Experimental Studies on Submerged Breakwater for Coastal Protection

by

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CERTIFICATION OF APPROVAL

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Approved by,

(Mr Teh Hee Min)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

December 2006

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

(ILYANA ADNAN)

ABSTRACT

This project is an experimental study on submerged breakwater for coastal protection by wave attenuation mechanisms. Basically this project is focusing on development of an effective submerged breakwater that will help the industry to reduce wave attack at erosion hot spots especially along Malaysia coastline. The effectiveness of this submerged breakwater will hopefully maintain the attractive values of its sandy beaches. The significant parameters to produce a minimum transmission coefficient of the wave are width and height of the breakwater with respect to its water depth. The main objective of the study is to develop submerged breakwater comprised of a plurality of modules that is effective in reducing wave heights. The early stage of the study is focusing on the literature review of the existing submerged breakwaters as well as the proposal of the model design, followed by the construction of the modules and the laboratory experiments. The experimental study consists of an experiment for wave period determination also the attenuation performance of proposed model in terms of transmission coefficient C_t in various configurations. From the experimental result, it is found that the proposed model of submerged breakwater is effective in attenuating wave energy in terms of wave transmission. The number of optimum row required to reduce sufficient wave height is three (3). It is better to have a sloping face at the seaward of the submerged breakwater than a vertical face. The wider the submerged breakwater, the better will be the performance and greater value of relative depth submergence, h/d presents better wave energy dissipation.

ACKNOWLEDGEMENT

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CHAPTER 1: INTRODUCTION

1.1 Background of Study

Malaysia has been a famous tourism centre for years. From its progressive urban development to the naturally beautiful beaches, this country is moving forward to achieve the mission to be a develop country by year 2020. However there are some problems faced especially on beach erosion that totally affected the hot spots due to variety of natural and man-made processes. Lots of programs have been implemented to recover the erosions including the Coastal Engineering Technical Center (CETC) as known as Coastal Engineering Control Unit (CECU), under the Department of Drainage and Irrigation (DDI) in the Ministry of Agriculture. The CECU is responsible for implementing coastal erosion control, engineering works for critical erosion areas, providing technical support to the National Coastal Erosion Control Council (NCECC), also technical advisory services to other government agencies, as well as collecting coastal engineering data.

In conjunction to that, coastal structures such as groin, artificial reef and detached, segmented, floating or submerged breakwater have been deployed to protect beach from erosion. As far as concerned, submerged breakwater is a good choice to work as it is able to dissipate wave energy and definitely produce sandy materials for beach nourishment. Besides, it has aesthetic value as compared to emerged or floating breakwaters. It does not need mooring system or bigger structure, but proven to be effective in reducing wave height also controlling sediment movement in the shallow water and sometimes use to protect fixed emerged breakwaters.

There are few shapes of submerged breakwaters exist includes rectangular, trapezoidal, triangular, hemi-cylinder and semi-circular. They could be rigid or flexible. Rigid submerged breakwater is a solid structure with certain percentage of porosity, while flexible submerged breakwater is a zero porosity structure with hollow that allows pressure difference in and outside it. Besides shapes, material used is also important in creating an effective submerged breakwater. Normally concrete is used as it produces porous, permeable and ductile structure. However, certain admixture needs to be applied to increase the strength. Take note that the structure must be environmental-friendly, thus the pH of the concrete mixture should be similar to natural sea water pH (8.3).

Submerged breakwaters work as a medium to reduce wave energy in terms of wave transmission. The wave energy attenuated in the lee of the breakwater is either dissipated by the structure or reflected as reflected wave energy. In conjunction to that, lots of experiments have been carried out to determine the optimum wave energy reduction. Further information on submerged breakwaters will be discussed in the Chapter 2.

1.2 Problem Statement

Tourism boom has some detrimental effect and put severe pressure on many sandy beaches. Unwise developments of beach resort often cause coastal erosion in some areas nearby. Many sandy beaches in tropical countries are often naturally sheltered by barrier reef. The reef dissipates wave energy and at the same time act as a source of sandy materials that nourish the beach. Human intervention and activities which include sea water pollutions, mining and other exploitation of the coral reefs frequently damage natural coral reefs. Then it will take sometime for the coral reef to regenerate since they are sensitive and slow grower marine growth. Thus they will unable to support other marine life and deprived of protection from wave attack. Significant losses in material and natural resources under such conditions have occurred in many places in Malaysia and many other tropical countries.

Due to big wave attack that causes erosion to occur, many researchers have come out with many solutions. However, there are few imperfections found out from those solutions where the structure could not work effectively. The intension is that the structure should maintain the optimum crest width or height to produce minimum transmission coefficient. But some designs created scour around the structure itself that affected the effectiveness of it after certain period of time. Submerged breakwater is one of the choices since it is an economical, efficient in breaking the steep waves and safe as it cannot fail catastrophically as it does not have a core. Still, there is a problem in choosing the right geometry to produce the most effective structure especially regarding its crest width and submergence.

1.3 Objectives of Study

The objectives of this study are as follows:

1) To develop two (2) designs of submerged breakwater comprised of a plurality of modules that is environment-friendly and effective in reducing the height of waves.
2) To study the effectiveness of applying the proposed designs as coastal protection system via laboratory experiments.
3) To compare the experimental results of the existing models by other researchers with those results of models proposed.

1.4 Scope of Work

The scope of work for this project can be divided into six (6) elements such as:

1) Literature Review

   Various types of existing submerged breakwaters proposed by other researchers have been studied including the experiments of hydraulic aspects of each.

2) Development of Model

   The model of new modular barrier reef is developed in such a way to reduce wave height by process of dissipating wave energy, yet protect shoreline from erosion.

3) Laboratory Set Up

The tools and equipments for laboratory experiments must be ready before the tests being carried out to ensure the accuracy of the results. Besides, it is important to familiarise the usage of each in order to avoid faulty during experiment that can cause delay of schedule.

4) Experiments

Laboratory experiments have been handled to test the coefficient of wave transmission and reflection, the amount of energy lost with respect of wave periods plus other hydraulic aspects such as flow pattern / behaviour.

5) Result Analysis and Interpretation

Analyses of the results from laboratory experiment are then interpreted and compared to those existing results of other researchers.

6) Report Write Up

As for documentation of the whole project, a report containing six (6) chapters is produced.

1.5 Significance of Study

As mentioned before, the natural coral reefs are getting obliterated by environment factors as well as human activities. It takes a long time for the coral reef to reproduce since they are sensitive organisms. In the other side, the lost of coral reef might cause serious erosion to the beach that affected tourism activities nearby. Therefore, the study of the submerged breakwaters is purposely done to create another product for coastal protection especially for erosion hot spots. This new design can hopefully help this country to prevent serious erosion of sandy beaches that affected tourism industry. Though there are few researches have been presented before, but there are still some things to be improved in terms of the effectiveness of the model to dissipate wave energy and at the same time generate sandy materials to the beach without being harmful to the marine environment.

CHAPTER 2: LITERATURE REVIEW

2.1 Wave Attenuation Mechanisms

Generally, attenuation is defined as the decreases of the amount, force, magnitude, or value of something; in this case wave. Wave attenuation for submerged breakwaters consists of a major mechanism known as wave transmission.

2.1.1 Wave Transmission

Wave transmission indicated as transmission coefficient, C_t is the major parameter among other variables that controls the response of the shoreline to the structure. It is defined as the ratio of the wave height directly shoreward of the breakwater, H_t to the wave height directly seaward of the breakwater, H_i.

$$C_t = \frac{H_t}{H_i} \tag{2.1}$$

The coefficient is ranging from 0 to 1, for which a value of 0 implies no transmission (normally when the structure is high or impermeable), and a value of 1 implies complete transmission (normally when there is no breakwater).

Krystian W. Pilarczyk, Rijkswaterstaat (2003) identified the factors controlling wave transmission include (1) crest height and (2) width, (3) structure slope, (4) core and armour material (permeability and roughness), (5) tidal and design level, (6) wave height and (7) period. While according to US Army Corps of Engineers wave transmission is depending on (1) the configuration and composition of the structure, (2) wave height and (3) period, and (4) water depth, also (5) time scale includes tidal variations, change in the incident waves and possibly longer-term change in water level. Yet, time scale can only be applied in real situation.

2.2 General

Beach protections are either hard or soft protection, or as a combination of both. Hard protection is define as coastal structures such as seawalls, revetments, and detached / submerged breakwaters, while soft protection is beach nourishment. Generally, soft protection is less effective since it needs high maintenance like re-nourishment in few years time. Thus, hard structures are more popular especially in serious erosion areas. A good hard structure like submerged breakwater can last for hundreds of years. As for example, a reef ball made of concrete with W.R. Grace's Force 10,000 micro silica has an expected life of 500 or more years (Reef Ball Foundation Inc.).

