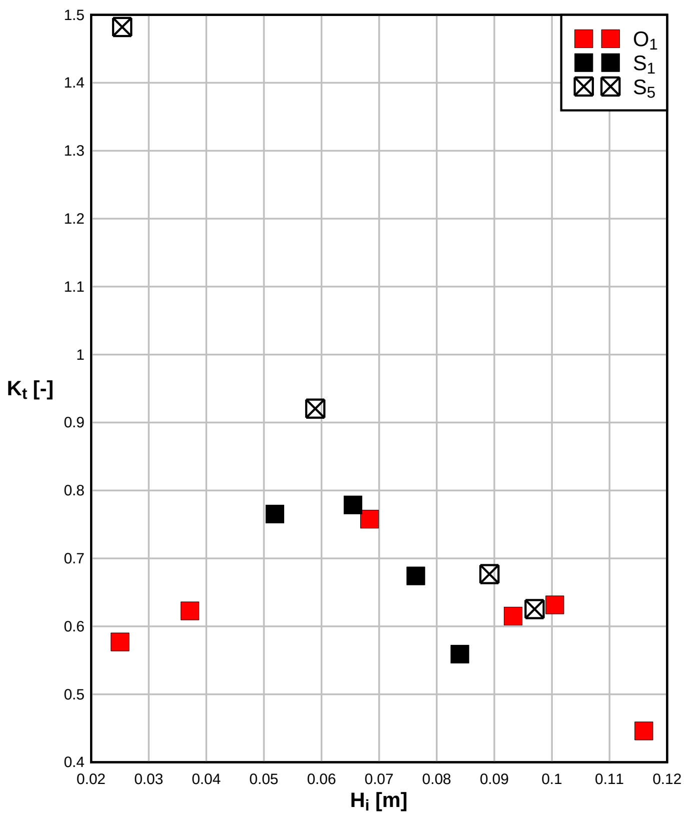


Figure 4.1 - Wave transmission coefficients for 1 tier base case structures; d=0.16m, T=3s

While single sandbags have not reduced the wave transmission from the oyster bag base case, the mixed designs were able to offer improvements due to the additional crest width that these designs permitted. These results are less obvious for lower wave periods and thus the transmission coefficients for the composite structures are compared for wave periods of 3 seconds in Figure 4.2. Results for all wave periods are provided in Appendix B.

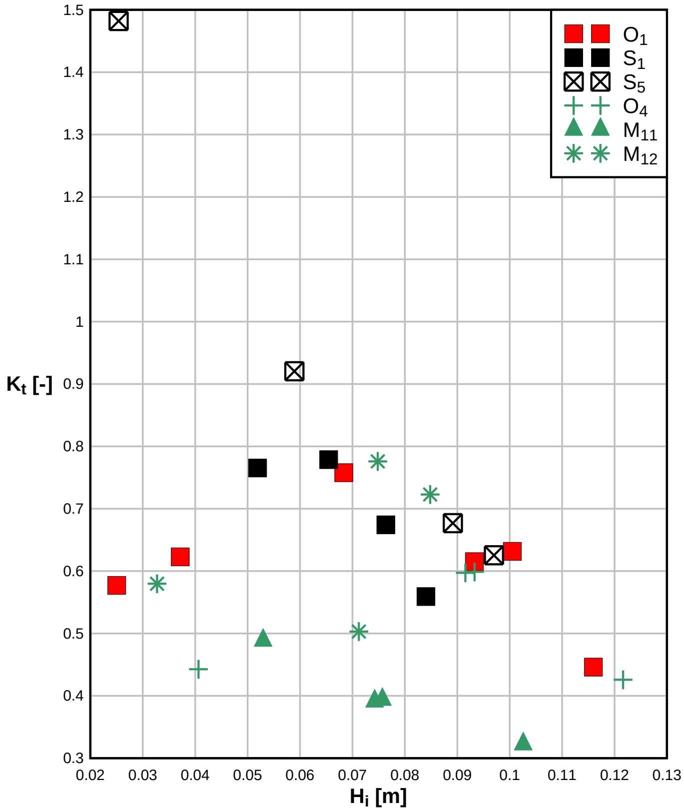


Figure 4.2 - Wave transmission coefficients for 1 tier structures; d=0.16m, T=3s

Lower transmission coefficients are revealed in Figure 4.2 for the composite arrangements. Configurations O_4 and M_{12} reduced the transmission coefficient from the values achieved by the single oyster bag, O_1, while M_{11} demonstrated the greatest change, with an average reduction of approximately 0.3.

These results indicate that 1 tier structures with 2 bags permitted less wave transmission than single bag arrangements. A Maccaferri sandbag behind the single oyster bag (M_{11}) performed better than the double oyster bag configuration (O_4), while the mixed design with the ELCOMAX sandbag (M_{12}) did not perform as well. Therefore, structures with the greater crest widths experienced less transmission, although sandbags with crest heights perfectly equivalent to the oyster bags will likely offer improved results.

4.3.2 Wave Transmission of 2 Tier Structures

The oyster bag base case (O_2) achieved significantly lower wave transmission coefficients than the sandbag base cases (S_2 and S_6), especially for wave periods of 2 and 3 seconds. These results are consistent with the findings for the 1 tier base structures, and are illustrated in Appendix B.

i. 0.16m Water Depth

The comparison of the mixed arrangements with the base cases revealed that coefficients for the composite designs were comparable to those for the oyster bags. Configurations M_{22} and M_{24} transmitted a similar proportion of incident wave heights to the base oyster case for all wave periods, while M_{21}, M_{23} and M_{25} were only comparable for 1 second waves. To highlight the differences in wave transmission for the mixed designs at a water depth of 0.16m, the transmission coefficients are compared for the 3 second wave period in Figure 4.3.

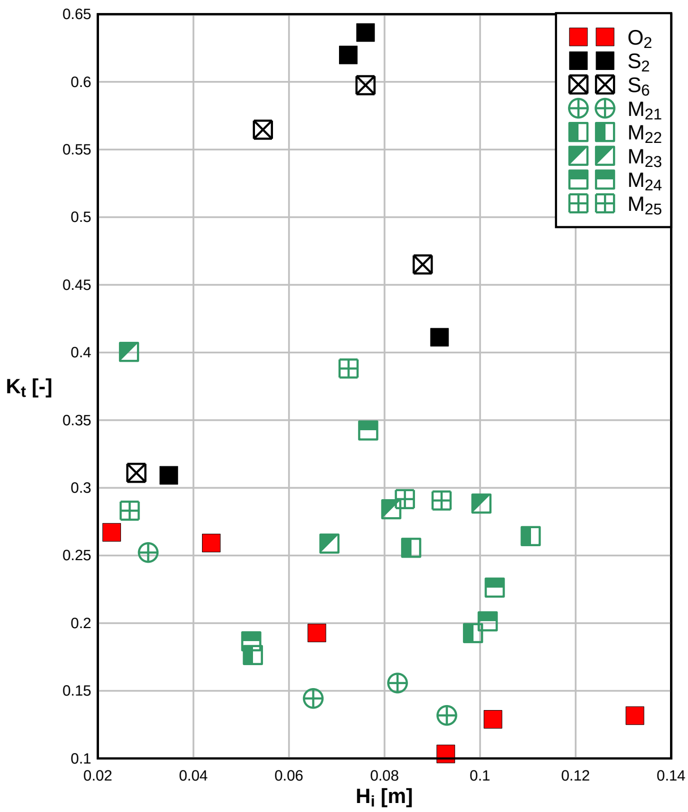


Figure 4.3 - Wave transmission coefficients for 2 tier structures; d=0.16m, T=3s

ii. 0.32m Water Depth

For d=0.32m, the effects of reflected waves within the wave flume were more pronounced. This increased the water levels that were recorded at the landward wave probe. As a result, transmission coefficients were enhanced, with some values greater than 1. Overtopping was also evident for the sandbag structures, adding to the enhanced wave transmission. These results indicate that greater freeboard is required to substantially reduce wave transmission, as per the 0.16m water depth data, with the oyster bag base case exhibiting lower coefficients compared to the sandbag only cases.

Transmission coefficients for the composite structures yielded similar results for both water depths of 0.32m and 0.16m. Configurations M_{22} and M_{24} afforded marginally lower wave transmission than the oyster bag base case, while configurations M_{21}, M_{23} and M_{25} offered similar results.

The wave transmission analysis for 2 tier structures underlined the importance of increasing crest height to reduce wave transmission. Composite structures with sandbags both behind and on top of the oyster bag reef marginally reduced wave transmission, with less transmission expected for larger crest heights.

4.3.3 Wave Transmission of 3 Tier Structures

The wave transmission for a range of 3 tier mixed structures was compared to the oyster bag structure and the Maccaferri sandbag structure. Only Maccaferri geotextile sandbags were used for the 3 tier structure testing.

i. 0.16m Water Depth

As data was not recorded for the 3 tier oyster bag structure (O_3) at a water depth of 0.16m, a base case comparison has not been conducted. However, the transmission coefficients for the sandbag base case as well as all 3 tier composite structures were examined.

For 1 second wave periods, all transmission coefficients ranged between 0.03 and 0.12, with no significant differences between the results for each design. Due to the low incident wave heights for T=1s, the transmission coefficients were likely influenced by the small reflected waves that propagated throughout the flume during testing. Configurations M_{35} and M_{34} provided the highest reduction in wave transmission across all wave conditions, with only 1 and 2 oyster bags in each structure respectively. A larger oyster reef, with 3 bags, is represented in configuration M_{33}, with this arrangement demonstrating comparable results. Reefs of 4 and 5 bags, as seen in configurations M_{32} and M_{31} only transmit marginally larger proportions of wave heights, making these options equally desirable for wave transmission at a flow depth of 0.16m. The differences in wave transmission are highlighted in Figure 4.4 for T=3s.

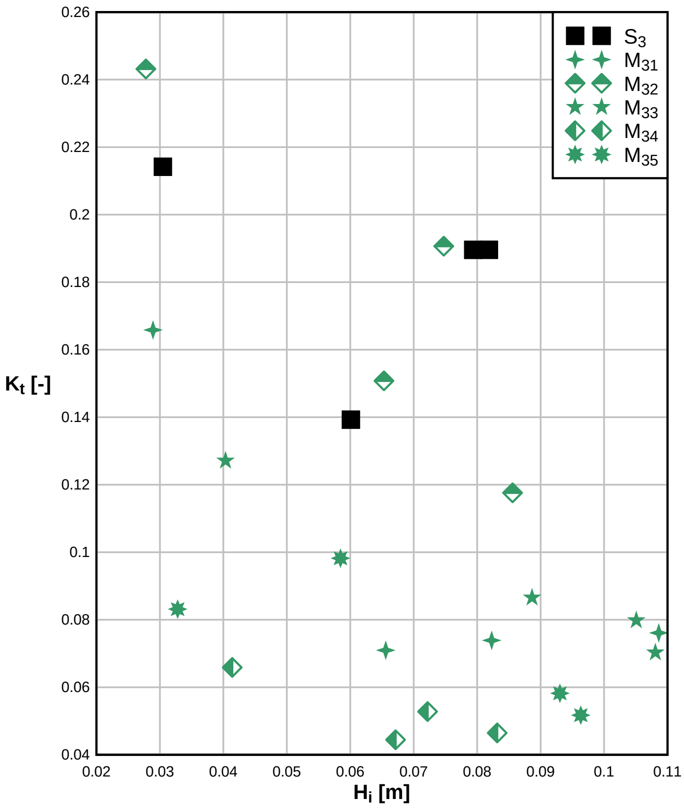


Figure 4.4 - Wave transmission coefficients for 3 tier structures; d=0.16m, T=3s

ii. 0.32m Water Depth

A crest height of 0.36m for the sandbag base case results in generous overtopping for a flow depth of 0.32m. As a result, significant wave transmission is permitted, compared to the 0.40m tall oyster base case (Figure 4.5).

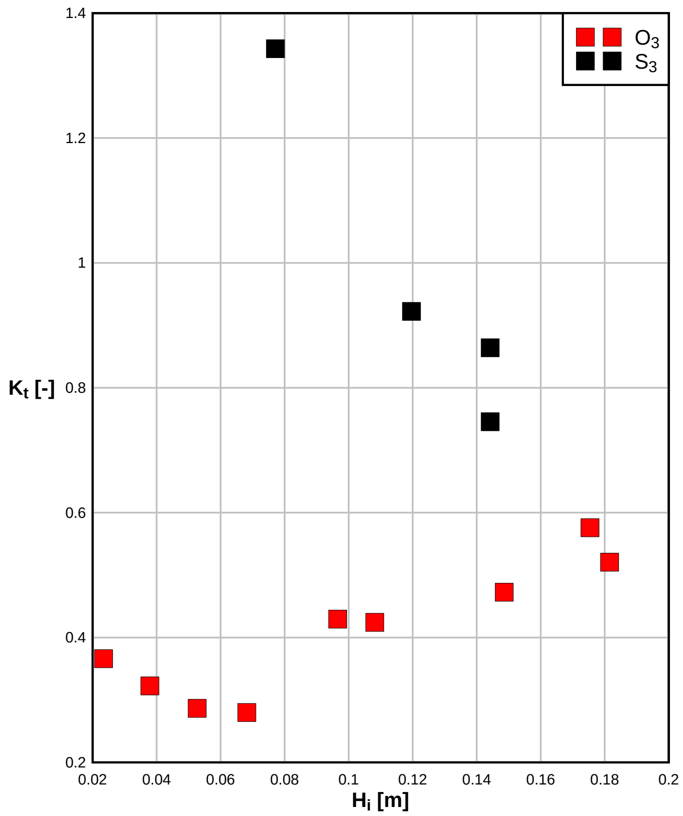


Figure 4.5 - Wave transmission coefficients for 3 tier oyster bag and sandbag structures; d=0.32m, T=3s

Minor differences were evident for 1 and 2 second waves across the range of mixed structures, while 3 second waves allowed significant wave transmission (Figure 4.6). The oyster bag structure demonstrated considerable reduction in wave height for 1 and 3 second waves in comparison to the other arrangements. The porous nature of the oyster reef was assumed to allow significant wave transmission through the structure. However, the larger crest height relative to the sandbag structures reduced the vulnerability to overtopping, and permitted lower wave heights through/over the structure. This again reveals the preference in using positive freeboard over using relatively impervious control measures.

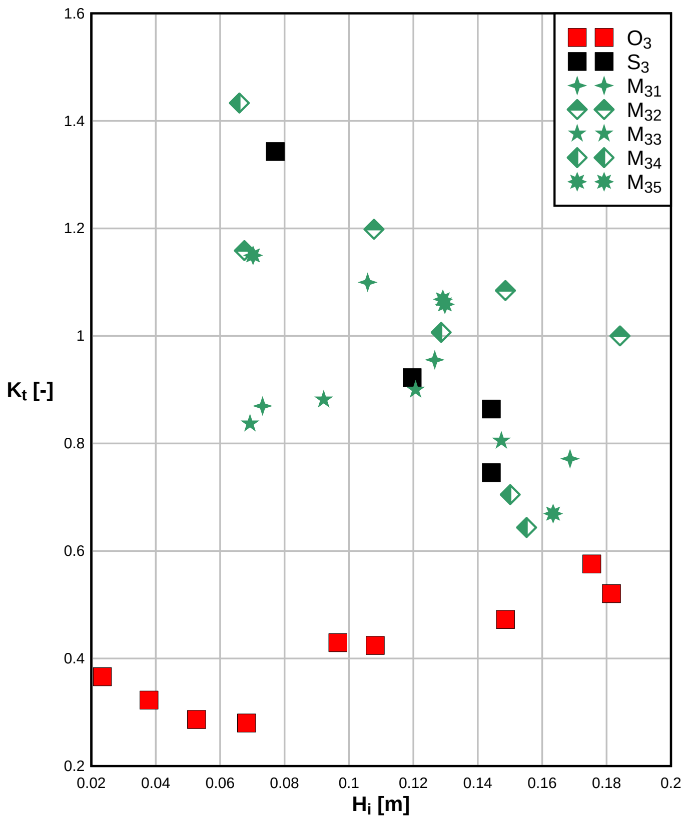


Figure 4.6 - Wave transmission coefficients for 3 tier structures; d=0.32m, T=3s

iii. 0.40m Water Depth

Results that were observed for the 0.40m water depth were similar to the findings for the water depth of 0.32m. Generous overtopping of the sandbag structure due to its relatively low crest height, resulted in high wave transmission for 1 and 3 second waves, compared to the oyster bag base case. For 2 second waves however, sandbag transmission coefficients were analogous to the oyster bag structure for similar incident wave heights.

Substantial overtopping due to crest height differences greatly impacted the wave transmission of the composite structures, giving high transmission coefficients. The results for 2 second waves were comparable for all configurations at incident wave heights in the vicinity of 0.15m. The wave heights measured at the landward probe for mixed structures may be significantly higher than those measured for the oyster bag base case, due to the large number of reflected waves and increased turbulence that accompanied successive testing in the wave flume.

4.3.4 Wave Transmission of Alternative Designs

Orienting the longitudinal axes of the bags parallel to wave attack did not improve wave transmission results compared to the oyster bag base case. However, increasing the width of the crest resulted in reduced wave transmission for 1 and 2 tier structures.

i. 1 Tier Structures

Designs O_5 and S_4, comprised of bags oriented parallel to wave attack, provided minimal improvement to wave transmission over the oyster bag base configuration. Structures M_{13} and M_{14} however, increased the crest width through the use of 3 bags, and produced transmission coefficients lower than the oyster bags.

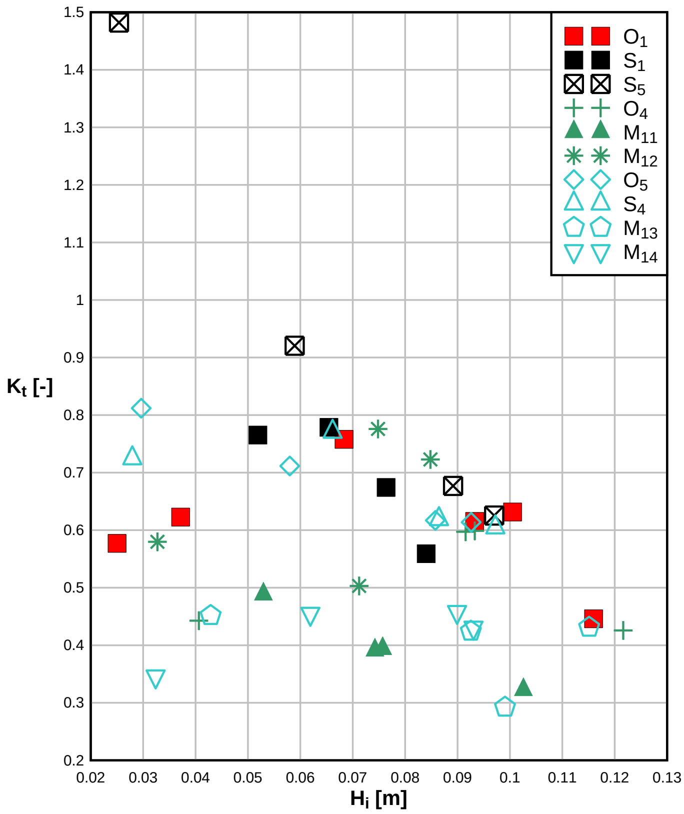


Figure 4.7 - Wave transmission coefficients for 1 tier structures including alternative designs; d=0.16m, T=3s

ii. 2 Tier Structures

Configuration O_6 was oriented with the longitudinal axes of the oyster bags parallel to wave attack. This arrangement resulted in higher wave transmission compared to the 2 tier oyster bag base case for d=0.16m and d=0.32m. This was likely caused by the structure failing to fill the width of the mini flume at the second tier. Contrastingly, a significant reduction in wave transmission was noted for the alternative design, M_{26}, for both water depths. The bags in this design were oriented perpendicular to wave attack, and contained a larger crest width, consisting of the oyster bag pyramid placed in front of 2 sandbags.

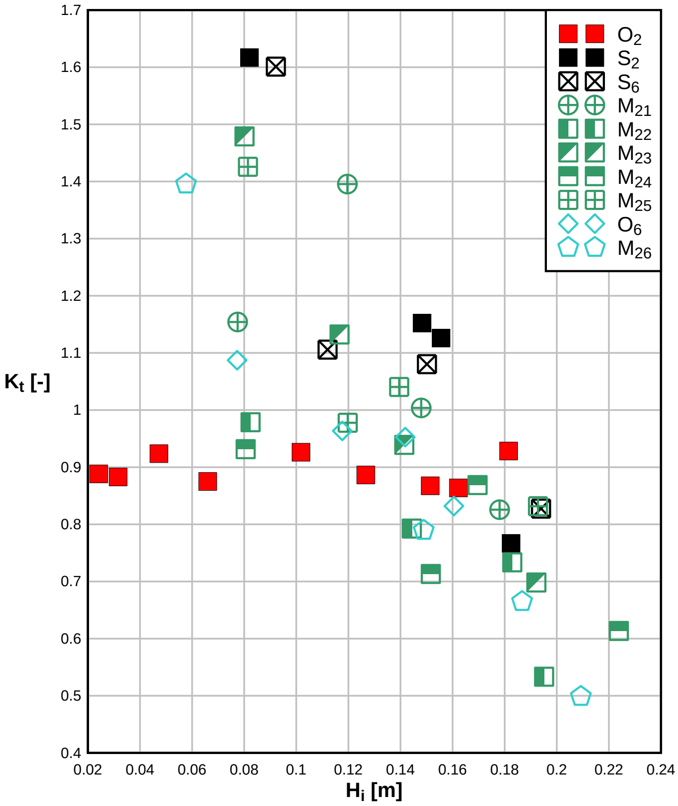


Figure 4.8 - Wave transmission coefficients for 2 tier structures including alternative designs; d=0.32m, T=3s

4.3.5 Discussion of Wave Transmission Results

Wave transmission was found to be higher for the sandbag structures than for the oyster bags, with lower heights causing increased overtopping for the sandbags. Observations of the mixed structures revealed similar transmission coefficients for 2 second waves across the spectrum of structures, while oyster bags permitted considerably smaller wave heights past the structure for wave periods of 1 and 3 seconds. The presence of reflected waves within the wave flume due to the high multitude of mixed bag experiments, likely increased the transmitted wave heights. Differences in crest height may have also impacted the results, with smaller crest heights allowing higher degrees of overtopping, and consequently larger transmitted waves.

Alternative design options with bags parallel to wave attack did not alter the results, while designs with an increased crest bag width, reduced wave transmission from the results of the initial oyster bag structures. All mixed designs with equivalent crest widths produced similar transmission coefficients for the tested wave conditions, with the alternative design structures of larger crest widths providing the greatest reduction in transmitted wave heights. It is expected that sandbag structures with identical crest heights to the oyster bags would be far better at reducing the transmission of waves, due to the relatively impervious nature of the bags. However, composite structures with smaller average crest heights but larger crest widths appeared to be a sufficient solution to reducing the heights of transmitted waves. The configurations that demonstrated the greatest reduction in wave transmission are summarised in Table 4.6.

Tier	Water Depth (m)	Optimal Design Configuration
1	0.16	M_{13} (M_{14}*)
2	0.16	M_{26}
	0.32	M_{26}
	Overall	M_{26}
3	0.16	M_{34}
	0.32	O_3
	0.40	O_3
	Overall	O_3

*Both geotextile materials produced similar results

Table 4.6 - Optimal oyster reef designs for wave transmission

4.4 Wave Reflection Analysis

To best understand how well each design reflected incident waves, reflection coefficients were determined. This coefficient is represented as follows.

$$K_r = \frac{H_r}{H_i}$$

Where: K_r = reflection coefficient

H_r = reflected wave height seaward of the structure

H_i = incident wave height at the toe of the structure

Due to the increased turbulence and overtopping that result from the superposition of incident and reflected waves, smaller wave reflection coefficients are preferred in design.

4.4.1 Wave Reflection of 1 Tier Structures

The single oyster bag and Maccaferri sandbag structures produced less reflection than the ELCOMAX sandbag across all wave conditions. Differences in the reflection coefficients for the sandbag structures were likely attributed to the thickness of geotextile fabric that was used, with the thicker ELCOMAX material increasing wave reflection.

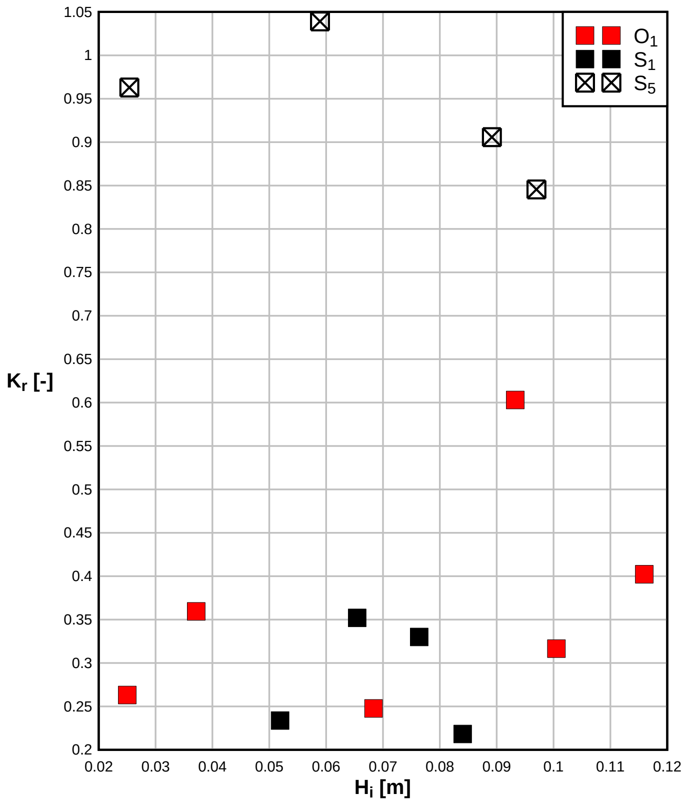


Figure 4.9 - Wave reflection coefficients for 1 tier oyster bag and sandbag structures; d=0.16m, T=3s

The double oyster bag structure produced reflected waves with similar heights for all wave periods to that of the single oyster bag base case. A substantial difference was observed between the single oyster bag and the mixed structures that were comprised of a single oyster bag followed by a single sandbag. The structure using the Maccaferri geotextile sandbag gave similar wave reflection to that of the oyster bags, while the ELCOMAX geotextile sandbag arrangement produced significantly greater reflection coefficients.

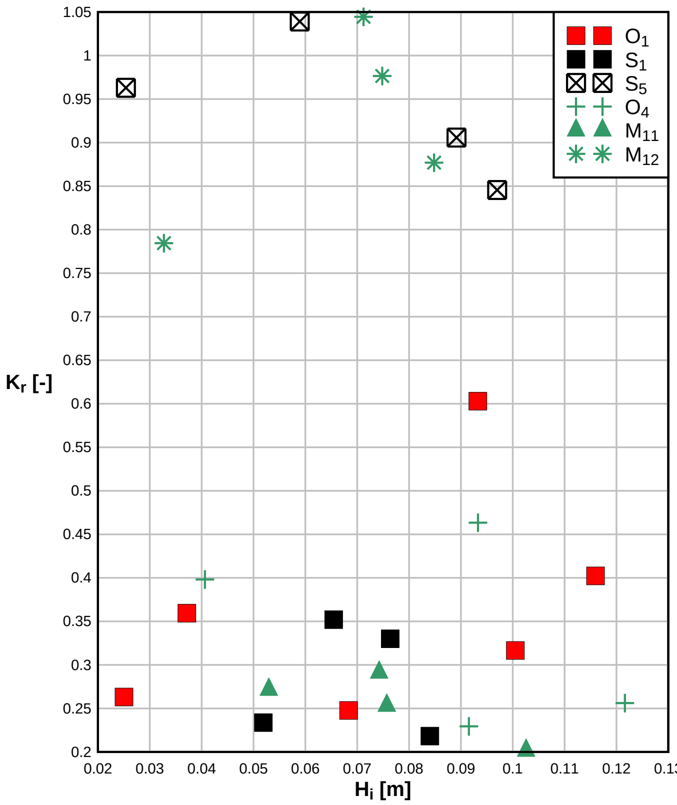


Figure 4.10 - Wave reflection coefficients for 1 tier structures; d=0.16m, T=3s

From the analysis of the reflection coefficients for the 1 tier structures, it is evident that the thicker material used for the sandbags provided greater reflected wave heights, while the double oyster bag and the mixed structure using the Maccaferri geotextile fabric did not vary the reflected wave heights significantly from the single oyster bag case.

4.4.2 Wave Reflection of 2 Tier Structures

Both sandbag configurations revealed substantially larger reflection coefficients than those produced by the oyster bag structure. The ELCOMAX sandbag also provided marginally greater reflection than the Maccaferri sandbags. These results are consistent for d=0.16m and d=0.32m.

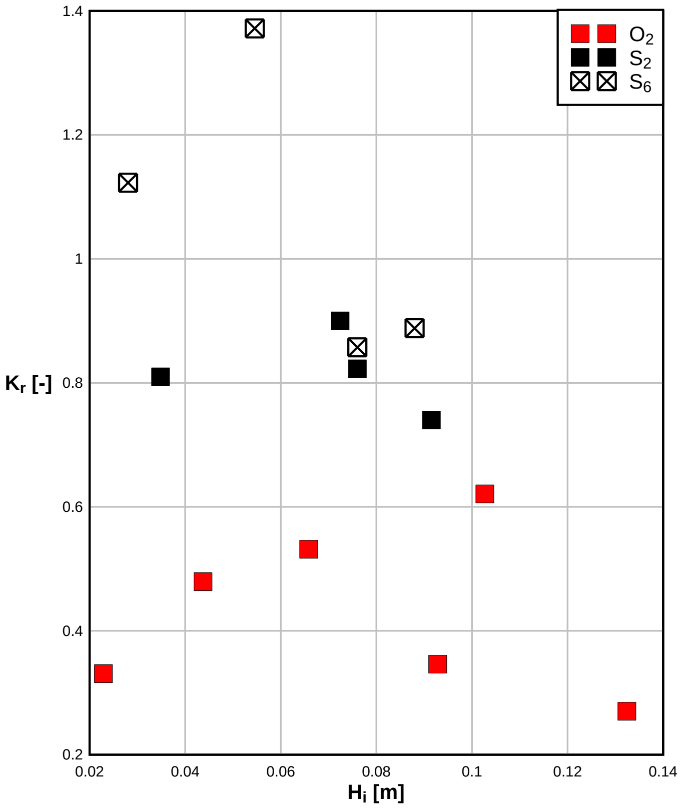


Figure 4.11 - Wave reflection coefficients for 2 tier oyster bag and sandbag structures; d=0.16m, T=3s

Of the mixed structures, configurations M_{22} and M_{24}, which contained Maccaferri sandbags, produced reflection coefficients with the same order of magnitude as those measured for the oyster bag case. All other mixed designs reflected higher proportions of the incident wave height, giving results similar to the sandbag structures.

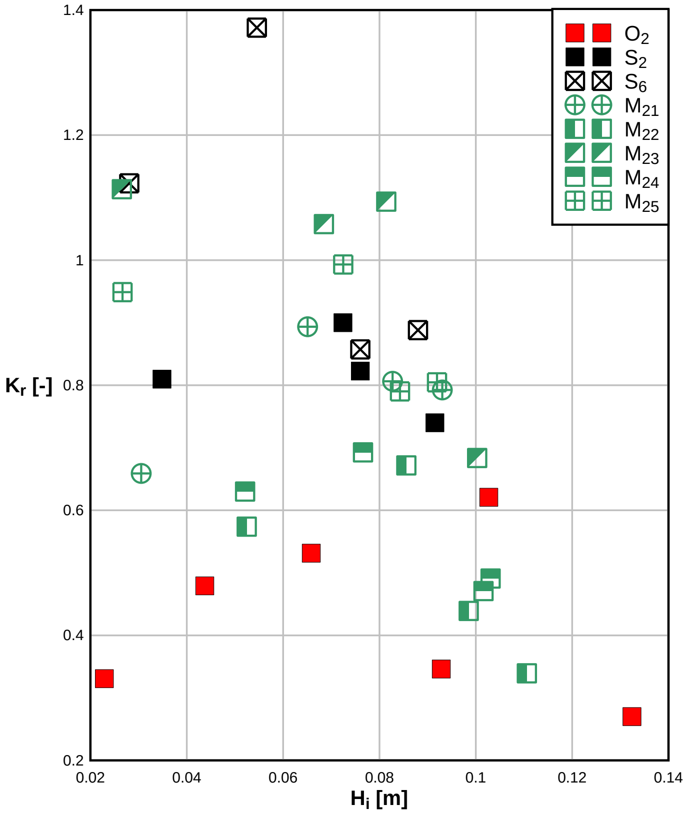


Figure 4.12 - Wave reflection coefficients for 2 tier structures; d=0.16m, T=3s

A trend was observed for the mixed structures, with larger reflection coefficients produced for smaller incident waves. However, this tendency may be exaggerated by the small existing waves that propagated around the flume during testing.

4.4.3 Wave Reflection of 3 Tier Structures

Due to a lack of data for the oyster bag structure at d=0.16m, a comparison was drawn between the sandbag structure and the mixed designs. Configurations M_{31} and M_{33}, with 2 oyster bags at the front face of the structure, produced the smallest reflection coefficients out of the mixed structures. The remainder of the composite configurations resulted in reflection coefficients of a similar order of magnitude to the sandbag structure, S_3.

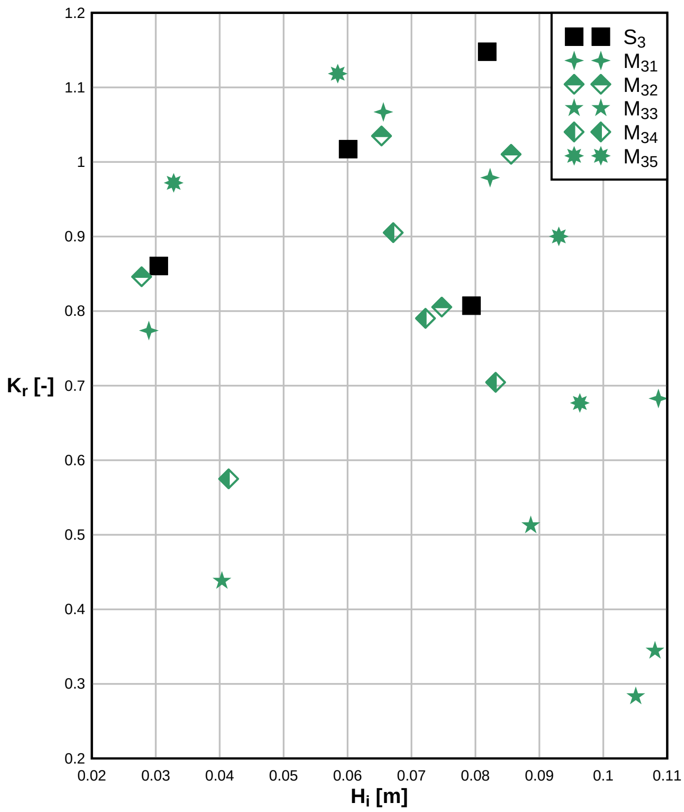


Figure 4.13 - Wave reflection coefficients for 3 tier structures; d=0.16m, T=3s

The sandbag structure was shown to produce substantially higher reflection coefficients than the oyster bag structure at d=0.32m and d=0.40m, although the difference between the coefficients was not as large at a water depth of 0.40m due to frequent overtopping. All of the mixed structures demonstrated large reflection coefficients compared to the oyster bag case. The results for these structures were of a similar order of magnitude to the sandbag structure, with configuration M_{33} producing the lowest coefficients on average for these arrangements.

