Determination of Wave Transmission Coefficients for Oyster Shell Bag Breakwaters

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ABSTRACT

Problems are inevitable in the use of oyster shell bag breakwaters. Oyster shell bag breakwaters have been used in many locations throughout the USA to quantify their ecological benefits, but little research has been conducted regarding their wave attenuating properties. Quantitative information has been produced for traditional structures, but nothing has been published to describe the attenuating properties of an oyster shell bag breakwater. Currently, projects employing oyster shell bag breakwaters would need to adopt published methodologies for determining the transmissive properties of traditional materials or conduct individualized experimentation for their project to determine the adequate dimensions necessary to handle the hydrodynamic loads applied to them. Projects using this methodology could over design or under design the oyster shell bag breakwaters. The objective is to resolve this issue by conducting laboratory experiments in a controlled setting and comparing those results to existing methodologies available in the published literature.

The results obtained in this report are a substantial finding in terms of constructing oyster shell bag breakwaters. The data obtained from testing is compared to published methodologies for measuring the wave transmission coefficient of low crested breakwaters (Van der Meer et al., 2005), which produces a distinguishable resemblance based on the 43 tests conducted during this study. However, additional testing should be conducted to enhance the initial findings by including practical application variables such as wave variability and structure placement in relation to the shoreline.

INTRODUCTION

The nation’s wetlands, which have naturally protected the shoreline for centuries are disappearing. Preventing this loss of wetlands along the coastlines has become a top priority. Previous research has shown that coastal wetlands can only survive when wave heights are below 0.14 m on average (Shafer, 2003). In some cases, increased wave energy along estuarine shorelines has risen above this threshold destroying the natural wetlands (Zalewski, 2002). The wave energy has been increasing as a result of global warming, increased boat activity, and excessive implementation of man-made structures (Davis J. E., 1998). Historically when the wetlands began to recede, hardened structures such as bulkheads and seawalls were implemented. Now, these hardened structures along the nation's shoreline have begun to stir debate amongst ecologists: they claim hardened structures eliminate vital habitat for marine life (Swann, 2008). In an effort to eliminate these structures, alternatives such as living shorelines are gaining popularity.

The key component of many living shoreline protection projects along high wave energy shorelines is a breakwater. These breakwaters are used in an attempt to protect wetlands from the damaging wave energy propagating towards shore. The breakwater is typically placed offshore leaving an aquatic zone between it and the shoreline. While energy dissipation is the primary goal of a breakwater, research has shown that they provide additional ecological habitat for aqueous as well as terrestrial biology. An evaluation performed on the Chesapeake Bay showed the installation of breakwaters created relatively instant habitat for various aquatic biology on the surface and within the pores of the breakwater structure (Davis, Takacs, & Schnabel, 2006).

Breakwaters are composed of various types of material and constructed in all sorts of shapes. While the materials vary, the most popular shape is a trapezoidal profile oriented parallel to the shoreline. Breakwaters are not a continuous length along the shoreline, which would create a dead zone between it and the shoreline during the ebb tide (Duhring, 2006). Instead, gaps are provided along the length of the breakwater to allow some portion of the wave energy to propagate through as well as provide an escape to aquatic life that would become trapped during ebb tide.

Common materials used in breakwaters are concrete, rock, and more recently oyster shells. In the past, breakwaters were constructed of durable, high-density rock, which was readily available. Examples of rock or rubble mound construction are ubiquitous in coastal defense and armament even today. The design and placement of these structures can be reviewed in the Coastal Engineering Manual (2002) which references Seelig (1980) for the estimation of the hydrodynamic properties relating to rubble mound breakwaters. Some of the other factors affecting the use of rock in breakwaters are the size, density, shape, and gradation (Poole, 1991).