The traditional concept of detached breakwater used to be simple. A shore-parallel rubble mound structure constructed out of any natural rock material or concrete, usually emergent, and placed at a distance seaward of the shoreline. Sometimes deployed singly and sometimes are segmented with gaps in between each other. Nowadays, those traditional concepts have been changed where the breakwaters become shallow, narrow-crested rubble mound, with a crest height below the still water level and without a traditional multilayer cross section (Ahrens, 1987). Yet, the purposes are still to partially attenuate waves to protect shoreline. Figure 2.1 illustrate a common submerged breakwater and its dimensions (X = distance from shoreline, B = crest width, R_C = freeboard, h = water depth, G = gap, L_S = crest length).

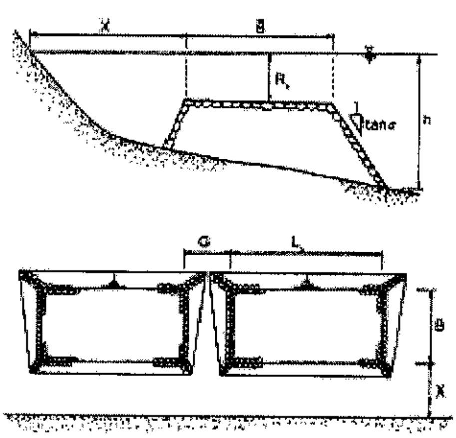


Figure 2.1: Submerged breakwater

The submerged breakwaters are invisible from the beach, and as wave encounter the structure, some of the wave energy will be dissipated while some will pass over the crest to reach the beach. Another speciality of submerged breakwater compared to higher structures is less costly. As a proof, the submerged breakwaters have been tested in laboratory and proven to be effective in reducing wave height. Ahrens (1987) also Ahrens and Fulford (1988) experimental tests showed that the submerged breakwater caused premature breaking of waves, thus dissipating wave energy more than natural sloping beach can do. (Stauble, D.K. and Tabar, J.R., 2003)

Additionally, submerged breakwater with its crest at or below still water level (SWL) can cause substantial wave attenuation and can be effectively used in places where tidal variations are small and only partial protection from waves is required, such as harbour entrance, beach protection, small craft harbours, etc (Kiran G.S., 2006). However, submerged breakwater is not suitable to be used in open sea area such as Langkawi Islands since the exposure to high waves are significant. As for example, fixed emerged breakwaters are used to protect the Langkawi International Airport and marinas around the island such as Telaga Harbour, Awana Porto Malai also Rebak Island Resort Marina.

There are various submerged breakwater designs proposed by several numbers of researchers, but need some improvements in order to create a more effective one. The submerged breakwaters are either fail to reduce wave height, produce high wave transmission, causing high wave reflection or fail to reduce wave energy towards the shore. Those failures could be caused by the geometry, numbers of array, water depth, wave period, incident wave climate, and breakwater crest width or structure freeboard; given by the distance between the water surface and structure crest (Figure 2.1). Relative crest width and relative depth of submergence of the crest below the water surface were identified as significant parameters in submerged breakwater (Dattatri et al., 1978).

Besides, many papers published did consider other characteristics such as beach slope, seabed and structures porosity or permeability, structure surface friction, distance of the structure from shoreline, also the orientation angle of the structure in their experiments. Still, most of the formulas proposed cannot be used in this research due to the laboratory experiment carried out was in one dimensional only.

In a journal, Hanson and Kraus (1989) stated that shoreline response to a breakwater is controlled by at least 14 variables. Eight of those are considered primary; (1) distance offshore; (2) length of the structure; (3) transmission characteristics of the structure; (4) beach slope and/or depth at the structure (controlled in part by the sand grain size); (5) mean wave height; (6) mean wave period; (7) orientation angle of the structure; and (8) predominant wave direction. While for segmented detached breakwaters, the gap between segments becomes another additional primary variable.

2.3 Physical Properties

2.3.1 Geometry

The geometry of submerged breakwater is one of the physical characteristic that affected the wave attenuation mechanisms. There are few shapes of submerged breakwaters exist including rectangular, triangular, hemi-cylinder, semi-circular and trapezoidal. Further performance of the breakwaters will be discussed in Section 2.4.

Generally, the geometry of a submerged breakwater is depending on its crest height relative to the water depth or freeboard, crest and base width, interlocking system and the spaces in between each module if any also its special features such as ripple shape, structure slope or openings and holes within the structure.

The relative submergence, R/H_o is recognized as a primary factor and is incorporated in all design equations, while relative crest width, B/L_o is known as central parameter even it is not always adequately accounted in design equations (US Army Corps Engineers, 2002). The relative submergence is less than zero when the structure is submerged and vice versa. Kiran G.S. et al. (2006) in the investigation of stability of breakwater defended by a seaward submerged reef stated that the optimum crest widths are B/L_o = 0.035-0.05 and B/d = 0.6-0.75. Where R = structure freeboard,

H_o = unreflected wave height, B = crest width, L_o = deepwater wavelength and d = water depth.

2.3.2 Material

Another significant property of a submerged breakwater is material. Submerged breakwaters used to be formed by armour rocks. The armour rocks can last for such a long time as it is durable and suit the marine environment. However, this kind of material is not a good choice to absorb wave energy as it is impermeable. In fact, high porosity and permeable structure has higher ability to absorb wave energy.

In conjunction to that, the submerged breakwaters now are made of concrete with certain special properties like density, durability, strength, porosity, permeability, and surface roughness. To be more environmental friendly, the pH of concrete mixture is designed to be similar to seawater pH, 8.3. The suitable pH is believed to not to harm the marine life, since it is able to inhibit the settlement and growth of many species of marine life.

In order to increase the strength and structural integrity, steel rebar reinforce or steel dust is mixed together with the concrete. However, steel is not a good material to be used in marine environment since steel can produce rust that harms the marine environment. Consequently, rubberized concrete is suggested to replace the steel. It can be used to increase toughness and at the same time reduce concrete rupture.

2.3.3 Numbers of Array

Numbers of array of submerged breakwater is another factor that affects the ability of the system in reducing wave height. Logically, when extra numbers of structures are lined up, the wave transmitted over the structures will be increased. Figure 2.2 and 2.3 below show the submerged breakwater arrangement in three arrays.

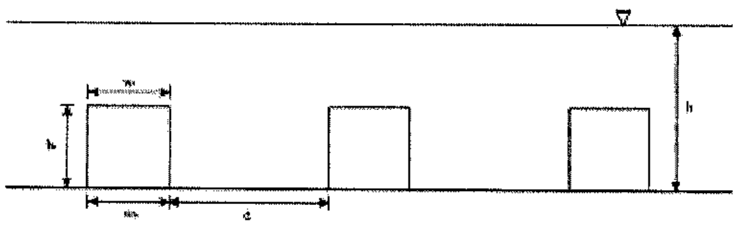


Figure 2.2: Rectangular in arrays (Y.-S. Cho et al., 2004)

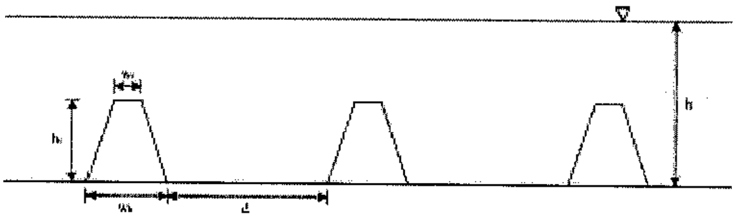


Figure 2.3: Trapezoidal in arrays (Y.-S. Cho et al., 2004)

2.4 Existing Design of Submerged Breakwaters

2.4.1 Experimental Design

Trapezoidal Submerged Breakwater

Tanaka (1976), in his research performed monochromatic wave tests includes both submerged and emerged crests as well as a broad range of crest widths. Based on the result, he established design curves that give the transmission coefficient, C_t as a function of the relative submergence, R/H_o (where R = structure freeboard; and H_o = unreflected deepwater wave height) and the relative crest width, B/L_o (where B = crest width of the structure; and L_o = deepwater wavelength). The notation of the parameters for the tests carried out is illustrated in Figure 2.4.

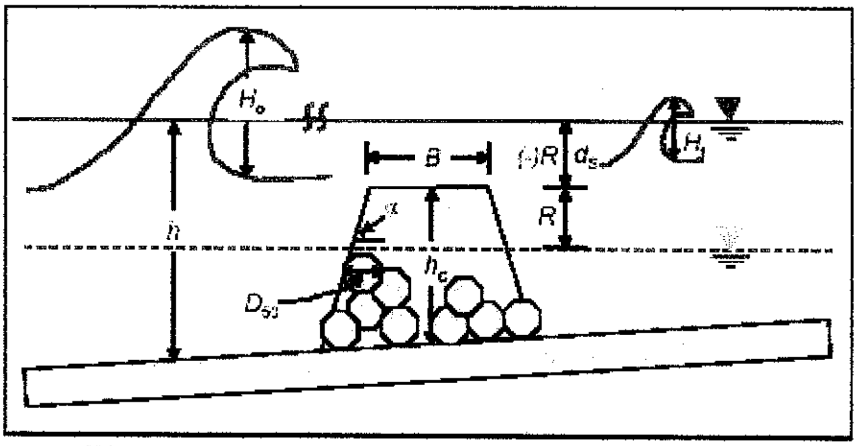


Figure 2.4: Tanaka (1976) submerged breakwater

Tanaka's work forms the basis of the Japan Ministry of Construction official guidelines on breakwater design. Until today, the curves provide the most comprehensive standard with which to compare predictive equations empirically derived from a limited set of data. The Tanaka design curves based on monochromatic waves presented in Figure 2.5 shows two significant roles in wave transmission; relative submergence R/H_o and relative crest width B/L_o. Negative values of relative submergence indicate submerged structure and vice versa.

