Submerged modular breakwaters for coastal protection

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Abstract

Submerged breakwaters are widely used for establishment and protection of coastal wetlands; nevertheless, construction of breakwaters in the sea domain has always been a challenge to engineers. This research introduces a number of submerged breakwaters that are made of a plurality of rectangular/triangular concrete modules. The wave transmission characteristics of the breakwaters are evaluated using small-scale physical modelling. A series of experiments are conducted in a wave flume to study the performance of the breakwaters in regular waves. Wave suppression ability of the breakwaters is quantified by the wave transmission coefficient. The effects of breakwater width, face type and configuration on wave transmission of the breakwaters are addressed in this paper.
Keywords: attenuation, coastal protection, submerged breakwater, wave transmission.

1 Introduction

Malaysia is blessed with a total of 4800km of coastlines at which a large population concentrates. Nevertheless, more than 28% of the coastlines are subjected to erosion. Thousands acres of coastal wetland have been invaded by the storm waves during monsoon seasons, resulting in loss of dwelling place for aquatic flora and fauna as well as wildlife. The drastic retreat of coastal vegetations (*e.g.* mangrove forest) has become a national threat and needs to be tackled immediately by the local authorities. Furthermore, damages to the coastal wetlands are also accelerated by the unplanned development and the effect of sea

WIT Transactions on Engineering Sciences, Vol 82, © 2014 WIT Press
www.witpress.com, ISSN 1743-3533 (on-line)
doi:10.2495/AFM140111

water rise. Therefore, various efforts have been implemented to restore the coastal wetlands.

Various coastal structures have been used to provide wave protection and adequate shoreline stabilization. The use of submerged breakwaters is particularly attractive in many shoreline restoration projects mainly due to the aesthetic reason. Submerged breakwaters have low crests even during low tides so as to preserve natural beauty of the coastal environment. One example of submerged breakwater application in Malaysia is the installation of three detached breakwaters in Kerteh bay, Malaysia. This is part of the dynamic coastal area along the east coast of Peninsular Malaysia which partially characterized by series of large and small hook-shaped bays with most part fully exposed to direct wave attack. Kerteh bay is situated within a town in the district of Kemaman in Southern Terengganu, Malaysia, about 30km north of Chukai. The coastal area fronting the Rantau Petronas Complex which consists of housing facilities, a school and a golf course, used to be seriously eroded. Three detached submerged breakwaters placed about 300m seawards from the original shoreline and beach nourishment was adapted to mitigate this problem more than 15 years ago. Two of the three submerged breakwater were 400m in length with a gap of 600m in between. The third submerged breakwater with a length of 200m was placed 400m away from the second submerged breakwater, moving from north to south. Recent assessment of the site revealed further erosions both south and north of the protected area. The shoreline response is currently under investigation and monitoring is still on-going.

Apart from conventional quarrystones breakwaters, there are various ingenious designs of submerged breakwaters have been proposed, tested, and commercialized with mixed success in the past decades, *e.g.* Beachsaver Reef (Bruno *et al.* [1]), Hex Reef (Mokhtar and Santhanam [2]), Aquareef (Hirose *et al.* [3]), and Reef Ball (Armono and Hall [4]). Each of these breakwater designs has different wave suppression mechanisms, *e.g.* reflection and energy dissipation. They cause premature breaking of waves, thus dissipating wave energy more than a natural sloping beach can do (Ahrems and Fulford [5]). Some of the controlling factors to wave transmission of these low-crested breakwaters are the breakwater geometry (*i.e.* crest height and width), structure slope, permeability and roughness, design water level, wave height and wave period (Pilarczyk and Rijkswaterstaat [6]). Wave transmission characteristics of the submerged breakwater would in turn govern the shoreline response. Some of the primary variables affecting a shoreline response to a breakwater include distance offshore, length of the structure, transmission characteristics of the structure, beach slope, mean wave height and period, orientation angle of the structure, predominant wave direction and gap between breakwater segment (Hanson and Kraus [7]).