Precast concrete armor units are another popular choice when constructing a breakwater. Precast concrete allows the designer to modify the shape of the breakwater to a level that he/she feels is the most effective. One concept has remained the same; the stability of the unit is provided by its self-weight. The units can be arranged in random patterns, a double row, or a single row. The double row arrangement allowed the rows to be staggered to give full protection to the shoreline while maintaining the necessary openings required for the ecology (Duhring, 2006). Finally, since the stability of the unit is controlled by its weight these structures are extremely large and require heavy equipment to install. The stress of the heavy equipment impedes the already fragile ecosystem the breakwater is trying to protect or restore (Bakker, Berge, Hakenberg, & Klabbers, 2003).

Oyster shell substrate used in the creation of breakwaters is becoming more popular. Natural oyster reefs have historically protected coastal shorelines. Society's encroachment on the coastline has destroyed many of theses natural defense structures. The degradation is caused, in part, by the constant manipulation of the coastline to satisfy the needs of society (Coen, et al., 2007). The benefits of oyster shell bag breakwaters significantly outweigh the traditional materials. Oyster shell substrate is a natural, renewable material that is inert and has been shown to enhance settlement of juvenile bivalves (Henderson & O'Neil, 2003). The use of oyster shell substrate in living shorelines also removes the material from the waste stream. When used to create a composite breakwater structure, oyster shell substrate is commonly placed in tubular mesh bags. These 'oyster shell bags' are then stacked or placed, often by hand, to create the composite breakwater. Finally, the most significant benefit associated with using oyster shells as a breakwater media is the sustainability. The oyster shells used in breakwaters do not have to be produced; it is a recycled product that would otherwise be discarded as waste from restaurants. The cost of oyster shells is also a product of sustainability. The cost of an oyster shell bag breakwater placement is \$60-\$70/m^3 as compared to a Wave Attenuation Device (WAD) at \$600-800/m or a rock breakwater at \$400-650/m (Boyd, 2007).

Oyster shell bag breakwaters have an added benefit of producing oysters. In a study conducted on the east coast, the production of oysters on multiple restoration projects was weighted against the initial cost of the respective project. The findings revealed that the cost of a restoration project would be recovered in a maximum of 14 years, if no maintenance was conducted on the reef. If the reef was "seeded" with juvenile oysters the recovery of the initial costs could be achieved in 5 years (Henderson & O'Neil, 2003).

Problems still remain in the use of oyster shells. Oyster shell bag breakwaters have been used in many locations throughout the USA to quantify their ecological benefits, but little research has been conducted regarding their attenuating properties. Quantitative information has been produced for traditional structures containing rock, and concrete armor units, but nothing has been published to describe the attenuating properties of an oyster shell bag breakwater. Currently, projects employing oyster shell bag breakwaters would need to adopt published methodologies for determining the transmissive properties of traditional materials or conduct individualized experimentation for their project to determine the adequate dimensions necessary to handle the hydrodynamic loads applied to them. Projects using this methodology could be over or under designing the oyster shell bag breakwaters. The remainder of this article is an attempt to resolve this issue by conducting laboratory experiments in a controlled setting and comparing those results to existing methodologies available in the published literature.

OBJECTIVE

Sufficient tests are conducted to determine transmission coefficients of waves attenuated by various dimensions of oyster shell bag breakwaters. The data from the testing is used to develop a non-dimensional graph that relates the wave characteristics to the breakwater dimensions. The transmission coefficient is also equated using the equations developed by Van der Meer (2005). The transmission coefficient obtained from Van der Meer (2005) and the coefficient determined through testing is compared in a one-to-one graph. This graph is then used to answer the question of the Van der Meer (2005) equations' validity when applied to oyster shell bag breakwaters.

METHODOLOGY

Definitions. The testing conducted in the study is designed to measure the transmitted wave height, H_t, which is attenuated by the structure. The incident wave height, H_i, is the wave height measured before the interaction of the structure. To simplify testing and analysis, and to minimize experimental errors, the incident wave height is measured as the wave height produced by the wave generator prior to the placement of any oyster shell bags in the testing area. All wave heights are measured as the difference in water level from the crest of a wave to the trough of the wave. The transmission coefficient, K_t, is measured by the ratio of the transmitted wave height to the incident wave height and is reported as a dimensionless parameter. The depth of the water, d, is measured as the still water level within the basin. The wave period, T, is defined as the time elapsed between the crest of two waves passing a stationary point; in this study that point is defined by the wave gage location. The wavelength, L, is defined as the horizontal distance between two wave crests. The structure crest width, B, is defined as the average width across the top of the structure measured by averaging the width measurement at three locations. The structure height, h_c, is defined as the height of the structure measured from the basin floor. The freeboard, R_c, is measured as the difference of the structure height and the depth of the still water level (U.S. Army Corps of Engineers, 2002). Most of the parameters are shown below in Figure 1.