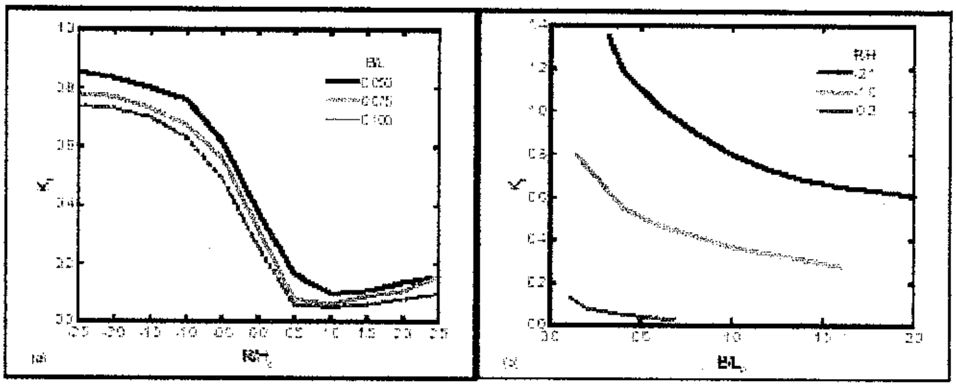


Figure 2.5: Wave Transmission design curves (redrawn from Tanaka 1976)

It can be concluded that a wider crest produces smaller C_t as compared to the narrow crested one. But as the relative submergence decrease, value of C_t will increase and sometimes greater than 1.0.

Trapezoidal Submerged Reef in Front of Breakwater

The study is simply focusing on the stability of breakwater defended by a seaward trapezoidal submerged reef as shown in Figure 2.6.

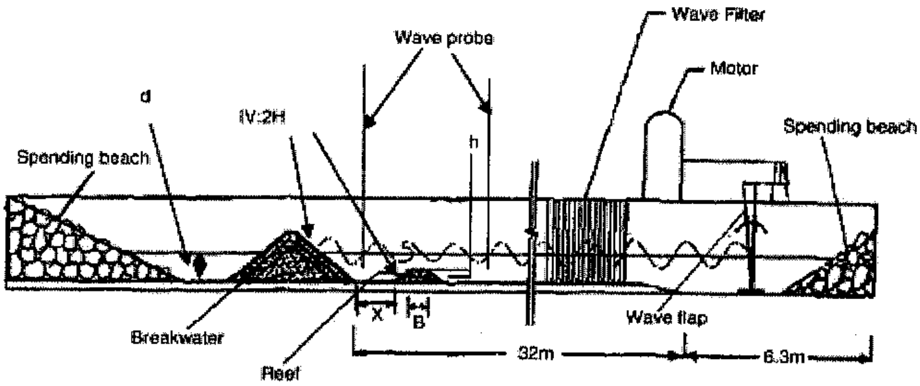


Figure 2.6: Experimental Setup

A regular wave of wide ranging heights and periods are used. The tests are carried out for different spacing between the breakwater and the reef, the different relative heights of the reef as well as different relative widths of it. Again, the transmitted wave coefficient, C_t is plotted in the Figure 2.7 for several relative crest height, *h/d*.

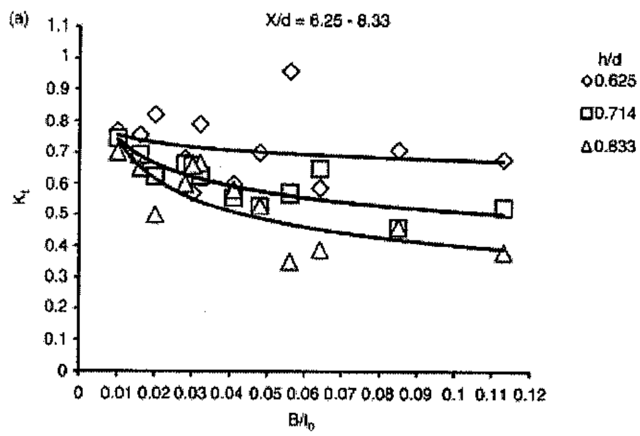


Figure 2.7: Transmission Coefficient vs B/L$_0$

The graph shows higher relative crest height gives lower C_t and vice versa. The conclusion part of the study stated that the optimum reef crest widths are B/L_o = 0.035 – 0.05 and B/d = 0.6 – 0.75 while the optimum crest height is when h/d = 0.625 – 0.833.

Porous Trapezoidal Submerged Breakwater

A numerical model investigation of wave transformation over a submerged permeable breakwater on a porous slope seabed by C.-P Tsai et al. (2005) has also covered geometry aspect. Since this investigation considered the seabed slope and its porosity that will not covered in this project, only geometry aspect is measured. Consider that the models are trapezoidal as shown in Figure 2.8.

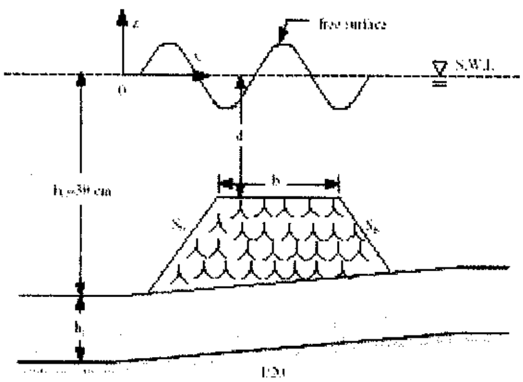


Figure 2.8: Ching-Piao Tsai et al. submerged breakwater

As usual, freeboard acts as an important parameter in breakwater study. A smaller freeboard has a higher ability of energy dissipation, but produces higher wave reflection. Besides, the wave period also influences the wave transformation over the structure. Figure 2.9 show that the significant wave reflection is appeared as longer wave period is applied.

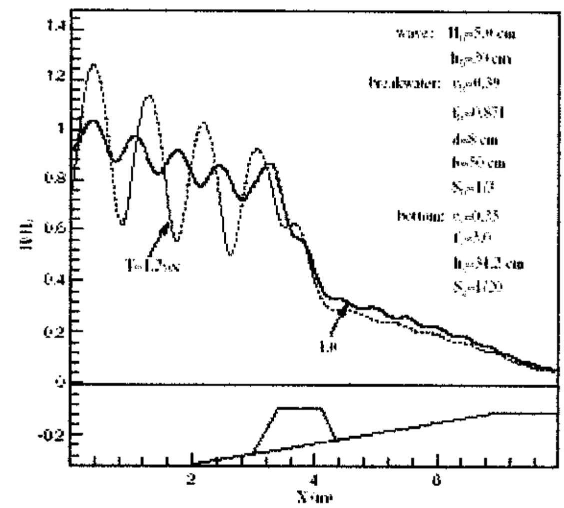


Figure 2.9: Effect of wave period on wave transformation

Again, crest width of submerged breakwater is meaningful to affect the wave height passing through the structure. The wider the crest, the more amount of wave energy will be dissipated due to greater volume of the structure. Figure 2.10 shows the result of numerical method ran comparing different crest width.

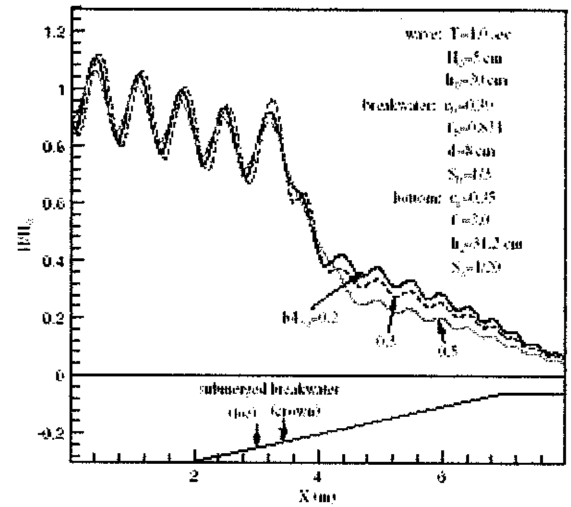


Figure 2.10: Effect of crest width on wave transformation

It can be concluded that broad-crested submerged breakwater is better compared to narrow-crested one. Figure 2.11 and 2.12 show the effect of wave surface elevation with different width.