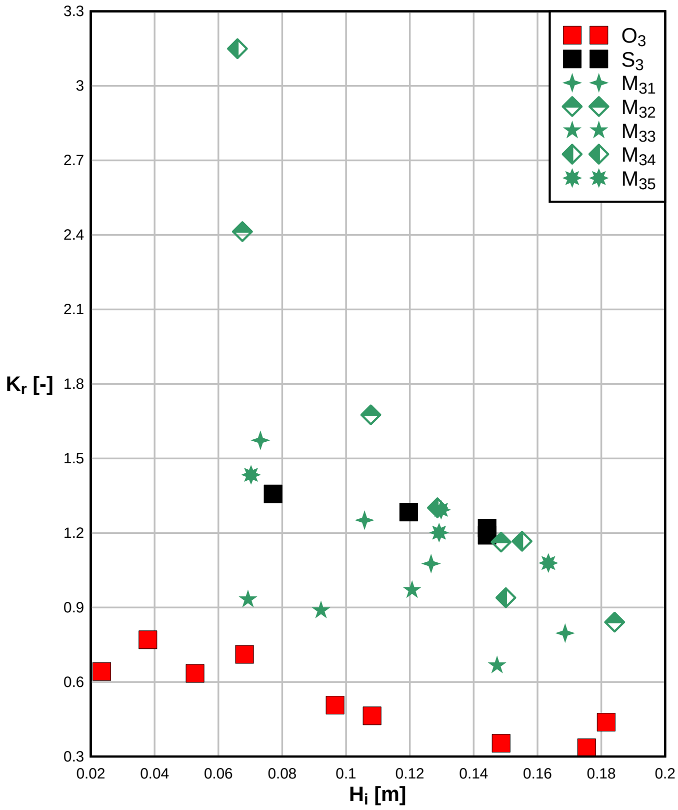


Figure 4.14 - Wave reflection coefficients for 3 tier structures; d=0.32m, T=3s

4.4.4 Wave Reflection of Alternative Designs

i. 1 Tier Structures

Analysis of wave transmission for the alternative 1 tier designs, produced findings that were consistent with the previous 1 tier experiments. The alternative design that increased the crest width of the structure, M_{13}, yielded similar results to the base cases of oysters and Maccaferri sandbags, while M_{14} used the ELCOMAX geotextile sandbag in the same arrangement and produced greater reflection coefficients. Alternative designs oriented parallel to wave attack, configurations O_5 and S_4, also yielded large reflection coefficients, analogous to the initial mixed structures. This comparison thus adds further argument to the use of the Maccaferri geotextile over the ELCOMAX material to reduce wave reflection.

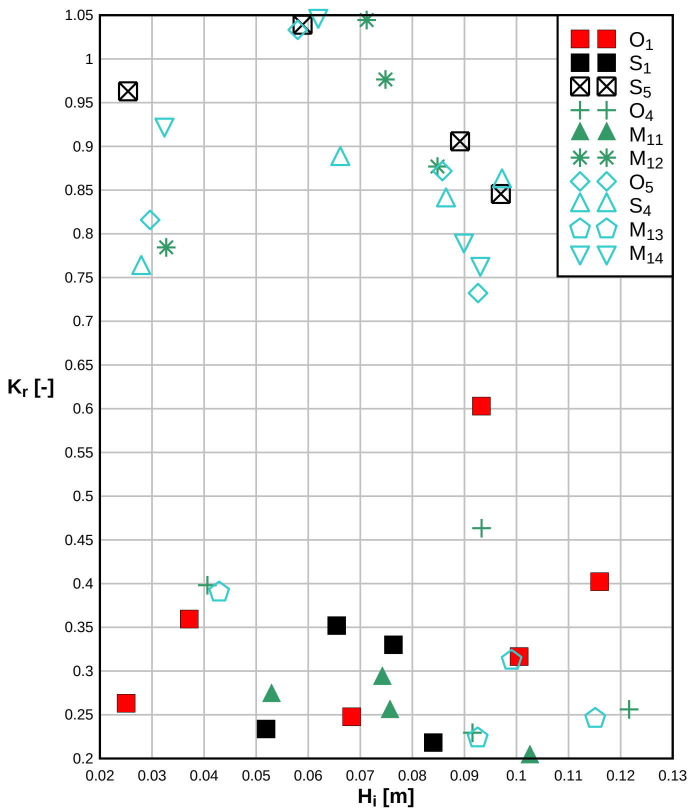


Figure 4.15 - Wave reflection coefficients for 1 tier structures including alternative designs; d=0.16m, T=3s

ii. 2 Tier Structures

The 2 tier alternative design, M_{26}, which employed a larger crest width, with 3 oyster bags followed by 2 sandbags, produced reflection coefficients similar in magnitude to those of the oyster bag base case. This design consisted of the exact same setup as the oyster bag structure for the 3 most seaward bags. The alternative design made up of bags parallel to wave attack, O_6, yielded reflection coefficients closer to the sandbag base structure. Comparisons of the alternative designs with the initial mixed structures are consistent for both 0.32m and 0.16m water depths.

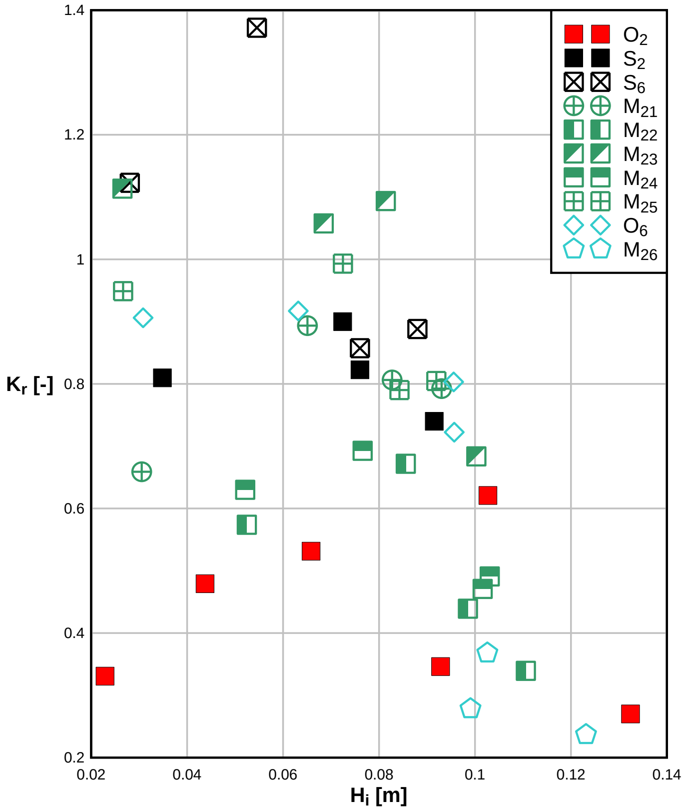


Figure 4.16 - Wave reflection coefficients for 2 tier structures including alternative designs; d=0.32m, T=3s

4.4.5 Discussion of Wave Reflection Results

Oyster bag structures as well as mixed structures with Maccaferri sandbags, yielded similar reflection coefficients across the range of wave conditions and water levels. Sandbags that used the thicker ELCOMAX geotextile fabric produced greater reflection coefficients on average. Reflection was lowest when oyster bags were used at the seaward face of the structure.

For the 2 tier structures, configurations M_{22} and M_{24}, which use the Maccaferri geotextile fabric, presented reflection coefficients that were analogous to the oyster bag structures. All other mixed designs that used the ELCOMAX geotextile material, resulted in greater reflection. This was consistent across both water depths of 0.16m and 0.32m. Increasing the crest bag width in configuration M_{26}, did not significantly alter the reflection coefficients from the oyster bag case. The reflection was however increased by changing the orientation of the bags such that the long edges were parallel to wave attack, with these results similar to those of the initial mixed designs.

The mixed 3 tier structures offered reflection that was similar to the sandbag case across all tested water depths. Reflection coefficients that corresponded to these structures were greater than the coefficients obtained for the oyster bag structures at 0.32m and 0.40m. At water depths of 0.16m and 0.32m, configuration M_{33} gave the lowest reflection coefficients for the mixed designs, but was still within range of the other mixed structures.

Therefore, it is evident that for smaller structures at lower water depths, the impact of sandbags on reflection is only substantial if thick material is used. For larger structures, the incorporation of sandbags into the structure greatly enhances the reflection of waves, with alternative cases revealing reduced reflection for a crest width increase that involves a front face of oyster bags, and increased reflection for structural orientation that is parallel to wave attack. However, these design changes were not tested in isolation, with an inconsistent proportion of oyster bags to sandbags for each alternative design.

For each tier and water depth, the ideal design configurations that reduce wave reflection, are presented in Table 4.7. Where reflection coefficients are similar, multiple designs have been given.

Tier	Water Depth (m)	Optimal Design Configuration
1	0.16	O_1, O_4, S_1, M_{11}, M_{13}
2	0.16	M_{22}
	0.32	O_2, M_{22}, M_{24}, M_{26}
	Overall	M_{22}
3	0.16	M_{33}
	0.32	O_3
	0.40	O_3
	Overall	O_3

Table 4.7 - Optimal oyster reef designs for wave reflection

4.5 Energy Dissipation Analysis

From the equation for dissipated energy given below, it is evident that increases in the transmitted and reflected energy will lead to reduced energy dissipation for a given quantity of incident energy.

$$E_d = E_i - E_t - E_r$$

Large numbers of small waves reflected off the back of the flume during experimentation, with the high multitude of tests preventing the water from becoming still. This turbulent water likely increased the measured transmitted wave heights and the resulting transmitted wave energy. Therefore, the energy dissipation that has been calculated throughout these experiments resulted in negative values for stronger wave conditions. Negative values indicate that energy has been created from processes other than the wave packets, and thus violate the formula. This data will still be used to compare the oyster reef designs, although it should be acknowledged that these values are not completely accurate.

Ideal energy dissipation values should be as high as possible for erosion control structures, ensuring that large portions of incident wave energy are not transmitted or reflected. As the incident wave height was increased, energy dissipation was also found to increase for most of the structures. This trend was consistent across all wave conditions and water levels for all tiers of structures.

4.5.1 Energy Dissipation of 1 Tier Structures

Designs that consisted of oyster bags or Maccaferri sandbags, demonstrated high levels of energy dissipation compared to configurations that contained ELCOMAX sandbags. As the use of the ELCOMAX sandbags has been shown to result in enhanced wave reflection (Chapter 4.4), there is consequently less dissipated energy. These observations were noted for all wave periods.

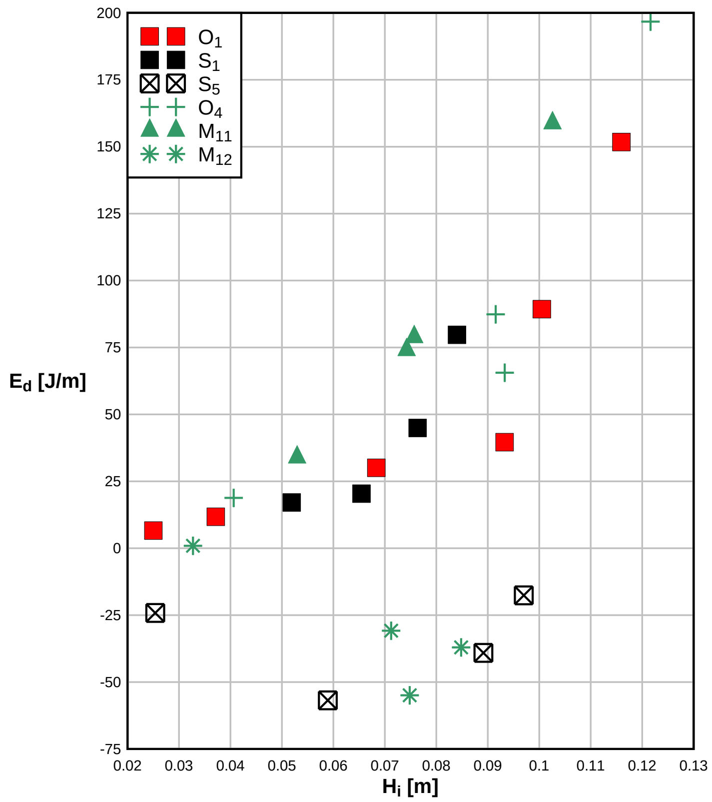


Figure 4.17 - Energy dissipation of 1 tier structures; d=0.16m, T=3s

4.5.2 Energy Dissipation of 2 Tier Structures

Measurements of energy dissipation for the 2 tier structures were heavily influenced by the effects of overtopping. This was particularly prominent for the ELCOMAX sandbag designs, with significantly lower values of energy dissipation recorded for these configurations. The oyster bag structure as well as arrangements M_{22} and M_{24}, which contained Maccaferri sandbags, all offered greater results. These configurations dissipated the most energy for all wave conditions and water levels. At a water depth of 0.32m, all structures offered lower values of energy dissipation.

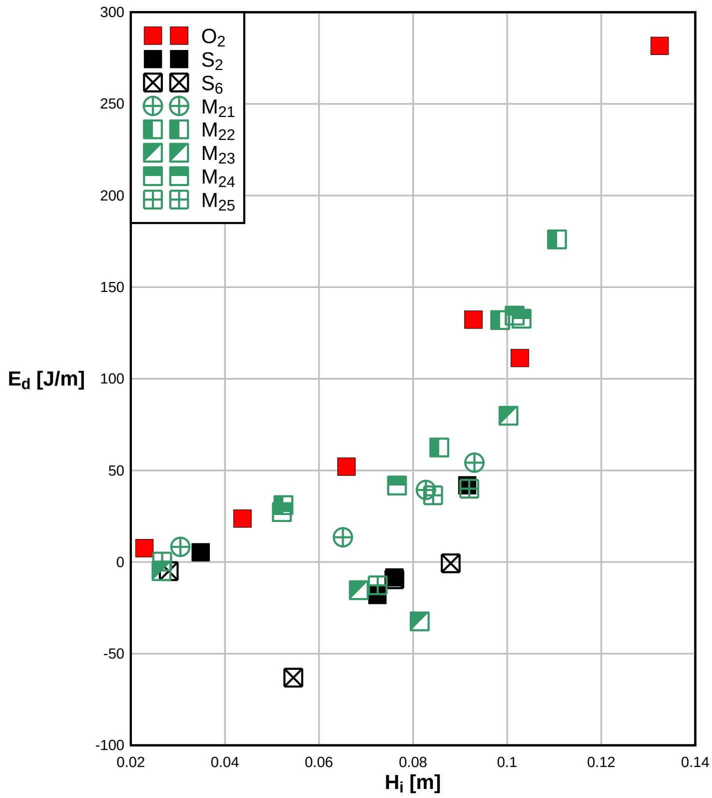


Figure 4.18 - Energy dissipation of 2 tier structures; d=0.16m, T=3s

4.5.3 Energy Dissipation of 3 Tier Structures

The oyster bag structure did not have data recorded for d=0.16m, and thus comparing the energy dissipation for the sandbag and mixed designs revealed configuration M_{33} to dissipate the most energy for all periods of waves.

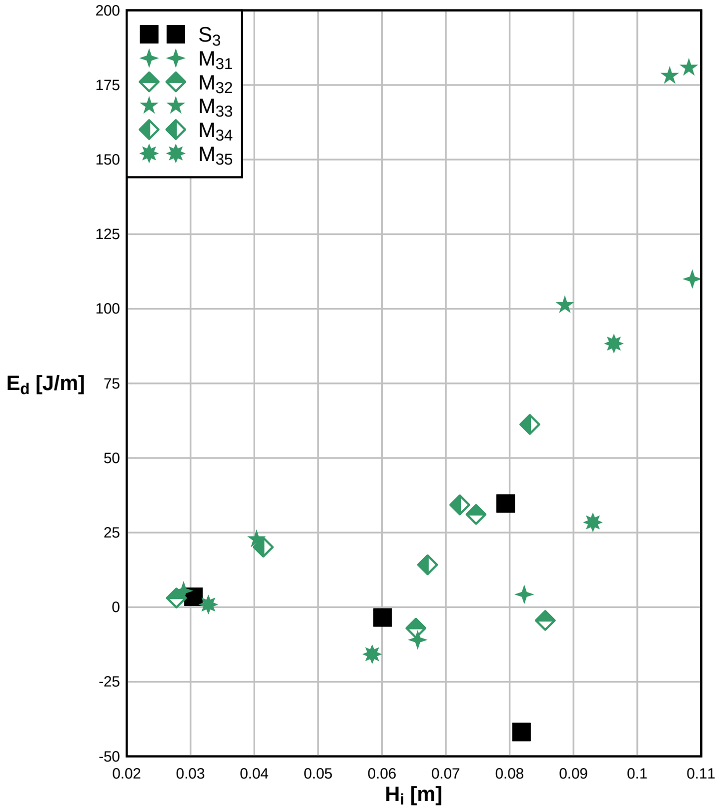


Figure 4.19 - Energy dissipation of 3 tier structures; d=0.16m, T=3s

However, for water depths of 0.32m and 0.40m, the oyster bag structure undoubtedly dissipated the most energy across all wave periods. At 3 second wave periods, the energy dissipation was much lower for all structures, similar to the results for the 2 tier structures.

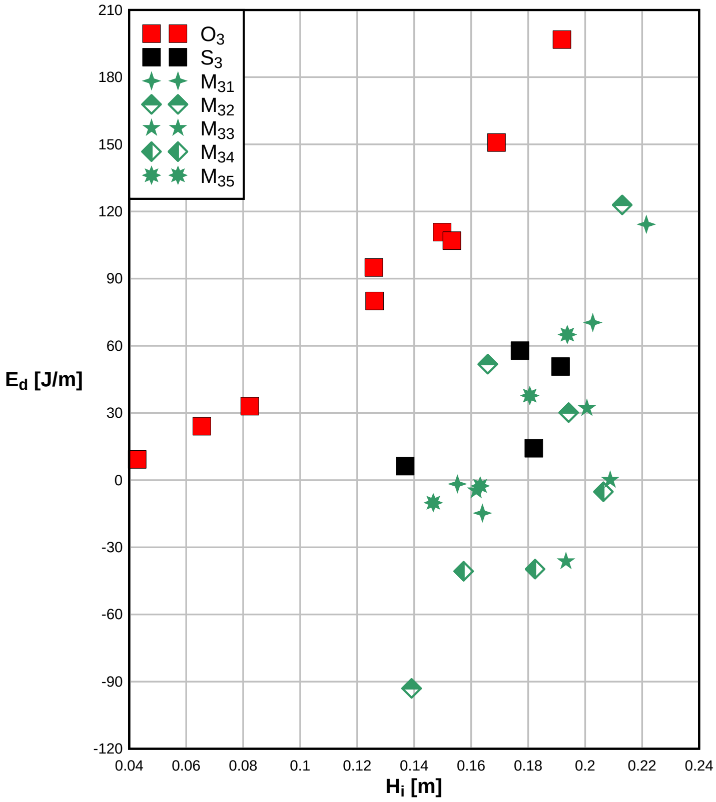


Figure 4.20 - Energy dissipation of 3 tier structures; d=0.32m, T=2s

4.5.4 Energy Dissipation of Alternative Designs

Analysis of the alternative 1 tier designs revealed high energy dissipation for M_{13}. This design consisted of a larger crest width with the double oyster bag and single Maccaferri sandbag. However, an identical setup with the ELCOMAX sandbag did not produce the same results. Both oyster bag and sandbag designs that were tested parallel to wave attack, also failed to demonstrate high values of energy dissipation. These observations were consistent across all wave periods.

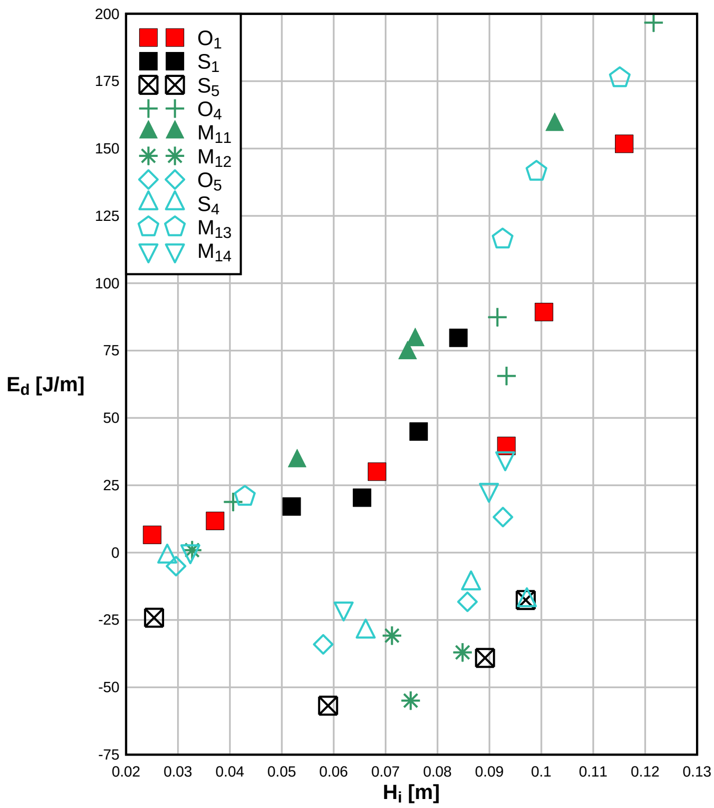


Figure 4.21 - Energy dissipation of 1 tier structures including alternative designs; d=0.16m, T=3s

Similar to the analysis of the alternative 1 tier designs, the 2 tier configuration, O_6, which was oriented parallel to wave attack, did not display high levels of energy dissipation. These results for O_6 were in the vicinity of the ELCOMAX sandbag design values. A larger crest width combined with the oyster bag pyramid and Maccaferri sandbags in design M_{26}, proved to dissipate more energy than the oyster bag structure, analogous to the results for M_{22} and M_{24}. This was particularly noteworthy for d=0.32m and T=3s.

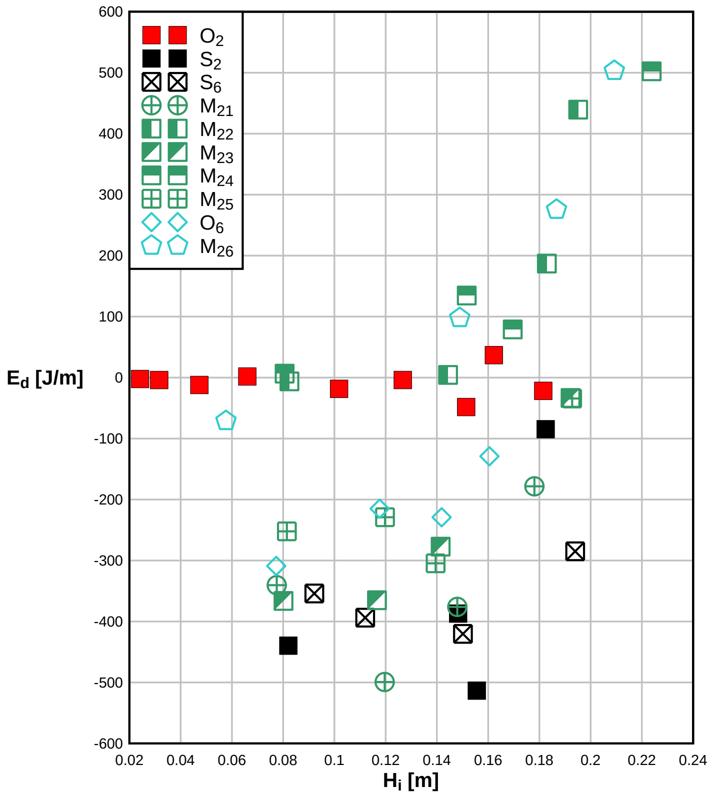


Figure 4.22 - Energy dissipation of 2 tier structures including alternative designs; d=0.32m, T=3s

4.5.5 Discussion of Energy Dissipation Results

An assessment of the energy dissipation that each structure provided in response to wave attack has yielded consistent results across the range of wave conditions and tier categories. The thicker ELCOMAX geotextile material demonstrated low levels of dissipated energy, coinciding with the previously discussed high reflection coefficients that ELCOMAX sandbags produced (Chapter 4.4).

For 1 tier designs that utilised oyster bags and Maccaferri sandbags, higher degrees of energy dissipation were recorded for all wave periods. However, for 2 and 3 tier structures, all sandbag structures were proven to be inferior to the oyster bag structures in terms of dissipating energy. At 3 second wave periods however, the difference in dissipated energy was reduced as a result of increased overtopping. Alternative designs revealed little improvement for structures oriented parallel to wave attack, while increased crest width using Maccaferri sandbags produced results akin to the oyster bag structures. The designs that recorded the greatest values of dissipated energy are presented in Table 4.8.

Tier	Water Depth (m)	Optimal Design Configuration
1	0.16	M_{13}
2	0.16	O_2, M_{22}, M_{24}, M_{26}
	0.32	M_{22}, M_{26}
	Overall	M_{22}, M_{26}
3	0.16	M_{33}
	0.32	O_3
	0.40	O_3
	Overall	O_3

Table 4.8 - Optimal oyster reef designs for energy dissipation

Again, it should be noted that the calculated values of energy dissipation contained inaccuracies relating to the turbulence and reflected waves present in the wave flume during testing. This instability resulted in enhanced wave heights that directly impacted the transmitted and reflected wave energy. As a result, dissipated wave energy that is lower than zero has been recorded for some wave conditions. Therefore, the values given here are merely used as a comparison to determine the optimal design for the configurations tested.

4.6 Comparison with Other Oyster Reef Designs

This research has produced results that are directly comparable to the outcomes of previous breakwater studies. A number of erosion control measures such as concrete pyramids and ReefBLKs (Allen 2013) have been analysed in terms of wave transmission, and are compared against a series of oyster reef and sandbag designs. The 3 tier oyster bag and sandbag structures, as well as the designs that performed best across the analysis of the four parameters have been used in the comparison with earlier research for select water depths.

Structure ID	Water Depth (m)
O_3	0.32
S_3	0.32
M_{13}	0.16
M_{26}	0.32
M_{33}	0.32

Table 4.9 - Water levels used for the comparison with previous literature

The wave transmission coefficient was found to be the most common parameter for evaluating the effectiveness of shoreline protection systems, and is therefore used to compare the oyster reef designs with previous studies. This was often measured against the non-dimensional height of the structure (Allen 2013; Harris 1996), which is calculated as the ratio of the crest height to the water depth, h_c/d. For each oyster reef design, the crest height was calculated as the sum of the average bag heights in each tier. Transmission coefficients were compared against designs with similar non-dimensional heights in Figure 4.23.

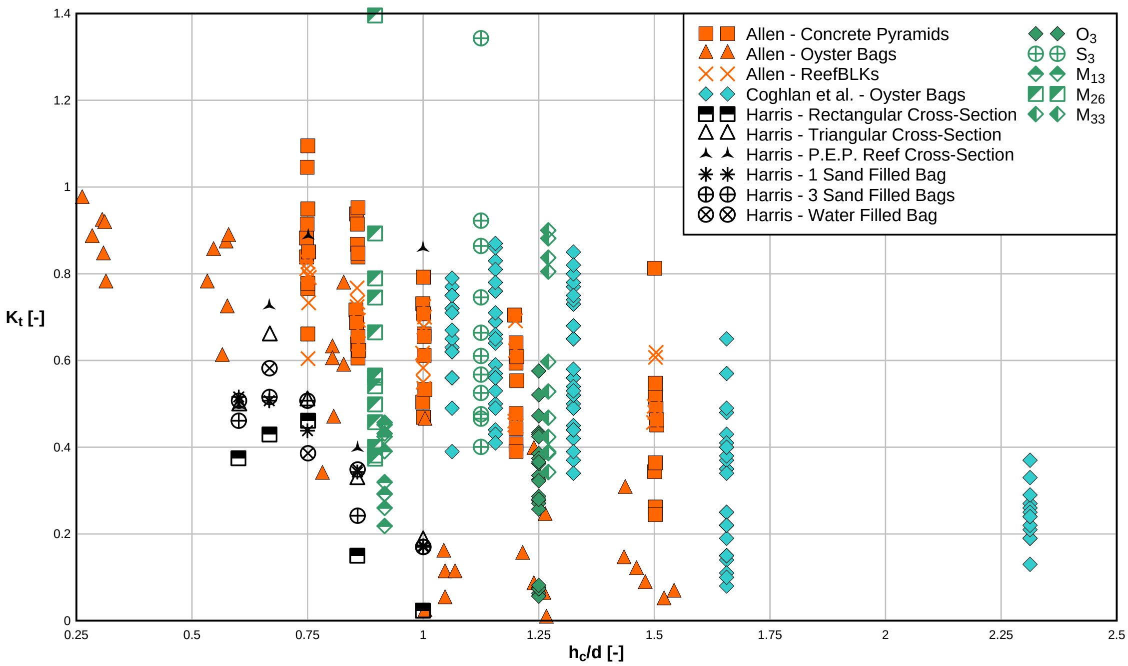


Figure 4.23 - Wave transmission coefficients for oyster reef designs and rubble mound breakwater structures

A comparison of wave transmission coefficients revealed that the results of the selected 2 and 3 tier oyster reef designs match well with the data obtained by Allen (2013) for the concrete pyramid and ReefBLK structures, allowing between approximately 40% and 80% wave transmission. The oyster bags developed by Allen (2013) showed similar results to the 1 tier design, M_{13}, and permitted significantly less wave transmission than the other designs that have been compared. As seen in Chapter 4.3.4, larger crest widths can lead to reduced wave transmission, and with a maximum crest width of 1.96m for Allen's oyster bag structure (Allen 2013), the corresponding transmission coefficients were seen to be lower than the results for the composite oyster and sandbag structures at similar non-dimensional heights. The plot of wave transmission coefficients in Figure 4.23 has also demonstrated consistent results between the oyster reef designs and the oyster bag structures evaluated by Coghlan et al. (2016), as well as the series of rigid and flexible membrane breakwaters modelled by Harris (1996).

5 Discussion

5.1 Optimal Design Solutions

To determine the optimal design solution for each tier of structures, all designs were ranked according to the ideal characteristics for an erosion control structure. A rank of 1 was given to the designs that best optimised the corresponding analysis. The optimal observations for each analysis are as follows:

- Stability
  - No displacement or rocking
- Wave Transmission
  - Low transmission coefficient
- Wave Reflection
  - Low Reflection coefficient
- Energy Dissipation
  - High dissipated energy

A stable oyster reef structure is pivotal to the survival and growth of the reef, as well as ensuring long term shoreline protection. Therefore, a weighting of 2 was given to all stability rankings when added to the final score. In ranking the stability of each design, displacement was prioritised above rocking, with the ideal design failing to displace or rock. A design that was displaced but did not rock was deemed to be inferior to a design that rocked but did not displace. Structures that required larger wave heights in order for instability to occur were ranked above those for which smaller wave heights initiated movement.

Designs with low wave transmission coefficients were seen to be best at reducing shoreline erosion and reducing the height of waves that pass the structure. Similarly, low reflection coefficients mean smaller waves are sent seaward, reducing the height of standing waves. Therefore, low values in these categories are ranked highest. Conversely, configurations with high values of dissipated energy were preferred as greater energy dissipation infers a reduction of transmitted and reflected wave energy.

5.1.1 Optimal Design Solutions for 1 Tier Structures

From the ranking system, it can be seen that configuration M_{13} ranked highest over the 4 categories for the 1 tier structures. This design consisted of the double oyster bag followed by a single Maccaferri geotextile sandbag. Despite having no oyster bags, the single Maccaferri sandbag structure ranked second, indicating its usefulness as an erosion control structure. However, configuration M_{11} followed closely behind and consisted of a single oyster bag followed by a single Maccaferri sandbag. Therefore, the analysis of the 1 tier structures at a water depth of 0.16m, suggest that a stable and effective artificial oyster reef can be designed using at least one oyster bag that is supported by a geotextile sandbag in lee of the structure. Increasing the crest width with additional oyster bags may help promote sustained reef growth, and can provide additional stability to the structure, as well as transmitted and reflected wave height reduction.

Analysis	**Structure ID**									
	O_1	**O_4**	**O_5**	**S_1**	**S_4**	**S_5**	**M_{11}**	**M_{12}**	**M_{13}**	**M_{14}**
Stability*	10	9	1	1	1	1	6	7	5	8
Transmission	8	4	6	9	5	10	3	7	1	1
Reflection	1	1	6	1	6	8	1	9	1	10
Energy Dissipation	4	2	6	5	8	9	2	10	1	6
Total	33	25	20	17	21	29	18	40	13	33
Final Rank	8	6	4	2	5	7	3	10	1	8

*All stability rankings are given a weighting of 2

Table 5.1 - Optimal design rankings for 1 tier structures

5.1.2 Optimal Design Solutions for 2 Tier Structures

The alternative design of configuration M_{26} made use of a larger crest width to provide greater stability and enhance the reduction of wave heights for both transmission and reflection. This design also produced the highest dissipation of energy and is the optimal design for the 2 tier structures for depths of 0.16m and 0.32m. Design M_{24} consisted of one oyster bag in front of 2 tiers of sandbags, and demonstrated comparable results across all tested parameters. From these designs it is evident that at least one sandbag on the lower tier behind the oyster reef as well as one sandbag on the upper tier is required to provide support against displacement and rocking. An increased crest width has also demonstrated improvements in all the measured parameters, indicating greater shoreline protection.