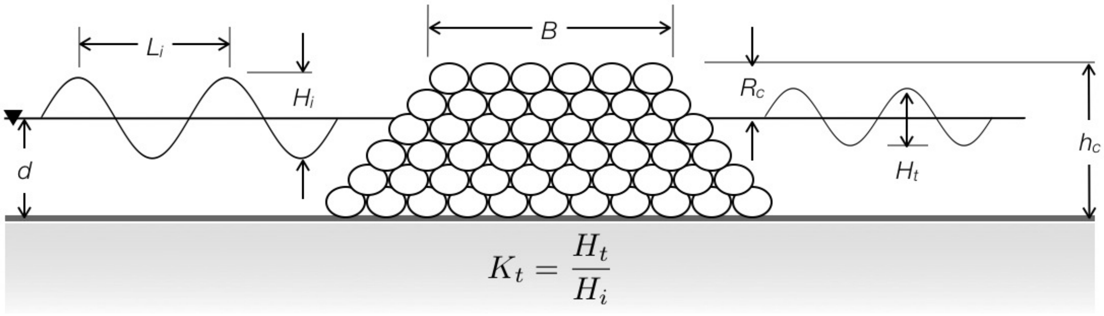

Figure 1: Definition sketch.

Experimental Setup. The tests performed in this study are conducted in the University of South Alabama's wave basin. The wave basin is 6.09 m (20 ft) wide and 9.14 m (30 ft) long. Waves are generated in the basin by a unidirectional bulkhead capable of producing monochromatic waves, which propagate across the basin to a sloping sand beach. For the tests conducted in this study, a splitter wall is built 0.76 m (2.5 ft) from the side of the basin, 4.88 m (16 ft) in length, beginning 0.61 m (2.0 ft) from the bulkhead's maximum stroke. The splitter wall built within the basin served to minimize the effects of refraction around the oyster shell bag breakwater being tested. The wall is constructed from timber and held in place using high-density armor stone. The upright portion of the wall is supported by triangular stanchions which are placed 0.61 m (2.0 ft) on center along the outboard side as shown in Figure 2.

Figure 2: Photo of the basin at the University of South Alabama after installing the splitter wall and re-slopping the beach face.

Wave Gages. The wave height measurements obtained during testing are determined using a two-wire capacitance gage. The gage is placed on the leeward side of the testing area. The gage is calibrated using the incident wave height prior to the placement of any material in the testing area. By doing so, the effects of the splitter wall could be eliminated since the baseline incident wave height and the transmitted wave height are both recorded with the partition wall in place and the only difference in the two recordings is due to the placement of the oyster shell bags in the testing area. The sampling rate of the gage is set at 10 Hz; the data is digitally recorded using a program created by National Instruments called LabView. This program records the data then exports it to a Microsoft Excel file for use in analysis.

Oyster Shell Bags. The composite breakwater structure is made up of oyster shell bags 0.75 m (2.5 ft) in length having a nominal diameter of 0.076 m (3 in). The bags are constructed using a 0.76 m (2.5 ft) section of 0.10 m (4 in) PVC pipe. An empty bag is placed in the pipe and tied on one end. Oyster shells are then scooped into the assemblage and shaken/compacted until full, then the open end is closed using a cable tie, Figure 3 shows a completed bag. The oyster shells and the netting material used in the project are obtained from the Alabama Department of Conservation and Natural Resources (ALDCNR)-Coastal Section. The netting material used in the study is distributed by Atlantic Aquaculture Supply, LLC. It is described as "Oyster Setting Bag Net" with openings of 0.017 m (5/8 in) and manufactured as a tube with a diameter of 0.123 m (4.5 in) (Atlantic Aquaculture).