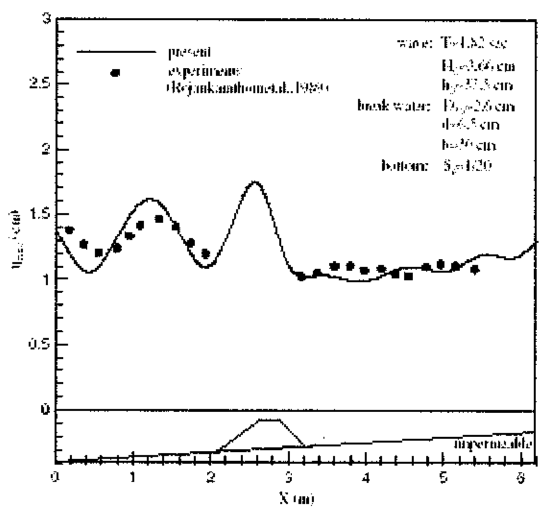


Figure 2.11: Effect of width (30 cm) on wave surface elevation

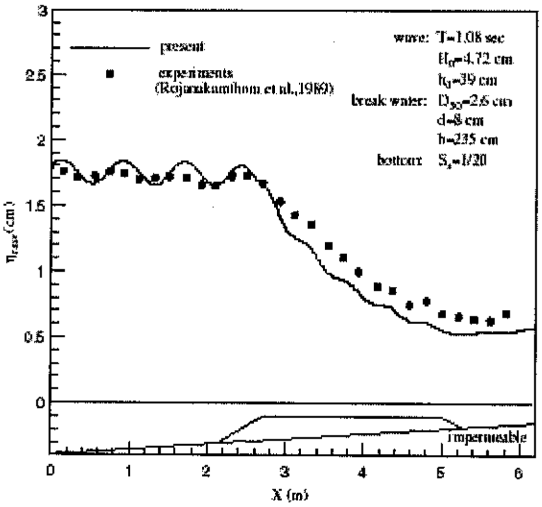


Figure 2.12: Effect of width (235 cm) on wave surface elevation

Besides geometry, other important parameters in breakwater study such as permeability and porosity of the structure as well as the seabed itself have been discussed. Porous structure has the ability to absorb and dissipate wave energy when the incident wave transmits over it. Higher porosity values of porous bottom lead to higher energy dissipation. Increasing the porosity and the friction of the submerged permeable breakwater means increasing the permeability and the flow resistance that will induces the significant wave decay.

Porous Structure in Front of Breakwater

In a research comparing rectangular, triangular and trapezoidal submerged porous structure in front of a breakwater (Figure 2.13, 2.14 and 2.15), H.-B Chen et al. (2005) stated that the wave reflection increases with freeboard, but decreases as the crest width increases. However, the wave reflection coefficient, C_r is decreases to a minimum point at a water depth, then increases with the further increases of water depth. The phenomena are tabulated in the Figure 2.16, and 2.17.

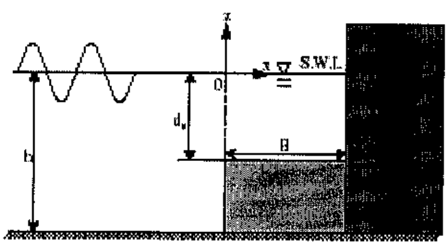


Figure 2.13: Rectangular porous structure in front of breakwater

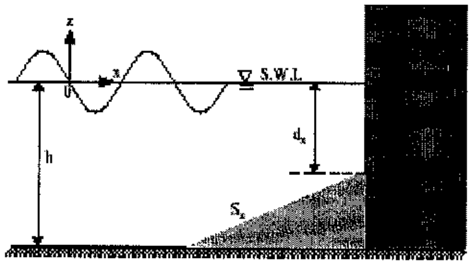


Figure 2.14: Triangular porous structure in front of breakwater

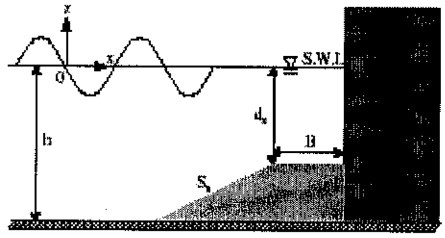


Figure 2.15: Trapezoidal porous structure in front of breakwater

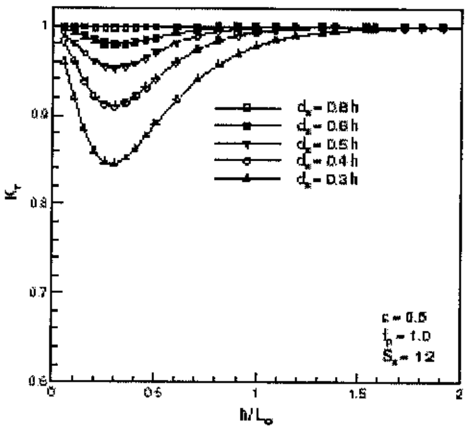


Figure 2.16: Effect of freeboard, d_s on reflection coefficient

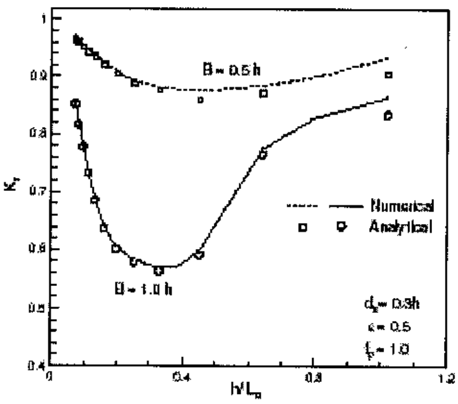


Figure 2.17: Effect of water depth on reflection coefficient

However, this experiment is conducted for inclined porous structure in front of vertical wall. Hence, the reflection might be occurred greater than the structures without vertical wall.

Rectangular and Trapezoidal Submerged Breakwater

A series of laboratory tests was carried out to investigate the strong reflection of regular water waves over a train of trapezoidal and rectangular submerged breakwaters by Y.-S Cho et al. (2004). The tests were to compare the reflecting capability of incident waves of both shapes. Figure 2.18 below is the arrangement of those structures during the tests.

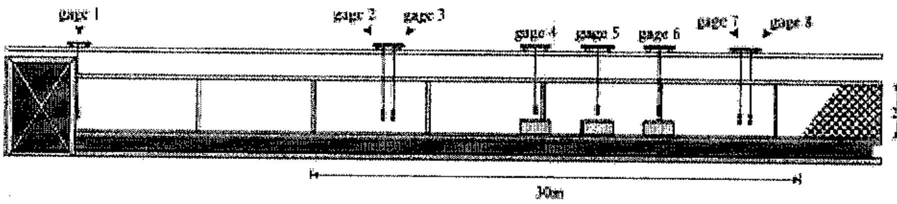


Figure 2.18: Train of submerged breakwater

It is found that the reflection coefficient of permeable submerged breakwaters is less than those of impermeable ones. The trapezoidal shape is recommended for a submerged breakwater in terms of reflecting capability and practical application. Figure 2.19 shows the comparison of reflection coefficient of both shapes, where rectangular structure has higher value of C_t when kh is less than 1.5. While as kh increase, the C_t value for trapezoidal structure is higher than the rectangular one. Noted that k = number of waves and h = water depth.

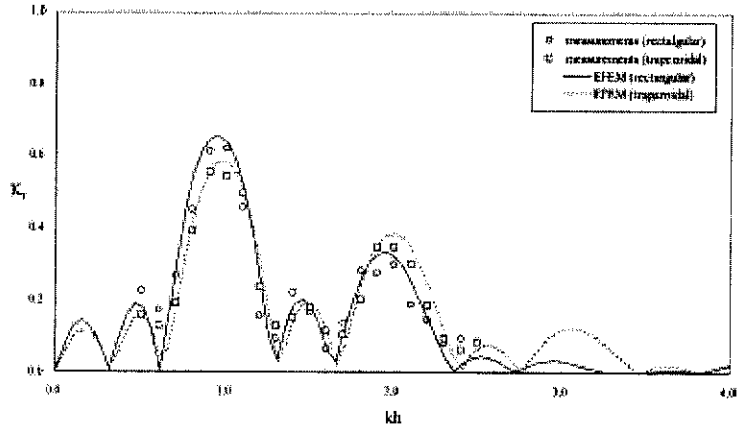


Figure 2.19: Comparison of rectangular and trapezoidal structure

Furthermore, the magnitude of reflection can be strengthened by increasing the number of arrays. Figure 2.20 shows distribution of reflection coefficients for different numbers of array. The reflection becomes stronger as the numbers of array increases. As for all shapes of structures, increasing the numbers of array will enforce the magnitude of reflection. Moreover, the energy distribution becomes more compact near the peak wave number as numbers of array increases.

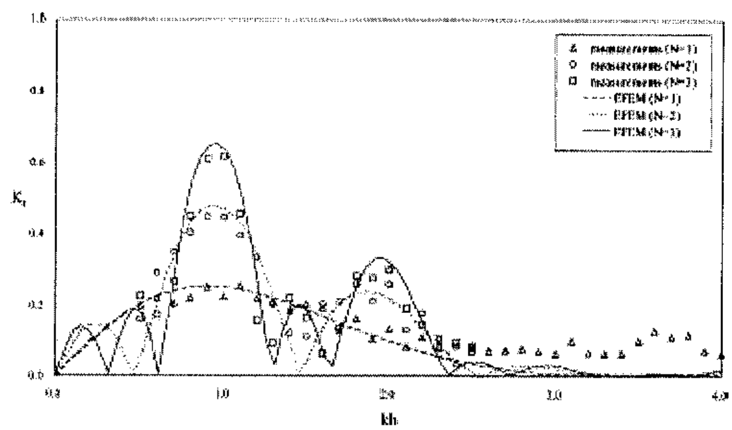


Figure 2.20: Effect of numbers of array on reflection coefficient

Rectangular vs. Hemi-cylindrical Submerged Breakwater

D.G. Stamos et al. (2003) had conducted a parametric experimental study to compare the reflection and transmission characteristics of submerged hemi-cylindrical and rectangular rigid as well as water-filled flexible breakwater models. Figures 2.21 and 2.22 show the dimensions of the rigid rectangular and hemi-cylindrical model.