Analysis		**Structure ID**									
		O_2	**O_6**	**S_2**	**S_6**	**M_{21}**	**M_{22}**	**M_{23}**	**M_{24}**	**M_{25}**	**M_{26}**
Stability*	**0.16m**	9	1	1	1	10	1	1	1	1	1
	0.32m	10	9	1	1	8	6	7	3	4	5
Transmission	**0.16m**	3	7	10	9	2	4	6	5	8	1
	0.32m	4	5	10	9	6	2	6	2	6	1
Reflection	**0.16m**	4	5	9	10	7	1	8	3	6	2
	0.32m	1	6	10	8	9	1	7	1	5	1
Energy Dissipation	**0.16m**	1	7	9	10	8	1	5	1	5	1
	0.32m	4	5	8	8	8	1	7	3	5	1
Total		55	55	60	58	76	24	55	23	45	19
Final Rank		5	5	9	8	10	3	5	2	4	1

*All stability rankings are given a weighting of 2

Table 5.2 - Optimal design rankings for 2 tier structures

5.1.3 Optimal Design Solutions for 3 Tier Structures

Configuration M_{34} ranked highest for the 3 tier structures. This design consisted of a double oyster bag wedged between two layers of sandbags. Despite performing best across the tested parameters, environmental concerns regarding the setup of the structure may see greater preference in configuration M_{33}. A sandbag centred on top of the double oyster bag may prevent growth of the reef for M_{34} and thus configuration M_{33} which uses three oyster bags at the seaward face of the structure, may prove to be more beneficial. Design M_{33} utilises an additional oyster bag to form a 2 tier, 3 bag oyster reef pyramid in front of a sandbag on each tier. This design is consistent with the ideal solutions for both 1 and 2 tier structures. Increasing the crest width of the 3 tier structures was not tested, but would likely lead to improved results, as is evident in the solutions for 1 and 2 tier structures. The oyster bag base structure, O_3, experienced considerable displacement during testing, and despite the increased weighting of the stability assessment, finished second in the ranking system. This highlights the strong dissipative characteristics of the porous oyster bags. However, with stability the main concern for the survival of the oyster reef, this design is not seen to be as reliable as configurations M_{33} and M_{34}.

Analysis		Structure ID						
		O_3	S_3	M_{31}	M_{32}	M_{33}	M_{34}	M_{35}
Stability*	0.16m	1	1	1	1	1	1	1
	0.32m	7	1	5	6	4	2	3
	0.40m	6	1	5	7	4	1	3
Transmission	0.16m	-	6	3	5	4	1	2
	0.32m	1	6	5	6	2	3	4
	0.40m	1	6	2	6	2	2	2
Reflection	0.16m	-	2	2	2	1	2	2
	0.32m	1	5	5	5	2	3	3
	0.40m	1	2	2	2	2	2	2
Energy Dissipation	0.16m	-	5	5	4	1	2	3
	0.32m	1	3	3	6	2	6	3
	0.40m	1	5	3	5	3	2	5
Total		34	46	52	69	37	31	40
Final Rank		2	5	6	7	3	1	4

*All stability rankings are given a weighting of 2

Table 5.3 - Optimal design rankings for 3 tier structures

5.2 Design Implications

Understanding how oyster bags respond to wave attack has led to the design of optimal oyster reef structures to prevent shoreline erosion. These designs have been evaluated to optimise wave attenuation and stability, providing sufficient evidence for successful deployment in estuarine environments with low wave energy.

Analysing the parameters of wave transmission, wave reflection, and energy dissipation has revealed the effectiveness of using a porous erosion control structure. Lower transmitted and reflected wave heights were recorded for the oyster bag structures compared to the sandbag composite designs. These results infer the use of sandbags purely for support, as the enhanced wave transmission and reflected wave heights are not beneficial to the surrounding waterway. By employing oyster bags at the seaward face of the structure, greater dissipated wave energy was recorded, highlighting the use of sandbags landward of the oyster reef.

The assessment of oyster bag stability revealed significant crest bag movement and displacement for designs that did not utilise sandbags landward of the oyster reef. All movement was effectively removed when sandbags were used both behind the reef and as crest bags. As a result, utilising sandbags both behind and on top of the oyster bags in a pyramidal configuration is assumed to provide the necessary support for long term reef growth in estuarine environments, where wave climates are consistent with the laboratory test conditions. The experimental setup involved testing wave periods of 1 to 3 seconds with wave heights ranging from 0.05 to 0.30m, suggesting that proposed deployment sites should exhibit low to moderate wave energy, reflective of small boat wakes.

The outcomes of this research indicate that the oyster reef designs are sufficient for mild shoreline protection against wave attack perpendicular to the structure. The effects of high velocity flows were not measured and thus these results suggest deployment of the reef is best in estuaries such as lagoons and lakes that do not exhibit strong currents.

5.3 Recommendations and Future Research Opportunities

The results of the oyster bag and sandbag modelling have yielded a number of shortcomings that should be addressed prior to field implementation. Recommendations have been provided in terms of design for the oyster bag/sandbag structures, as well as the testing procedure.

Assessments of stability revealed that asymmetrical designs are prone to oyster bag rocking, and it is advised that all bags consist of identical dimensions for future design. Tethering all oyster bags together is also recommended to limit the movement of individual bags, while overall displacement should be prevented through the use of sandbags both above and behind the oyster bag reef. Designs performed best when the crest height was greater than the water depth, and thus positive freeboard is recommended for field implementation. Additionally, larger crest widths have proven to reduce wave transmission and reflection, and should be incorporated into the design if possible.

While it is recommended that the oyster reefs be placed in lower intertidal zones that allow aerial exposure between 10% and 50% to enhance growth (Ridge et al. 2015), if specific sites are proposed for oyster reef deployment, undertaking a detailed case study that uses wave hindcasting and refraction modelling, would provide greater optimisation for the field positioning of these structures (Coghlan et al. 2016). Further environmental considerations may also be adopted to optimise the designs with a greater focus on oyster growth. The ranking system used to determine the optimal design, took into account the four parameters that were measured for each configuration, with the importance of a stable oyster reef taking precedence over the other parameters, as the stability assessment was given a weighting of 2. To further prioritise the growth of the oyster reef, an environmental factor that accounts for the number of sandbags in each design is recommended for the ranking system. This would highlight the designs with a larger ratio of oyster bags to sandbags.

The physical modelling of oyster bag and sandbag design structures has revealed the potential for successful oyster reef deployment in estuaries where wave climates are similar to the laboratory conditions. However, further analysis of oyster reef performance under a variety of conditions will provide a heightened understanding of the suitability of these reefs to a range of environments. To establish a more comprehensive coastal engineering design for the oyster reef, a number of additional tests may be conducted, such as:

- Testing the oyster bag/sandbag designs under oblique wave attack;
- Testing the oyster bag/sandbag designs under irregular wave attack;
- Testing the oyster bag/sandbag designs under high velocity currents, similar to flood events;
- Assessing the durability of the oyster bag/sandbag designs by increasing the duration of wave attack;
- Measuring the Reynolds stresses and drag force coefficients on the oyster bag/sandbag designs during channel flow;
- Quantifying the impact of sandbags on oyster reef growth;
- Conducting field tests to assess reef growth and analyse the performance of the designs during adverse weather conditions.

For future laboratory tests, it is recommended that 3 probe arrays are used for all wave probe measurements. The method proposed by Mansard and Funke (1980) uses 3 wave probes to separate incident and reflected waves, permitting the accurate calculation of wave heights. As seen in the research for the oyster bags and sandbags, transmitted wave heights were heavily influenced by turbulent waters and reflected waves within the flume. This resulted in wave transmission that was overstated, as small reflected wave heights were not separated from the water level data.

If the oyster reef designs are implemented in the field, performance monitoring should be undertaken by comparing cross-sectional surveys seaward and landward of the structures, with a nearby control site that has a similar wave climate and sediment composition (Coghlan et al. 2016). By monitoring the bathymetry of the site, the shoreline change for the oyster bag and sandbag designs can be directly compared to studies for other oyster reefs and living shorelines (Piazza et al. 2005; Risinger 2012; Scyphers et al. 2011; Stricklin et al. 2009; Walles 2014).

6 Conclusion

Rising tides and increasingly frequent storm surges have led to intensified erosion within estuaries and rivers. As a result, ecologically friendly solutions have been proposed as alternatives to man-made structures in order to save costs and aid the deteriorating environment. The development of an oyster reef is one solution that has gathered significant interest over recent years. Limited studies have revealed that oyster bag structures can produce wave transmission characteristics that are comparable to other rubble mound breakwaters, while the stability of these structures has been revealed to be inadequate. As a result, sandbags have been tested together with oyster bags to reduce the movement from wave attack, and to determine the optimal oyster reef design for use as an erosion control structure.

A range of configurations were tested against wave attack, and analysed according to a variety of parameters. The addition of sandbags behind the oyster bag reef prevented landward displacement, while further sandbags on top of the oyster reef prevented all movement. Both Maccaferri and ELCOMAX geotextile sandbags were found to provide sufficient stability to the oyster bags. However, the Maccaferri sandbags were shown to consolidate during testing, and consequently moulded to the shape of the grooves between oyster bags, providing a more rigid structure. This resulted in a greater resistance to rocking and displacement.

Wave transmission was found to be lower for structures with fewer sandbags. The addition of sandbags appeared to increase wave transmission, although the extent of this rise was likely exaggerated by the small waves that propagated throughout the flume during testing. Sandbags with crest heights identical to the oyster bags are expected to provide lower wave transmission, as smaller sandbags allowed waves to overtop the structure. The increase in wave transmission was overcome through the use of alternative design options that increased the crest width of the structure. Wave reflection was also increased with the addition of sandbags, particularly for designs with sandbags at the seaward face of the structure. Sandbags that used the thicker ELCOMAX geotextile material provided greater wave reflection compared to sandbags that were made from the Maccaferri geotextile material. As a result, all optimal design solutions utilised oyster bags at the seaward face with Maccaferri sandbags as support. Oyster bags were also shown to generate the highest values of dissipated energy, coincident with the lower wave transmission and reflection that these bags offered. Across the range of wave conditions, structures with greater freeboard gave lower wave transmission and reflection coefficients and higher values of energy dissipation, while designs that increased crest width gave the most favourable results.

For field implementation, it is recommended that the dimensions of all bags are made equivalent. Bags of the same size reduce the instability that accompanies asymmetry, while bags of lower crest heights permit greater overtopping. The analysis that has been undertaken provides sufficient evidence for the successful use of the optimal designs in estuarine environments. However, further laboratory testing and field studies are recommended to completely optimise the design for the proposed site.

The physical modelling of the oyster bag/sandbag structures has revealed optimal designs that exhibit ideal coastal engineering aspects for use as an erosion control measure, as well as provide stability for the growth and survival of an oyster reef.

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Appendix A

Stability Assessment Data

i. 1 Tier Structures

Configuration	Type of Structure	Water Depth (m)	Wave Period (s)	Incident Wave Height (m)	
				Crest Bag/Structure Rocking	Displacement of Structure
O_1	Oyster	0.16	1	0.072	-
O_1	Oyster	0.16	2	0.049	0.086
O_1	Oyster	0.16	3	0.037	0.068
S_1	Sand	0.16	1	-	-
S_1	Sand	0.16	2	-	-
S_1	Sand	0.16	3	-	-
S_5	Sand	0.16	1	-	-
S_5	Sand	0.16	2	-	-
S_5	Sand	0.16	3	-	-
O_4	Oyster	0.16	1	-	-
O_4	Oyster	0.16	2	-	0.092
O_4	Oyster	0.16	3	-	0.092
M_{11}	Mixed	0.16	1	-	-
M_{11}	Mixed	0.16	2	0.092	-
M_{11}	Mixed	0.16	3	0.074	-
M_{12}	Mixed	0.16	1	-	-
M_{12}	Mixed	0.16	2	0.069	-
M_{12}	Mixed	0.16	3	0.071	-
M_{13}	Mixed	0.16	1	-	-
M_{13}	Mixed	0.16	2	0.106	-
M_{13}	Mixed	0.16	3	0.093	-
M_{14}	Mixed	0.16	1	-	-
M_{14}	Mixed	0.16	2	0.065	-
M_{14}	Mixed	0.16	3	0.062	-
O_5	Oyster	0.16	1	-	-
O_5	Oyster	0.16	2	-	-
O_5	Oyster	0.16	3	-	-
S_4	Sand	0.16	1	-	-
S_4	Sand	0.16	2	-	-
S_4	Sand	0.16	3	-	-

Table A.1 - Incident wave heights that induced movement for 1 tier structures; d=0.16m

ii. 2 Tier Structures

Configuration	Type of Structure	Water Depth (m)	Wave Period (s)	Incident Wave Height (m)	
				Crest Bag/Structure Rocking	Displacement of Structure
O_2	Oyster	0.16	1	-	-
O_2	Oyster	0.16	2	0.113	-
O_2	Oyster	0.16	3	0.093	-
S_2	Sand	0.16	1	-	-
S_2	Sand	0.16	2	-	-
S_2	Sand	0.16	3	-	-
S_6	Sand	0.16	1	-	-
S_6	Sand	0.16	2	-	-
S_6	Sand	0.16	3	-	-
M_{21}	Mixed	0.16	1	-	-
M_{21}	Mixed	0.16	2	0.072	-
M_{21}	Mixed	0.16	3	0.065	-
M_{22}	Mixed	0.16	1	-	-
M_{22}	Mixed	0.16	2	-	-
M_{22}	Mixed	0.16	3	-	-
M_{23}	Mixed	0.16	1	-	-
M_{23}	Mixed	0.16	2	-	-
M_{23}	Mixed	0.16	3	-	-
M_{24}	Mixed	0.16	1	-	-
M_{24}	Mixed	0.16	2	-	-
M_{24}	Mixed	0.16	3	-	-
M_{25}	Mixed	0.16	1	-	-
M_{25}	Mixed	0.16	2	-	-
M_{25}	Mixed	0.16	3	-	-
M_{26}	Mixed	0.32	1	-	-
M_{26}	Mixed	0.32	2	-	-
M_{26}	Mixed	0.32	3	-	-
O_6	Oyster	0.32	1	-	-
O_6	Oyster	0.32	2	-	-
O_6	Oyster	0.32	3	-	-

Table A.2 - Incident wave heights that induced movement for 2 tier structures; d=0.16m

Configuration	Type of Structure	Water Depth (m)	Wave Period (s)	Incident Wave Height (m)	
				Crest Bag/Structure Rocking	Displacement of Structure
O_2	Oyster	0.32	1	0.105	-
O_2	Oyster	0.32	2	0.089	0.137
O_2	Oyster	0.32	3	0.047	0.102
S_2	Sand	0.32	1	-	-
S_2	Sand	0.32	2	-	-
S_2	Sand	0.32	3	-	-
S_6	Sand	0.32	1	-	-
S_6	Sand	0.32	2	-	-
S_6	Sand	0.32	3	-	-
M_{21}	Mixed	0.32	1	0.079	-
M_{21}	Mixed	0.32	2	-	0.143
M_{21}	Mixed	0.32	3	-	0.077
M_{22}	Mixed	0.32	1	-	-
M_{22}	Mixed	0.32	2	-	0.153
M_{22}	Mixed	0.32	3	-	0.144
M_{23}	Mixed	0.32	1	-	-
M_{23}	Mixed	0.32	2	-	0.146
M_{23}	Mixed	0.32	3	-	0.080
M_{24}	Mixed	0.32	1	-	-
M_{24}	Mixed	0.32	2	-	-
M_{24}	Mixed	0.32	3	0.152	-
M_{25}	Mixed	0.32	1	-	-
M_{25}	Mixed	0.32	2	-	-
M_{25}	Mixed	0.32	3	0.139	-
M_{26}	Mixed	0.32	1	0.108	-
M_{26}	Mixed	0.32	2	0.073	-
M_{26}	Mixed	0.32	3	0.058	0.149
O_6	Oyster	0.32	1	-	-
O_6	Oyster	0.32	2	-	0.118
O_6	Oyster	0.32	3	-	0.077

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

iii. 3 Tier Structures

Configuration	Type of Structure	Water Depth (m)	Wave Period (s)	Incident Wave Height (m)	
				Crest Bag/Structure Rocking	Displacement of Structure
O_3	Oyster	0.32	1	-	-
O_3	Oyster	0.32	2	0.126	0.153
O_3	Oyster	0.32	3	0.097	0.108
S_3	Sand	0.32	1	-	-
S_3	Sand	0.32	2	-	-
S_3	Sand	0.32	3	-	-
M_{31}	Mixed	0.32	1	-	-
M_{31}	Mixed	0.32	2	-	-
M_{31}	Mixed	0.32	3	-	0.106
M_{32}	Mixed	0.32	1	0.075	-
M_{32}	Mixed	0.32	2	0.139*	-
M_{32}	Mixed	0.32	3	0.068*	0.149
M_{33}	Mixed	0.32	1	-	-
M_{33}	Mixed	0.32	2	0.162	-
M_{33}	Mixed	0.32	3	0.069	-
M_{34}	Mixed	0.32	1	-	-
M_{34}	Mixed	0.32	2	-	-
M_{34}	Mixed	0.32	3	0.129	-
M_{35}	Mixed	0.32	1	-	-
M_{35}	Mixed	0.32	2	0.181	-
M_{35}	Mixed	0.32	3	0.129	-

*This wave height induced both rocking as well as crest bag displacement.

Table A.4 - Incident wave heights that induced movement for 3 tier structures; d=0.32m

Configuration	Type of Structure	Water Depth (m)	Wave Period (s)	Incident Wave Height (m)	
				Crest Bag/Structure Rocking	Displacement of Structure
O_3	Oyster	0.4	1	0.123	-
O_3	Oyster	0.4	2	0.128	0.142
O_3	Oyster	0.4	3	0.046	0.137
S_3	Sand	0.4	1	-	-
S_3	Sand	0.4	2	-	-
S_3	Sand	0.4	3	-	-
M_{31}	Mixed	0.4	1	-	-
M_{31}	Mixed	0.4	2	-	0.175
M_{31}	Mixed	0.4	3	-	0.083
M_{32}	Mixed	0.4	1	0.066	-
M_{32}	Mixed	0.4	2	0.082	0.129
M_{32}	Mixed	0.4	3	0.037	0.076
M_{33}	Mixed	0.4	1	-	-
M_{33}	Mixed	0.4	2	0.160	-
M_{33}	Mixed	0.4	3	0.087	-
M_{34}	Mixed	0.4	1	-	-
M_{34}	Mixed	0.4	2	-	-
M_{34}	Mixed	0.4	3	-	-
M_{35}	Mixed	0.4	1	-	-
M_{35}	Mixed	0.4	2	0.164	-
M_{35}	Mixed	0.4	3	0.104	-

Table A.5 - Incident wave heights that induced movement for 3 tier structures; d=0.40m

Appendix B

Wave Transmission Plots

i. 1 Tier Structures

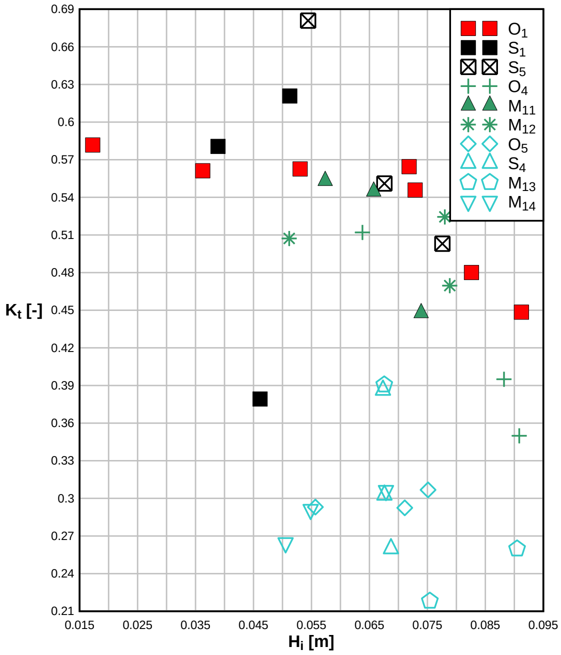

Figure B.1 - Wave transmission coefficients for all 1 tier structures; d=0.16m, T=1s

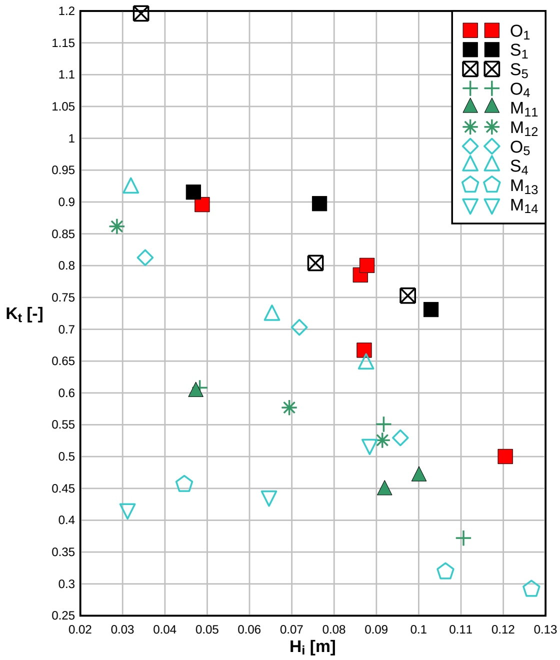

Figure B.2 - Wave transmission coefficients for all 1 tier structures; d=0.16m, T=2s

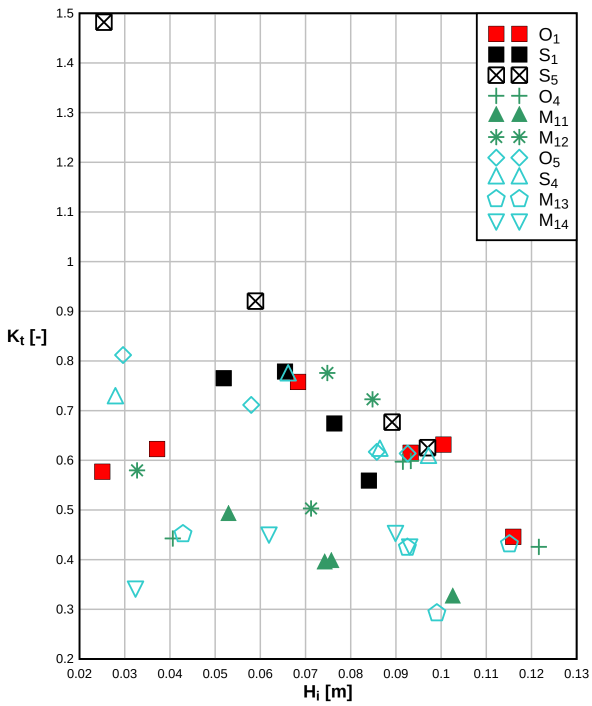

Figure B.3 - Wave transmission coefficients for all 1 tier structures; d=0.16m, T=3s

ii. 2 Tier Structures

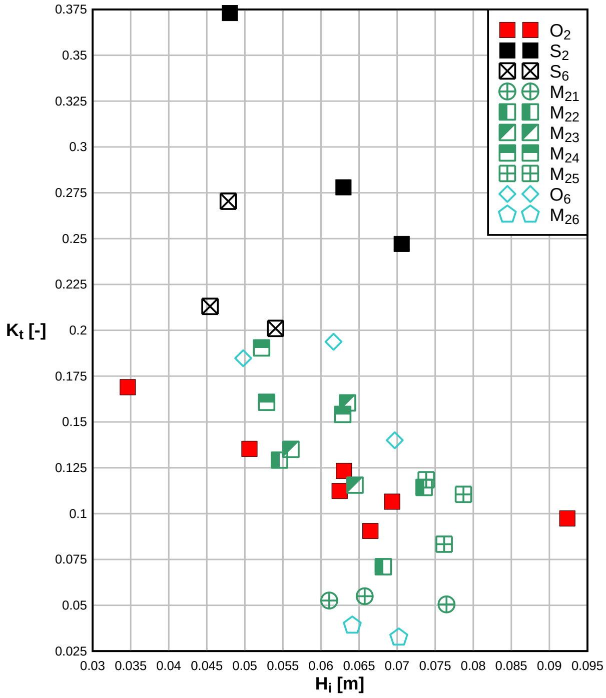

Figure B.4 - Wave transmission coefficients for all 2 tier structures; d=0.16m, T=1s

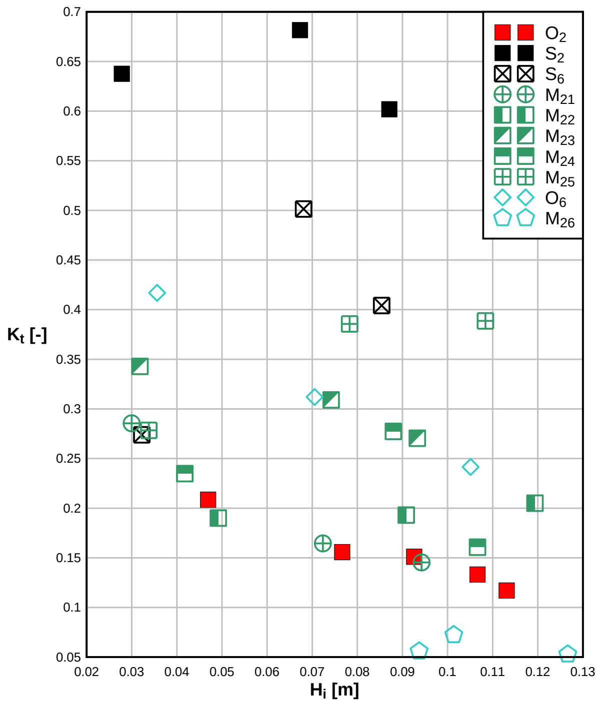

Figure B.5 - Wave transmission coefficients for all 2 tier structures; d=0.16m, T=2s

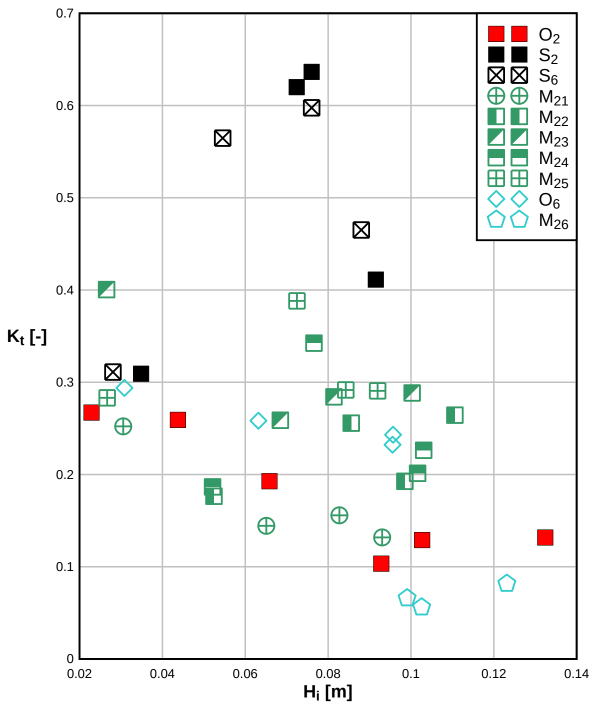

Figure B.6 - Wave transmission coefficients for all 2 tier structures; d=0.16m, T=3s

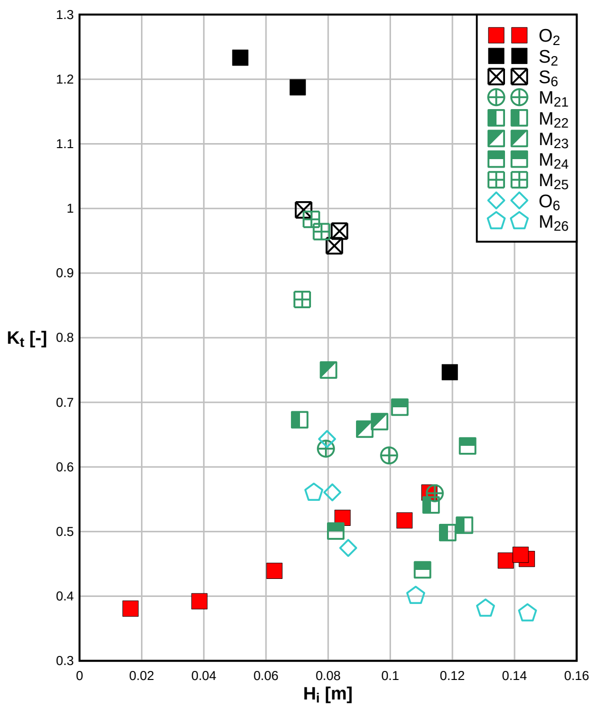

Figure B.7 - Wave transmission coefficients for all 2 tier structures; d=0.32m, T=1s

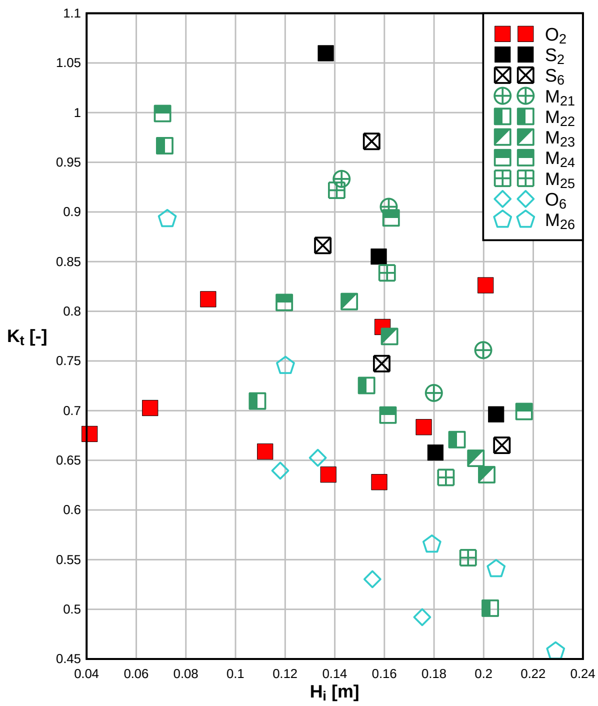

Figure B.8 - Wave transmission coefficients for all 2 tier structures; d=0.32m, T=2s

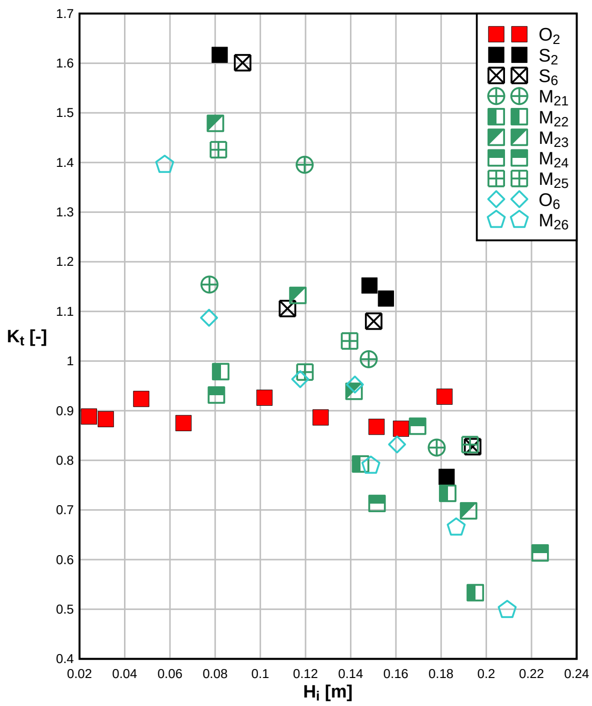

Figure B.9 - Wave transmission coefficients for all 2 tier structures; d=0.32m, T=3s

iii. 3 Tier Structures

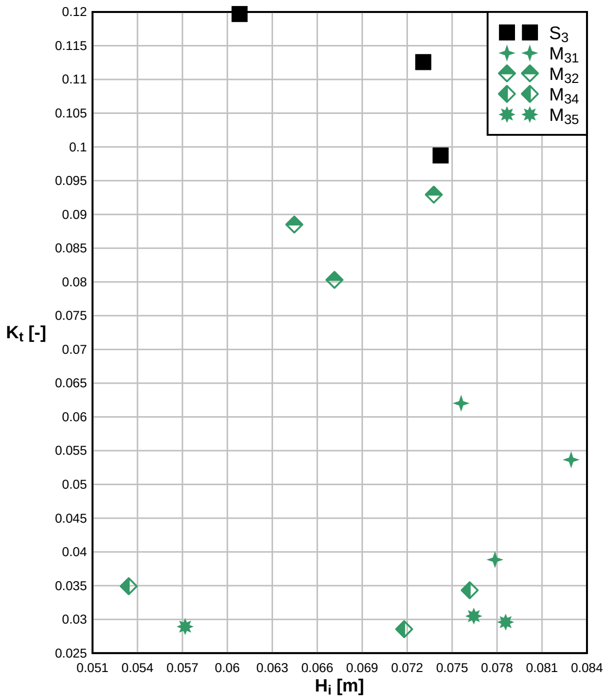

Figure B.10 - Wave transmission coefficients for all 3 tier structures; d=0.16m, T=1s

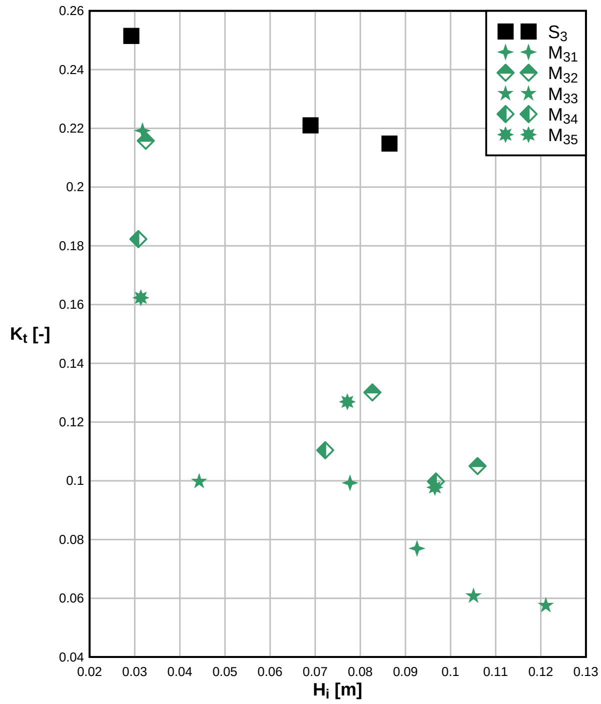

Figure B.11 - Wave transmission coefficients for all 3 tier structures; d=0.16m, T=2s

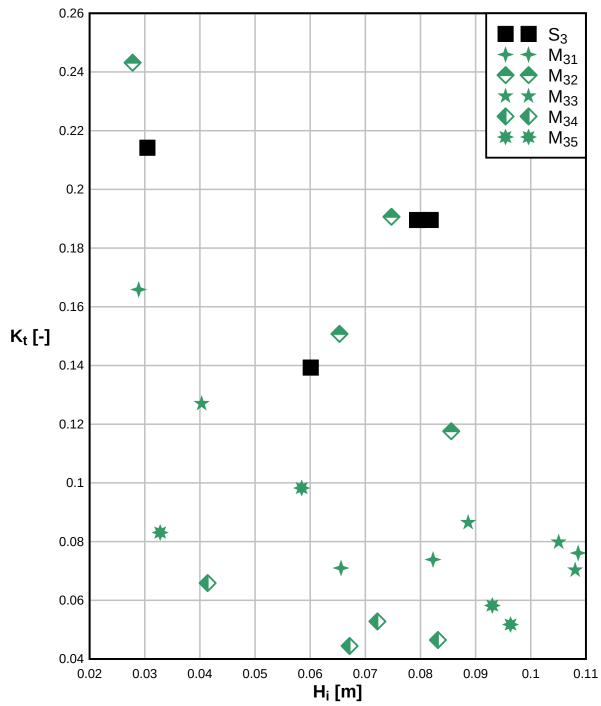

Figure B.12 - Wave transmission coefficients for all 3 tier structures; d=0.16m, T=3s