In this study, submerged breakwaters comprising a plurality of concrete modules were developed. These breakwater modules presented in rectangular or triangular forms (as shown in Fig. 1), could be assembled and yield submerged breakwaters of various configurations. The advantages of the modular breakwaters as compared to the submerged, fixed breakwaters are shorter construction period, mobility, and ability to be recycled. This study aims at evaluating the wave transmission characteristics of the submerged modular breakwaters with respect to the effects of breakwater width, face type and configuration.

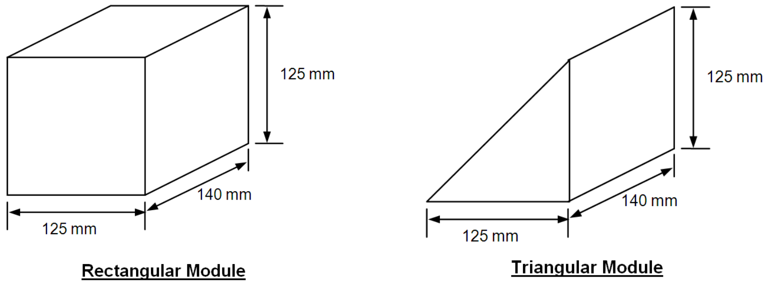


Figure 1: Breakwater modules.

2 Experimental set-up

A series of laboratory tests on the submerged modular breakwaters were conducted in a 12-m wave flume at the Hydraulics Laboratory of the *Universiti Teknologi PETRONAS*. The test models were located at the mid-length of the wave flume and were subjected to steady monochromatic non-breaking waves. A flap-type wave paddle was installed at one end of the flume to generate a series of regular waves of varying properties. At the other end of the flume, a wave absorber was installed to minimize the reflected waves in the flume. A movable carriage for wave probe was rested on two steel rails at the sidewall tops of the flume. The tests were conducted for 13 wave periods, ranging from 0.6–2.0s in water depths of 20, 25 and 30cm. The wave envelops in front of the breakwater was recorded using the moving-probe method. The wave records were subsequently decomposed into incident and reflected wave heights. The transmitted waves past the test models were measured by a probe placed at 1m away from the leeside of the test model. Summary of the model properties and the test parameters are indicated in Table 1. Note that the breakwater models were subjected to regular waves in transitional waters throughout the test program. A total of 195 test runs were conducted in this study.

3 Results and analysis

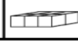
Wave attenuation performance of the submerged modular breakwater models is quantified by the transmission coefficient C_t,

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

where H_i and H_t are the mean incident and transmitted wave heights, respectively. The greater the wave transmission, the larger the C_t value will be.

Table 1: Test parameters for the submerged modular breakwaters.

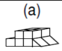
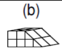
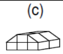
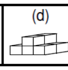
CASE 1: Effect of submerged breakwater width

	(a) 	(b) 	(c) 
(a) Breakwater dimensions			
Width, *b* (cm)	12.5	25.0	37.5
Height, *h* (cm)	12.5	12.5	12.5
Length(cm)	28.0	28.0	28.0
(b) Testing environments			
Water depth, *d* (cm)	20	20	20
Wave period range, *T* (s)	0.6 - 2.0	0.6 - 2.0	0.6 - 2.0
Wave height range, H_i (s)	3.0 - 6.3	3.0 - 6.4	3.0 - 6.5
(c) Dimensionless parameters			
h/d	0.625	0.625	0.625
b/d	0.625	1.250	1.875

CASE 2: Effect of submerged breakwater faces

	(a) 	(b) 	(c) 
(a) Breakwater dimensions			
Width, *b* (cm)	50.0	50.0	50.0
Height, *h* (cm)	12.5	12.5	12.5
Length(cm)	28.0	28.0	28.0
(b) Testing environments			
Water depth, *d* (cm)	20 & 25	20 & 25	20 & 25
Wave period range, *T* (s)	0.6 - 2.0	0.6 - 2.0	0.6 - 2.0
Wave height range, H_i (s)	3.0 - 6.8	3.0 - 6.8	3.0 - 6.8
(c) Dimensionless parameters			
h/d	0.500	0.500	0.500
b/d	2.0 & 2.5	2.0 & 2.5	2.0 & 2.5