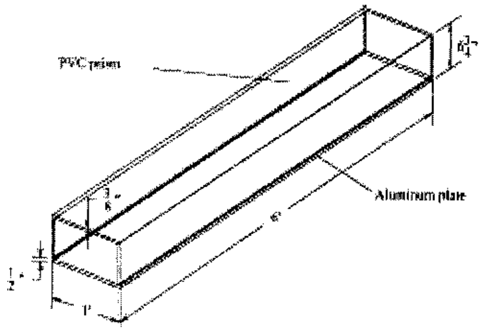


Figure 2.21: Rigid rectangular model

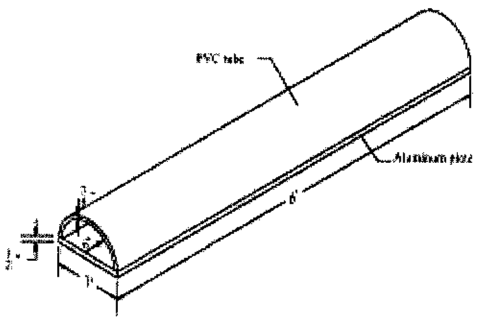


Figure 2.22: Rigid hemi-cylindrical model

For these rigid breakwaters, the results show that rectangular models are more effective than hemi-cylindrical ones in terms of reduction of transmitted waves. Figure 2.23 and 2.24 show the variations of reflection, transmission, and energy coefficients with *kh* for the rigid rectangular and hemi-cylindrical models at two different water depths. The results show that the transmission coefficient, C_t is larger in the case of hemi-cylindrical model and for all values of *kh*. Again, k = wave numbers and h = water depth.

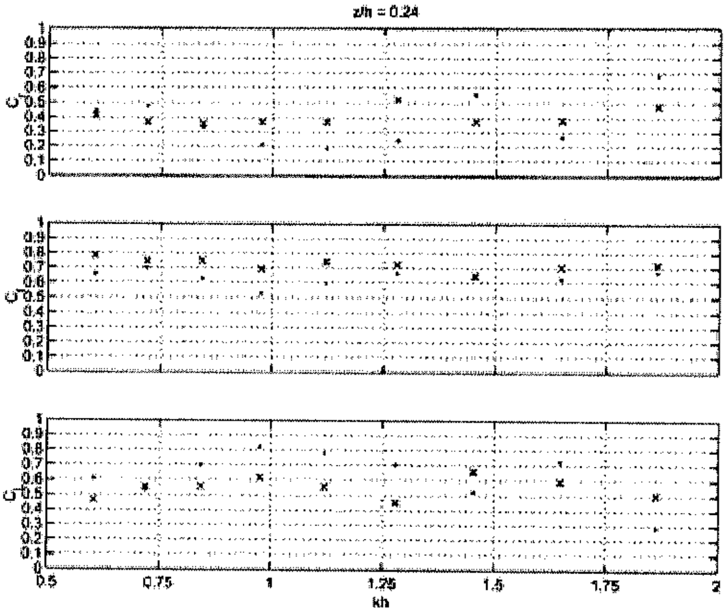


Figure 2.23: Variation of wave coefficients with *kh* at water depth 22.5cm (x = hemi-cylindrical, • = rectangular)

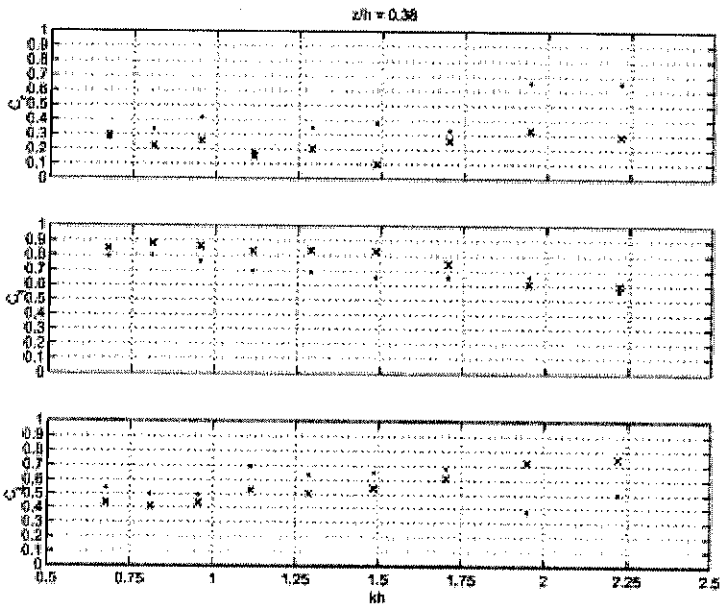


Figure 2.24: Variation of wave coefficients with *kh* at water depth 27.5cm (x = hemi-cylindrical, • = rectangular)

Whereas Figure 2.25 and 2.26 below show the water-filled flexible submerged rectangular and hemi-cylindrical breakwaters.

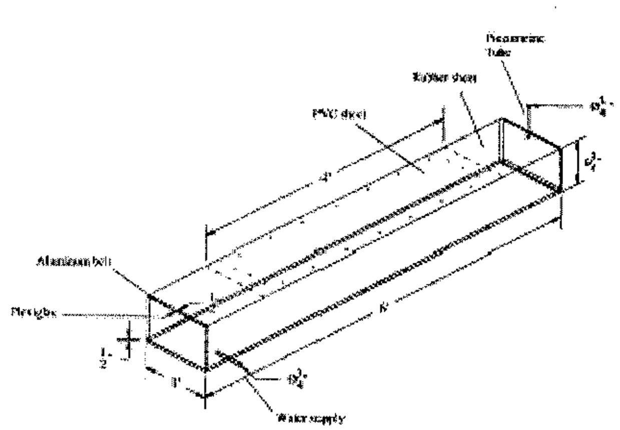


Figure 2.25: Flexible rectangular model

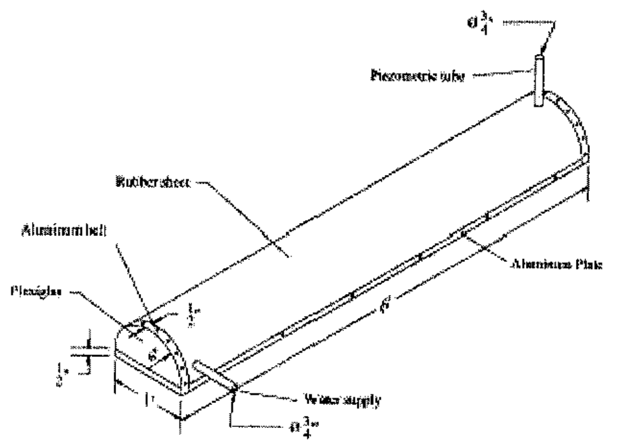


Figure 2.26: Flexible hemi-cylindrical model

For flexible breakwaters, the hemi-cylindrical models gives better wave reflection than the rectangular ones, but the energy loss induced by the rectangular breakwater is much larger and more significant to result in an overall better efficiency in terms of reduction of wave transmission. The effects of internal pressure show that the lowest pressurized flexible models considered in this work are the most effective in the reduction of the transmitted wave height.

Figure 2.27 and 2.28 show the variations of reflection, transmission, and energy loss coefficients with kh for the rectangular and hemi-cylindrical models for two different wave height under the lowest internal pressure condition considered in this work, represented by $y/h = 0.007$ (where y = internal pressure head).