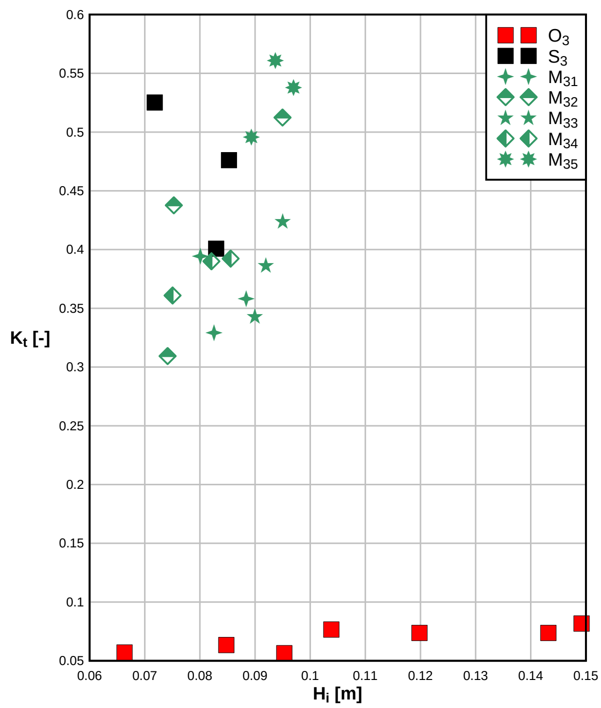

Figure B.13 - Wave transmission coefficients for all 3 tier structures; d=0.32m, T=1s

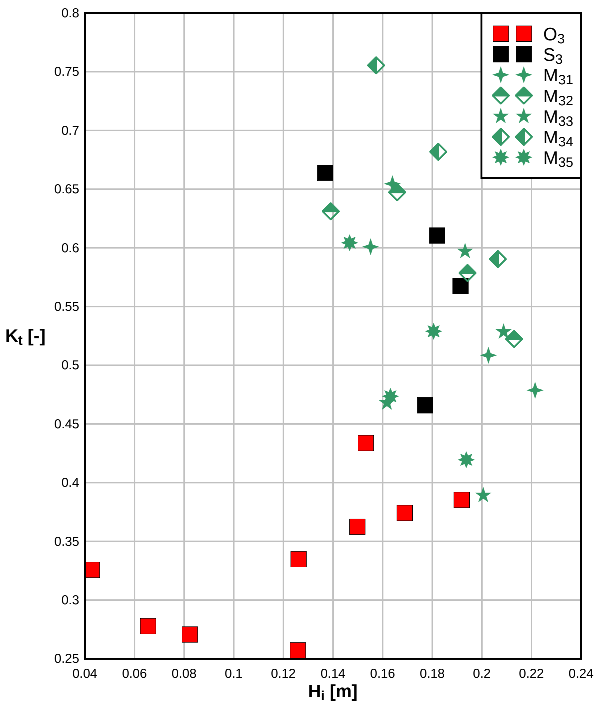

Figure B.14 - Wave transmission coefficients for all 3 tier structures; d=0.32m, T=2s

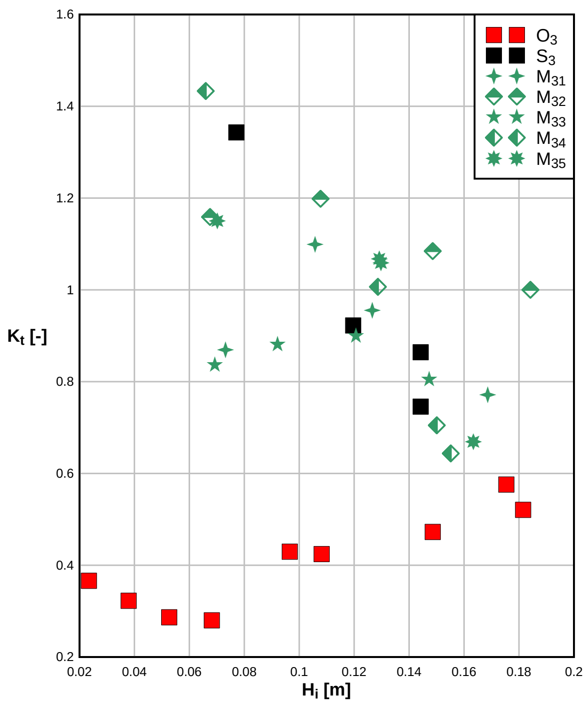

Figure B.15 - Wave transmission coefficients for all 3 tier structures; d=0.32m, T=3s

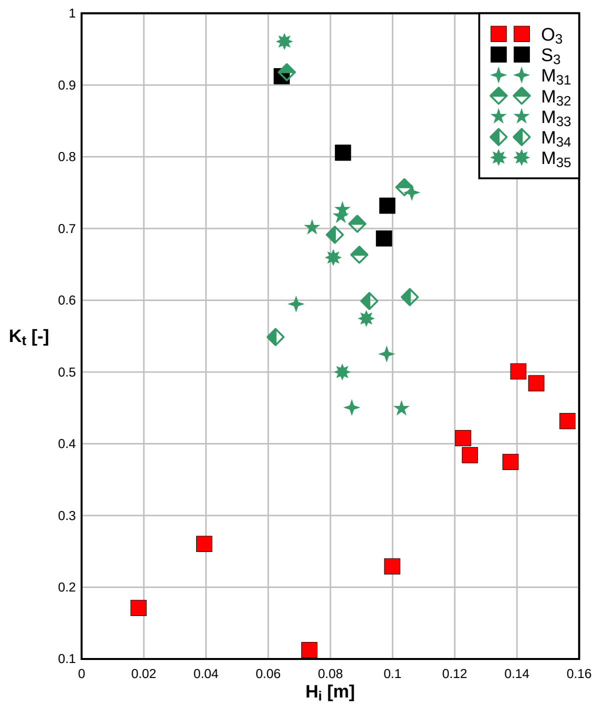

Figure B.16 - Wave transmission coefficients for all 3 tier structures; d=0.40m, T=1s

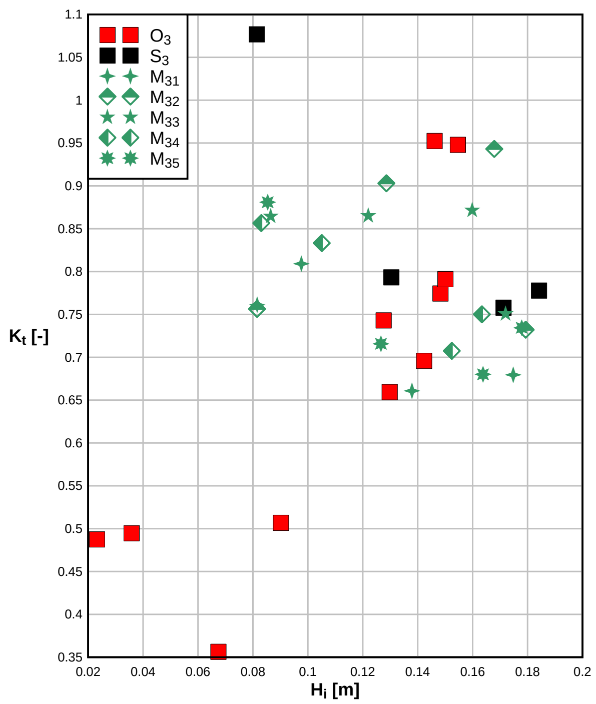

Figure B.17 - Wave transmission coefficients for all 3 tier structures; d=0.40m, T=2s

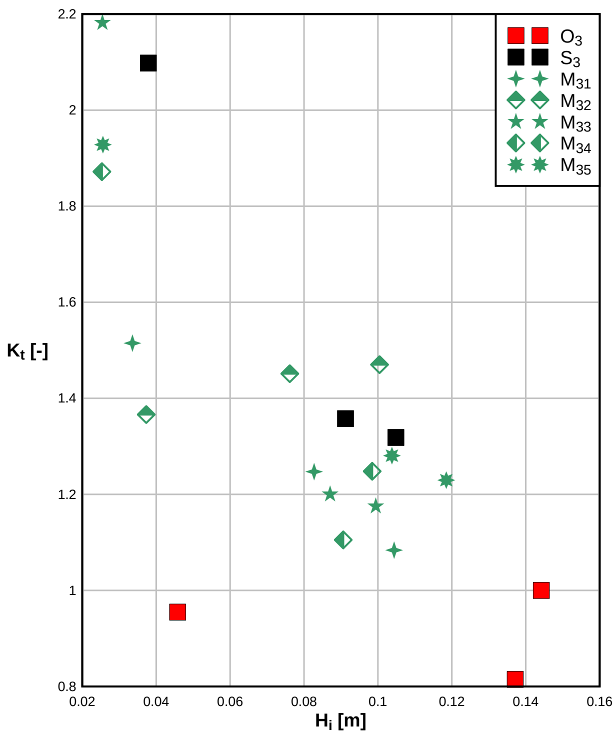

Figure B.18 - Wave transmission coefficients for all 3 tier structures; d=0.40m, T=3s

Appendix C

Wave Reflection Plots

i. 1 Tier Structures

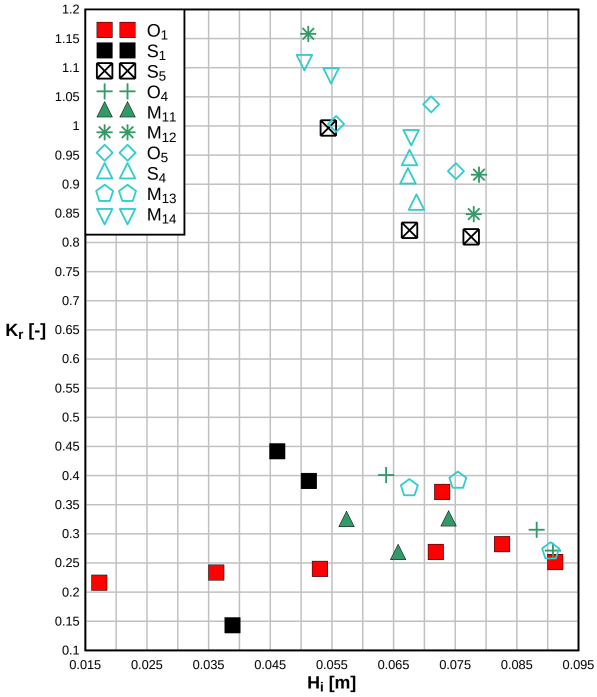

Figure C.1 - Wave reflection coefficients for all 1 tier structures; d=0.16m, T=1s

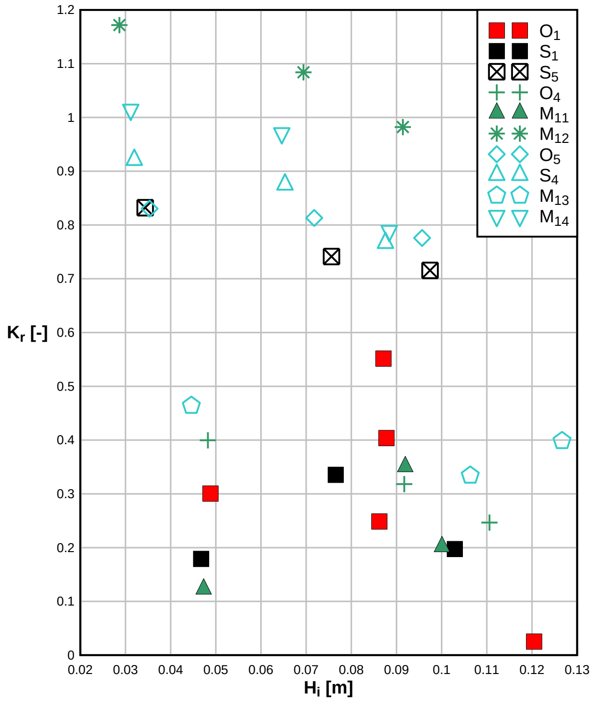

Figure C.2 - Wave reflection coefficients for all 1 tier structures; d=0.16m, T=2s

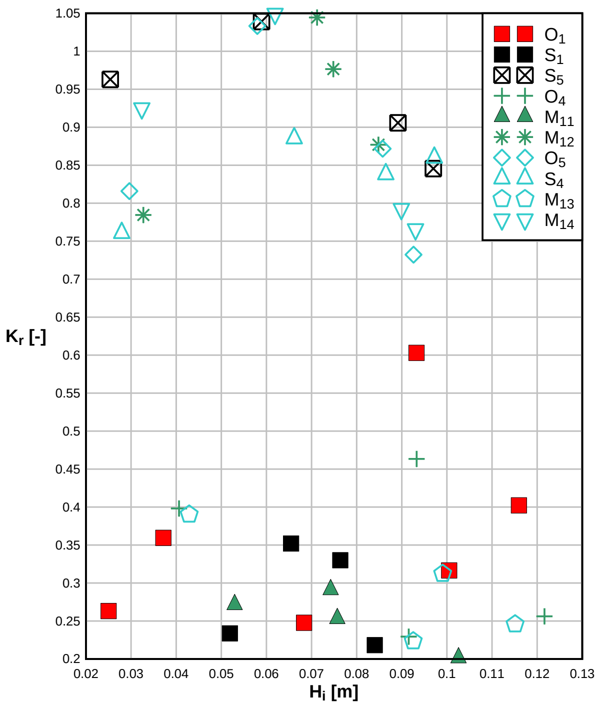

Figure C.3 - Wave reflection coefficients for all 1 tier structures; d=0.16m, T=3s

ii. 2 Tier Structures

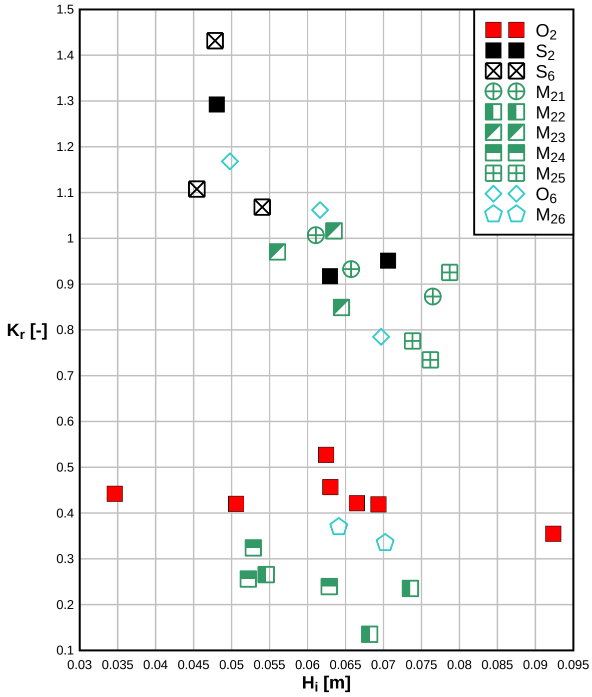

Figure C.4 - Wave reflection coefficients for all 2 tier structures; d=0.16m, T=1s

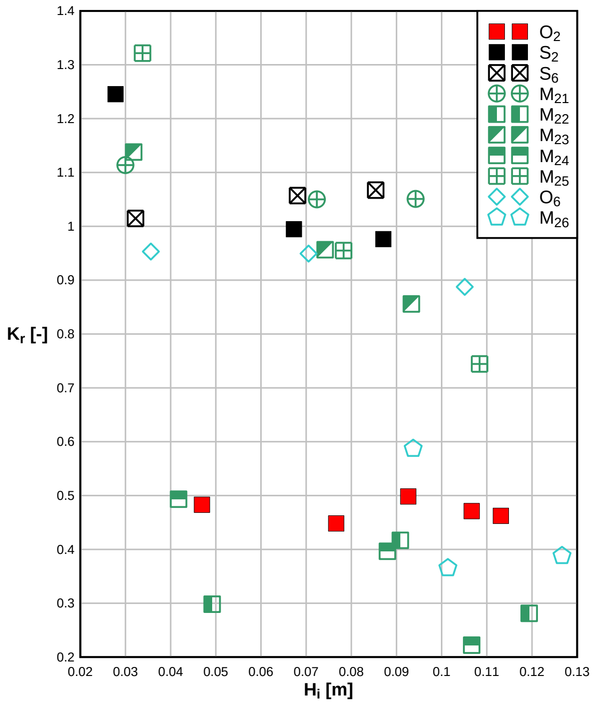

Figure C.5 - Wave reflection coefficients for all 2 tier structures; d=0.16m, T=2s

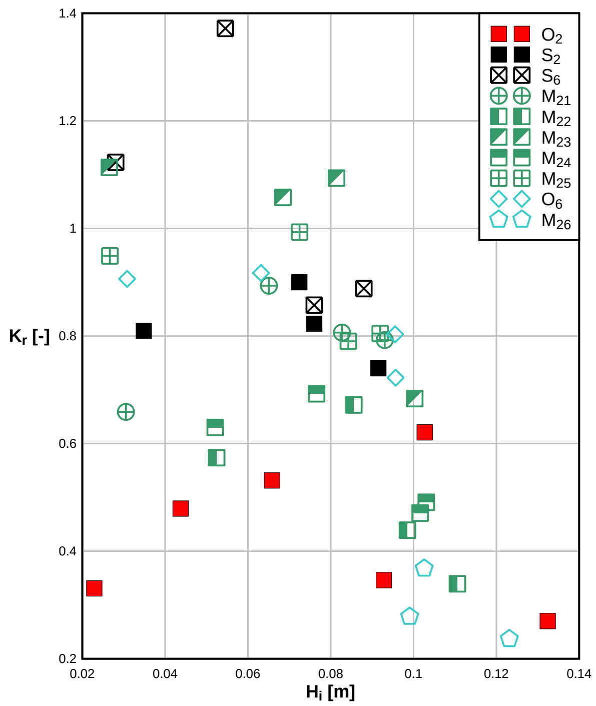

Figure C.6 - Wave reflection coefficients for all 2 tier structures; d=0.16m, T=3s

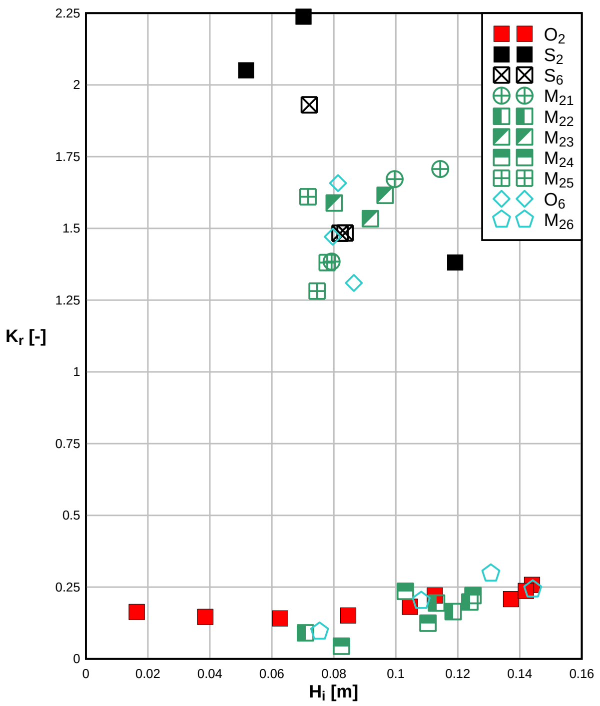

Figure C.7 - Wave reflection coefficients for all 2 tier structures; d=0.32m, T=1s

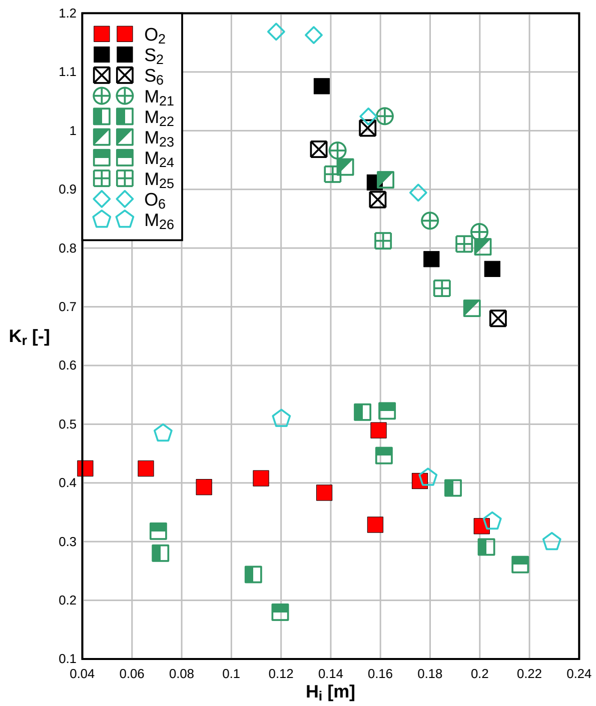

Figure C.8 - Wave reflection coefficients for all 2 tier structures; d=0.32m, T=2s

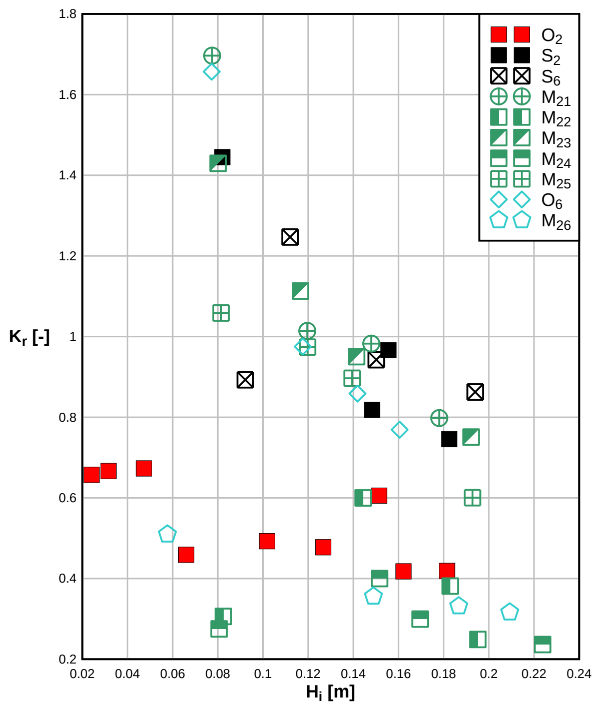

Figure C.9 - Wave reflection coefficients for all 2 tier structures; d=0.32m, T=3s

iii. 3 Tier Structures

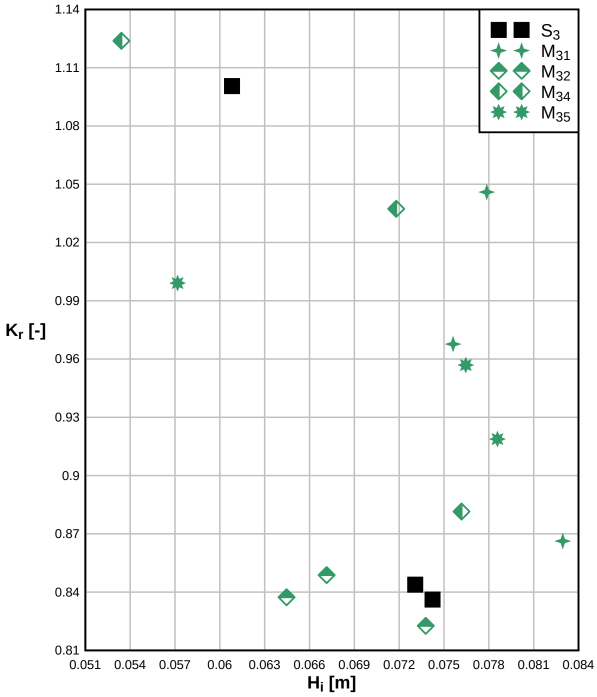

Figure C.10 - Wave reflection coefficients for all 3 tier structures; d=0.16m, T=1s

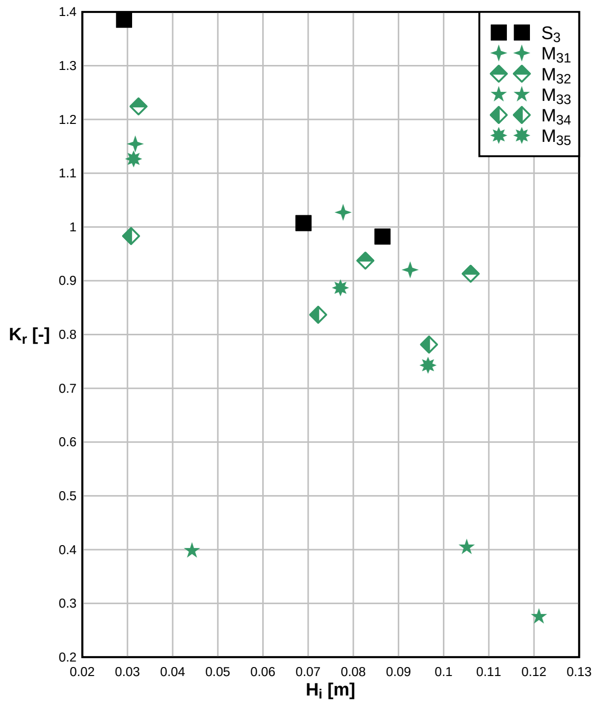

Figure C.11 - Wave reflection coefficients for all 3 tier structures; d=0.16m, T=2s

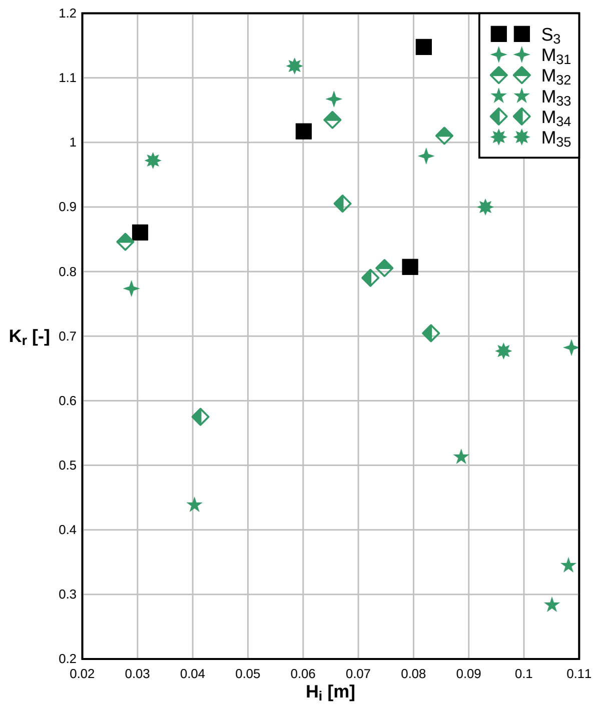

Figure C.12 - Wave reflection coefficients for all 3 tier structures; d=0.16m, T=3s

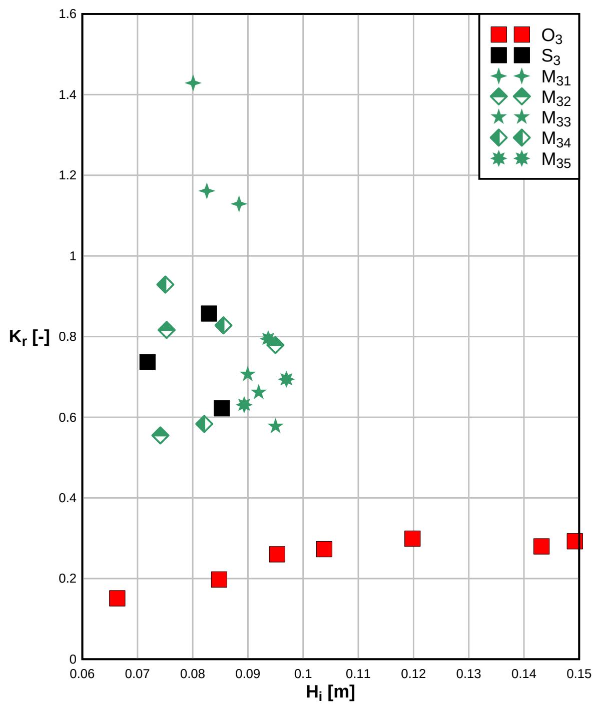

Figure C.13 - Wave reflection coefficients for all 3 tier structures; d=0.32m, T=1s

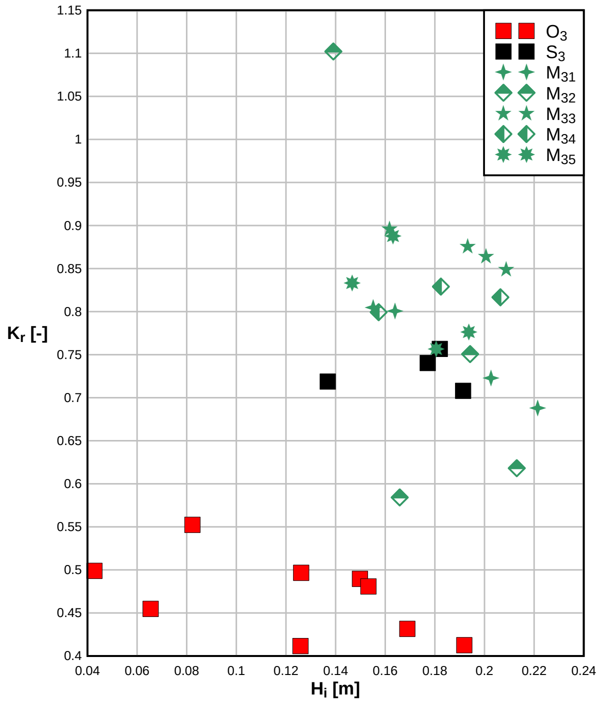

Figure C.14 - Wave reflection coefficients for all 3 tier structures; d=0.32m, T=2s

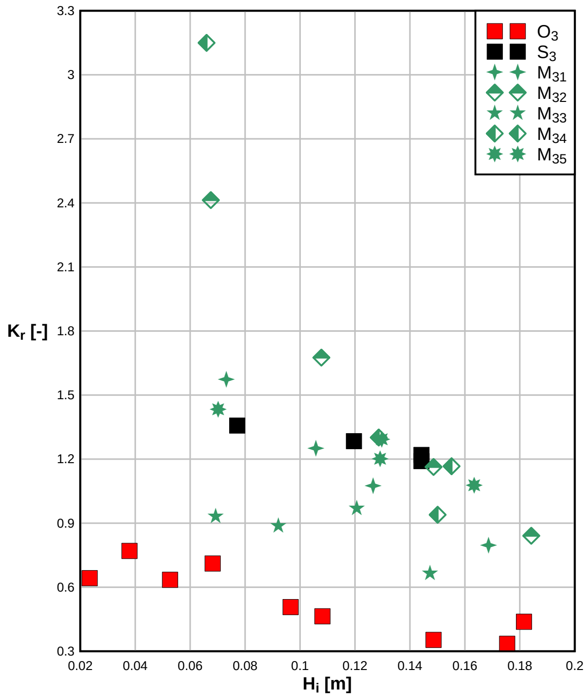

Figure C.15 - Wave reflection coefficients for all 3 tier structures; d=0.32m, T=3s

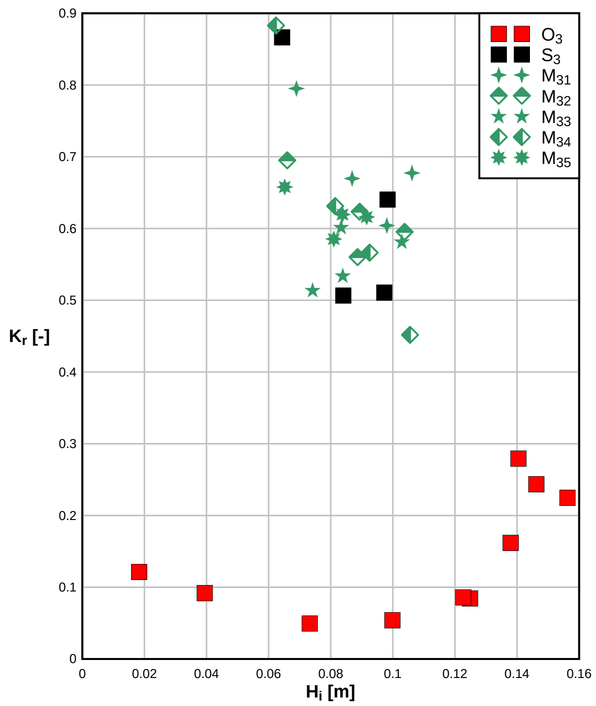

Figure C.16 - Wave reflection coefficients for all 3 tier structures; d=0.40m, T=1s

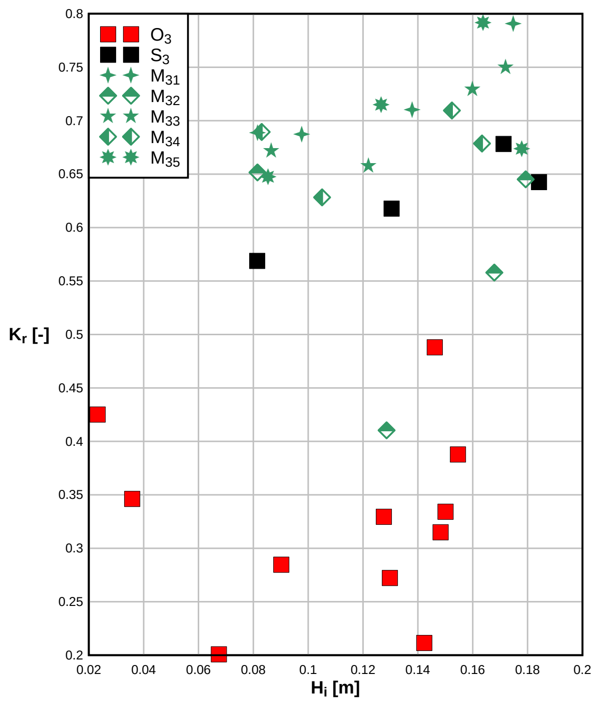

Figure C.17 - Wave reflection coefficients for all 3 tier structures; d=0.40m, T=2s

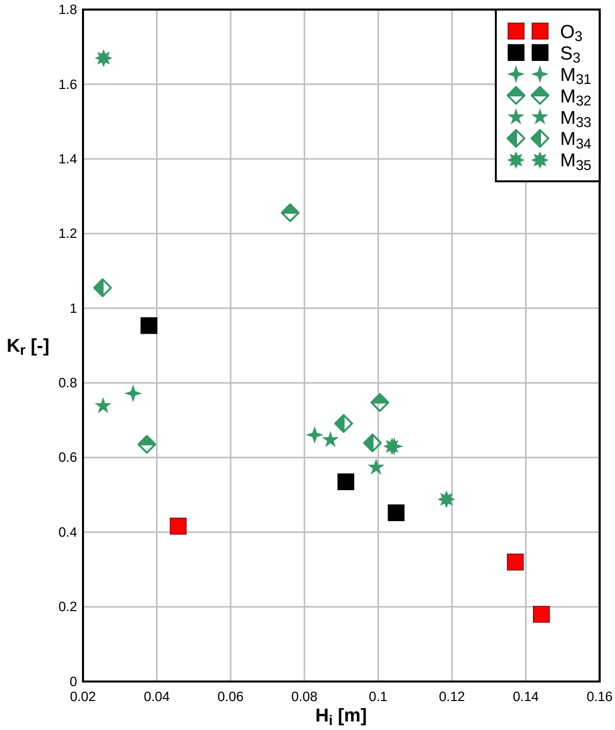

Figure C.18 - Wave reflection coefficients for all 3 tier structures; d=0.40m, T=3s