CASE 3: Effect of submerged breakwater configurations

	(a) 	(b) 	(c) 	(d) 
(a) Breakwater dimensions				
Width, *b* (cm)	50.0	50.0	37.5	37.5
Height, *h* (cm)	25.0	25.0	25.0	25.0
Length(cm)	28.0	28.0	28.0	28.0
(b) Testing environments				
Water depth, *d* (cm)	25 & 30	25 & 30	25 & 30	25 & 30
Wave period range, *T* (s)	0.6 - 2.0	0.6 - 2.0	0.6 - 2.0	0.6 - 2.0
Wave height range, H_i (s)	3.3 - 9.7	3.3 - 9.7	3.3 - 9.7	3.3 - 9.7
(c) Dimensionless parameters				
h/d	0.83 & 1.00	0.83 & 1.00	0.83 & 1.00	0.83 & 1.00
b/d	1.67 - 2.00	1.67 - 2.00	1.67 - 2.00	1.67 - 2.00

Note that the wave attenuation performance of a breakwater is inversely proportional to its wave transmission coefficient. The following sections present the wave transmission characteristics of the submerged modular breakwaters with respect to the effects of breakwater width, face and configuration. The C_t values were plotted against the incident wave steepness parameter, H_i/gT^2, where g and T are gravitational acceleration and wave period, respectively.

3.1 Effect of the breakwater width

Three breakwater models consisting of single, double and triple rows of rectangular modules were tested in a water depth of 20 cm. These yield the relative breakwater widths (b/d) of 0.625, 1.250 and 1.875 for the present experiment. The crest freeboard, R_c (the height from the breakwater crest to the still water level) was set at -7.5cm. Note that R_c<0 indicates the breakwater is in submergence. The details of the test parameters are given in Table 1.

Fig. 2 displays the C_t of the single-, double- and triple-row breakwaters in 20cm water depth. Best-fit curves were drawn to illustrate wave transmission characteristics of the respective test models corresponded the wave steepness parameter. It is seen from the figure that the C_t of the test models reduces as H_i/gT^2 increases from 0.003-0.010. This shows that the wave steepness is an important parameter in affecting the wave transmission of the submerged modular breakwater models of multiple rows within the test range, *i.e.* the high steepness waves tend to be suppressed in a greater extent. As H_i/gT^2>0.010 the reduction of C_t of the test models is almost invisible. The C_t of the single-, double- and triple-row breakwaters are constant at 0.70, 0.55, and 0.20, respectively. It is also clear from Fig. 2 that a rapid reduction of C_t as the number of breakwater rows increases, particularly at H_i/gT^2>0.005. This is mainly due to the fact that the additional surface area resulted from the extension of breakwater

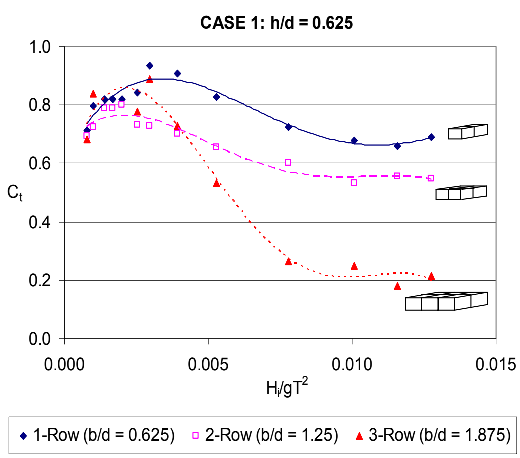


Figure 2: Effect of the breakwater width.

width would create greater frictional stress to interfere with the advancing waves. Hence, the relative breakwater width is another significant parameter to be considered in the design of the submerged breakwaters.

3.2 Effect of the breakwater face type

The influence of breakwater seaward and shoreward faces on wave transmission was explored by three types of 4-row models as shown in Table 1. These models had identical dimensions, *i.e.* 12.5cm high, 50cm wide and 28cm long, with upright/inclined seaward and shoreward surfaces. The test models were tested in two water depths, *i.e.* 20 and 25cm, giving the breakwater height-to-water depth ratios (h/d) of 0.500 and 0.625.