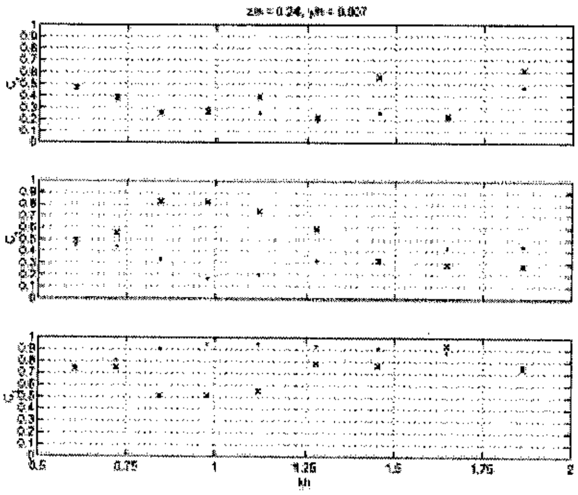


Figure 2.27: Variation of wave coefficients with *kh* at water depth 22.5cm (x = hemi-cylindrical, • = rectangular)

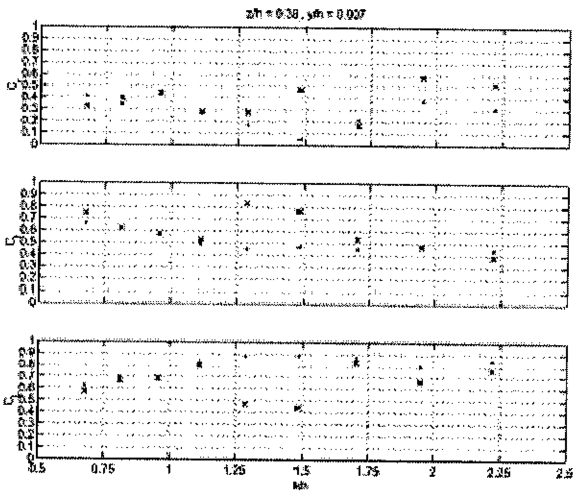


Figure 2.28: Variation of wave coefficients with *kh* at water depth 27.5cm (x = hemi-cylindrical, • = rectangular)

From both types of submerged breakwaters, it can be concluded that the higher wave reflection, lower wave transmission and higher energy loss are obtained consistently at the lower submergence depth ratio. Consequently, Table 2.1 and 2.2 tabulated the overall results of both and presented that the flexible breakwaters are more efficient in attenuating transmitted waves.

Table 2.1: Average wave coefficients of rigid models

	Water depth (h), [cm]	z/h	Cr	Ct	CL
Hemi-cylindrical	22.5	0.24	40%	72%	55%
Rectangular	22.5	0.24	38%	64%	63%
Hemi-cylindrical	27.5	0.38	24%	78%	55%
Rectangular	27.5	0.38	40%	69%	57%

Table 2.2: Average wave coefficients of flexible models

	Water depth (h), [cm]	z/h	y/h	Cr	Ct	CL
Hemi-cylindrical	22.5	0.24	0.007	38%	54%	69%
Rectangular	22.5	0.24	0.007	32%	35%	87%
Hemi-cylindrical	22.5	0.24	0.141	49%	59%	60%
Rectangular	22.5	0.24	0.141	33%	53%	74%
Hemi-cylindrical	22.5	0.24	0.282	46%	67%	53%
Rectangular	22.5	0.24	0.282	36%	52%	74%
Hemi-cylindrical	27.5	0.38	0.007	38%	61%	66%
Rectangular	27.5	0.38	0.007	29%	51%	79%
Hemi-cylindrical	27.5	0.38	0.141	37%	74%	53%
Rectangular	27.5	0.38	0.141	29%	60%	72%
Hemi-cylindrical	27.5	0.38	0.282	34%	78%	51%
Rectangular	27.5	0.38	0.282	33%	61%	70%

2.4.2 Advance Design

Reef Ball

An array of perforated hollow hemispherical shaped artificial reefs (HSAR) can be used as a submerged breakwater to provide opportunities for environmental enhancement, aesthetics and wave protection in coastal areas due to their special characteristics that differ from the conventional breakwaters. These characteristics include an extra ability to promote water circulation and provide a fish habitat enhancement capability.

For stability purpose, submerged breakwaters like Reef Balls are designed so that over half of the weight is in the bottom near the sea floor. All sizes of Reef Balls have withstood, without movement, heavy tropical storms in as little as 20 feet of water without anchors. The opening in the top of the unit breaks up the lifting force of the hydrofoil effect common to dome shapes. Side holes are wider near the center of the walls and narrow near the units' surface. This feature creates small vortexes which further reduce lifting forces. Reef Balls can be cast up to double the standard weight to accommodate high energy zones, or they can be cast at 75% of the standard weight to save concrete for bay, deep or protected water locations.

In this paper written by H D Armano and K.R. Hall, a study of the parameters influencing wave transmission through the proposed submerged breakwater is presented based on two dimensional tests using regular and irregular water waves conducted at Queens University Coastal Engineering Research Laboratory (QUCERL). The influences of wave steepness H_i/gT^2, reef proportion h/B, submergence depth h/d and reef configurations on wave transmission were studied (where H_i = incident wave height, g = gravitational acceleration, T = wave period, h = wave height, B = crest width and d = water depth).

Figure 2.29 and 2.30 are the typical HSAR units and the proposed breakwater.

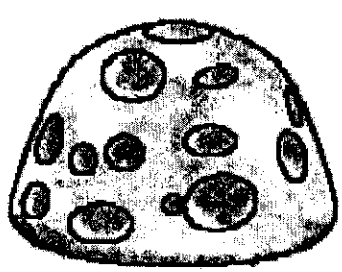


Figure 2.29: Reef Ball

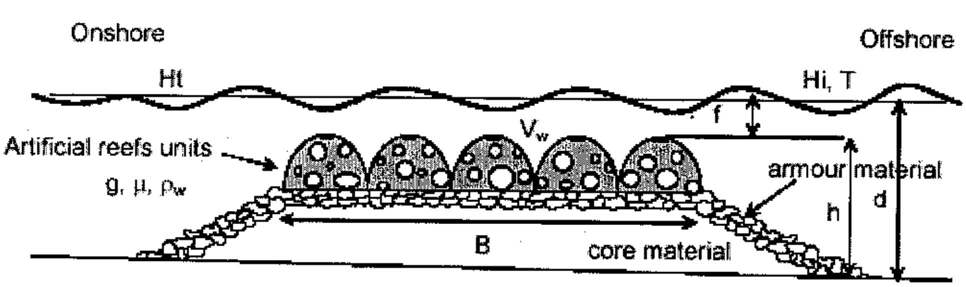


Figure 2.30: Configuration of Reef Balls

A qualitative parametric analysis was performed to examine the effects of the external and dimensional variables on the wave transmission through HSAR breakwaters. The wave transmission coefficient, C_t has been plotted against depth submergence, wave height, wave period, reef crest width, and reef configuration to observe and identify if any relationship or trends were present. When plotting C_t against the specific independent variables above, all other variables were held constant. Figure 2.31 and 2.32 shown the relationship between wave transmission and wave steepness H_i/gT^2 differentiated by relative depth submergence h/d, and reef proportion h/B.

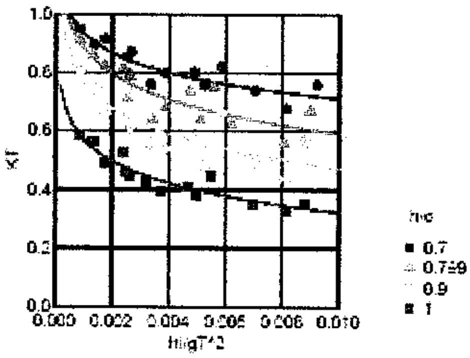


Figure 2.31: Wave transmission coefficient for *h/B* = 0.350

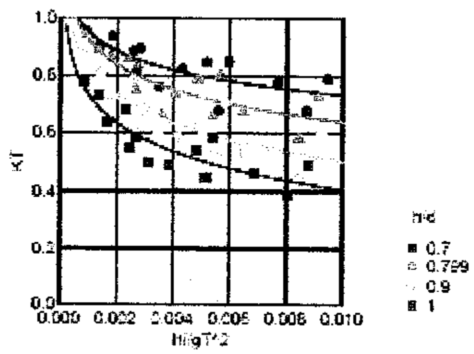


Figure 2.32: Wave transmission coefficient for h/B = 0.583

As for the conclusion, Armono and Hall stated that the factors influence wave transmission are water depth, incident wave height and period, as well as reef configuration. Wave height reduction is found to be influenced by the wave steepness, depth of submergence, and reef geometry. It is found that about 60% of the incoming wave energy was reduced on average. Until today, lots of Reef Balls have been deployed all over the world.

Prefabricated Erosion Prevention (P.E.P) Reefs and Beachsaver Reefs

Two types of modular narrow-crested submerged breakwater have been deployed in many erosion hot spots especially in United States; (P.E.P) Reefs and Beachsaver Reefs. Both properties are almost the same, with triangular cross section and ability to reduce wave heights, maintain a stable shoreline position, retaining the existing volume of sand on the beach as well as protecting the beach from storm waves. Figure 2.33 and 2.34 are the illustrations of both submerged breakwaters.