Appendix D

Energy Dissipation Plots

i. 1 Tier Structures

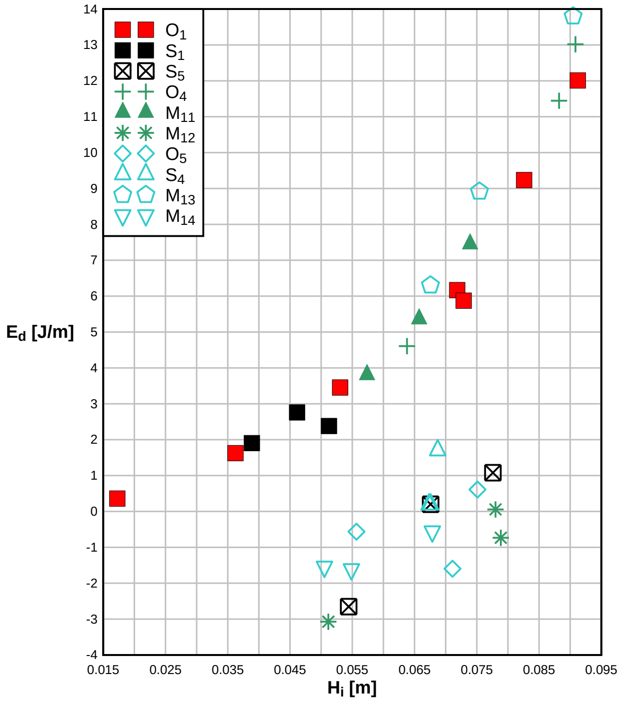

Figure D.1 - Energy dissipation of all 1 tier structures; d=0.16m, T=1s

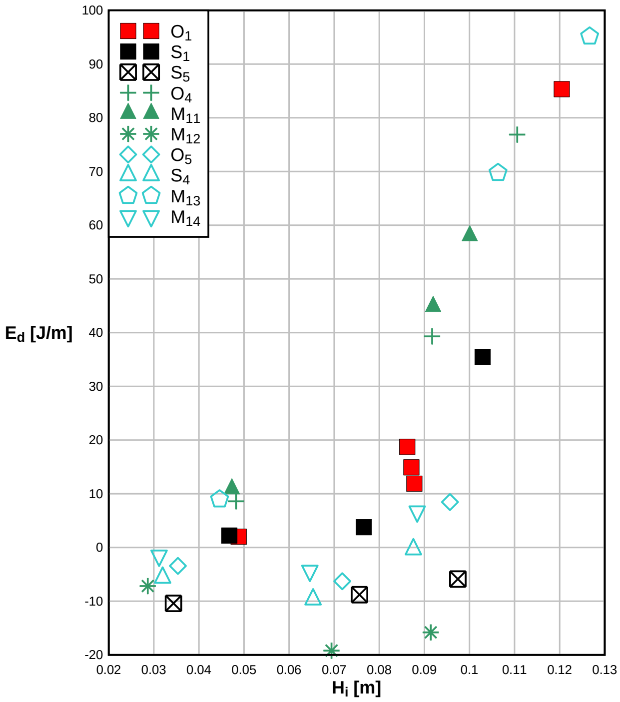

Figure D.2 - Energy dissipation of all 1 tier structures; d=0.16m, T=2s

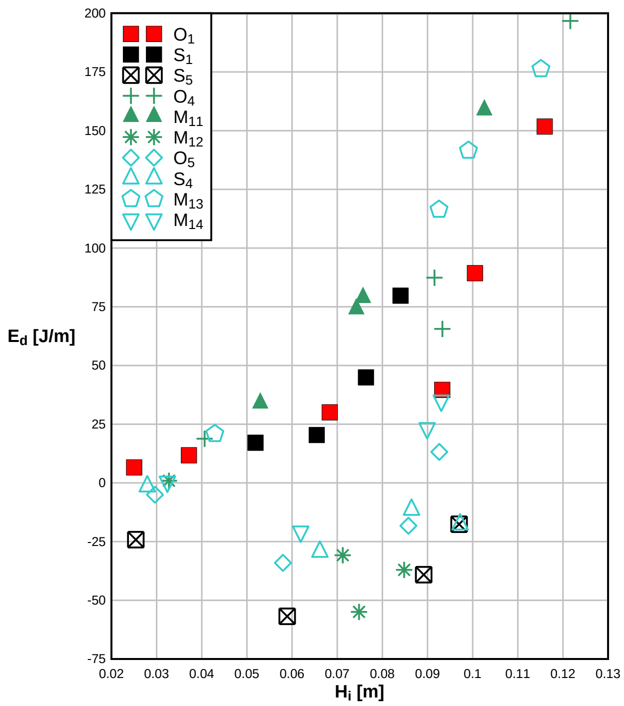

Figure D.3 - Energy dissipation of all 1 tier structures; d=0.16m, T=3s

ii. 2 Tier Structures

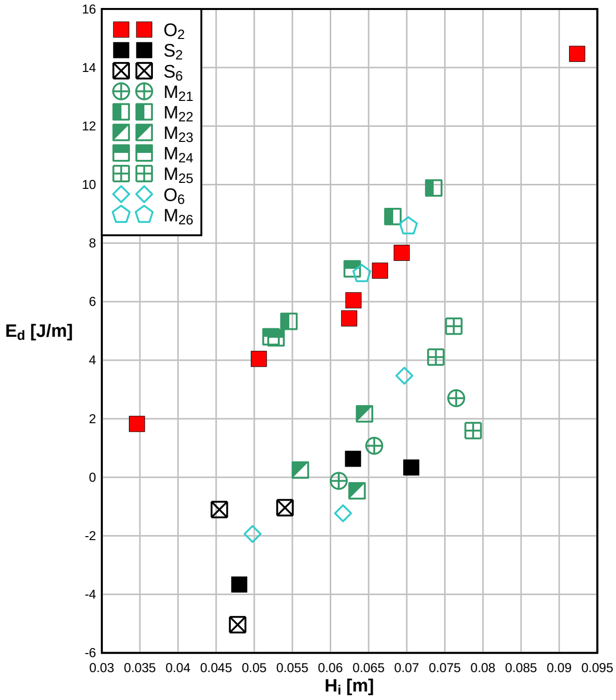

Figure D.4 - Energy dissipation of all 2 tier structures; d=0.16m, T=1s

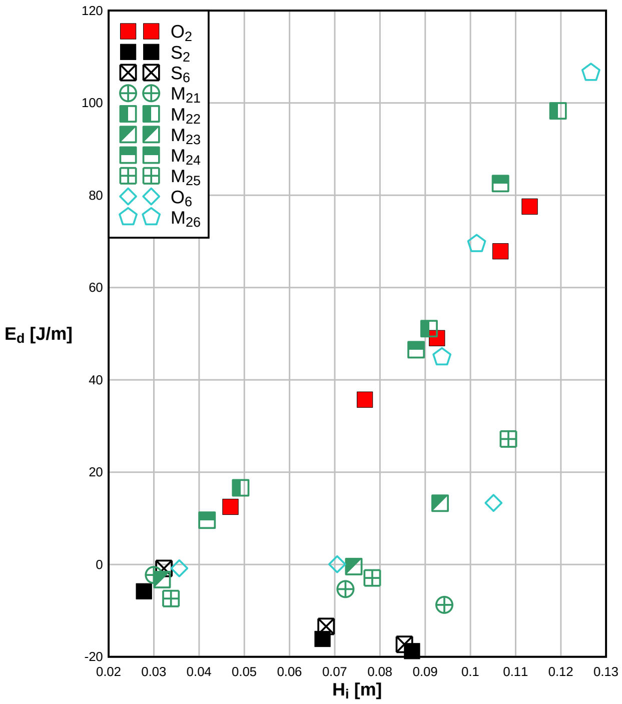

Figure D.5 - Energy dissipation of all 2 tier structures; d=0.16m, T=2s

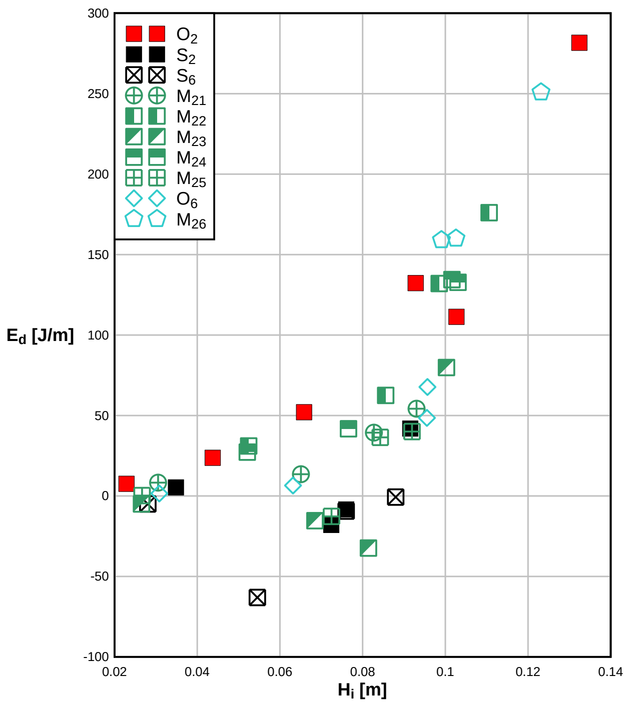

Figure D.6 - Energy dissipation of all 2 tier structures; d=0.16m, T=3s

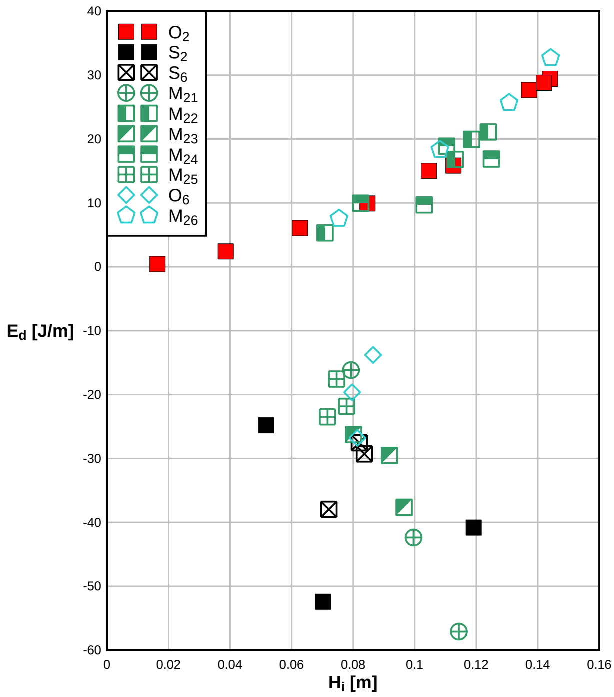

Figure D.7 - Energy dissipation of all 2 tier structures; d=0.32m, T=1s

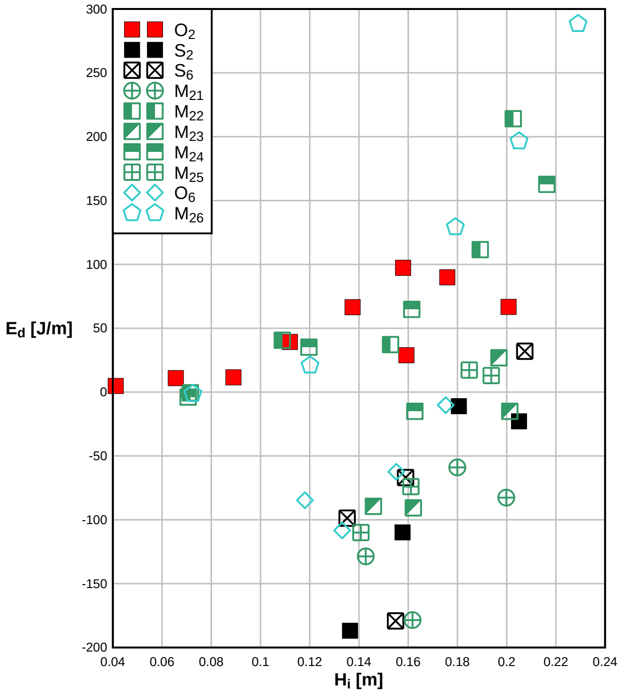

Figure D.8 - Energy dissipation of all 2 tier structures; d=0.32m, T=2s

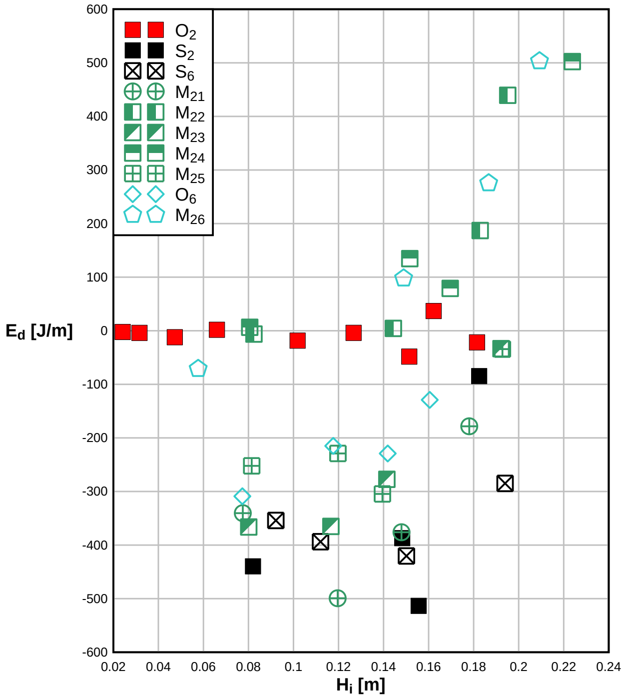

Figure D.9 - Energy dissipation of all 2 tier structures; d=0.32m, T=3s

iii. 3 Tier Structures

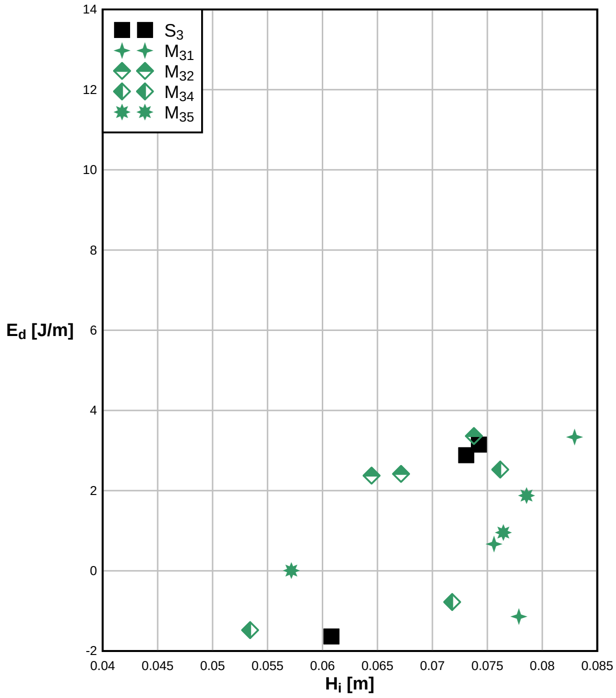

Figure D.10 - Energy dissipation of all 3 tier structures; d=0.16m, T=1s

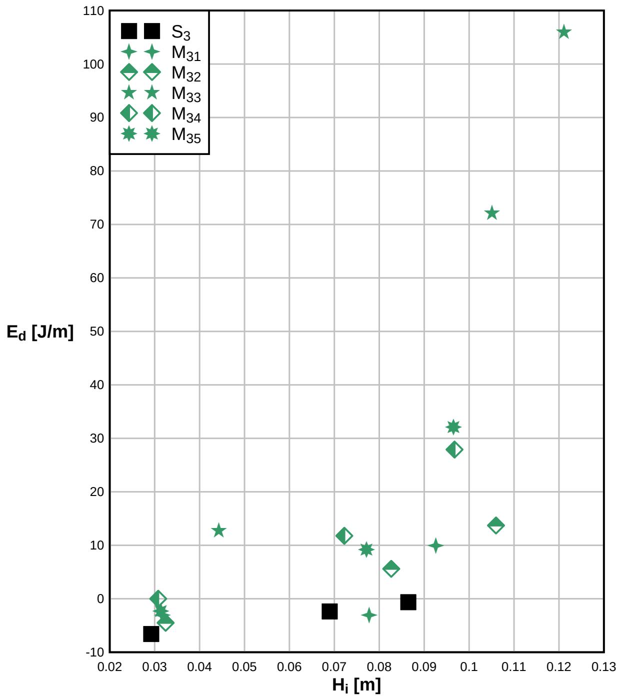

Figure D.11 - Energy dissipation of all 3 tier structures; d=0.16m, T=2s

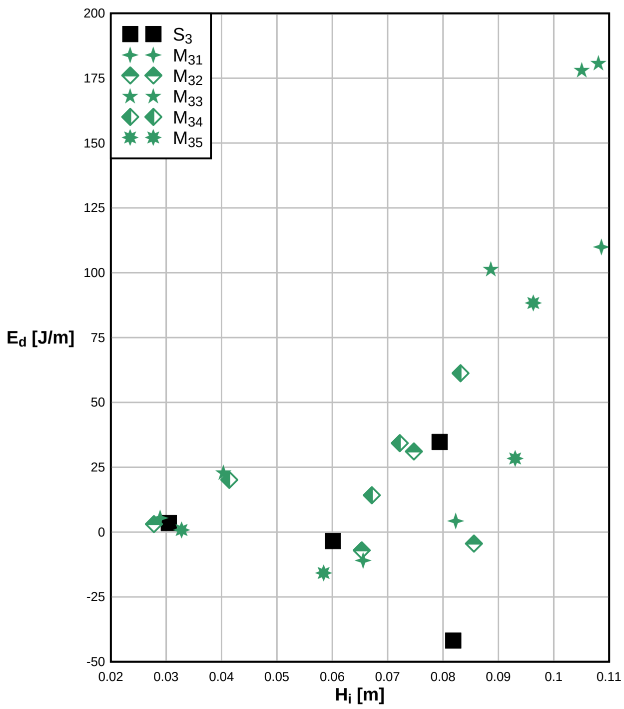

Figure D.12 - Energy dissipation of all 3 tier structures; d=0.16m, T=3s

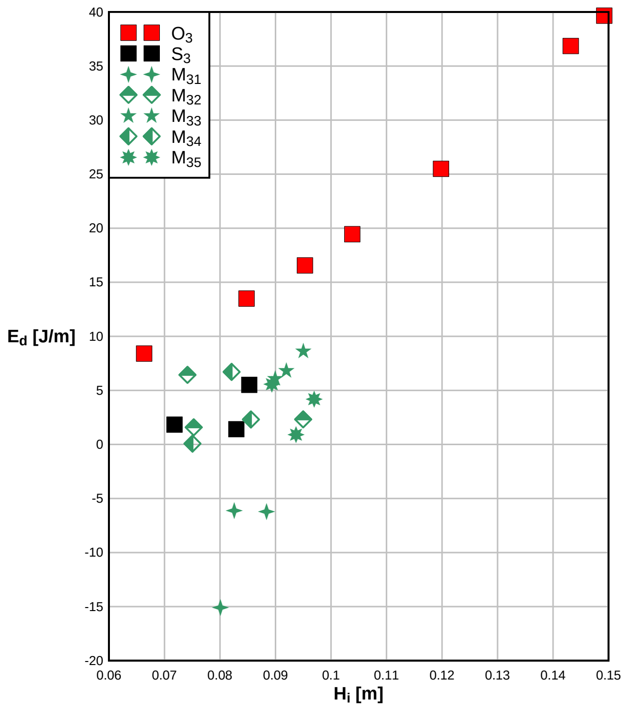

Figure D.13 - Energy dissipation of all 3 tier structures; d=0.32m, T=1s

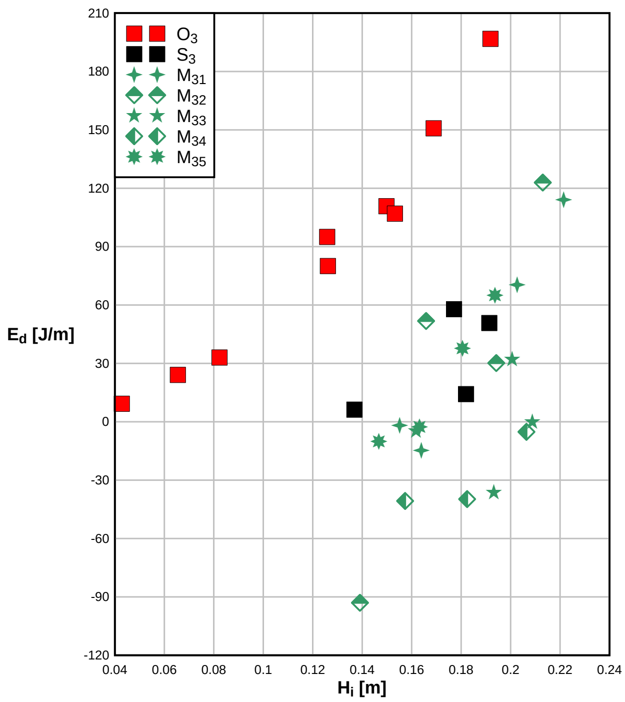

Figure D.14 - Energy dissipation of all 3 tier structures; d=0.32m, T=2s

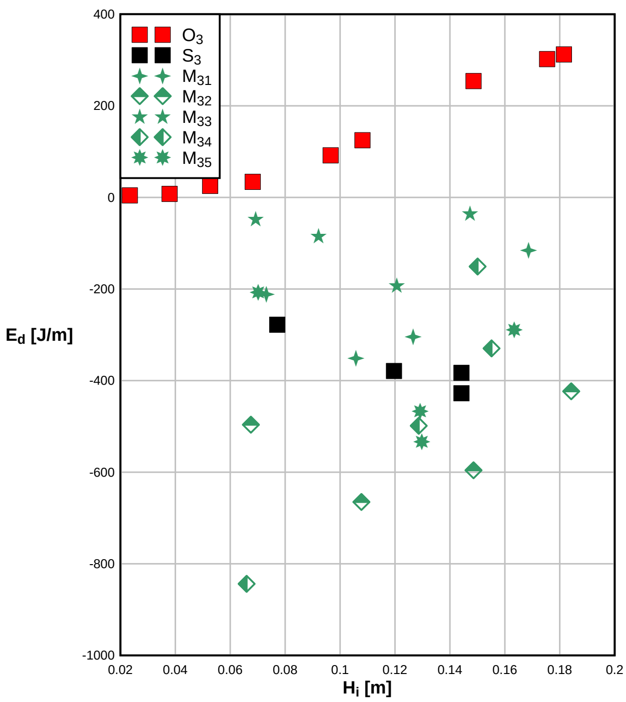

Figure D.15 - Energy dissipation of all 3 tier structures; d=0.32m, T=3s

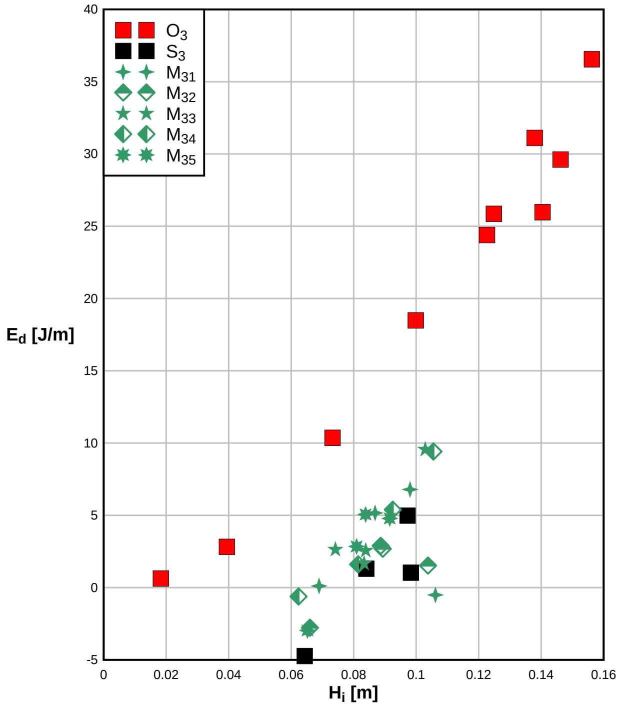

Figure D.16 - Energy dissipation of all 3 tier structures; d=0.40m, T=1s

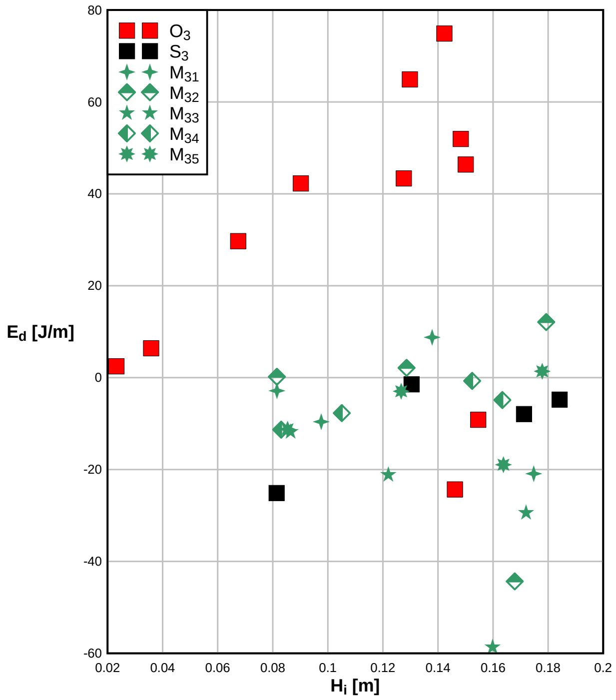

Figure D.17 - Energy dissipation of all 3 tier structures; d=0.40m, T=2s

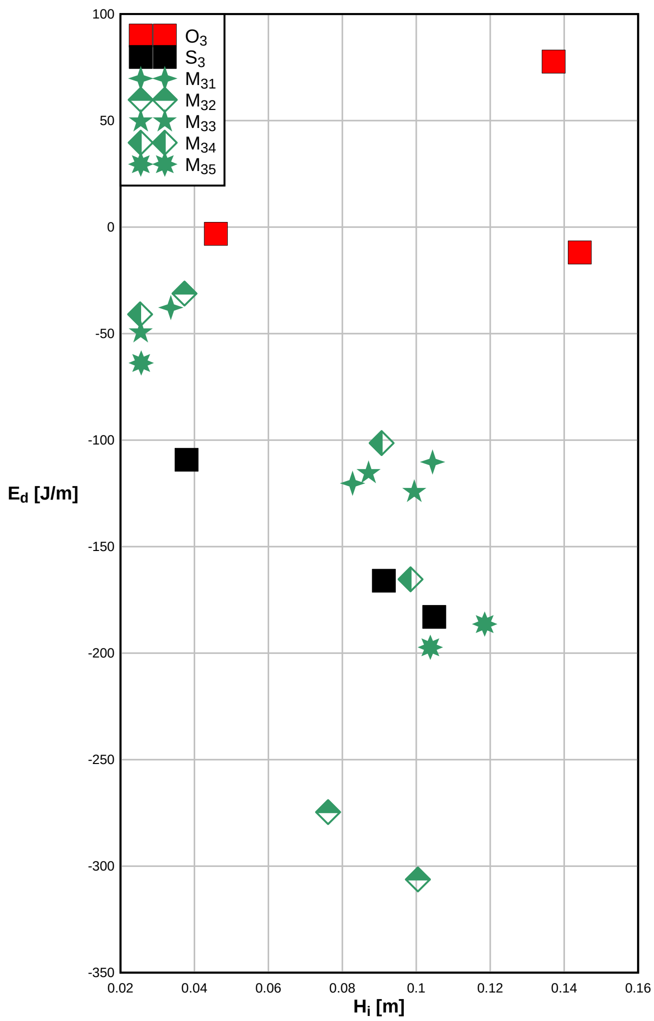

Figure D.18 - Energy dissipation of all 3 tier structures; d=0.40m, T=3s

Appendix E

Test Data & Calculated Parameters

Test	ID	Calibration Factor	d (mm)	T (s)	h_c (mm)	B (mm)	B/d	h_c/d	Observations	H_i (m)	H_t (m)	H_r (m)	K_t	K_r	E_i (J/m)	E_t (J/m)	E_r (J/m)	E_d (J/m)
1	O_1	0.1	160	1	160	330	2.0625	1	no bag movement	0.017	0.010	0.004	0.582	0.216	0.584	0.198	0.027	0.359
2	O_1	0.2	160	1	160	330	2.0625	1	no bag movement	0.036	0.020	0.008	0.561	0.234	2.577	0.811	0.141	1.624
3	O_1	0.3	160	1	160	330	2.0625	1	slight rocking, front lifts	0.053	0.030	0.013	0.563	0.240	5.520	1.747	0.318	3.455
4	O_1	0.4	160	1	160	330	2.0625	1	rocking	0.072	0.041	0.019	0.564	0.269	10.129	3.227	0.733	6.169
5	O_1	0.5	160	1	160	330	2.0625	1	rocking	0.091	0.041	0.023	0.448	0.252	16.327	3.284	1.033	12.010
6	O_1	0.6	160	1	160	330	2.0625	1	rocking, waves break just before structure	0.083	0.040	0.023	0.480	0.282	13.387	3.085	1.067	9.234
7	O_1	0.7	160	1	160	330	2.0625	1	rocking, waves break before structure	0.073	0.040	0.027	0.546	0.372	10.422	3.105	1.443	5.875
8	O_1	0.2	160	2	160	330	2.0625	1	rocking	0.049	0.044	0.015	0.896	0.301	18.696	15.008	1.689	1.999
9	O_1	0.3	160	2	160	330	2.0625	1	rocking and 150mm displacement	0.086	0.068	0.021	0.785	0.249	58.323	35.982	3.608	18.733
10	O_1	0.4	160	2	160	330	2.0625	1	rocking and 300mm displacement	0.120	0.060	0.003	0.500	0.025	113.899	28.492	0.072	85.334
11	O_1	0.5	160	2	160	330	2.0625	1	waves break before structure, rocking and 200-250mm displacement	0.088	0.070	0.035	0.800	0.404	60.464	38.731	9.859	11.874
12	O_1	0.6	160	2	160	330	2.0625	1	waves break well short of structure, rocking and 150mm displacement	0.087	0.058	0.048	0.667	0.552	59.560	26.509	18.124	14.927
13	O_1	0.2	160	3	160	330	2.0625	1	no bag movement	0.025	0.014	0.007	0.577	0.263	11.050	3.680	0.765	6.605
14	O_1	0.3	160	3	160	330	2.0625	1	rocking	0.037	0.023	0.013	0.623	0.359	24.367	9.451	3.149	11.767
15	O_1	0.4	160	3	160	330	2.0625	1	rocking and 100mm displacement	0.068	0.052	0.017	0.758	0.248	82.466	47.357	5.060	30.049
16	O_1	0.5	160	3	160	330	2.0625	1	rocking and 280mm displacement	0.101	0.063	0.032	0.632	0.317	178.356	71.156	17.877	89.323
17	O_1	0.6	160	3	160	330	2.0625	1	waves break at structure, rocking and 250mm displacement	0.116	0.052	0.047	0.446	0.402	237.426	47.242	38.421	151.764
18	O_1	0.7	160	3	160	330	2.0625	1	waves break well short of structure, rocking and 120mm displacement	0.093	0.057	0.056	0.615	0.603	153.580	58.112	55.848	39.621
19	O_2	0.2	160	1	320	330	2.0625	2	no bag movement	0.035	0.006	0.015	0.169	0.442	2.350	0.067	0.459	1.824
20	O_2	0.3	160	1	320	330	2.0625	2	no bag movement	0.051	0.007	0.021	0.135	0.420	5.023	0.092	0.886	4.044
21	O_2	0.4	160	1	320	330	2.0625	2	no bag movement	0.069	0.007	0.029	0.107	0.419	9.434	0.107	1.657	7.670
22	O_2	0.5	160	1	320	330	2.0625	2	no bag movement	0.092	0.009	0.033	0.097	0.355	16.733	0.159	2.105	14.469
23	O_2	0.6	160	1	320	330	2.0625	2	waves break just before structure, no bag movement	0.066	0.006	0.028	0.091	0.421	8.674	0.071	1.541	7.062
24	O_2	0.7	160	1	320	330	2.0625	2	waves break just before structure, no bag movement	0.063	0.008	0.029	0.123	0.457	7.790	0.118	1.625	6.046
25	O_2	0.8	160	1	320	330	2.0625	2	waves break well short of structure, no bag movement	0.062	0.007	0.033	0.112	0.527	7.651	0.097	2.126	5.428
26	O_2	0.2	160	2	320	330	2.0625	2	no bag movement	0.047	0.010	0.023	0.209	0.483	17.283	0.752	4.031	12.500
27	O_2	0.3	160	2	320	330	2.0625	2	no bag movement	0.077	0.012	0.034	0.156	0.448	46.104	1.118	9.264	35.721
28	O_2	0.4	160	2	320	330	2.0625	2	crest bag rocking	0.113	0.013	0.052	0.117	0.462	100.395	1.377	21.457	77.561
29	O_2	0.5	160	2	320	330	2.0625	2	waves break just before structure, less crest bag rocking	0.107	0.014	0.050	0.133	0.471	89.258	1.583	19.817	67.858
30	O_2	0.6	160	2	320	330	2.0625	2	waves break well short of structure, no bag movement	0.093	0.014	0.046	0.151	0.498	67.297	1.536	16.711	49.051
31	O_2	0.2	160	3	320	330	2.0625	2	no bag movement	0.023	0.006	0.008	0.267	0.331	9.247	0.660	1.012	7.575
32	O_2	0.3	160	3	320	330	2.0625	2	no bag movement	0.044	0.011	0.021	0.259	0.479	33.768	2.269	7.755	23.745
33	O_2	0.4	160	3	320	330	2.0625	2	no bag movement	0.066	0.013	0.035	0.193	0.531	76.524	2.843	21.612	52.069
34	O_2	0.5	160	3	320	330	2.0625	2	crest bag rocking	0.093	0.010	0.032	0.103	0.346	152.138	1.625	18.231	132.282
35	O_2	0.6	160	3	320	330	2.0625	2	waves break at structure, crest bag rocking	0.132	0.017	0.036	0.132	0.270	309.605	5.369	22.591	281.645
36	O_2	0.7	160	3	320	330	2.0625	2	waves break before structure, no rocking nor displacement	0.103	0.013	0.064	0.129	0.621	186.229	3.098	71.790	111.342
37	O_2	0.1	320	1	320	330	1.03125	1	no bag movement	0.016	0.006	0.003	0.381	0.163	0.527	0.076	0.014	0.437
38	O_2	0.2	320	1	320	330	1.03125	1	no bag movement	0.039	0.015	0.006	0.392	0.146	2.917	0.449	0.062	2.406
39	O_2	0.3	320	1	320	330	1.03125	1	no bag movement	0.063	0.028	0.009	0.439	0.141	7.712	1.488	0.153	6.071
40	O_2	0.4	320	1	320	330	1.03125	1	slight crest bag rocking	0.085	0.044	0.013	0.521	0.151	14.055	3.820	0.321	9.915
41	O_2	0.5	320	1	320	330	1.03125	1	crest bag rocking	0.105	0.054	0.019	0.517	0.182	21.457	5.740	0.708	15.009
42	O_2	0.6	320	1	320	330	1.03125	1	crest bag rocking	0.113	0.063	0.025	0.560	0.221	24.863	7.809	1.209	15.844
43	O_2	0.7	320	1	320	330	1.03125	1	waves break at structure, crest bag rocking	0.137	0.062	0.029	0.455	0.208	36.921	7.647	1.604	27.670
44	O_2	0.8	320	1	320	330	1.03125	1	waves break at structure, crest bag rocking	0.144	0.066	0.037	0.458	0.258	40.656	8.515	2.703	29.438
45	O_2	0.9	320	1	320	330	1.03125	1	waves break before structure, crest bag rocking	0.142	0.066	0.034	0.464	0.237	39.530	8.515	2.216	28.800
46	O_2	0.2	320	2	320	330	1.03125	1	no bag movement	0.041	0.028	0.017	0.677	0.425	13.316	6.095	2.401	4.819
47	O_2	0.3	320	2	320	330	1.03125	1	slight crest bag rocking	0.066	0.046	0.028	0.703	0.424	33.752	16.665	6.081	11.005