Figure 3: Photo of a completed oyster shell bag that is used in testing. The bags are nominally 0.076 m (3 in) in diameter and 0.82 m (30 in) long. A total of 120 bags are produced for the testing.

The oyster shells obtained from ALDCNR are mature eastern oyster, *Crassostrea virginica* shells that were recovered from the extinct reefs located along the shores of Mobile Bay in Alabama. A sample of the oyster shells are supplied to Southern Earth Sciences to determine its grain size distribution using ASTM standards for aggregate. A summary of the findings is provided in Figure 4.

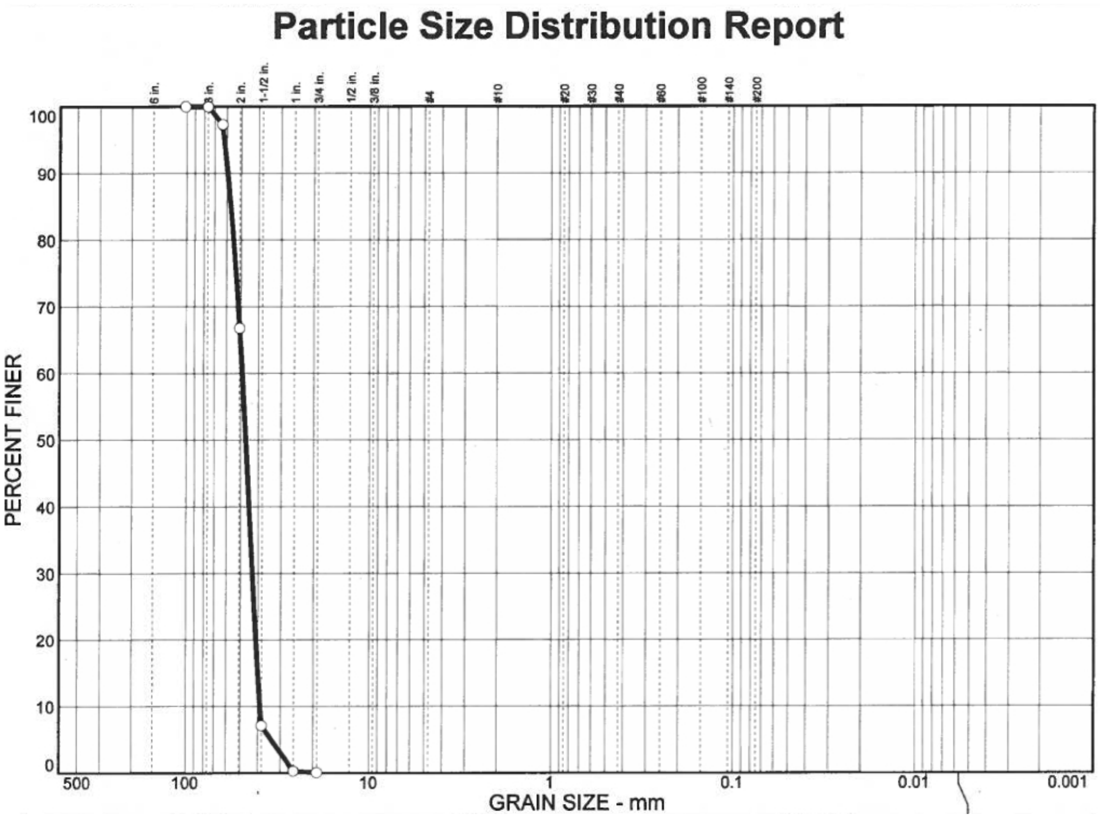

Figure 4: Grain Size Distribution Graph Supplied by Southern Earth Sciences

Scaling. The testing performed in this study did not follow a specific scale, although a Froude scaling with respect to a project on Mon Louis Island in Alabama produced almost a 1:1 scale. Since the results are dimensionless and only a function of the wave height and the structure size no further scaling is considered. The only portion of the testing that could be scaled is the size of the oyster shells. Scaling the oyster shells is not possible since the scaling would need to be controlled by both Froude and Reynolds number scaling. Scaling effects could have been reduced if oyster shells of a smaller size were available in a large enough quantity, but acquiring oyster shells of the proper size was not feasible within the scope of the study. In addition, smaller shells tend to escape through the mesh of bagging material. Furthermore, reducing the size of the shells, either by obtaining smaller shells, which are difficult to find, or by mechanical means, may introduce a strong bias in the results due to a corresponding decrease in structure porosity.

Experimental Procedure. A matrix is constructed to produce a range of values, which would be adequate to describe the attenuation of wave height and period by bagged oyster shells. The matrix contains 36 unique combinations of structure height and crest width. Seven additional tests are conducted using different wave characteristics, resulting in a total of 43 unique experiments. The height of the structure is varied from 1 bag high to 6 bags high, which yields a structure height 1.5 times greater than the still water depth. The crest width is also varied for each structure height. Structure crest widths vary from 4 bags to 19 bags, yielding a total of six unique crest widths. The largest crest width is proportional to the incident wavelength.