Figs 3 and 4 present the C_t of test models at h/d=0.500 and 0.625, respectively. At h/d = 0.500 (Fig. 3), C_t of the test models gradually decrease with the increasing H_i/gT^2. The longer the period of the waves, the greater the energy transmitted to the leeside of the breakwater because longer period waves have their energies distributed more uniformly in the water column. It is noticed from the figure that C_t>1 at H_i/gT^2<0.004, for all the test models. This is due to the non-breaking waves that were steepened when propagating over the test model. Wave attenuation by the test models is observed at H_i/gT^2>0.005; however, the amount of energy reduction is rather small. It is also evident that wave transmission ability of the test models is not much influenced by the type of frontal/shoreward surfaces at h/d=0.5.

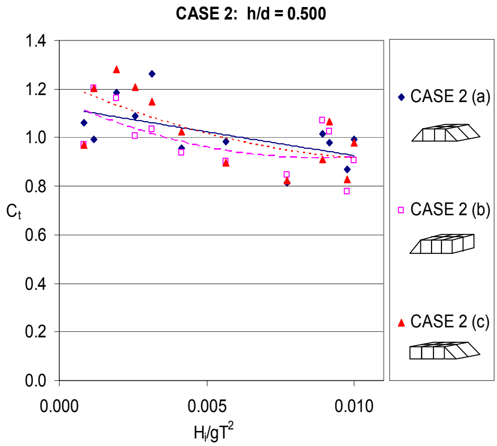


Figure 3: Effect of the breakwater faces for h/d = 0.500.

At h/d=0.625 (Fig. 4), wave attenuation performance of the test models improves significantly. This shows that the test models are only effective in shallower waters whereby the crest freeboard magnitude is relatively small. This allows the steepened waves to break over the submerged breakwater due to limited shoaling depth. Unlike Fig. 3, the effect of breakwater face type is a lot more evident in Fig. 4. The inclined frontal surface tends to reduce wave energy more than the inclined rear surface. This might be due to the fact that the shoaling of waves is more experienced by waves that first approach the inclined frontal surface of the breakwater; the waves subsequently reduce in size due to energy dissipation by breaking and frictional loss. Also note that the C_t of CASE 2(a) is higher than those of other test models. This is mainly due to the limited crest surface area for energy dissipation. In summary, the effect of breakwater face type is only prominent when the breakwater is applied in shallower waters, *e.g.* *h/d*=0.625.

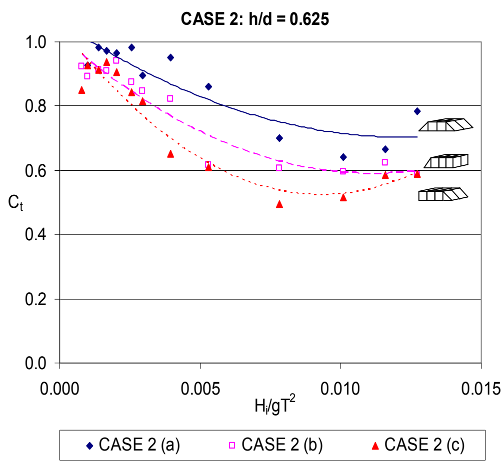


Figure 4: Effect of the breakwater faces for *h/d* = 0.625.

4 Effect of the breakwater configuration

In this study, four models of different configurations were developed at which the models consisted of two layers of modules as shown in Table 1. Models (a) and (b) comprised 4 and 3 rows of module, respectively. These models have a common height of 25cm and were tested in 25 and 30cm water depths. These contribute *h/d* ratios of 0.833 and 1.000 for the present experiment.