Test	ID	Calibration Factor	d (mm)	T (s)	h_c (mm)	B (mm)	B/d	h_c/d	Observations	H_i (m)	H_t (m)	H_r (m)	K_t	K_r	E_i (J/m)	E_t (J/m)	E_r (J/m)	E_d (J/m)
48	O_2	0.4	320	2	320	330	1.03125	1	crest bag rocking	0.089	0.072	0.035	0.812	0.393	62.116	40.975	9.588	11.553
49	O_2	0.5	320	2	320	330	1.03125	1	crest bag rocking	0.112	0.074	0.046	0.659	0.408	98.291	42.663	16.349	39.279
50	O_2	0.6	320	2	320	330	1.03125	1	crest bag rocking, entire structure displacement 180mm	0.137	0.087	0.053	0.636	0.383	148.156	59.860	21.767	66.529
51	O_2	0.7	320	2	320	330	1.03125	1	crest bag rocking, entire structure displacement 250mm	0.158	0.099	0.052	0.628	0.329	195.708	77.206	21.149	97.352
52	O_2	0.8	320	2	320	330	1.03125	1	crest bag rocking, entire structure displacement 300mm	0.201	0.166	0.066	0.826	0.326	316.385	215.982	33.688	66.716
53	O_2	0.9	320	2	320	330	1.03125	1	waves break before structure, crest bag rocking, entire structure displacement 230mm	0.176	0.120	0.071	0.683	0.403	242.719	113.366	39.478	89.875
54	O_2	1	320	2	320	330	1.03125	1	waves break well short of structure, crest bag rocking, entire structure displacement 120mm	0.159	0.125	0.078	0.784	0.490	199.024	122.410	47.720	28.893
55	O_2	0.2	320	3	320	330	1.03125	1	no bag movement	0.024	0.021	0.016	0.888	0.657	10.288	8.118	4.443	-2.273
56	O_2	0.3	320	3	320	330	1.03125	1	no bag movement	0.032	0.028	0.021	0.883	0.667	17.631	13.745	7.836	-3.950
57	O_2	0.4	320	3	320	330	1.03125	1	crest bag rocking	0.047	0.044	0.032	0.924	0.673	39.460	33.671	17.877	-12.088
58	O_2	0.5	320	3	320	330	1.03125	1	crest bag rocking	0.066	0.058	0.030	0.875	0.459	76.889	58.876	16.192	1.821
59	O_2	0.6	320	3	320	330	1.03125	1	crest bag rocking, entire structure displacement 250mm	0.102	0.094	0.050	0.926	0.493	183.003	157.006	44.422	-18.425
60	O_2	0.7	320	3	320	330	1.03125	1	crest bag rocking and sliding, entire structure displacement 490mm	0.127	0.112	0.061	0.886	0.478	283.359	222.644	64.636	-3.921
61	O_2	0.8	320	3	320	330	1.03125	1	crest bag rocking and sliding, entire structure displacement 1010mm, probe pushed back	0.162	0.140	0.068	0.864	0.418	464.709	346.717	81.147	36.845
62	O_2	0.9	320	3	320	330	1.03125	1	waves break before structure, crest bag rocking, entire structure displacement 960mm	0.182	0.168	0.076	0.928	0.419	581.724	501.322	102.043	-21.641
63	O_2	1	320	3	320	330	1.03125	1	waves break well short of structure, crest bag rocking, entire structure displacement 810mm	0.151	0.131	0.092	0.867	0.606	404.813	304.641	148.461	-48.289
64	O_3	0.2	160	1	400	330	2.0625	2.5	no bag movement	0.035	0.031	0.014	0.889	0.415	2.341	1.852	0.404	0.086
65	O_3	0.6	160	3	400	330	2.0625	2.5	no bag movement	0.125	0.010	0.046	0.077	0.367	275.837	1.646	37.141	237.050
66	O_3	0.3	320	1	400	330	1.03125	1.25	no bag movement	0.066	0.004	0.010	0.057	0.151	8.633	0.028	0.197	8.408
67	O_3	0.4	320	1	400	330	1.03125	1.25	no bag movement	0.085	0.005	0.017	0.063	0.198	14.102	0.057	0.552	13.494
68	O_3	0.5	320	1	400	330	1.03125	1.25	slight crest bag rocking, front lifts	0.095	0.005	0.025	0.056	0.260	17.818	0.057	1.206	16.555
69	O_3	0.6	320	1	400	330	1.03125	1.25	slight crest bag rocking, front lifts	0.104	0.008	0.028	0.077	0.273	21.149	0.124	1.576	19.450
70	O_3	0.7	320	1	400	330	1.03125	1.25	small sections of waves break before structure, slight crest bag rocking, front lifts	0.120	0.009	0.036	0.074	0.299	28.164	0.153	2.519	25.492
71	O_3	0.8	320	1	400	330	1.03125	1.25	small sections of waves break before structure, slight crest bag rocking, front lifts	0.143	0.011	0.040	0.074	0.280	40.223	0.218	3.149	36.856
72	O_3	0.9	320	1	400	330	1.03125	1.25	waves break well short of structure, slight crest bag rocking, front lifts	0.149	0.012	0.044	0.082	0.292	43.685	0.291	3.736	39.658
73	O_3	0.2	320	2	400	330	1.03125	1.25	no bag movement	0.043	0.014	0.021	0.326	0.499	14.370	1.524	3.577	9.268
74	O_3	0.3	320	2	400	330	1.03125	1.25	no bag movement	0.065	0.018	0.030	0.278	0.455	33.623	2.594	6.953	24.076
75	O_3	0.4	320	2	400	330	1.03125	1.25	no bag movement	0.082	0.022	0.045	0.271	0.552	53.142	3.893	16.215	33.034
76	O_3	0.5	320	2	400	330	1.03125	1.25	crest bag rocking	0.126	0.032	0.052	0.257	0.412	124.260	8.214	21.047	94.999
77	O_3	0.6	320	2	400	330	1.03125	1.25	crest bag rocking	0.126	0.042	0.063	0.335	0.497	124.818	13.993	30.787	80.038
78	O_3	0.7	320	2	400	330	1.03125	1.25	crest bag rocking	0.150	0.054	0.073	0.362	0.490	176.137	23.135	42.229	110.773
79	O_3	0.8	320	2	400	330	1.03125	1.25	crest bag rocking, entire structure displacement 210mm	0.192	0.074	0.079	0.385	0.413	288.855	42.881	49.170	196.804
80	O_3	0.9	320	2	400	330	1.03125	1.25	waves break before structure, crest bag rocking, entire structure displacement 170mm	0.169	0.063	0.073	0.374	0.432	223.847	31.344	41.689	150.814
81	O_3	1	320	2	400	330	1.03125	1.25	waves break well short of structure, crest bag rocking, entire structure displacement 100mm	0.153	0.066	0.074	0.434	0.481	184.226	34.662	42.591	106.974
82	O_3	0.2	320	3	400	330	1.03125	1.25	no bag movement	0.023	0.009	0.015	0.366	0.642	9.689	1.299	3.998	4.392
83	O_3	0.3	320	3	400	330	1.03125	1.25	no bag movement	0.038	0.012	0.029	0.323	0.770	25.364	2.639	15.040	7.684
84	O_3	0.4	320	3	400	330	1.03125	1.25	slight lifting at front of crest bag	0.053	0.015	0.033	0.287	0.635	48.976	4.023	19.737	25.215
85	O_3	0.5	320	3	400	330	1.03125	1.25	slight lifting at front of crest bag	0.068	0.019	0.048	0.280	0.711	82.088	6.436	41.528	34.124
86	O_3	0.6	320	3	400	330	1.03125	1.25	crest bag rocking	0.097	0.041	0.049	0.430	0.507	164.612	30.373	42.283	91.956
87	O_3	0.7	320	3	400	330	1.03125	1.25	crest bag rocking, entire structure displacement 200mm	0.108	0.046	0.050	0.424	0.464	206.537	37.191	44.422	124.924
88	O_3	0.8	320	3	400	330	1.03125	1.25	crest bag rocking, entire structure displacement 1040mm, probe 9 pushed and knocked over	0.149	0.070	0.053	0.473	0.353	389.867	87.067	48.684	254.115
89	O_3	0.9	320	3	400	330	1.03125	1.25	waves half break before structure, crest bag rocking, entire structure displacement 1320mm	0.182	0.095	0.080	0.521	0.438	581.724	157.737	111.731	312.256
90	O_3	1	320	3	400	330	1.03125	1.25	waves break well short of structure, crest bag rocking, entire structure displacement 1250mm	0.175	0.101	0.059	0.576	0.335	543.200	180.140	61.005	302.056
91	O_3	0.1	400	1	400	330	0.825	1	no bag movement	0.018	0.003	0.002	0.171	0.121	0.657	0.019	0.010	0.628
92	O_3	0.2	400	1	400	330	0.825	1	no bag movement	0.039	0.010	0.004	0.260	0.092	3.050	0.207	0.026	2.817
93	O_3	0.3	400	1	400	330	0.825	1	no bag movement	0.073	0.008	0.004	0.112	0.049	10.521	0.133	0.026	10.362
94	O_3	0.4	400	1	400	330	0.825	1	slight crest bag rocking	0.100	0.023	0.005	0.229	0.054	19.571	1.027	0.057	18.486

Test	ID	Calibration Factor	d (mm)	T (s)	h_c (mm)	B (mm)	B/d	h_c/d	Observations	H_i (m)	H_t (m)	H_r (m)	K_t	K_r	E_i (J/m)	E_t (J/m)	E_r (J/m)	E_d (J/m)
95	O_3	0.5	400	1	400	330	0.825	1	crest bag rocking	0.125	0.048	0.011	0.384	0.084	30.587	4.513	0.218	25.856
96	O_3	0.6	400	1	400	330	0.825	1	crest bag rocking	0.123	0.050	0.011	0.408	0.086	29.521	4.911	0.218	24.393
97	O_3	0.7	400	1	400	330	0.825	1	crest bag rocking	0.138	0.052	0.022	0.375	0.162	37.327	5.240	0.977	31.110
98	O_3	0.8	400	1	400	330	0.825	1	waves break at structure, crest bag rocking	0.146	0.071	0.036	0.484	0.244	41.941	9.839	2.488	29.614
99	O_3	0.9	400	1	400	330	0.825	1	waves break just before structure, crest bag rocking	0.140	0.070	0.039	0.501	0.279	38.697	9.709	3.017	25.971
100	O_3	1	400	1	400	330	0.825	1	waves break well short of structure, crest bag rocking	0.156	0.067	0.035	0.432	0.225	47.893	8.921	2.419	36.554
101	O_3	0.1	400	2	400	330	0.825	1	no bag movement	0.023	0.011	0.010	0.487	0.425	4.235	1.006	0.765	2.463
102	O_3	0.2	400	2	400	330	0.825	1	no bag movement	0.036	0.018	0.012	0.495	0.346	10.067	2.464	1.206	6.396
103	O_3	0.3	400	2	400	330	0.825	1	slight crest bag rocking	0.067	0.024	0.014	0.356	0.201	35.683	4.531	1.439	29.712
104	O_3	0.4	400	2	400	330	0.825	1	slight crest bag rocking	0.090	0.046	0.026	0.507	0.285	63.835	16.394	5.173	42.267
105	O_3	0.5	400	2	400	330	0.825	1	crest bag rocking	0.130	0.086	0.035	0.659	0.272	132.184	57.478	9.795	64.910
106	O_3	0.6	400	2	400	330	0.825	1	crest bag rocking	0.128	0.095	0.042	0.743	0.329	127.752	70.525	13.869	43.358
107	O_3	0.7	400	2	400	330	0.825	1	major crest bag rocking, entire structure displacement 90mm	0.142	0.099	0.030	0.696	0.211	158.960	76.962	7.108	74.891
108	O_3	0.8	400	2	400	330	0.825	1	major crest bag rocking, entire structure displacement 280mm	0.148	0.115	0.047	0.774	0.315	172.544	103.479	17.122	51.943
109	O_3	0.9	400	2	400	330	0.825	1	major crest bag rocking, entire structure displacement 330mm	0.150	0.119	0.050	0.791	0.334	176.765	110.633	19.743	46.389
110	O_3	1	400	2	400	330	0.825	1	waves break at landward side of structure, major crest bag rocking, entire structure displacement 330m	0.155	0.147	0.060	0.948	0.388	187.596	168.555	28.209	-9.167
111	O_3	1.1	400	2	400	330	0.825	1	waves break just before structure, major crest bag rocking, entire structure displacement 350mm	0.146	0.139	0.071	0.952	0.488	167.619	152.035	39.915	-24.332
112	O_3	0.3	400	3	400	330	0.825	1	crest bag rocking	0.046	0.044	0.019	0.955	0.416	37.039	33.768	6.415	-3.144
113	O_3	0.7	400	3	400	330	0.825	1	crest bag rocking, entire structure displacement 180mm, crest bag displaced to back of structure	0.137	0.112	0.044	0.815	0.320	332.136	220.412	34.011	77.713
114	O_3	0.8	400	3	400	330	0.825	1	crest bag rocking, entire structure displacement 650mm, crest bag displaced	0.144	0.144	0.026	1.000	0.180	367.177	367.177	11.897	-11.897
115	S_1	0.5	160	1	120	360	2.25	0.75	No bag movement	0.039	0.023	0.015	0.589	0.394	2.931	1.018	0.455	1.457
116	S_1	0.6	160	1	120	360	2.25	0.75	No bag movement	0.053	0.026	0.022	0.488	0.414	5.572	1.327	0.954	3.291
117	S_1	0.7	160	1	120	360	2.25	0.75	No bag movement	0.056	0.025	0.020	0.451	0.359	6.123	1.246	0.791	4.085
118	S_1	0.5	160	1	120	360	2.25	0.75	No bag movement	0.039	0.023	0.006	0.581	0.143	2.965	0.999	0.061	1.904
119	S_1	0.6	160	1	120	360	2.25	0.75	No bag movement	0.046	0.017	0.020	0.379	0.442	4.175	0.600	0.815	2.760
120	S_1	0.7	160	1	120	360	2.25	0.75	No bag movement	0.051	0.032	0.020	0.621	0.391	5.154	1.986	0.787	2.381
121	S_1	0.2	160	2	120	360	2.25	0.75	No bag movement	0.047	0.043	0.008	0.915	0.179	17.145	14.370	0.550	2.225
122	S_1	0.4	160	2	120	360	2.25	0.75	No bag movement	0.103	0.075	0.020	0.731	0.197	83.123	44.422	3.238	35.462
123	S_1	0.5	160	2	120	360	2.25	0.75	No bag movement	0.077	0.069	0.026	0.897	0.335	45.991	37.039	5.173	3.778
124	S_1	0.3	160	3	120	360	2.25	0.75	No bag movement	0.052	0.040	0.012	0.765	0.234	47.558	27.856	2.599	17.103
125	S_1	0.5	160	3	120	360	2.25	0.75	No bag movement	0.084	0.047	0.018	0.559	0.218	124.632	38.965	5.938	79.729
126	S_1	0.6	160	3	120	360	2.25	0.75	No bag movement	0.065	0.051	0.023	0.779	0.352	75.652	45.878	9.374	20.400
127	S_1	0.7	160	3	120	360	2.25	0.75	No bag movement	0.076	0.051	0.025	0.674	0.330	102.971	46.813	11.217	44.941
128	M_{11}	0.5	160	1	140	490	3.0625	0.875	slight lifting at front of oyster bag	0.074	0.033	0.024	0.448	0.322	10.720	2.150	1.114	7.457
129	M_{11}	0.6	160	1	140	490	3.0625	0.875	slight rocking of oyster bag	0.057	0.032	0.018	0.553	0.321	6.457	1.977	0.667	3.814
130	M_{11}	0.7	160	1	140	490	3.0625	0.875	slight rocking of oyster bag	0.066	0.036	0.017	0.545	0.265	8.478	2.517	0.594	5.368
131	M_{11}	0.2	160	2	140	490	3.0625	0.875	slight rocking of oyster bag	0.047	0.028	0.006	0.602	0.123	17.561	6.362	0.267	10.933
132	M_{11}	0.4	160	2	140	490	3.0625	0.875	rocking of oyster bag	0.100	0.047	0.020	0.469	0.202	78.578	17.306	3.208	58.064
133	M_{11}	0.5	160	2	140	490	3.0625	0.875	rocking of oyster bag	0.092	0.041	0.032	0.447	0.351	66.344	13.285	8.166	44.893
134	M_{11}	0.3	160	3	140	490	3.0625	0.875	slight rocking of oyster bag	0.053	0.026	0.014	0.489	0.272	49.502	11.832	3.656	34.014
135	M_{11}	0.5	160	3	140	490	3.0625	0.875	rocking of oyster bag	0.103	0.033	0.021	0.323	0.202	185.775	19.350	7.559	158.866
136	M_{11}	0.6	160	3	140	490	3.0625	0.875	rocking of oyster bag	0.074	0.029	0.022	0.391	0.291	97.302	14.911	8.261	74.129
137	M_{11}	0.7	160	3	140	490	3.0625	0.875	rocking of oyster bag	0.076	0.030	0.019	0.394	0.253	101.203	15.727	6.499	78.977
138	M_{24}	0.5	160	1	260	360	2.25	1.625	no bag movement	0.052	0.010	0.013	0.190	0.256	5.345	0.194	0.350	4.801
139	M_{24}	0.6	160	1	260	360	2.25	1.625	no bag movement	0.053	0.008	0.017	0.161	0.324	5.481	0.142	0.575	4.764
140	M_{24}	0.7	160	1	260	360	2.25	1.625	no bag movement	0.063	0.010	0.015	0.154	0.239	7.751	0.184	0.444	7.122
141	M_{24}	0.2	160	2	260	360	2.25	1.625	no bag movement	0.042	0.010	0.021	0.235	0.493	13.683	0.755	3.329	9.600

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142	M_{24}	0.4	160	2	260	360	2.25	1.625	no bag movement	0.107	0.017	0.024	0.161	0.222	89.258	2.305	4.408	82.545
143	M_{24}	0.5	160	2	260	360	2.25	1.625	no bag movement	0.088	0.024	0.035	0.277	0.397	60.766	4.674	9.554	46.539
144	M_{24}	0.3	160	3	260	360	2.25	1.625	no bag movement	0.052	0.010	0.033	0.187	0.630	47.932	1.669	19.022	27.241
145	M_{24}	0.5	160	3	260	360	2.25	1.625	no bag movement	0.103	0.023	0.051	0.226	0.491	187.596	9.605	45.203	132.788
146	M_{24}	0.6	160	3	260	360	2.25	1.625	no bag movement	0.102	0.020	0.048	0.201	0.471	182.271	7.388	40.408	134.475
147	M_{24}	0.7	160	3	260	360	2.25	1.625	no bag movement	0.077	0.026	0.053	0.342	0.693	103.564	12.142	49.678	41.744
148	M_{24}	0.4	320	1	260	360	1.125	0.8125	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
149	M_{24}	0.4	320	1	260	360	1.125	0.8125	no bag movement	0.082	0.041	0.004	0.501	0.044	13.336	3.344	0.026	9.966
150	M_{24}	0.6	320	1	260	360	1.125	0.8125	no bag movement	0.110	0.049	0.014	0.441	0.124	23.903	4.644	0.370	18.889
151	M_{24}	0.8	320	1	260	360	1.125	0.8125	no bag movement	0.125	0.079	0.028	0.633	0.221	30.602	12.244	1.493	16.866
152	M_{24}	0.9	320	1	260	360	1.125	0.8125	no bag movement	0.103	0.071	0.024	0.693	0.235	20.844	9.996	1.155	9.693
153	M_{24}	0.3	320	2	260	360	1.125	0.8125	no bag movement	0.071	0.071	0.022	0.999	0.318	39.112	39.043	3.948	-3.879
154	M_{24}	0.5	320	2	260	360	1.125	0.8125	no bag movement	0.120	0.097	0.022	0.809	0.180	112.392	73.541	3.629	35.221
155	M_{24}	0.8	320	2	260	360	1.125	0.8125	no bag movement	0.216	0.151	0.056	0.699	0.261	367.177	179.470	24.987	162.719
156	M_{24}	0.9	320	2	260	360	1.125	0.8125	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
157	M_{24}	0.9	320	2	260	360	1.125	0.8125	no bag movement	0.161	0.112	0.072	0.696	0.447	204.546	98.953	40.797	64.796
158	M_{24}	1	320	2	260	360	1.125	0.8125	no bag movement	0.163	0.145	0.085	0.894	0.523	207.736	166.040	56.744	-15.048
159	M_{24}	0.5	320	3	260	360	1.125	0.8125	no bag movement	0.081	0.075	0.022	0.932	0.275	114.611	99.451	8.674	6.487
160	M_{24}	0.8	320	3	260	360	1.125	0.8125	no bag movement	0.170	0.147	0.051	0.869	0.299	507.873	383.315	45.540	79.018
161	M_{24}	0.9	320	3	260	360	1.125	0.8125	oyster bag and crest sand bag rocking	0.224	0.137	0.053	0.613	0.236	884.620	332.896	49.414	502.310
162	M_{24}	1	320	3	260	360	1.125	0.8125	oyster bag and crest sand bag rocking	0.152	0.108	0.061	0.713	0.400	406.071	206.537	64.971	134.563
163	M_{22}	0.5	160	1	280	360	2.25	1.75	no bag movement	0.068	0.005	0.009	0.071	0.135	9.121	0.046	0.167	8.908
164	M_{22}	0.6	160	1	280	360	2.25	1.75	no bag movement	0.055	0.007	0.014	0.129	0.266	5.837	0.097	0.412	5.328
165	M_{22}	0.7	160	1	280	360	2.25	1.75	no bag movement	0.074	0.008	0.017	0.114	0.235	10.611	0.139	0.587	9.885
166	M_{22}	0.2	160	2	280	360	2.25	1.75	no bag movement	0.049	0.009	0.015	0.190	0.298	18.986	0.686	1.689	16.611
167	M_{22}	0.4	160	2	280	360	2.25	1.75	no bag movement	0.119	0.024	0.034	0.205	0.281	111.833	4.701	8.846	98.286
168	M_{22}	0.5	160	2	280	360	2.25	1.75	no bag movement	0.091	0.018	0.038	0.193	0.417	64.770	2.414	11.254	51.102
169	M_{22}	0.3	160	3	280	360	2.25	1.75	no bag movement	0.052	0.009	0.030	0.176	0.574	48.568	1.512	15.992	31.064
170	M_{22}	0.5	160	3	280	360	2.25	1.75	no bag movement	0.099	0.019	0.043	0.193	0.439	171.415	6.362	33.046	132.007
171	M_{22}	0.6	160	3	280	360	2.25	1.75	no bag movement	0.111	0.029	0.038	0.264	0.339	215.982	15.089	24.863	176.030
172	M_{22}	0.7	160	3	280	360	2.25	1.75	no bag movement	0.086	0.022	0.057	0.256	0.672	129.326	8.454	58.366	62.506
173	M_{22}	0.4	320	1	280	360	1.125	0.875	no bag movement	0.071	0.048	0.006	0.673	0.091	9.848	4.460	0.081	5.306
174	M_{22}	0.6	320	1	280	360	1.125	0.875	no bag movement	0.118	0.059	0.020	0.498	0.165	27.549	6.844	0.748	19.957
175	M_{22}	0.8	320	1	280	360	1.125	0.875	no bag movement	0.113	0.061	0.022	0.541	0.195	25.113	7.354	0.950	16.808
176	M_{22}	0.9	320	1	280	360	1.125	0.875	no bag movement	0.124	0.063	0.025	0.510	0.198	30.113	7.828	1.182	21.102
177	M_{22}	0.3	320	2	280	360	1.125	0.875	no bag movement	0.071	0.069	0.020	0.967	0.280	40.091	37.463	3.149	-0.521
178	M_{22}	0.5	320	2	280	360	1.125	0.875	no bag movement	0.109	0.077	0.027	0.710	0.244	92.969	46.823	5.533	40.613
179	M_{22}	0.8	320	2	280	360	1.125	0.875	entire structure displacement 70mm	0.203	0.102	0.059	0.501	0.291	322.340	80.959	27.258	214.123
180	M_{22}	0.9	320	2	280	360	1.125	0.875	entire structure displacement 50mm	0.189	0.127	0.074	0.671	0.391	281.120	126.499	43.045	111.576
181	M_{22}	1	320	2	280	360	1.125	0.875	entire structure displacement 30mm	0.153	0.111	0.080	0.725	0.521	183.285	96.428	49.658	37.199
182	M_{22}	0.5	320	3	280	360	1.125	0.875	no bag movement	0.082	0.081	0.025	0.979	0.306	120.025	114.968	11.245	-6.188
183	M_{22}	0.8	320	3	280	360	1.125	0.875	entire structure displacement 240mm	0.195	0.104	0.049	0.533	0.249	672.418	191.265	41.689	439.463
184	M_{22}	0.9	320	3	280	360	1.125	0.875	entire structure displacement 380mm	0.183	0.134	0.070	0.734	0.381	590.802	317.869	85.905	187.028
185	M_{22}	1	320	3	280	360	1.125	0.875	entire structure displacement 260mm	0.144	0.114	0.087	0.793	0.600	367.976	231.178	132.423	4.375
186	O_4	0.5	160	1	160	600	3.75	1	slight rocking of front bag	0.091	0.032	0.025	0.350	0.271	16.193	1.982	1.191	13.019
187	O_4	0.6	160	1	160	600	3.75	1	slight rocking of front bag	0.088	0.035	0.027	0.395	0.307	15.267	2.382	1.439	11.446
188	O_4	0.7	160	1	160	600	3.75	1	slight rocking of front bag	0.064	0.033	0.026	0.512	0.401	7.984	2.093	1.284	4.607

Test	ID	Calibration Factor	d (mm)	T (s)	h_c (mm)	B (mm)	B/d	h_c/d	Observations	H_i (m)	H_t (m)	H_r (m)	K_t	K_r	E_i (J/m)	E_t (J/m)	E_r (J/m)	E_d (J/m)
189	O_4	0.2	160	2	160	600	3.75	1	no bag movement	0.048	0.029	0.019	0.608	0.400	18.266	6.757	2.917	8.593
190	O_4	0.4	160	2	160	600	3.75	1	both bags rock, entire structure displacement 100mm	0.111	0.041	0.027	0.372	0.247	95.992	13.285	5.837	76.869
191	O_4	0.5	160	2	160	600	3.75	1	both bags rock, entire structure displacement 70mm	0.092	0.051	0.029	0.551	0.318	66.028	20.040	6.685	39.303
192	O_4	0.3	160	3	160	600	3.75	1	little to no bag movement	0.041	0.018	0.016	0.443	0.398	29.145	5.712	4.620	18.813
193	O_4	0.5	160	3	160	600	3.75	1	both bags rock, entire structure displacment 110mm	0.092	0.055	0.021	0.597	0.229	147.954	52.778	7.789	87.386
194	O_4	0.6	160	3	160	600	3.75	1	both bags rock, entire structure displacement 200mm	0.122	0.052	0.031	0.426	0.256	261.230	47.357	17.145	196.729
195	O_4	0.7	160	3	160	600	3.75	1	both bags rock, entire structure displacement 80mm	0.093	0.056	0.043	0.599	0.463	153.683	55.103	32.998	65.582
196	M_{13}	0.5	160	1	146.67	960	6	0.917	slight rocking of front bag	0.090	0.024	0.024	0.260	0.270	16.059	1.085	1.173	13.801
197	M_{13}	0.6	160	1	146.67	960	6	0.917	slight rocking of front bag	0.075	0.016	0.030	0.218	0.392	11.161	0.531	1.711	8.919
198	M_{13}	0.7	160	1	146.67	960	6	0.917	slight rocking of front bag	0.068	0.026	0.026	0.391	0.379	8.954	1.366	1.284	6.304
199	M_{13}	0.2	160	2	146.67	960	6	0.917	no bag movement	0.046	0.027	0.019	0.589	0.420	16.394	5.694	2.889	7.812
200	M_{13}	0.2	160	2	146.67	960	6	0.917	no bag movement	0.045	0.020	0.021	0.457	0.464	15.595	3.251	3.359	8.984
201	M_{13}	0.4	160	2	146.67	960	6	0.917	rocking of front bag	0.107	0.039	0.033	0.370	0.313	89.573	12.244	8.797	68.532
202	M_{13}	0.4	160	2	146.67	960	6	0.917	rocking of front bag	0.106	0.034	0.036	0.319	0.334	88.734	9.046	9.918	69.771
203	M_{13}	0.5	160	2	146.67	960	6	0.917	rocking of front bag	0.120	0.041	0.045	0.346	0.380	112.245	13.438	16.193	82.615
204	M_{13}	0.5	160	2	146.67	960	6	0.917	rocking of front bag	0.127	0.037	0.050	0.292	0.399	125.875	10.720	19.991	95.164
205	M_{13}	0.3	160	3	146.67	960	6	0.917	no bag movement	0.043	0.019	0.017	0.452	0.390	32.474	6.627	4.948	20.898
206	M_{13}	0.5	160	3	146.67	960	6	0.917	rocking of front bag	0.093	0.039	0.021	0.424	0.224	151.214	27.243	7.559	116.412
207	M_{13}	0.6	160	3	146.67	960	6	0.917	rocking of front bag	0.115	0.050	0.028	0.431	0.246	233.973	43.538	14.149	176.285
208	M_{13}	0.7	160	3	146.67	960	6	0.917	rocking of front bag	0.099	0.029	0.031	0.292	0.312	173.274	14.815	16.904	141.555
209	M_{26}	0.7	160	1	286.6666667	490	3.0625	1.791666667	no bag movement	0.064	0.003	0.024	0.039	0.370	8.063	0.012	1.102	6.949
210	M_{26}	0.8	160	1	286.6666667	490	3.0625	1.791666667	no bag movement	0.070	0.002	0.024	0.032	0.335	9.674	0.010	1.085	8.579
211	M_{26}	0.4	160	2	286.6666667	490	3.0625	1.791666667	no bag movement	0.101	0.007	0.037	0.072	0.365	80.660	0.422	10.775	69.463
212	M_{26}	0.5	160	2	286.6666667	490	3.0625	1.791666667	slight rocking of oyster crest bag	0.127	0.007	0.049	0.053	0.388	125.875	0.352	18.961	106.562
213	M_{26}	0.6	160	2	286.6666667	490	3.0625	1.791666667	slight rocking of oyster crest bag	0.094	0.005	0.055	0.056	0.587	68.902	0.216	23.754	44.932
214	M_{26}	0.5	160	3	286.6666667	490	3.0625	1.791666667	slight rocking of oyster crest bag	0.099	0.007	0.028	0.066	0.278	173.274	0.755	13.438	159.082
215	M_{26}	0.6	160	3	286.6666667	490	3.0625	1.791666667	slight rocking of oyster crest bag	0.123	0.010	0.029	0.082	0.237	267.734	1.788	15.040	250.905
216	M_{26}	0.7	160	3	286.6666667	490	3.0625	1.791666667	slight rocking of oyster crest bag	0.103	0.006	0.038	0.056	0.368	185.775	0.586	25.154	160.034
217	M_{26}	0.4	320	1	286.6666667	490	1.53125	0.895833333	no bag movement	0.075	0.042	0.007	0.560	0.096	11.152	3.501	0.102	7.549
218	M_{26}	0.6	320	1	286.6666667	490	1.53125	0.895833333	rocking of oyster crest bag	0.108	0.043	0.022	0.401	0.203	22.962	3.688	0.945	18.329
219	M_{26}	0.8	320	1	286.6666667	490	1.53125	0.895833333	rocking of oyster crest bag	0.131	0.050	0.039	0.381	0.298	33.494	4.862	2.974	25.658
220	M_{26}	0.9	320	1	286.6666667	490	1.53125	0.895833333	rocking of oyster crest bag	0.144	0.054	0.035	0.374	0.243	40.780	5.694	2.401	32.684
221	M_{26}	0.3	320	2	286.6666667	490	1.53125	0.895833333	rocking of oyster crest bag	0.073	0.065	0.035	0.893	0.484	41.260	32.902	9.683	-1.325
222	M_{26}	0.5	320	2	286.6666667	490	1.53125	0.895833333	major rocking of crest oyster bag, and slight rocking of base oyster bag	0.120	0.090	0.061	0.745	0.509	113.277	62.906	29.386	20.985
223	M_{26}	0.8	320	2	286.6666667	490	1.53125	0.895833333	major rocking of crest oyster bag, and slight rocking of base oyster bag	0.205	0.111	0.069	0.541	0.334	329.863	96.428	36.904	196.531
224	M_{26}	0.9	320	2	286.6666667	490	1.53125	0.895833333	major rocking of crest oyster bag, and slight rocking of base oyster bag	0.229	0.105	0.069	0.458	0.299	411.546	86.240	36.904	288.401
225	M_{26}	1	320	2	286.6666667	490	1.53125	0.895833333	major rocking of crest oyster bag, and slight rocking of base oyster bag	0.179	0.101	0.073	0.565	0.409	251.890	80.510	42.139	129.240
226	M_{26}	0.5	320	3	286.6666667	490	1.53125	0.895833333	major rocking of crest oyster bag, and slight rocking of base oyster bag	0.058	0.081	0.029	1.396	0.510	58.748	114.433	15.267	-70.952
227	M_{26}	0.8	320	3	286.6666667	490	1.53125	0.895833333	major rocking of crest oyster bag, and slight rocking of base oyster bag	0.149	0.118	0.053	0.789	0.356	391.514	244.019	49.560	97.935
228	M_{26}	0.9	320	3	286.6666667	490	1.53125	0.895833333	major rocking of crest oyster bag, and slight rocking of base oyster bag	0.209	0.104	0.066	0.499	0.316	773.148	192.419	77.438	503.291
229	M_{26}	1	320	3	286.6666667	490	1.53125	0.895833333	major rocking of crest oyster bag, and slight rocking of base oyster bag	0.187	0.124	0.062	0.665	0.332	615.352	272.114	67.685	275.553
230	M_{33}	0.5	160	1	406.6666667	360	2.25	2.541666667	no bag movement (repeated as probe 9 in wrong spot)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
231	M_{33}	0.5	160	1	406.6666667	360	2.25	2.541666667	no bag movement	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
232	M_{33}	0.6	160	1	406.6666667	360	2.25	2.541666667	no bag movement	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
233	M_{33}	0.7	160	1	406.6666667	360	2.25	2.541666667	no bag movement	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
234	M_{33}	0.2	160	2	406.6666667	360	2.25	2.541666667	no bag movement	0.044	0.004	0.018	0.100	0.398	15.398	0.153	2.440	12.804
235	M_{33}	0.4	160	2	406.6666667	360	2.25	2.541666667	no bag movement	0.121	0.007	0.033	0.058	0.276	115.147	0.382	8.747	106.017