A structure side slope of 1:1.5 (H:V) is kept constant throughout testing. The water depth remains constant throughout the experiment as well. For selected experiments where the freeboard is greater than zero, three additional trials are run using a larger wave height and longer wave period to produce overtopping. The larger wave provides additional data of the variation between wave heights for a similar structure. To reduce the contamination of reflection of the wave energy from the shoreline, the trials are conducted in "bursts." After each trial the basin is allowed to return to rest. The data used from each "burst" consists of the first three or four waves, which reach the wave gage and before the first wave transmitted is able to reach the shore and return to the wave gage. An average root-mean-square transmitted wave height, H_t, is obtained for each experiment by averaging the RMS wave height in each burst. The graphs provided are in terms of dimensionless parameters of the relationship between the structure and the incident wave characteristics.

RESULTS

The objective of the testing is to produce the measured transmission coefficients of various oyster shell bag breakwater dimensions for a single wave height which is shown below in Table 1. The RMS incident wave height used in this testing was 0.10 m (0.301 ft) with a period of 1.34 sec and wavelength of 2.17 m (6.60 ft).

Table 1: Transmission coefficients for an incident wave height of 0.10 m (0.301ft). Physical dimensions are in meters.

Crest Width, B	Structure Height, h_c	Transmission Coefficient, K_t
0.38	0.08	0.97
0.84	0.09	0.92
1.30	0.08	0.89
1.62	0.09	0.84
1.89	0.09	0.78
0.60	0.09	0.91
0.41	0.17	0.87
0.83	0.16	0.85
1.30	0.16	0.78
1.62	0.17	0.72
1.93	0.16	0.61
0.61	0.17	0.88
0.41	0.24	0.78
0.84	0.24	0.59
1.30	0.23	0.60
1.60	0.23	0.47
1.93	0.23	0.34
0.61	0.23	0.63

Crest Width, B	Structure Height, h_c	Transmission Coefficient, K_t
0.41	0.29	0.46
0.89	0.31	0.11
1.30	0.30	0.05
1.61	0.29	0.02
1.96	0.30	0.11
0.61	0.30	0.16
0.43	0.36	0.15
0.89	0.37	0.06
1.30	0.36	0.39
1.60	0.37	0.24
1.96	0.37	0.01
0.61	0.36	0.09
0.42	0.43	0.12
0.89	0.45	0.05
1.32	0.42	0.31
1.62	0.42	0.14
1.96	0.45	0.06
0.61	0.43	0.08

In addition to the original testing a second incident wave height of 0.17 m (0.524 ft) is used when the freeboard of the breakwater is greater than zero. The corresponding wave period is 2.03 sec with a wavelength of 3.51 m (10.7 ft). A summary of these values is provided in Table 2.