Fig. 5 exhibits the comparison of C_t for the test models arranged in various configurations at *h/d* = 0.833. It is found that the C_t curves developed for the respective test models are well agreeable with each other by having a similar trend whereby C_t diminishes with the increasing H_i/gT^2. Apparently, the submerged breakwater of four rows performs more efficiently than those of three rows. It once again proves that (i) the width of the submerged breakwater does play an important role in affecting the wave attenuation performance; and (ii) the greater the surface area of the breakwater crest, the better will be the wave energy dissipation mechanism of the breakwater. For the 3-row models, the CASE 3(c) model performs more effectively than the CASE 3(d) model in reducing the incoming wave energy. This is mainly attributed to the triggering of energy dissipation by the sloping seaward face of the model. For the 4-row models, the CASE 3(b) model, which has a constant sloping seaward face extending from its toe to the crest, is a better submerged breakwater than the CASE 3(a) model. It is capable of reducing the wave height up to 60% at H_i/gT^2=0.009. The CASE 3(a) model is a better reflective breakwater due to the upright feature of the upper front face.

C_t of test models at h/d = 1.000 is demonstrated in Fig. 6. Note that at h/d = 1 the breakwater crest is located at the still water level. In general, the test models are better wave attenuators in shallower waters due to intense wave interactions

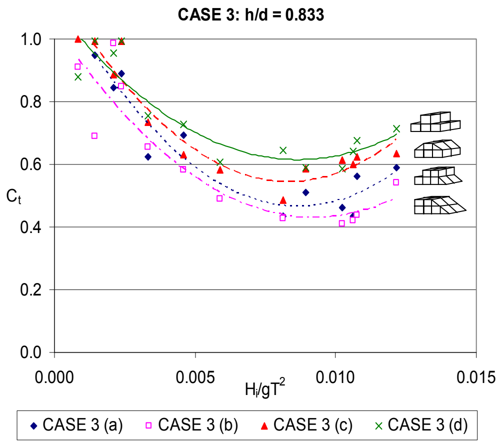


Figure 5: Effect of the breakwater configurations for h/d = 0.833.

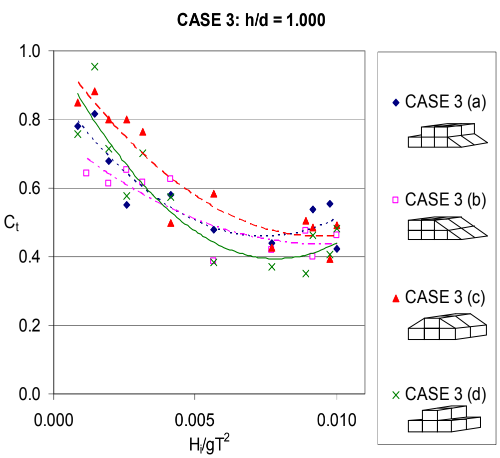


Figure 6: Effect of the breakwater configuration for h/d = 1.000.

with the structure. The C_t of the 4-row models are almost comparable to each other. It is interesting to note that the CASE 3(d) model, which has only 3 rows of module, has the lowest C_t at H_i/gT^2>0.004. This is principally attributed to the reduction of incident wave energy through reflection by the impermeable vertical face of the model in relatively shallow waters. For H_i/gT^2<0.004, the CASE 3(b) model seems to be the most effective wave attenuator. In short, wave transmission characteristics of the submerged breakwater are strongly governed by its configuration, which is virtually controlled by the method of assembly of the submerged modules.

5 Conclusion

Different configurations of submerged breakwaters made of rectangular and triangular modules were proposed for coastal wetland protection in this study. The following can be concluded from the test results within the test limit:

1. Waves of high steepness limited the wave transmission past the submerged breakwater models regardless of their configurations.
2. The degree of wave transmission of the submerged modular breakwaters was restricted by its crest width at which the wave-structure interactions were prominent.
3. In larger submergence depth (h/d=0.5), the submerged modular breakwaters steepened waves at H_i/gT^2<0.005. Wave suppression by the breakwaters became remarkable when tested in smaller submergence depth (h/d≥0.625).
4. The influence of the face type of the submerged breakwater on wave attenuation was remarkable in shallow waters. Breakwaters with sloping seaward faces outperformed those with vertical faces.

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