Test	ID	Calibration Factor	d (mm)	T (s)	h_c (mm)	B (mm)	B/d	h_c/d	Observations	H_i (m)	H_t (m)	H_r (m)	K_t	K_r	E_i (J/m)	E_t (J/m)	E_r (J/m)	E_d (J/m)
236	M_{33}	0.5	160	2	406.6666667	360	2.25	2.541666667	no bag movement	0.105	0.006	0.043	0.061	0.405	86.705	0.320	14.223	72.163
237	M_{33}	0.3	160	3	406.6666667	360	2.25	2.541666667	no bag movement	0.040	0.005	0.018	0.127	0.438	28.742	0.464	5.520	22.758
238	M_{33}	0.5	160	3	406.6666667	360	2.25	2.541666667	no bag movement	0.105	0.008	0.030	0.080	0.283	194.970	1.243	15.661	178.067
239	M_{33}	0.6	160	3	406.6666667	360	2.25	2.541666667	no bag movement	0.108	0.008	0.037	0.070	0.345	206.298	1.020	24.490	180.788
240	M_{33}	0.7	160	3	406.6666667	360	2.25	2.541666667	no bag movement	0.089	0.008	0.045	0.087	0.513	138.777	1.040	36.483	101.254
241	M_{33}	0.6	320	1	406.6666667	360	1.125	1.270833333	no bag movement	0.092	0.036	0.061	0.387	0.663	16.597	2.479	7.286	6.832
242	M_{33}	0.8	320	1	406.6666667	360	1.125	1.270833333	no bag movement, slight lifting of 2nd tier oyster bag	0.095	0.040	0.055	0.424	0.578	17.713	3.181	5.918	8.614
243	M_{33}	0.9	320	1	406.6666667	360	1.125	1.270833333	no bag movement, slight lifting of 2nd tier oyster bag	0.090	0.031	0.064	0.343	0.707	15.881	1.865	7.945	6.071
244	M_{33}	0.7	320	2	406.6666667	360	1.125	1.270833333	rocking of 2nd tier oyster bag and crest sand bag	0.162	0.076	0.145	0.468	0.896	205.342	44.979	164.968	-4.606
245	M_{33}	0.8	320	2	406.6666667	360	1.125	1.270833333	rocking of 2nd tier oyster bag and crest sand bag	0.193	0.115	0.169	0.597	0.876	293.119	104.498	224.887	-36.267
246	M_{33}	0.9	320	2	406.6666667	360	1.125	1.270833333	rocking of 2nd tier oyster bag and crest sand bag	0.209	0.110	0.177	0.529	0.849	342.079	95.557	246.410	0.111
247	M_{33}	1	320	2	406.6666667	360	1.125	1.270833333	rocking of 2nd tier oyster bag and crest sand bag	0.201	0.078	0.173	0.389	0.864	315.891	47.893	235.846	32.153
248	M_{33}	0.6	320	3	406.6666667	360	1.125	1.270833333	rocking of 2nd tier oyster bag and crest sand bag	0.069	0.058	0.065	0.837	0.933	84.751	59.389	73.708	-48.346
249	M_{33}	0.8	320	3	406.6666667	360	1.125	1.270833333	rocking of 2nd tier oyster bag and crest sand bag	0.092	0.081	0.082	0.882	0.889	149.987	116.582	118.433	-85.027
250	M_{33}	0.9	320	3	406.6666667	360	1.125	1.270833333	rocking of 2nd tier oyster bag and crest sand bag	0.121	0.109	0.117	0.900	0.970	257.206	208.337	242.070	-193.201
251	M_{33}	1	320	3	406.6666667	360	1.125	1.270833333	rocking of 2nd tier oyster bag and crest sand bag	0.147	0.119	0.098	0.805	0.667	383.315	248.463	170.544	-35.692
252	M_{33}	0.7	400	1	406.6666667	360	0.9	1.016666667	slight lifting/rocking of 2nd tier oyster bag	0.084	0.061	0.045	0.726	0.534	13.807	7.286	3.932	2.589
253	M_{33}	0.8	400	1	406.6666667	360	0.9	1.016666667	slight lifting/rocking of 2nd tier oyster bag	0.074	0.052	0.038	0.702	0.514	10.793	5.316	2.846	2.631
254	M_{33}	0.9	400	1	406.6666667	360	0.9	1.016666667	slight lifting/rocking of 2nd tier oyster bag	0.083	0.060	0.050	0.717	0.602	13.642	7.019	4.936	1.687
255	M_{33}	1	400	1	406.6666667	360	0.9	1.016666667	slight lifting/rocking of 2nd tier oyster bag	0.103	0.046	0.060	0.450	0.581	20.781	4.200	7.019	9.561
256	M_{33}	0.4	400	2	406.6666667	360	0.9	1.016666667	slight lifting of 2nd tier oyster bag	0.087	0.075	0.058	0.865	0.672	58.748	43.942	26.538	-11.732
257	M_{33}	0.6	400	2	406.6666667	360	0.9	1.016666667	slight lifting/rocking of 2nd tier oyster bag	0.122	0.106	0.080	0.865	0.658	116.822	87.431	50.543	-21.152
258	M_{33}	0.9	400	2	406.6666667	360	0.9	1.016666667	rocking of 2nd tier oyster bag/crest bag (oysters and sand pushed around)	0.172	0.129	0.129	0.751	0.750	232.234	130.910	130.751	-29.426
259	M_{33}	1	400	2	406.6666667	360	0.9	1.016666667	rocking of 2nd tier oyster bag/crest bag (oysters and sand pushed around - greater shift of sand)	0.160	0.139	0.117	0.872	0.729	200.594	152.446	106.724	-58.576
260	M_{33}	0.3	400	3	406.6666667	360	0.9	1.016666667	no bag movement to gentle lifting of 2nd tier oyster bag	0.025	0.056	0.019	2.183	0.739	11.448	54.548	6.247	-49.346
261	M_{33}	0.7	400	3	406.6666667	360	0.9	1.016666667	rocking of 2nd tier oyster bag/crest bag	0.087	0.105	0.056	1.201	0.648	133.913	193.113	56.222	-115.422
262	M_{33}	0.8	400	3	406.6666667	360	0.9	1.016666667	rocking of 2nd tier oyster bag/crest bag	0.099	0.117	0.057	1.176	0.574	174.648	241.423	57.478	-124.253
263	M_{31}	0.7	400	1	430	360	0.9	1.075	no bag movement	0.069	0.041	0.055	0.595	0.795	9.332	3.304	5.905	0.123
264	M_{31}	0.8	400	1	430	360	0.9	1.075	no bag movement	0.087	0.039	0.058	0.451	0.670	14.815	3.013	6.642	5.161
265	M_{31}	0.9	400	1	430	360	0.9	1.075	no bag movement	0.098	0.052	0.059	0.525	0.604	18.877	5.211	6.887	6.779
266	M_{31}	1	400	1	430	360	0.9	1.075	no bag movement	0.106	0.080	0.072	0.750	0.678	22.131	12.463	10.164	-0.496
267	M_{31}	0.4	400	2	430	360	0.9	1.075	no bag movement	0.082	0.062	0.056	0.761	0.689	52.175	30.235	24.766	-2.826
268	M_{31}	0.6	400	2	430	360	0.9	1.075	no bag movement	0.098	0.079	0.067	0.809	0.688	74.833	48.976	35.385	-9.527
269	M_{31}	0.9	400	2	430	360	0.9	1.075	slight rocking of 2nd tier oyster bag/crest bag	0.138	0.091	0.098	0.661	0.710	149.308	65.173	75.314	8.821
270	M_{31}	1	400	2	430	360	0.9	1.075	slight rocking of 2nt tier oyster bag/crest bag, entire structure displacement 140mm	0.175	0.119	0.138	0.679	0.791	239.700	110.633	149.987	-20.920
271	M_{31}	0.3	400	3	430	360	0.9	1.075	no bag movement	0.034	0.051	0.026	1.515	0.772	19.941	45.765	11.897	-37.720
272	M_{31}	0.7	400	3	430	360	0.9	1.075	slight rocking of 2nd tier oyster bag/crest bag, entire structure displacement 90mm	0.083	0.103	0.055	1.248	0.661	120.939	188.281	52.899	-120.241
273	M_{31}	0.8	400	3	430	360	0.9	1.075	slight rocking of 2nd tier oyster bag/crest bag, entire structure displacement 210mm	0.104	0.113	0.066	1.084	0.631	192.419	226.138	76.524	-110.243
274	M_{32}	0.7	400	1	430	330	0.825	1.075	crest bag rocking	0.066	0.061	0.046	0.918	0.695	8.543	7.197	4.127	-2.780
275	M_{32}	0.8	400	1	430	330	0.825	1.075	crest bag rocking	0.089	0.059	0.056	0.663	0.623	15.650	6.887	6.081	2.681
276	M_{32}	0.9	400	1	430	330	0.825	1.075	crest bag rocking	0.089	0.063	0.050	0.707	0.560	15.420	7.697	4.838	2.885
277	M_{32}	1	400	1	430	330	0.825	1.075	crest bag rocking	0.104	0.079	0.062	0.757	0.595	21.137	12.128	7.490	1.519
278	M_{32}	0.4	400	2	430	330	0.825	1.075	crest bag rocking	0.082	0.062	0.053	0.756	0.652	52.134	29.824	22.131	0.179
279	M_{32}	0.6	400	2	430	330	0.825	1.075	major rocking of crest bag, minor displacement of crest bag approx. 30mm at one end	0.129	0.116	0.053	0.903	0.410	129.768	105.808	21.845	2.115
280	M_{32}	0.9	400	2	430	330	0.825	1.075	crest bag displacement 900mm	0.168	0.158	0.094	0.943	0.558	221.155	196.680	68.832	-44.358
281	M_{32}	1	400	2	430	330	0.825	1.075	crest bag displacement 950mm	0.179	0.131	0.116	0.732	0.645	252.330	135.234	105.010	12.086
282	M_{32}	0.3	400	3	430	330	0.825	1.075	crest bag rocking	0.037	0.051	0.024	1.366	0.635	24.583	45.878	9.918	-31.212

Test	ID	Calibration Factor	d (mm)	T (s)	h_c (mm)	B (mm)	B/d	h_c/d	Observations	H_i (m)	H_t (m)	H_r (m)	K_t	K_r	E_i (J/m)	E_t (J/m)	E_r (J/m)	E_d (J/m)
283	M_{32}	0.7	400	3	430	330	0.825	1.075	crest bag displacement 1150mm	0.076	0.111	0.096	1.451	1.256	102.380	215.615	161.421	-274.656
284	M_{32}	0.8	400	3	430	330	0.825	1.075	crest bag displacement 1500mm	0.100	0.148	0.075	1.470	0.747	178.133	384.948	99.451	-306.265
285	M_{34}	0.7	400	1	400	360	0.9	1	no bag movement	0.062	0.034	0.055	0.549	0.883	7.635	2.299	5.952	-0.616
286	M_{34}	0.8	400	1	400	360	0.9	1	no bag movement	0.081	0.056	0.051	0.691	0.631	13.014	6.219	5.186	1.609
287	M_{34}	0.9	400	1	400	360	0.9	1	no bag movement	0.093	0.055	0.052	0.599	0.566	16.802	6.027	5.390	5.385
288	M_{34}	1	400	1	400	360	0.9	1	no bag movement	0.106	0.064	0.048	0.604	0.452	21.858	7.984	4.460	9.413
289	M_{34}	0.4	400	2	400	360	0.9	1	no bag movement	0.083	0.071	0.057	0.857	0.689	54.159	39.740	25.743	-11.324
290	M_{34}	0.6	400	2	400	360	0.9	1	no bag movement	0.105	0.088	0.066	0.833	0.628	86.653	60.162	34.205	-7.714
291	M_{34}	0.9	400	2	400	360	0.9	1	no bag movement	0.152	0.108	0.108	0.707	0.710	182.346	91.263	91.794	-0.711
292	M_{34}	1	400	2	400	360	0.9	1	no bag movement	0.163	0.123	0.111	0.750	0.679	209.541	117.905	96.510	-4.873
293	M_{34}	0.3	400	3	400	360	0.9	1	no bag movement	0.025	0.047	0.027	1.872	1.055	11.322	39.670	12.596	-40.945
294	M_{34}	0.7	400	3	400	360	0.9	1	no bag movement	0.091	0.100	0.063	1.105	0.691	145.030	177.134	69.271	-101.375
295	M_{34}	0.8	400	3	400	360	0.9	1	no bag movement	0.098	0.123	0.063	1.248	0.639	171.197	266.644	69.897	-165.344
296	M_{35}	0.7	400	1	380	360	0.9	0.95	no bag movement	0.065	0.063	0.043	0.961	0.658	8.342	7.697	3.608	-2.963
297	M_{35}	0.8	400	1	380	360	0.9	0.95	no bag movement	0.084	0.042	0.052	0.500	0.619	13.786	3.444	5.287	5.055
298	M_{35}	0.9	400	1	380	360	0.9	0.95	no bag movement	0.092	0.053	0.056	0.575	0.616	16.462	5.442	6.247	4.773
299	M_{35}	1	400	1	380	360	0.9	0.95	no bag movement	0.081	0.053	0.047	0.660	0.585	12.864	5.598	4.408	2.858
300	M_{35}	0.4	400	2	380	360	0.9	0.95	no bag movement	0.085	0.075	0.055	0.881	0.648	57.226	44.422	23.998	-11.194
301	M_{35}	0.6	400	2	380	360	0.9	0.95	no bag movement	0.127	0.091	0.091	0.716	0.715	125.875	64.458	64.368	-2.951
302	M_{35}	0.9	400	2	380	360	0.9	0.95	rocking of oyster bag and crest bag	0.164	0.111	0.130	0.680	0.792	210.548	97.467	132.024	-18.944
303	M_{35}	1	400	2	380	360	0.9	0.95	rocking of oyster bag and crest bag, crest bag shifts towards 2nd tier sand bag B	0.178	0.131	0.120	0.735	0.674	248.376	134.106	112.834	1.435
304	M_{35}	0.3	400	3	380	360	0.9	0.95	no bag movement	0.026	0.049	0.043	1.928	1.670	11.575	43.045	32.284	-63.753
305	M_{35}	0.7	400	3	380	360	0.9	0.95	rocking of oyster bag and crest bag	0.104	0.133	0.065	1.280	0.631	190.230	311.808	75.652	-197.230
306	M_{35}	0.8	400	3	380	360	0.9	0.95	rocking of oyster bag and crest bag, crest bag shifts towards 2nd tier sand bag B	0.118	0.146	0.058	1.230	0.488	247.938	375.203	59.068	-186.332
307	S_3	0.7	400	1	360	360	0.9	0.9	no bag movement	0.064	0.059	0.056	0.912	0.866	8.118	6.757	6.095	-4.733
308	S_3	0.8	400	1	360	360	0.9	0.9	no bag movement	0.097	0.067	0.050	0.686	0.511	18.552	8.735	4.838	4.980
309	S_3	0.9	400	1	360	360	0.9	0.9	no bag movement	0.084	0.068	0.043	0.806	0.507	13.858	8.995	3.556	1.307
310	S_3	1	400	1	360	360	0.9	0.9	no bag movement	0.098	0.072	0.063	0.732	0.640	18.961	10.155	7.774	1.032
311	S_3	0.4	400	2	360	360	0.9	0.9	no bag movement	0.081	0.088	0.046	1.077	0.569	51.994	60.291	16.824	-25.121
312	S_3	0.6	400	2	360	360	0.9	0.9	no bag movement	0.130	0.103	0.081	0.793	0.618	133.464	83.986	50.938	-1.460
313	S_3	0.9	400	2	360	360	0.9	0.9	no bag movement	0.171	0.130	0.116	0.758	0.678	230.123	132.184	105.865	-7.926
314	S_3	1	400	2	360	360	0.9	0.9	no bag movement	0.184	0.143	0.118	0.778	0.643	266.191	161.068	109.904	-4.781
315	S_3	0.3	400	3	360	360	0.9	0.9	no bag movement	0.038	0.079	0.036	2.098	0.953	25.332	111.511	23.029	-109.207
316	S_3	0.7	400	3	360	360	0.9	0.9	no bag movement	0.091	0.124	0.049	1.358	0.535	146.942	270.878	42.067	-166.003
317	S_3	0.8	400	3	360	360	0.9	0.9	no bag movement	0.105	0.138	0.047	1.318	0.452	194.157	337.472	39.670	-182.985
318	S_3	0.6	320	1	360	360	1.125	1.125	no bag movement	0.072	0.038	0.053	0.525	0.737	10.115	2.790	5.487	1.838
319	S_3	0.8	320	1	360	360	1.125	1.125	no bag movement	0.085	0.041	0.053	0.476	0.622	14.264	3.233	5.520	5.511
320	S_3	0.9	320	1	360	360	1.125	1.125	no bag movement	0.083	0.033	0.071	0.401	0.857	13.499	2.168	9.918	1.413
321	S_3	0.7	320	2	360	360	1.125	1.125	no bag movement	0.137	0.091	0.098	0.664	0.719	146.942	64.770	75.918	6.254
322	S_3	0.8	320	2	360	360	1.125	1.125	no bag movement	0.177	0.083	0.131	0.466	0.740	246.192	53.426	134.912	57.855
323	S_3	0.9	320	2	360	360	1.125	1.125	no bag movement	0.182	0.111	0.138	0.611	0.757	259.885	96.865	148.799	14.221
324	S_3	1	320	2	360	360	1.125	1.125	no bag movement	0.191	0.109	0.136	0.568	0.708	287.441	92.594	144.095	50.752
325	S_3	0.6	320	3	360	360	1.125	1.125	no bag movement	0.077	0.104	0.105	1.343	1.357	105.010	189.426	193.461	-277.877
326	S_3	0.8	320	3	360	360	1.125	1.125	no bag movement	0.120	0.110	0.154	0.922	1.284	252.683	215.003	416.632	-378.952
327	S_3	0.9	320	3	360	360	1.125	1.125	no bag movement	0.144	0.108	0.176	0.746	1.220	367.177	204.149	546.117	-383.090
328	S_3	1	320	3	360	360	1.125	1.125	slight displacement of crest bag, approx 100mm at one end - 50mm average	0.144	0.125	0.172	0.864	1.191	367.177	274.179	520.625	-427.627
329	M_{35}	0.6	320	1	380	360	1.125	1.1875	no bag movement	0.089	0.044	0.056	0.496	0.632	15.661	3.847	6.247	5.567

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330	M_{35}	0.8	320	1	380	360	1.125	1.1875	no bag movement	0.094	0.053	0.074	0.561	0.795	17.225	5.419	10.885	0.922
331	M_{35}	0.9	320	1	380	360	1.125	1.1875	no bag movement	0.097	0.052	0.067	0.538	0.695	18.457	5.339	8.912	4.206
332	M_{35}	0.7	320	2	380	360	1.125	1.1875	no bag movement	0.147	0.089	0.122	0.604	0.833	168.916	61.679	117.302	-10.066
333	M_{35}	0.8	320	2	380	360	1.125	1.1875	slight lifting of oyster bag and crest bag	0.163	0.077	0.145	0.474	0.888	208.939	46.899	164.612	-2.572
334	M_{35}	0.9	320	2	380	360	1.125	1.1875	rocking of oyster bag and crest bag,crest bag shifts towards 2nd tier sand bag B	0.194	0.081	0.150	0.419	0.777	294.547	51.814	177.689	65.044
335	M_{35}	1	320	2	380	360	1.125	1.1875	rocking of oyster bag and crest bag,crest bag shifts towards 2nd tier sand bag B	0.181	0.096	0.137	0.529	0.757	255.872	71.649	146.437	37.786
336	M_{35}	0.6	320	3	380	360	1.125	1.1875	slight lifting of oyster bag and crest bag	0.070	0.081	0.101	1.150	1.434	87.067	115.147	179.135	-207.215
337	M_{35}	0.8	320	3	380	360	1.125	1.1875	rocking of oyster bag and crest bag,crest bag shifts towards 2nd tier sand bag B	0.129	0.138	0.155	1.068	1.201	294.547	336.096	425.178	-466.726
338	M_{35}	0.9	320	3	380	360	1.125	1.1875	rocking of oyster bag and crest bag,crest bag shifts towards 2nd tier sand bag B	0.130	0.137	0.168	1.059	1.293	297.414	333.504	497.598	-533.689
339	M_{35}	1	320	3	380	360	1.125	1.1875	rocking of oyster bag and crest bag,crest bag shifts towards 2nd tier sand bag B	0.163	0.109	0.176	0.670	1.079	471.468	211.354	549.042	-288.928
340	M_{34}	0.6	320	1	400	360	1.125	1.25	no bag movement	0.082	0.032	0.048	0.390	0.583	13.225	2.012	4.502	6.711
341	M_{34}	0.8	320	1	400	360	1.125	1.25	no bag movement	0.075	0.027	0.070	0.361	0.929	11.050	1.439	9.536	0.074
342	M_{34}	0.9	320	1	400	360	1.125	1.25	no bag movement	0.086	0.034	0.071	0.392	0.828	14.370	2.212	9.848	2.310
343	M_{34}	0.7	320	2	400	360	1.125	1.25	no bag movement	0.157	0.119	0.126	0.755	0.799	194.350	110.896	124.167	-40.713
344	M_{34}	0.8	320	2	400	360	1.125	1.25	slight rocking of oyster bags and crest bag	0.182	0.124	0.151	0.682	0.829	261.230	121.429	179.545	-39.743
345	M_{34}	0.9	320	2	400	360	1.125	1.25	slight rocking of oyster bags and crest bag	0.206	0.122	0.169	0.590	0.817	334.418	116.582	223.017	-5.181
346	M_{34}	1	320	2	400	360	1.125	1.25	slight rocking of oyster bags and crest bag	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
347	M_{34}	0.6	320	3	400	360	1.125	1.25	no bag movement	0.066	0.095	0.208	1.433	3.150	76.889	157.947	762.759	-843.816
348	M_{34}	0.8	320	3	400	360	1.125	1.25	rocking of oyster bags/crest bag	0.129	0.129	0.167	1.007	1.301	292.264	296.122	494.815	-498.673
349	M_{34}	0.9	320	3	400	360	1.125	1.25	rocking of oyster bags/crest bag	0.150	0.106	0.141	0.705	0.939	397.803	197.655	350.996	-150.848
350	M_{34}	1	320	3	400	360	1.125	1.25	rocking of oyster bags/crest bag	0.155	0.100	0.181	0.644	1.167	425.178	176.137	578.714	-329.674
351	M_{32}	0.6	320	1	430	330	1.03125	1.34375	slight rocking of crest bag	0.074	0.023	0.041	0.309	0.555	10.784	1.032	3.319	6.433
352	M_{32}	0.8	320	1	430	330	1.03125	1.34375	rocking of crest bag	0.095	0.049	0.074	0.512	0.779	17.701	4.647	10.738	2.316
353	M_{32}	0.9	320	1	430	330	1.03125	1.34375	rocking of crest bag	0.075	0.033	0.061	0.438	0.816	11.115	2.129	7.407	1.579
354	M_{32}	0.7	320	2	430	330	1.03125	1.34375	crest bag displacement 750mm (from original spot, approx 250mm from toe)	0.139	0.088	0.153	0.631	1.102	151.830	60.464	184.415	-93.049
355	M_{32}	0.8	320	2	430	330	1.03125	1.34375	crest bag displacement 750mm	0.166	0.107	0.097	0.647	0.584	215.819	90.416	73.637	51.766
356	M_{32}	0.9	320	2	430	330	1.03125	1.34375	crest bag displacement 700mm	0.194	0.112	0.146	0.579	0.751	295.978	99.063	166.757	30.158
357	M_{32}	1	320	2	430	330	1.03125	1.34375	crest bag displacement 720mm	0.213	0.111	0.132	0.522	0.618	356.087	97.138	136.043	122.906
358	M_{32}	0.6	320	3	430	330	1.03125	1.34375	crest bag displacement 1000mm	0.068	0.078	0.163	1.159	2.413	80.510	108.106	468.758	-496.354
359	M_{32}	0.8	320	3	430	330	1.03125	1.34375	crest bag displacement 1150mm	0.108	0.129	0.181	1.198	1.675	205.103	294.547	575.712	-665.156
360	M_{32}	0.9	320	3	430	330	1.03125	1.34375	crest bag displacement 1250mm, entire structure displacement 100mm	0.149	0.161	0.173	1.084	1.163	389.867	458.444	527.299	-595.876
361	M_{32}	1	320	3	430	330	1.03125	1.34375	crest bag displacement 1100mm, entire structure displacement 100mm	0.184	0.184	0.155	1.000	0.841	598.930	598.930	423.461	-423.461
362	M_{31}	0.6	320	1	430	360	1.125	1.34375	no bag movement	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
363	M_{31}	0.8	320	1	430	360	1.125	1.34375	no bag movement to slight lifting of 2nd tier oyster bag	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
364	M_{31}	0.9	320	1	430	360	1.125	1.34375	no bag movement to slight lifting of 2nd tier oyster bag	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
366	M_{31}	0.6	320	1	430	360	1.125	1.34375	no bag movement	0.088	0.032	0.100	0.358	1.130	15.333	1.968	19.571	-6.206
367	M_{31}	0.8	320	1	430	360	1.125	1.34375	no bag movement to slight lifting of 2nd tier oyster bag	0.083	0.027	0.096	0.329	1.162	13.377	1.451	18.053	-6.128
368	M_{31}	0.9	320	1	430	360	1.125	1.34375	no bag movement to slight lifting of 2nd tier oyster bag	0.080	0.032	0.114	0.395	1.429	12.586	1.959	25.686	-15.059
365	M_{31}	0.7	320	2	430	360	1.125	1.34375	slight lifting of 2nd tier oyster bag and crest bag	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
369	M_{31}	0.7	320	2	430	360	1.125	1.34375	slight lifting of 2nd tier oyster bag and crest bag	0.155	0.093	0.125	0.601	0.805	188.968	68.258	122.410	-1.700
370	M_{31}	0.8	320	2	430	360	1.125	1.34375	slight rocking of 2nd tier oyster bag and crest bag	0.164	0.107	0.131	0.655	0.801	210.951	90.416	135.234	-14.700
371	M_{31}	0.9	320	2	430	360	1.125	1.34375	slight rocking of 2nd tier oyster bag and crest bag - 20mm entire structure displacement	0.203	0.103	0.147	0.509	0.723	322.340	83.376	168.555	70.410
372	M_{31}	1	320	2	430	360	1.125	1.34375	slight rocking of 2nd tier oyster bag and crest bag	0.221	0.106	0.152	0.479	0.688	384.948	88.316	182.346	114.286
373	M_{31}	0.6	320	3	430	360	1.125	1.34375	slight lifting of front 2nd tier oyster bag	0.073	0.064	0.115	0.870	1.573	94.528	71.508	233.973	-210.952
374	M_{31}	0.8	320	3	430	360	1.125	1.34375	rocking of 2nd tier oyster bag and crest bag, entire structure displacement 100mm	0.106	0.116	0.132	1.100	1.252	197.655	239.098	309.751	-351.194
375	M_{31}	0.9	320	3	430	360	1.125	1.34375	rocking of 2nd tier oyster bag and crest bag, entire structure displacement 290mm	0.127	0.121	0.136	0.956	1.077	283.219	258.678	328.351	-303.810
376	M_{31}	1	320	3	430	360	1.125	1.34375	rocking of 2nd tier oyster bag and crest bag, entire structure displacement 300mm	0.169	0.130	0.134	0.772	0.797	502.255	299.140	318.984	-115.868

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377	M_{31}	0.5	160	1	430	360	2.25	2.6875	no bag movement	0.083	0.004	0.072	0.054	0.866	13.499	0.039	10.129	3.331
378	M_{31}	0.6	160	1	430	360	2.25	2.6875	no bag movement	0.078	0.003	0.081	0.039	1.046	11.897	0.018	13.014	-1.135
379	M_{31}	0.7	160	1	430	360	2.25	2.6875	no bag movement	0.076	0.005	0.073	0.062	0.968	11.217	0.043	10.503	0.671
380	M_{31}	0.2	160	2	430	360	2.25	2.6875	no bag movement	0.032	0.007	0.037	0.219	1.155	7.906	0.380	10.539	-3.013
381	M_{31}	0.4	160	2	430	360	2.25	2.6875	no bag movement	0.078	0.008	0.080	0.099	1.027	47.433	0.468	50.031	-3.066
382	M_{31}	0.5	160	2	430	360	2.25	2.6875	no bag movement	0.093	0.007	0.085	0.077	0.920	67.297	0.400	56.974	9.924
383	M_{31}	0.3	160	3	430	360	2.25	2.6875	no bag movement	0.029	0.005	0.022	0.166	0.774	14.767	0.406	8.846	5.515
384	M_{31}	0.5	160	3	430	360	2.25	2.6875	no bag movement	0.066	0.005	0.070	0.071	1.067	75.979	0.383	86.524	-10.928
385	M_{31}	0.6	160	3	430	360	2.25	2.6875	no bag movement	0.109	0.008	0.074	0.076	0.683	208.337	1.207	97.138	109.992
386	M_{31}	0.7	160	3	430	360	2.25	2.6875	no bag movement	0.082	0.006	0.081	0.074	0.979	119.569	0.653	114.611	4.305
387	M_{32}	0.5	160	1	430	330	2.0625	2.6875	no bag movement	0.064	0.006	0.054	0.088	0.837	8.154	0.064	5.717	2.373
388	M_{32}	0.6	160	1	430	330	2.0625	2.6875	no bag movement	0.067	0.005	0.057	0.080	0.849	8.846	0.057	6.372	2.417
389	M_{32}	0.7	160	1	430	330	2.0625	2.6875	no bag movement	0.074	0.007	0.061	0.093	0.823	10.679	0.092	7.227	3.361
390	M_{32}	0.2	160	2	430	330	2.0625	2.6875	no bag movement	0.032	0.007	0.040	0.216	1.224	8.261	0.385	12.380	-4.503
391	M_{32}	0.4	160	2	430	330	2.0625	2.6875	no bag movement	0.083	0.011	0.077	0.130	0.937	53.629	0.907	47.128	5.594
392	M_{32}	0.5	160	2	430	330	2.0625	2.6875	no bag movement	0.106	0.011	0.097	0.105	0.913	88.159	0.972	73.494	13.694
393	M_{32}	0.3	160	3	430	330	2.0625	2.6875	no bag movement	0.028	0.007	0.024	0.243	0.846	13.637	0.806	9.761	3.070
394	M_{32}	0.5	160	3	430	330	2.0625	2.6875	no bag movement	0.065	0.010	0.068	0.151	1.035	75.326	1.712	80.660	-7.045
395	M_{32}	0.6	160	3	430	330	2.0625	2.6875	no bag movement	0.086	0.010	0.086	0.118	1.010	129.326	1.788	131.992	-4.455
396	M_{32}	0.7	160	3	430	330	2.0625	2.6875	no bag movement	0.075	0.014	0.060	0.191	0.805	98.622	3.584	63.968	31.069
397	M_{34}	0.5	160	1	400	360	2.25	2.5	no bag movement	0.053	0.002	0.060	0.035	1.124	5.598	0.007	7.071	-1.479
398	M_{34}	0.6	160	1	400	360	2.25	2.5	no bag movement	0.076	0.003	0.067	0.034	0.881	11.385	0.013	8.846	2.525
399	M_{34}	0.7	160	1	400	360	2.25	2.5	no bag movement	0.072	0.002	0.074	0.029	1.037	10.115	0.008	10.885	-0.778
400	M_{34}	0.2	160	2	400	360	2.25	2.5	no bag movement	0.031	0.006	0.030	0.182	0.983	7.445	0.247	7.197	0.001
401	M_{34}	0.4	160	2	400	360	2.25	2.5	no bag movement	0.072	0.008	0.060	0.110	0.837	40.939	0.499	28.668	11.773
402	M_{34}	0.5	160	2	400	360	2.25	2.5	no bag movement	0.097	0.010	0.076	0.100	0.781	73.494	0.732	44.868	27.895
403	M_{34}	0.3	160	3	400	360	2.25	2.5	no bag movement	0.041	0.003	0.024	0.066	0.575	30.269	0.131	10.010	20.128
404	M_{34}	0.5	160	3	400	360	2.25	2.5	no bag movement	0.067	0.003	0.061	0.044	0.905	79.616	0.157	65.240	14.218
405	M_{34}	0.6	160	3	400	360	2.25	2.5	no bag movement	0.072	0.004	0.057	0.053	0.790	92.034	0.257	57.478	34.299
406	M_{34}	0.7	160	3	400	360	2.25	2.5	no bag movement	0.083	0.004	0.059	0.046	0.704	122.133	0.264	60.615	61.255
407	M_{35}	0.5	160	1	380	360	2.25	2.375	no bag movement	0.057	0.002	0.057	0.029	0.999	6.415	0.005	6.404	0.005
408	M_{35}	0.6	160	1	380	360	2.25	2.375	no bag movement	0.076	0.002	0.073	0.031	0.957	11.469	0.011	10.503	0.956
409	M_{35}	0.7	160	1	380	360	2.25	2.375	no bag movement	0.079	0.002	0.072	0.030	0.919	12.113	0.011	10.226	1.876
410	M_{35}	0.2	160	2	380	360	2.25	2.375	no bag movement	0.031	0.005	0.035	0.162	1.127	7.731	0.204	9.813	-2.285
411	M_{35}	0.4	160	2	380	360	2.25	2.375	no bag movement	0.077	0.010	0.068	0.127	0.887	46.728	0.752	36.786	9.190
412	M_{35}	0.5	160	2	380	360	2.25	2.375	no bag movement	0.097	0.009	0.072	0.098	0.743	73.161	0.699	40.373	32.089
413	M_{35}	0.3	160	3	380	360	2.25	2.375	no bag movement	0.033	0.003	0.032	0.083	0.972	18.995	0.131	17.947	0.916
414	M_{35}	0.5	160	3	380	360	2.25	2.375	no bag movement	0.058	0.006	0.065	0.098	1.118	60.356	0.582	75.507	-15.734
415	M_{35}	0.6	160	3	380	360	2.25	2.375	no bag movement	0.093	0.005	0.084	0.058	0.900	152.858	0.518	123.889	28.451
416	M_{35}	0.7	160	3	380	360	2.25	2.375	no bag movement	0.096	0.005	0.065	0.052	0.677	163.865	0.439	75.074	88.352
417	S_3	0.5	160	1	360	360	2.25	2.25	no bag movement	0.074	0.007	0.062	0.099	0.836	10.811	0.105	7.559	3.147
418	S_3	0.6	160	1	360	360	2.25	2.25	no bag movement	0.061	0.007	0.067	0.120	1.101	7.256	0.104	8.788	-1.636
419	S_3	0.7	160	1	360	360	2.25	2.25	no bag movement	0.073	0.008	0.062	0.113	0.844	10.476	0.133	7.460	2.884
420	S_3	0.2	160	2	360	360	2.25	2.25	no bag movement	0.029	0.007	0.041	0.251	1.386	6.706	0.424	12.874	-6.592
421	S_3	0.4	160	2	360	360	2.25	2.25	no bag movement	0.069	0.015	0.069	0.221	1.007	37.327	1.823	37.872	-2.368
422	S_3	0.5	160	2	360	360	2.25	2.25	no bag movement	0.086	0.019	0.085	0.215	0.982	58.663	2.707	56.597	-0.641
423	S_3	0.3	160	3	360	360	2.25	2.25	no bag movement	0.030	0.007	0.026	0.214	0.861	16.394	0.752	12.142	3.500