Table 2: Transmission coefficients for larger incident wave height of 0.17 m (0.524 ft). Physical dimensions are in meters.

Crest Width, B	Structure Height, h_c	Transmission Coefficient, K_t
1.96	0.30	0.09
0.61	0.30	0.36
1.96	0.37	0.02
0.61	0.36	0.14
1.62	0.42	0.06
1.96	0.45	0.03
0.61	0.43	0.10

From the data in Table 1 the following non-dimensional relationship, shown in Figure 5, is developed between the ratio of the structure height and water depth (h_c/d) versus the measured transmission coefficient (K_t), for the testing conducted using the smaller wave. The variation of measured K_t in a two-dimensional parameter space is provided in Figure 6, which demonstrates the wave attenuation characteristics as a function of non-dimensional structure height and length.

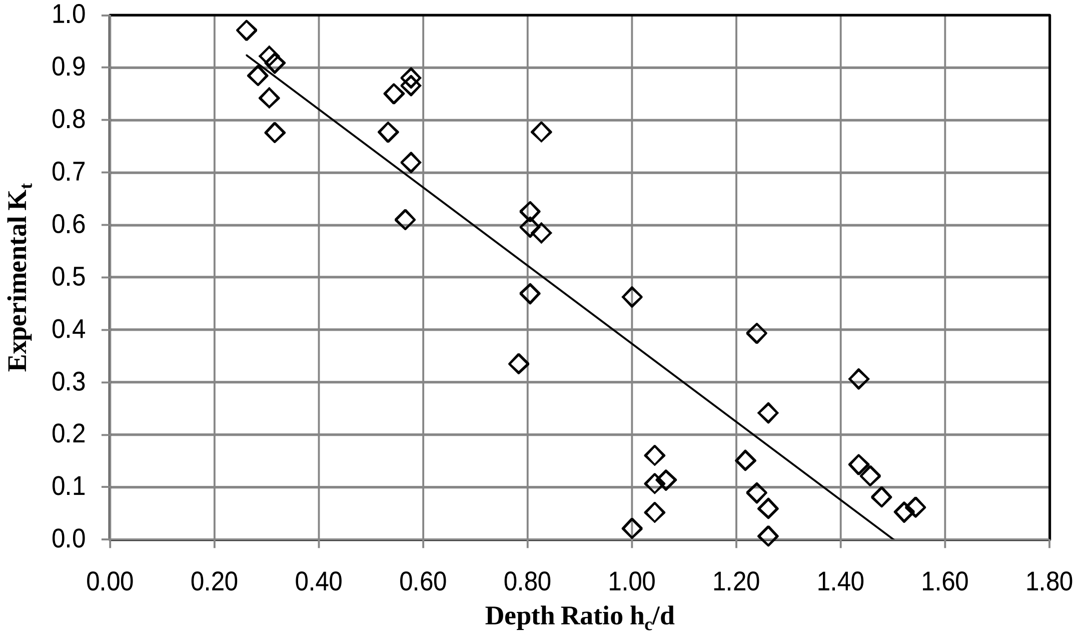

Figure 5: Graph of the relationship of the structure height and water depth vs. the measured transmission coefficient of the small wave used during the tests.