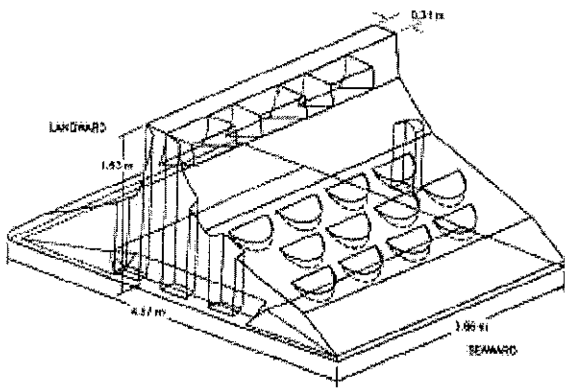


Figure 2.33: Prefabricated Erosion Prevention (P.E.P) Reefs

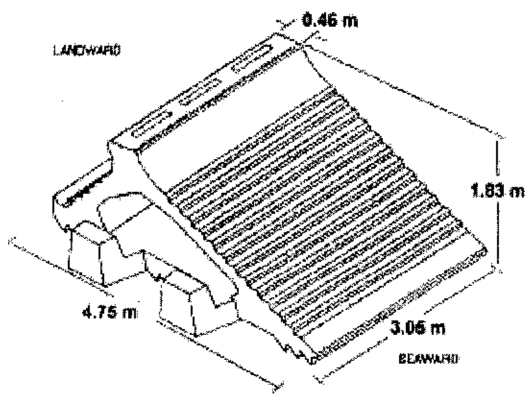


Figure 2.34: Beachsaver Reefs

These structures have been tested in real marine environment and they appear to have limited effectiveness in wave attenuation. The settlement of the units has also reduced the freeboard depth and and thus the ability to trip the incoming waves. Browder (1994) indicated that the freeboard was the most important variable in submerged breakwater design. The shallower the breakwater, the more wave attenuation is afforded. If the crest of the structure is close to the surface, it may also produce structure-induced currents. Bruno et al. (1996) observed higher wave energy reduction when the reef crest was closer to the water surface and the wave heights were larger. These narrow-crested designs with steep landward facing slope, experienced scour on the landward base with minimal wave attenuating effect. Filter cloth and a geotextile mattress used on two of the New Jersey sites appeared to minimize but not eliminate scour and settlement.

Hex Reef

Noraieni H.M. et al. (1997) looked for the ability of the reef to dissipate wave energy using modular units of rectangular reefs with interlocking system named Hex Reef. The tests involved are velocity profile, wave transmission profile, and stability of the structure. Figure 2.35 illustrates Hex Reef and its combinations.

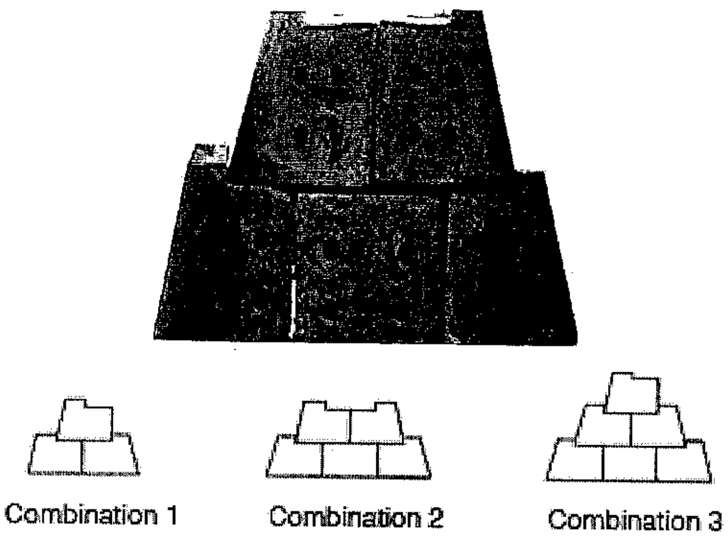


Figure 2.35: Hex Reef

From the result obtained, the wave height of the approaching wave upstream is much higher compare to the transmitted one. The waves are observed to break after the structure by evidence of disturbance. Figure 2.36 shows the result of transmission coefficient C_t due to wave steepness H_i/gT^2 for various combinations of Hex Reef at similar water depth, 3.7 m.

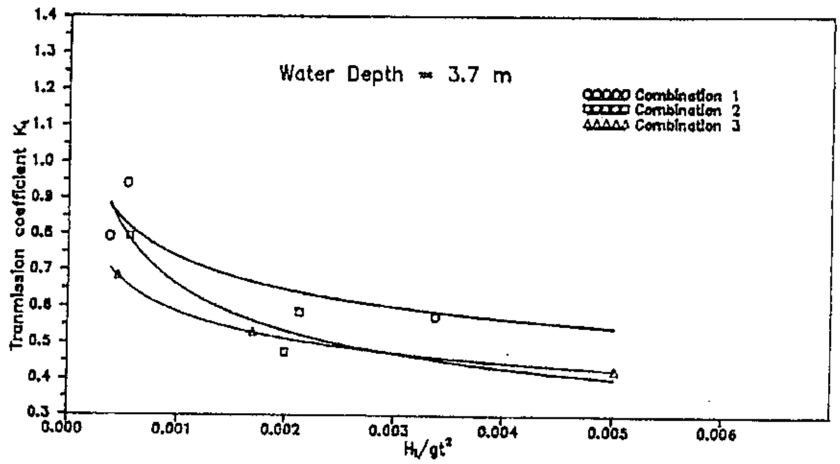


Figure 2.36: Transmission coefficient vs. H_i/gT^2

For larger wave period, higher transmission coefficient will be obtained and decreasing of transmission coefficient with the decreasing of wave steepness. The energy dissipated against the wave period was also plotted (Figure 2.37). Another plotted graph was transmission coefficient C_t vs. ratio of submergence with depth *(d-h)/d* (Figure 2.38).

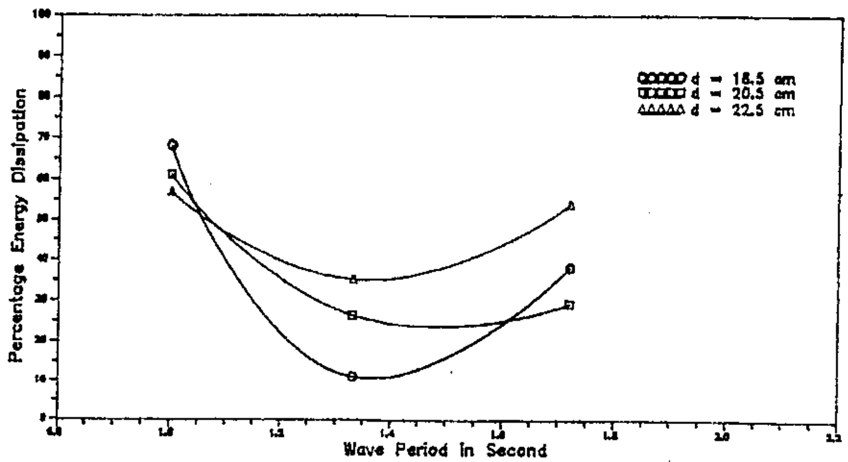


Figure 2.37: Energy Dissipation vs. wave period

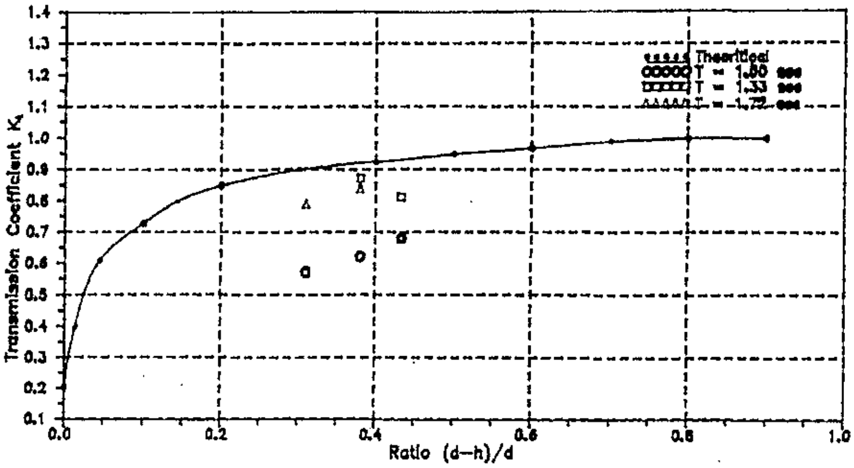


Figure 2.38: Transmission coefficient vs. (d-h)/d

The graphs show that the structure is no longer effective if the *(d-h)/d* is more than 0.4. It was also stated that C_t is lower for higher and shorter wave, which is a good condition for coastal protection.

For wave energy dissipation, wave breaking is an important mechanism. When the wave passes the reef front, the wave steepness due to shoaling and eventually breaks. In this case, the wave breaks after passing the structure. Generally, wave breaking happens when wave height over depth ratio H/d exceeds certain values ($H/d > 0.7$ or $d/H < 1.3$). Overall result shows that wave is transmitted for more than 40% while energy dissipated for 20 – 70%.

As the conclusion, the wave transmission through the reef was found to be dependent upon the characteristic dimension of the structure and the incoming wave condition. The dimension and representation of the reef can be characterized by the depth of the water level above the reef (freeboard, F), the height of the structure h, and the crest width B. The incoming wave condition can be described by its height and period which can be characterized by wave steepness parameter.

For stability test, extreme events are excepted where in normal conditions, the models are found to be stable. However in high wave heights and low wave period, the model structure has shown some weakness as the top layer seems to be moving back and forth at the hinge (interlocking system), but the base layers are observed to remain almost intact. At 10 cm wave height, damage of the structure is observed as some units of the modules became dislocated and fallen off from the system.

Additionally, base plates were placed at the bottom of the bed before placing the reef to reduce the initial movement and further instability of the whole structure system. Besides, the vertical locking system is not sufficient and the top modules tend to dislodge. The dimension for the groove has to be increased.