Test	ID	Calibration Factor	d (mm)	T (s)	h_c (mm)	B (mm)	B/d	h_c/d	Observations	H_i (m)	H_t (m)	H_r (m)	K_t	K_r	E_i (J/m)	E_t (J/m)	E_r (J/m)	E_d (J/m)
424	S_3	0.5	160	3	360	360	2.25	2.25	no bag movement	0.060	0.008	0.061	0.139	1.017	63.768	1.237	65.983	-3.451
425	S_3	0.6	160	3	360	360	2.25	2.25	no bag movement	0.079	0.015	0.064	0.190	0.807	111.247	3.998	72.497	34.751
426	S_3	0.7	160	3	360	360	2.25	2.25	no bag movement	0.082	0.016	0.094	0.190	1.148	118.297	4.252	155.859	-41.814
427	S_4	0.5	160	1	120	903.3333333	5.645833333	0.75	no bag movement	0.067	0.026	0.061	0.386	0.910	8.896	1.328	7.369	0.199
428	S_4	0.6	160	1	120	903.3333333	5.645833333	0.75	no bag movement	0.069	0.018	0.059	0.260	0.865	9.264	0.626	6.931	1.707
429	S_4	0.7	160	1	120	903.3333333	5.645833333	0.75	no bag movement	0.068	0.020	0.064	0.303	0.942	8.962	0.822	7.945	0.195
430	S_4	0.2	160	2	120	903.3333333	5.645833333	0.75	no bag movement	0.032	0.029	0.029	0.922	0.921	8.012	6.814	6.800	-5.603
431	S_4	0.4	160	2	120	903.3333333	5.645833333	0.75	no bag movement	0.065	0.047	0.057	0.722	0.875	33.478	17.468	25.658	-9.648
432	S_4	0.5	160	2	120	903.3333333	5.645833333	0.75	no bag movement	0.088	0.057	0.067	0.646	0.767	60.162	25.099	35.385	-0.322
433	S_4	0.3	160	3	120	903.3333333	5.645833333	0.75	no bag movement	0.028	0.020	0.021	0.725	0.761	13.776	7.241	7.977	-1.442
434	S_4	0.5	160	3	120	903.3333333	5.645833333	0.75	no bag movement	0.066	0.051	0.059	0.771	0.886	77.291	45.962	60.615	-29.286
435	S_4	0.6	160	3	120	903.3333333	5.645833333	0.75	no bag movement	0.086	0.054	0.072	0.619	0.838	131.992	50.622	92.755	-11.384
436	S_4	0.7	160	3	120	903.3333333	5.645833333	0.75	no bag movement	0.097	0.059	0.084	0.605	0.860	166.864	61.070	123.426	-17.631
437	O_5	0.5	160	1	150	930	5.8125	0.9375	no bag movement	0.056	0.016	0.056	0.293	1.003	6.081	0.522	6.123	-0.564
438	O_5	0.6	160	1	150	930	5.8125	0.9375	no bag movement	0.075	0.023	0.069	0.307	0.922	11.069	1.042	9.417	0.610
439	O_5	0.7	160	1	150	930	5.8125	0.9375	no bag movement	0.071	0.021	0.074	0.292	1.037	9.918	0.848	10.666	-1.596
440	O_5	0.2	160	2	150	930	5.8125	0.9375	no bag movement	0.035	0.029	0.029	0.813	0.830	9.800	6.471	6.757	-3.428
441	O_5	0.4	160	2	150	930	5.8125	0.9375	slight lifting of front of bags	0.072	0.050	0.058	0.703	0.813	40.443	19.991	26.738	-6.286
442	O_5	0.5	160	2	150	930	5.8125	0.9375	slight lifting of front of bags	0.096	0.051	0.074	0.529	0.776	71.837	20.140	43.246	8.451
443	O_5	0.3	160	3	150	930	5.8125	0.9375	no bag movement to gentle lifting	0.030	0.024	0.024	0.812	0.816	15.496	10.215	10.315	-5.034
444	O_5	0.5	160	3	150	930	5.8125	0.9375	slight lifting of front of bags	0.058	0.041	0.060	0.712	1.033	59.357	30.052	63.370	-34.065
445	O_5	0.6	160	3	150	930	5.8125	0.9375	slight lifting of front of bags	0.093	0.057	0.068	0.614	0.732	151.419	57.037	81.184	13.198
446	O_5	0.7	160	3	150	930	5.8125	0.9375	slight lifting of front of bags	0.086	0.053	0.075	0.617	0.872	129.895	49.443	98.705	-18.253
447	O_6	0.6	320	1	310	930	2.90625	0.96875	no bag movement	0.081	0.046	0.135	0.561	1.658	12.984	4.082	35.683	-26.781
448	O_6	0.8	320	1	310	930	2.90625	0.96875	no bag movement	0.086	0.041	0.113	0.475	1.310	14.666	3.304	25.161	-13.799
449	O_6	0.9	320	1	310	930	2.90625	0.96875	no bag movement	0.080	0.051	0.117	0.643	1.471	12.449	5.151	26.933	-19.635
450	O_6	0.7	320	2	310	930	2.90625	0.96875	entire structure displacement 180mm	0.118	0.075	0.138	0.640	1.169	109.322	44.719	149.308	-84.705
451	O_6	0.8	320	2	310	930	2.90625	0.96875	entire structure displacement 310mm	0.133	0.087	0.155	0.653	1.163	139.170	59.260	188.205	-108.295
452	O_6	0.9	320	2	310	930	2.90625	0.96875	entire structure displacement 310mm	0.175	0.086	0.157	0.492	0.894	240.991	58.366	192.805	-10.179
453	O_6	1	320	2	310	930	2.90625	0.96875	entire structure displacement 180mm	0.155	0.082	0.159	0.530	1.024	188.968	53.142	198.241	-62.415
454	O_6	0.6	320	3	310	930	2.90625	0.96875	slight rocking of crest bags, entire structure displacement 250mm	0.077	0.084	0.128	1.087	1.657	105.523	124.725	289.706	-308.908
455	O_6	0.8	320	3	310	930	2.90625	0.96875	slight rocking of crest bags, entire structure displacement 750mm	0.118	0.113	0.115	0.963	0.975	244.409	226.891	232.446	-214.928
456	O_6	0.9	320	3	310	930	2.90625	0.96875	slight rocking of crest bags, entire structure displacement 810mm	0.142	0.135	0.122	0.953	0.859	355.302	322.490	261.904	-229.092
457	O_6	1	320	3	310	930	2.90625	0.96875	slight rocking of crest bags, entire structure displacement 770mm	0.161	0.134	0.123	0.832	0.769	454.884	314.905	269.030	-129.052
458	S_2	0.6	320	1	240	360	1.125	0.75	no bag movement	0.052	0.064	0.106	1.233	2.051	5.249	7.984	22.079	-24.814
459	S_2	0.8	320	1	240	360	1.125	0.75	no bag movement	0.070	0.083	0.157	1.188	2.238	9.674	13.642	48.443	-52.410
460	S_2	0.9	320	1	240	360	1.125	0.75	no bag movement	0.119	0.089	0.165	0.747	1.381	27.856	15.529	53.142	-40.815
461	S_2	0.7	320	2	240	360	1.125	0.75	no bag movement	0.136	0.145	0.147	1.060	1.076	145.934	163.900	168.916	-186.882
462	S_2	0.8	320	2	240	360	1.125	0.75	no bag movement	0.158	0.135	0.144	0.855	0.912	195.203	142.731	162.304	-109.832
463	S_2	0.9	320	2	240	360	1.125	0.75	no bag movement	0.205	0.143	0.157	0.696	0.765	329.863	159.942	192.805	-22.884
464	S_2	1	320	2	240	360	1.125	0.75	no bag movement	0.181	0.119	0.141	0.658	0.781	255.872	110.720	156.172	-11.020
465	S_2	0.6	320	3	240	360	1.125	0.75	no bag movement	0.082	0.133	0.118	1.617	1.445	118.751	310.485	247.938	-439.673
466	S_2	0.8	320	3	240	360	1.125	0.75	no bag movement	0.148	0.171	0.121	1.152	0.818	388.224	515.410	259.885	-387.072
467	S_2	0.9	320	3	240	360	1.125	0.75	no bag movement	0.156	0.175	0.150	1.126	0.966	427.328	541.745	398.967	-513.385
468	S_2	1	320	3	240	360	1.125	0.75	no bag movement	0.182	0.140	0.136	0.767	0.746	587.768	345.555	326.844	-84.630
469	M_{21}	0.6	320	1	360.8333333	360	1.125	1.127604167	crest bag rocking	0.079	0.050	0.110	0.628	1.384	12.331	4.868	23.632	-16.169
470	M_{21}	0.8	320	1	360.8333333	360	1.125	1.127604167	crest bag rocking	0.100	0.062	0.167	0.618	1.672	19.473	7.433	54.415	-42.375

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471	M_{21}	0.9	320	1	360.8333333	360	1.125	1.127604167	crest bag rocking	0.114	0.064	0.195	0.559	1.707	25.644	8.024	74.713	-57.093
472	M_{21}	0.7	320	2	360.8333333	360	1.125	1.127604167	crest bag displaced 850mm, entire structure displaced 170mm	0.143	0.133	0.138	0.933	0.966	159.942	139.301	149.308	-128.667
473	M_{21}	0.8	320	2	360.8333333	360	1.125	1.127604167	crest bag displaced 900mm, entire structure displaced 400mm	0.162	0.146	0.166	0.905	1.025	205.342	168.266	215.615	-178.539
474	M_{21}	0.9	320	2	360.8333333	360	1.125	1.127604167	crest bag displaced 750mm, entire structure displaced 300mm	0.200	0.152	0.165	0.761	0.827	313.428	181.485	214.596	-82.653
475	M_{21}	1	320	2	360.8333333	360	1.125	1.127604167	crest bag displaced 670mm, entire structure displaced 200mm	0.180	0.129	0.152	0.718	0.847	254.098	130.910	182.159	-58.970
476	M_{21}	0.6	320	3	360.8333333	360	1.125	1.127604167	crest bag displaced 1300mm, entire structure displaced 200mm	0.077	0.089	0.131	1.154	1.697	106.037	141.242	305.223	-340.428
477	M_{21}	0.8	320	3	360.8333333	360	1.125	1.127604167	crest bag displaced 1600mm, entire structure displaced 900mm	0.120	0.167	0.121	1.395	1.014	252.683	492.039	259.885	-499.241
478	M_{21}	0.9	320	3	360.8333333	360	1.125	1.127604167	crest bag displaced 1700mm, entire structure displaced 1150mm	0.148	0.149	0.145	1.004	0.983	386.584	389.456	373.188	-376.060
479	M_{21}	1	320	3	360.8333333	360	1.125	1.127604167	crest bag displaced 1600mm, entire structure displaced 750mm	0.178	0.147	0.142	0.826	0.798	559.831	381.685	356.480	-178.335
480	M_{21}	0.5	160	1	360.8333333	360	2.25	2.255208333	no bag movement	0.061	0.003	0.062	0.053	1.007	7.320	0.020	7.422	-0.122
481	M_{21}	0.6	160	1	360.8333333	360	2.25	2.255208333	no bag movement	0.076	0.004	0.067	0.050	0.873	11.479	0.029	8.747	2.702
482	M_{21}	0.7	160	1	360.8333333	360	2.25	2.255208333	no bag movement	0.066	0.004	0.061	0.055	0.933	8.478	0.026	7.377	1.076
483	M_{21}	0.2	160	2	360.8333333	360	2.25	2.255208333	no bag movement	0.030	0.009	0.033	0.285	1.114	7.052	0.575	8.747	-2.270
484	M_{21}	0.4	160	2	360.8333333	360	2.25	2.255208333	crest bag rocking	0.072	0.012	0.076	0.165	1.050	41.100	1.112	45.315	-5.328
485	M_{21}	0.5	160	2	360.8333333	360	2.25	2.255208333	crest bag rocking	0.094	0.014	0.099	0.145	1.051	69.688	1.473	76.962	-8.747
486	M_{21}	0.3	160	3	360.8333333	360	2.25	2.255208333	no bag movement	0.031	0.008	0.020	0.252	0.659	16.470	1.048	7.152	8.271
487	M_{21}	0.5	160	3	360.8333333	360	2.25	2.255208333	crest bag rocking	0.065	0.009	0.058	0.144	0.894	74.785	1.559	59.710	13.516
488	M_{21}	0.6	160	3	360.8333333	360	2.25	2.255208333	crest bag rocking	0.093	0.012	0.074	0.132	0.792	152.858	2.656	95.992	54.210
489	M_{21}	0.7	160	3	360.8333333	360	2.25	2.255208333	crest bag rocking	0.083	0.013	0.067	0.156	0.806	120.848	2.931	78.579	39.338
490	O_6	0.5	160	1	310	930	5.8125	1.9375	no bag movement	0.050	0.009	0.058	0.185	1.168	4.862	0.166	6.634	-1.938
491	O_6	0.6	160	1	310	930	5.8125	1.9375	no bag movement	0.062	0.012	0.065	0.194	1.062	7.456	0.280	8.406	-1.230
492	O_6	0.7	160	1	310	930	5.8125	1.9375	no bag movement	0.070	0.010	0.055	0.140	0.785	9.528	0.187	5.871	3.470
493	O_6	0.2	160	2	310	930	5.8125	1.9375	no bag movement	0.036	0.015	0.034	0.417	0.953	9.957	1.731	9.046	-0.820
494	O_6	0.4	160	2	310	930	5.8125	1.9375	no bag movement	0.071	0.022	0.067	0.312	0.949	39.043	3.801	35.187	0.056
495	O_6	0.5	160	2	310	930	5.8125	1.9375	no bag movement	0.105	0.025	0.093	0.242	0.888	86.705	5.060	68.304	13.342
496	O_6	0.3	160	3	310	930	5.8125	1.9375	no bag movement	0.031	0.009	0.028	0.294	0.906	16.776	1.448	13.776	1.552
497	O_6	0.5	160	3	310	930	5.8125	1.9375	no bag movement	0.063	0.016	0.058	0.258	0.917	70.455	4.701	59.260	6.493
498	O_6	0.6	160	3	310	930	5.8125	1.9375	no bag movement	0.096	0.022	0.077	0.232	0.803	161.209	8.698	103.988	48.523
499	O_6	0.7	160	3	310	930	5.8125	1.9375	no bag movement	0.096	0.023	0.069	0.243	0.722	161.633	9.554	84.368	67.711
500	S_2	0.5	160	1	240	360	2.25	1.5	no bag movement	0.048	0.018	0.062	0.373	1.292	4.525	0.630	7.559	-3.663
501	S_2	0.6	160	1	240	360	2.25	1.5	no bag movement	0.071	0.017	0.067	0.247	0.951	9.778	0.597	8.846	0.335
502	S_2	0.7	160	1	240	360	2.25	1.5	no bag movement	0.063	0.018	0.058	0.278	0.917	7.774	0.601	6.542	0.631
503	S_2	0.2	160	2	240	360	2.25	1.5	no bag movement	0.028	0.018	0.035	0.638	1.245	6.061	2.464	9.400	-5.803
504	S_2	0.4	160	2	240	360	2.25	1.5	no bag movement	0.067	0.046	0.067	0.682	0.995	35.534	16.507	35.154	-16.127
505	S_2	0.5	160	2	240	360	2.25	1.5	no bag movement	0.087	0.052	0.085	0.602	0.976	59.517	21.560	56.723	-18.766
506	S_2	0.3	160	3	240	360	2.25	1.5	no bag movement	0.035	0.011	0.028	0.309	0.810	21.438	2.050	14.055	5.332
507	S_2	0.5	160	3	240	360	2.25	1.5	no bag movement	0.076	0.048	0.063	0.636	0.823	102.043	41.340	69.063	-8.360
508	S_2	0.6	160	3	240	360	2.25	1.5	no bag movement	0.072	0.045	0.065	0.620	0.900	92.594	35.583	75.001	-17.990
509	S_2	0.7	160	3	240	360	2.25	1.5	no bag movement	0.092	0.038	0.068	0.411	0.740	147.852	25.008	80.959	41.885
510	M_{23}	0.6	320	1	280	370	1.15625	0.875	no bag movement	0.092	0.060	0.141	0.658	1.534	16.529	7.167	38.887	-29.524
511	M_{23}	0.8	320	1	280	370	1.15625	0.875	no bag movement	0.080	0.060	0.127	0.750	1.588	12.596	7.085	31.781	-26.270
512	M_{23}	0.9	320	1	280	370	1.15625	0.875	no bag movement	0.097	0.065	0.156	0.670	1.615	18.290	8.214	47.720	-37.644
513	M_{23}	0.7	320	2	280	370	1.15625	0.875	entire structure displacement 60mm	0.146	0.118	0.137	0.810	0.938	166.972	109.496	146.942	-89.466
514	M_{23}	0.8	320	2	280	370	1.15625	0.875	entire structure displacement 130mm	0.162	0.126	0.149	0.775	0.916	206.138	123.704	173.092	-90.657
515	M_{23}	0.9	320	2	280	370	1.15625	0.875	entire structure displacement 170mm	0.201	0.128	0.161	0.636	0.802	317.869	128.380	204.546	-15.058
516	M_{23}	1	320	2	280	370	1.15625	0.875	entire structure displacement 100mm	0.197	0.128	0.137	0.652	0.697	304.156	129.326	147.954	26.877
517	M_{23}	0.6	320	3	280	370	1.15625	0.875	entire structure displacement 40mm	0.080	0.118	0.115	1.479	1.430	113.366	247.938	231.685	-366.257

Test	ID	Calibration Factor	d (mm)	T (s)	h_c (mm)	B (mm)	B/d	h_c/d	Observations	H_i (m)	H_t (m)	H_r (m)	K_t	K_r	E_i (J/m)	E_t (J/m)	E_r (J/m)	E_d (J/m)
518	M_{23}	0.8	320	3	280	370	1.15625	0.875	entire structure displacement 350mm	0.117	0.132	0.130	1.132	1.113	240.130	307.848	297.414	-365.132
519	M_{23}	0.9	320	3	280	370	1.15625	0.875	entire structure displacement 600mm	0.141	0.133	0.134	0.939	0.950	353.342	311.587	318.984	-277.229
520	M_{23}	1	320	3	280	370	1.15625	0.875	entire structure displacement 480mm	0.192	0.134	0.144	0.698	0.751	652.050	317.869	367.577	-33.395
521	M_{25}	0.6	320	1	265	370	1.15625	0.828125	no bag movement	0.072	0.062	0.115	0.859	1.610	10.076	7.437	26.125	-23.486
522	M_{25}	0.8	320	1	265	370	1.15625	0.828125	no bag movement	0.078	0.075	0.108	0.964	1.381	11.897	11.059	22.683	-21.846
523	M_{25}	0.9	320	1	265	370	1.15625	0.828125	no bag movement	0.075	0.073	0.096	0.983	1.282	10.921	10.557	17.936	-17.572
524	M_{25}	0.7	320	2	265	370	1.15625	0.828125	no bag movement - possible slight rocking	0.141	0.130	0.130	0.922	0.926	155.548	132.184	133.336	-109.972
525	M_{25}	0.8	320	2	265	370	1.15625	0.828125	no bag movement - possible slight rocking	0.161	0.135	0.131	0.839	0.812	203.674	143.262	134.428	-74.017
526	M_{25}	0.9	320	2	265	370	1.15625	0.828125	slight rocking of oyster bag and crest bag	0.185	0.117	0.135	0.633	0.732	268.006	107.299	143.429	17.279
527	M_{25}	1	320	2	265	370	1.15625	0.828125	slight rocking of oyster bag and crest bag	0.194	0.107	0.156	0.552	0.807	294.547	89.731	191.842	12.974
528	M_{25}	0.6	320	3	265	370	1.15625	0.828125	no bag movement	0.081	0.116	0.086	1.426	1.059	117.122	238.069	131.228	-252.175
529	M_{25}	0.8	320	3	265	370	1.15625	0.828125	maybe slight rocking of oyster bag and crest bag	0.120	0.117	0.117	0.978	0.974	253.213	242.070	240.130	-228.986
530	M_{25}	0.9	320	3	265	370	1.15625	0.828125	oyster bag and crest bag rocking	0.139	0.145	0.125	1.040	0.897	343.621	371.982	276.252	-304.614
531	M_{25}	1	320	3	265	370	1.15625	0.828125	oyster bag and crest bag rocking	0.193	0.160	0.116	0.832	0.600	656.312	453.995	236.593	-34.276
532	S_6	0.6	320	1	250	370	1.15625	0.78125	no bag movement	0.084	0.081	0.124	0.965	1.484	13.729	12.784	30.235	-29.290
533	S_6	0.8	320	1	250	370	1.15625	0.78125	no bag movement	0.072	0.072	0.139	0.998	1.930	10.199	10.155	38.009	-37.964
534	S_6	0.9	320	1	250	370	1.15625	0.78125	no bag movement	0.082	0.077	0.122	0.942	1.483	13.195	11.715	29.026	-27.546
535	S_6	0.7	320	2	250	370	1.15625	0.78125	no bag movement	0.135	0.117	0.131	0.866	0.968	143.429	107.644	134.493	-98.708
536	S_6	0.8	320	2	250	370	1.15625	0.78125	no bag movement	0.155	0.150	0.156	0.971	1.005	188.205	177.467	189.924	-179.185
537	S_6	0.9	320	2	250	370	1.15625	0.78125	no bag movement	0.159	0.119	0.140	0.747	0.883	198.241	110.720	154.441	-66.920
538	S_6	1	320	2	250	370	1.15625	0.78125	no bag movement	0.207	0.138	0.141	0.665	0.680	337.472	149.308	156.172	31.992
539	S_6	0.6	320	3	250	370	1.15625	0.78125	no bag movement	0.092	0.148	0.082	1.601	0.893	149.987	384.458	119.569	-354.040
540	S_6	0.8	320	3	250	370	1.15625	0.78125	no bag movement	0.112	0.124	0.140	1.106	1.247	221.527	270.878	344.394	-393.746
541	S_6	0.9	320	3	250	370	1.15625	0.78125	no bag movement	0.150	0.162	0.142	1.080	0.943	398.136	464.709	353.733	-420.307
542	S_6	1	320	3	250	370	1.15625	0.78125	no bag movement	0.194	0.161	0.167	0.827	0.863	664.340	454.884	494.351	-284.895
543	S_6	0.5	160	1	250	370	2.3125	1.5625	no bag movement	0.045	0.010	0.050	0.213	1.108	4.048	0.184	4.967	-1.102
544	S_6	0.6	160	1	250	370	2.3125	1.5625	no bag movement	0.054	0.011	0.058	0.201	1.068	5.727	0.231	6.535	-1.039
545	S_6	0.7	160	1	250	370	2.3125	1.5625	no bag movement	0.048	0.013	0.068	0.270	1.432	4.487	0.328	9.196	-5.038
546	S_6	0.2	160	2	250	370	2.3125	1.5625	no bag movement	0.032	0.009	0.033	0.274	1.015	8.150	0.612	8.390	-0.851
547	S_6	0.4	160	2	250	370	2.3125	1.5625	no bag movement	0.068	0.034	0.072	0.501	1.057	36.383	9.146	40.656	-13.419
548	S_6	0.5	160	2	250	370	2.3125	1.5625	no bag movement	0.085	0.035	0.091	0.404	1.067	57.226	9.349	65.173	-17.296
549	S_6	0.3	160	3	250	370	2.3125	1.5625	no bag movement	0.028	0.009	0.032	0.311	1.123	13.900	1.345	17.526	-4.972
550	S_6	0.5	160	3	250	370	2.3125	1.5625	no bag movement	0.055	0.031	0.075	0.565	1.372	52.536	16.750	98.870	-63.084
551	S_6	0.6	160	3	250	370	2.3125	1.5625	no bag movement	0.076	0.045	0.065	0.598	0.857	102.043	36.433	75.001	-9.391
552	S_6	0.7	160	3	250	370	2.3125	1.5625	no bag movement	0.088	0.041	0.078	0.465	0.888	136.724	29.574	107.846	-0.697
553	M_{25}	0.5	160	1	265	370	2.3125	1.65625	no bag movement	0.074	0.009	0.057	0.118	0.776	10.693	0.150	6.436	4.107
554	M_{25}	0.6	160	1	265	370	2.3125	1.65625	no bag movement	0.076	0.006	0.056	0.083	0.735	11.385	0.079	6.143	5.163
555	M_{25}	0.7	160	1	265	370	2.3125	1.65625	no bag movement	0.079	0.009	0.073	0.111	0.926	12.157	0.148	10.413	1.595
556	M_{25}	0.2	160	2	265	370	2.3125	1.65625	no bag movement	0.034	0.009	0.045	0.278	1.322	8.954	0.694	15.639	-7.379
557	M_{25}	0.4	160	2	265	370	2.3125	1.65625	no bag movement	0.078	0.030	0.075	0.386	0.955	48.105	7.152	43.869	-2.916
558	M_{25}	0.5	160	2	265	370	2.3125	1.65625	no bag movement	0.108	0.042	0.081	0.389	0.744	92.221	13.931	51.097	27.193
559	M_{25}	0.3	160	3	265	370	2.3125	1.65625	no bag movement	0.027	0.008	0.025	0.283	0.949	12.552	1.006	11.301	0.245
560	M_{25}	0.5	160	3	265	370	2.3125	1.65625	no bag movement	0.072	0.028	0.072	0.388	0.993	92.755	13.977	91.475	-12.698
561	M_{25}	0.6	160	3	265	370	2.3125	1.65625	no bag movement	0.092	0.027	0.074	0.291	0.805	149.274	12.611	96.646	40.017
562	M_{25}	0.7	160	3	265	370	2.3125	1.65625	no bag movement	0.084	0.025	0.067	0.292	0.790	125.377	10.666	78.283	36.428
563	M_{23}	0.5	160	1	280	370	2.3125	1.75	no bag movement	0.056	0.008	0.054	0.135	0.970	6.164	0.112	5.804	0.248
564	M_{23}	0.6	160	1	280	370	2.3125	1.75	no bag movement	0.064	0.007	0.055	0.116	0.849	8.154	0.109	5.878	2.168

Test	ID	Calibration Factor	d (mm)	T (s)	h_c (mm)	B (mm)	B/d	h_c/d	Observations	H_i (m)	H_t (m)	H_r (m)	K_t	K_r	E_i (J/m)	E_t (J/m)	E_r (J/m)	E_d (J/m)
565	M_{23}	0.7	160	1	280	370	2.3125	1.75	no bag movement	0.063	0.010	0.065	0.160	1.016	7.906	0.203	8.166	-0.463
566	M_{23}	0.2	160	2	280	370	2.3125	1.75	no bag movement	0.032	0.011	0.036	0.343	1.138	7.945	0.934	10.288	-3.277
567	M_{23}	0.4	160	2	280	370	2.3125	1.75	no bag movement	0.074	0.023	0.071	0.309	0.956	43.209	4.127	39.530	-0.448
568	M_{23}	0.5	160	2	280	370	2.3125	1.75	no bag movement	0.093	0.025	0.080	0.270	0.856	68.304	4.998	50.031	13.275
569	M_{23}	0.3	160	3	280	370	2.3125	1.75	no bag movement	0.027	0.011	0.030	0.400	1.113	12.419	1.992	15.398	-4.970
570	M_{23}	0.5	160	3	280	370	2.3125	1.75	no bag movement	0.068	0.018	0.072	0.259	1.058	82.768	5.544	92.594	-15.370
571	M_{23}	0.6	160	3	280	370	2.3125	1.75	no bag movement	0.081	0.023	0.089	0.284	1.094	117.032	9.451	139.958	-32.377
572	M_{23}	0.7	160	3	280	370	2.3125	1.75	no bag movement	0.100	0.029	0.069	0.288	0.684	177.578	14.767	82.996	79.815
573	M_{14}	0.5	160	1	146.6666667	970	6.0625	0.916666667	no bag movement	0.051	0.013	0.056	0.264	1.113	5.010	0.350	6.205	-1.545
574	M_{14}	0.6	160	1	146.6666667	970	6.0625	0.916666667	no bag movement	0.055	0.016	0.060	0.291	1.090	5.905	0.500	7.019	-1.614
575	M_{14}	0.7	160	1	146.6666667	970	6.0625	0.916666667	no bag movement	0.068	0.021	0.067	0.306	0.984	9.033	0.846	8.747	-0.561
576	M_{14}	0.2	160	2	146.6666667	970	6.0625	0.916666667	no bag movement	0.031	0.013	0.032	0.418	1.014	7.620	1.328	7.836	-1.544
577	M_{14}	0.4	160	2	146.6666667	970	6.0625	0.916666667	rocking of front bag	0.065	0.028	0.063	0.438	0.970	32.759	6.275	30.849	-4.364
578	M_{14}	0.5	160	2	146.6666667	970	6.0625	0.916666667	rocking of front bag	0.088	0.046	0.070	0.519	0.789	61.330	16.507	38.146	6.678
579	M_{14}	0.3	160	3	146.6666667	970	6.0625	0.916666667	no bag movement	0.032	0.011	0.030	0.346	0.925	18.508	2.212	15.826	0.470
580	M_{14}	0.5	160	3	146.6666667	970	6.0625	0.916666667	rocking of front bag	0.062	0.028	0.065	0.454	1.049	67.685	13.977	74.497	-20.789
581	M_{14}	0.6	160	3	146.6666667	970	6.0625	0.916666667	rocking of front bag	0.090	0.041	0.071	0.458	0.792	142.731	29.892	89.573	23.266
582	M_{14}	0.7	160	3	146.6666667	970	6.0625	0.916666667	rocking of front bag	0.093	0.040	0.071	0.430	0.765	152.858	28.319	89.573	34.966
583	S_5	0.5	160	1	120	370	2.3125	0.75	no bag movement	0.054	0.037	0.054	0.681	0.997	5.811	2.694	5.770	-2.654
584	S_5	0.6	160	1	120	370	2.3125	0.75	no bag movement	0.068	0.037	0.055	0.551	0.821	8.962	2.721	6.040	0.201
585	S_5	0.7	160	1	120	370	2.3125	0.75	no bag movement	0.078	0.039	0.063	0.503	0.810	11.810	2.989	7.743	1.079
586	S_5	0.2	160	2	120	370	2.3125	0.75	no bag movement	0.034	0.041	0.029	1.196	0.832	9.264	13.255	6.415	-10.406
587	S_5	0.4	160	2	120	370	2.3125	0.75	no bag movement	0.076	0.061	0.056	0.804	0.741	44.868	29.011	24.655	-8.799
588	S_5	0.5	160	2	120	370	2.3125	0.75	no bag movement	0.097	0.073	0.070	0.753	0.716	74.497	42.229	38.146	-5.877
589	S_5	0.3	160	3	120	370	2.3125	0.75	no bag movement	0.025	0.038	0.024	1.482	0.963	11.385	25.008	10.557	-24.181
590	S_5	0.5	160	3	120	370	2.3125	0.75	no bag movement	0.059	0.054	0.061	0.920	1.039	61.298	51.934	66.186	-56.822
591	S_5	0.6	160	3	120	370	2.3125	0.75	no bag movement	0.089	0.060	0.081	0.677	0.906	140.352	64.302	115.147	-39.096
592	S_5	0.7	160	3	120	370	2.3125	0.75	no bag movement	0.097	0.061	0.082	0.625	0.846	166.112	64.971	118.751	-17.610
593	M_{12}	0.5	160	1	140	700	4.375	0.875	no bag movement	0.051	0.026	0.059	0.507	1.158	5.135	1.321	6.887	-3.073
594	M_{12}	0.6	160	1	140	700	4.375	0.875	slight rocking of oyster bag	0.078	0.041	0.066	0.524	0.849	11.940	3.284	8.600	0.056
595	M_{12}	0.7	160	1	140	700	4.375	0.875	slight rocking of oyster bag	0.079	0.037	0.072	0.470	0.916	12.200	2.690	10.244	-0.734
596	M_{12}	0.2	160	2	140	700	4.375	0.875	no bag movement	0.029	0.025	0.034	0.862	1.172	6.443	4.783	8.846	-7.186
597	M_{12}	0.4	160	2	140	700	4.375	0.875	rocking of oyster bag	0.069	0.040	0.075	0.577	1.084	37.804	12.586	44.422	-19.205
598	M_{12}	0.5	160	2	140	700	4.375	0.875	rocking of oyster bag	0.091	0.048	0.090	0.526	0.982	65.577	18.124	63.259	-15.806
599	M_{12}	0.3	160	3	140	700	4.375	0.875	no bag movement	0.033	0.019	0.026	0.580	0.784	18.913	6.357	11.639	0.917
600	M_{12}	0.5	160	3	140	700	4.375	0.875	rocking of oyster bag	0.071	0.036	0.074	0.503	1.044	89.573	22.670	97.714	-30.811
601	M_{12}	0.6	160	3	140	700	4.375	0.875	rocking of oyster bag	0.085	0.061	0.074	0.723	0.877	127.062	66.389	97.714	-37.041
602	M_{12}	0.7	160	3	140	700	4.375	0.875	rocking of oyster bag	0.075	0.058	0.073	0.776	0.977	98.870	59.517	94.285	-54.932