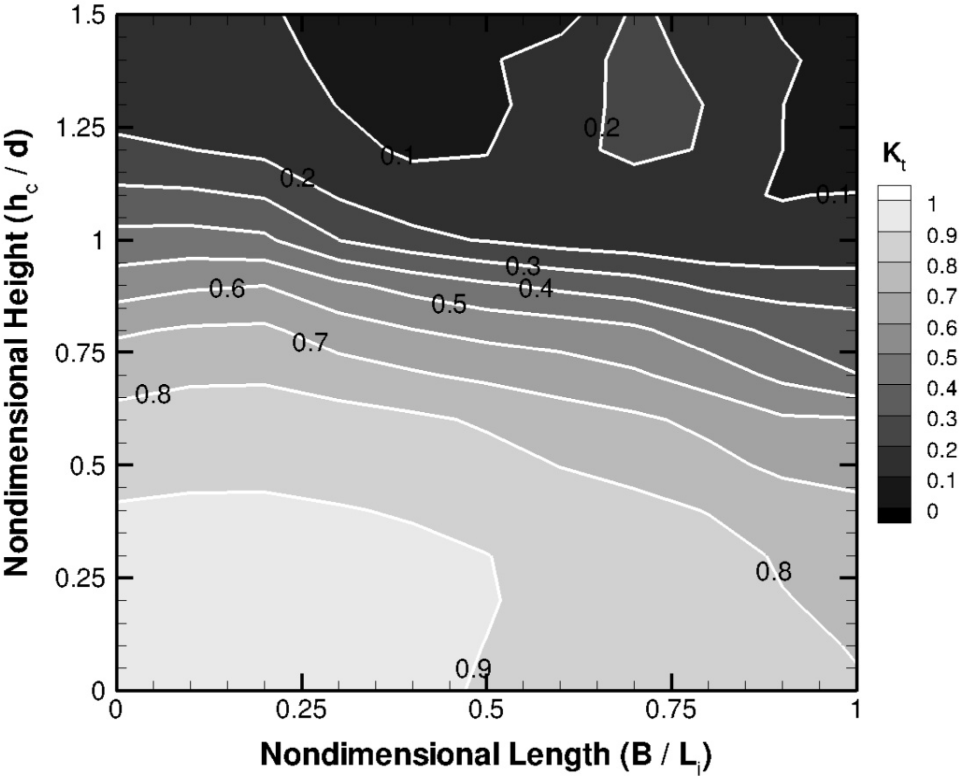

Figure 6: Variation of *K_t* as a function of non-dimensional structure length and height.

DISCUSSION

The results obtained from the testing are compared to published methodologies for estimating transmission coefficients. The Coastal Engineering Manual (2002) provides information on how to calculate the transmission coefficient using equations formulated by Van der Meer (U.S. Army Corps of Engineers, 2002). The equations given by Van der Meer et al. (2005) are a continuation of previous literature published by d'Angremond et al. (1996) and Van der Meer and d'Angremond (1992). The formulae depend primarily upon non-dimensional relationships between the incident wave height and the physical characteristics of the structure. The final equations published in Van der Meer et al. (2005) are shown below.

$$\text{For } \frac{B}{H_i} < 8 \qquad K_t = -0.40\frac{R_c}{H_i} + 0.64\left(\frac{B}{H_i}\right)^{-0.31}\left(1 - e^{-0.50\xi}\right)$$

$$\text{For } \frac{B}{H_i} > 12 \qquad K_t = -0.35\frac{R_c}{H_i} + 0.51\left(\frac{B}{H_i}\right)^{-0.65}\left(1 - e^{-0.41\xi}\right)$$

Note that a gap exists in the range $8 < B/H_i < 12$, where the Van der Meer et al. (2005) equations give a discontinuity in this range and it is suggested that linear interpolation is used for values of B/H_i that fall within this range. Additionally, Van der Meer et al. (2005) suggests limits for the maximum and minimum values of K_t. The lower limit, K_{tl}, is defined as a constant 0.05. The upper limit K_{tu}, is given a linear dependency on B/H_i and is determined by the equation given below.

$$K_{tu} = -0.006\frac{B}{H_i} + 0.93$$

The transmission coefficients of the structures tested are calculated using the parameters described by Van der Meer et al. (2005). These coefficients are then compared to the transmission coefficients determined from the test data from Table 1 and Table 2 by using a one-to-one graph shown in Figure 7.

From Figure 7, one can see the similarities in the two determinations of the transmission coefficient. With a slope of approximately one, the Van der Meer et al. (2005) equation is shown to be adequate in estimating the wave height attenuation of an oyster shell bag breakwater. However, Figure 7 shows the predicted K_t values from Van der Meer et al. (2005) are an under estimate from the measured values obtained through testing. This could be a result of the porosity of the oyster shell bag breakwaters being different than the rubble breakwaters used in the Van der Meer et al. (2005) tests.

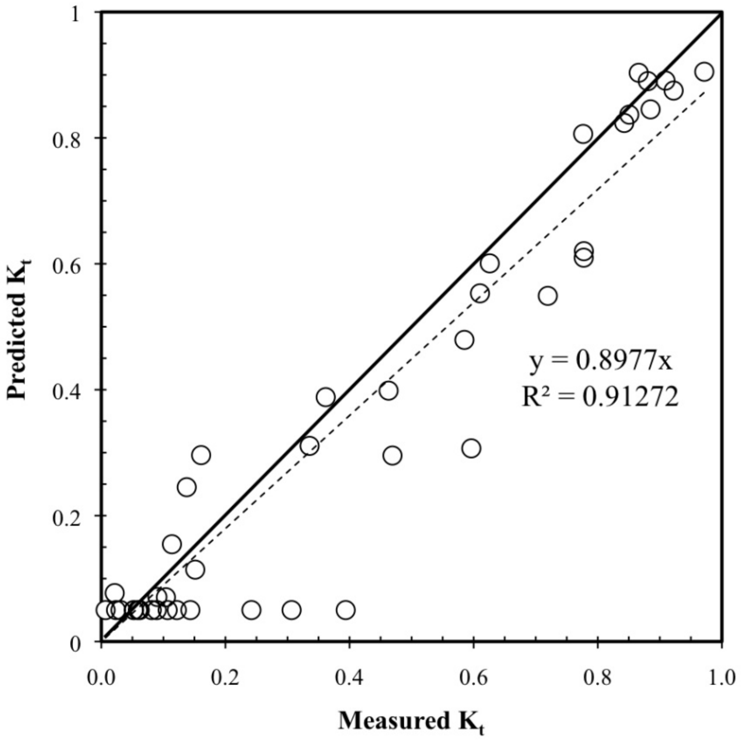

Figure 7: A comparison of measured and predicted transmission coefficients using the predictive equations of Van der Meer et al. (2005). Open symbols (o) represent measured data, the dashed line is a linear regression with a zero intercept, and the dark solid line represents perfect agreement.

Also shown in the graph is the product of the forced lower limit of the Van der Meer et al. (2005) equations. Based on the research performed by Van der Meer et al. (2005), the equations are no longer valid for predicting K_t, once the freeboard of the structure becomes positive. Through the limited testing performed during this research it is also obvious that predicting K_t becomes difficult once the freeboard becomes positive. This is shown in Figure 7 from the results. As the dimensionless freeboard becomes larger the data become skewed. The skew is likely due to outside variables affecting the transmissive properties of the structure. As the freeboard becomes larger, the transmissive properties of the structure become more reliant on factors such as run up and overtopping which are not accounted for in the predictive equations given by Van der Meer et al. (2005).

CONCLUSIONS

The results obtained in this report are a substantial finding in terms of constructing oyster shell bag breakwaters. The resulting data obtained from testing is compared to published methodologies for measuring the wave transmission coefficient for low crested breakwaters (Van der Meer et al., 2005), which produces a distinguishable resemblance based on the 43 tests conducted during this study. In general, experimental testing suggests that:

1) The transmission coefficient decreases with increasing dimensionless freeboard.

2) The transmission coefficient decreases with increasing dimensionless crest width.

3) The methodology of Van der Meer et al. (2005) provides realistic values of K_t within the range of tested parameters.

However, additional testing should be continued, even though the overall data presented from the testing is similar to the predictive equations. The additional testing should focus on the areas within the results where the comparison with Van der Meer et al. (2005) was not in agreement. More specifically, the variation of wave characteristics over a single structure dimension should be examined. Using this data, one could obtain a better understanding of the relationship between the wave characteristics (i.e. wave period, length, and height) and the structure dimensions associated in the transmissive properties, which could ultimately lead to more predictive formulae. Furthermore, testing should be extended outside the "ideal setting" to include more realistic applications, where irregular wave, reflection, and other non-pure transmissive characteristics are included in the predictive formulae.

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