Aquareef

The intention to care of the environmental aspect of coastal has resulted in the development of more friendly artificial reefs creating better conditions for the marine environment. An example of such a structure is Aquareef, which is protected by Aqua blocks (Figure 2.39 and 2.40). The first developments were reported by Asakawa and Hamaguchi in 1991 in a paper in which the transmission characteristics with regular waves were presented. More detailed descriptions of the functional and technical design of these reefs can be found in (Hirose et al., 2002).

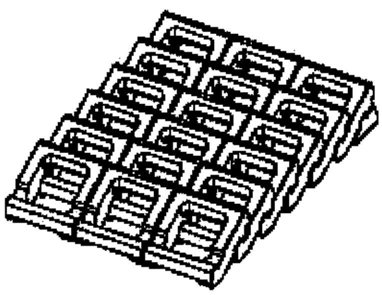


Figure 2.39: Aqua blocks

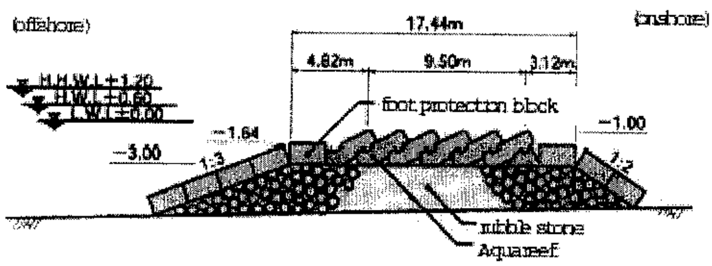


Figure 2.40: Aquareef place on rubble mound

Development of this block and reef structure was supported recently by an extensive model investigation (with random waves) related to transmissivity and stability aspects. Both aspects were tested in a wide range of wave and submergence conditions, as is evident from the transmission graphs in Figure 2.41 and 2.42.

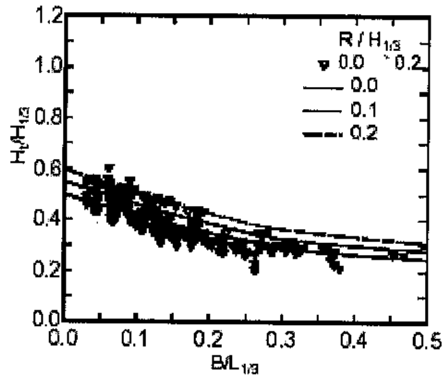


Figure 2.41: Wave transmission coefficient on Aquareef

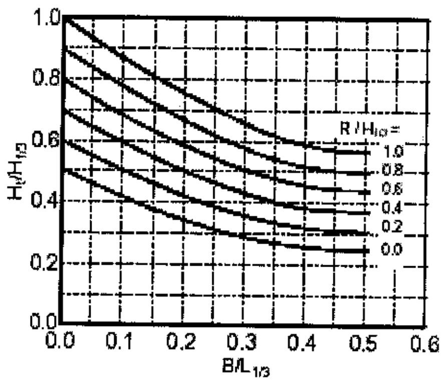


Figure 2.42: General transmission characteristic

The graphs show the relation between the wave height transmission coefficient $H_t/H_{1/3}$ and the relative wave length $B/L_{1/3}$ (where H_t = transmitted wave height recorded on the landward side, $H_{1/3}$ = significant wave height and $L_{1/3}$ = significant wavelength at the toe of the rubble mound, and B = crest width of the units). A number of these reefs have already been constructed and some experience of their functioning has been gained.

CHAPTER 3: MODEL DESCRIPTION

3.1 Introduction

Physical modelling of the submerged breakwater is the most important part of the study since the dimension and other characteristics of the model will reflect the overall result of the study. Generally, the dimension of the existing models and prototype of submerged breakwaters are varied according to water depth and wave period. Since the experiment is done in one dimension, the only concerned parameters are the crest height h and width B.

Besides those, the material of the model is also another significant criterion affecting the wave attenuation. The porosity, permeability and surface friction of it were found to be other factors that help to dissipate wave energy. However the scope of this study is only focusing on the structure's dimension. Thus the material use for the physical model can be anything as long as it can sustain the wave and able to attenuate wave energy.

3.2 Design Concept of Submerged Breakwater

Basically there are two (2) types of submerged breakwater modules proposed in this project; rectangular and triangular. From the literature review discussed in Chapter 2, it is found that most of the existing models are trapezoidal and triangular, while a number of them are modular. Both shapes proposed are easy to be constructed and simple. When both are combined together, they could formed various configurations (refer Section 4.3) compared to other shapes like hemi-cylinder or semi-circular. Rectangular module itself is significant in raising the height of the submerged breakwater. It also provides sudden change in water depth to create collision with water particles that helps reducing the wave energy. Triangular module however assists the rectangular modules in providing slope and wider base width for scour protection.

The modular type of submerged breakwater is implemented in this project as it could produce various configurations with different widths and heights with respect to water depths. In real situation, modular type of submerged breakwater will be easier to deploy as compared to a massive structure with similar size. Besides, it is also helpful in fulfilling the demand of a particular area according to its water depth, wave period, and incident wave height. However a modular submerged breakwater needs a system to interlock each module so that it will maintain its position on the seabed and stick to each other even in critical wave condition. This modular submerged breakwater can be applied in various locations with different wave parameters as the configuration can be modified accordingly.

3.3 Physical Modelling

Prior to the physical modelling, the actual size of a prototype is determined. From the studies of several research papers, the prototype size for 2.40 m water depth is determined to be 1.00 m (length) x 1.12 m (width) x 1.00 m (height). This size is a customized dimension that can be changed depending on the water depth. As for this study, the prototype size is sized down using geometric similarity to suit the wave flume with maximum water depth of 30 cm. The ratio of the prototype to the model is 1:8. As a result, the model size is finalized to be 12.5 cm (length) x 14.0 cm (width) x 12.5 cm (height). Illustration of a unit of rectangular model is shown in Figure 3.1.

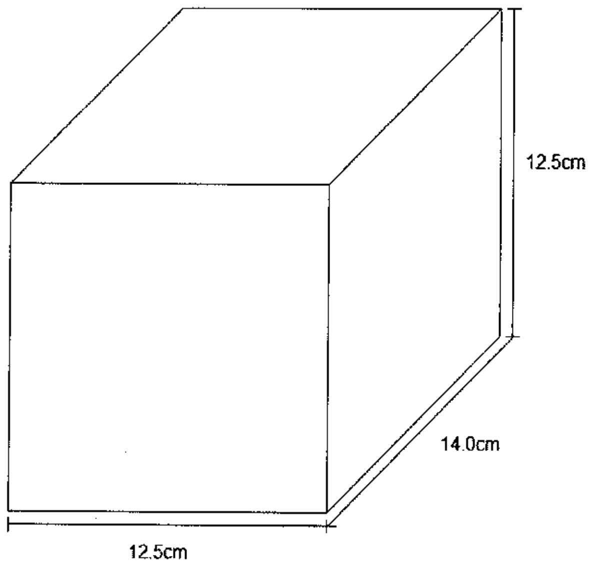


Figure 3.1: Rectangular module

From the rectangular module, the idea was extended for the design of triangular module so that the combination of both will produce different formation with different characteristics. The dimension of a triangular unit is 12.5 cm (length) x 14.0 cm (width) x 12.5 cm (height). The illustrations the module is shown in Figure 3.2.

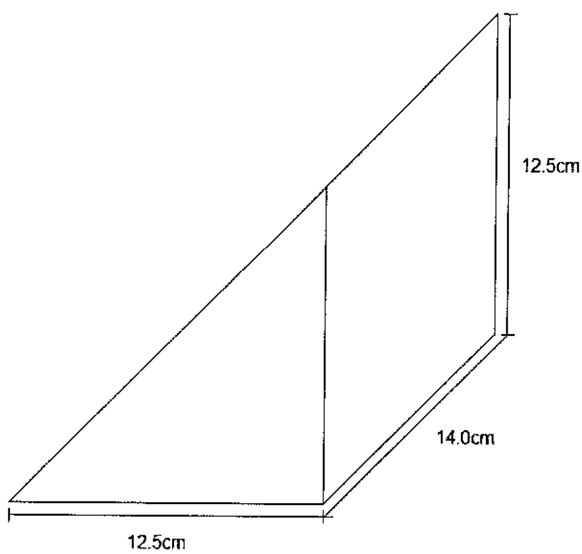


Figure 3.2: Triangular module

3.4 Model Construction Materials

Throughout the study of submerged breakwater, concrete is found to be the most effective, cheap also easy to cast material. The porosity and permeability as well as its shape can be adjusted according to requirement. However the scope of this study is only focusing on the shape of the modular submerged breakwater instead of its material. Any kind of material can be used as long as the density of the modules is greater than the density of water, with the intention that the structure is submerged.

The first stage of model fabrication is done in a factory, using steel box filled with concrete. The earlier plan was to build a module made of solid steel so that its heavy weight can help it to sustain the wave attack. But due to financial constrain and limitation of project scope only 10 rectangular modules were constructed made of steel box filled with concrete. Figure 3.3 shows the rectangular module.

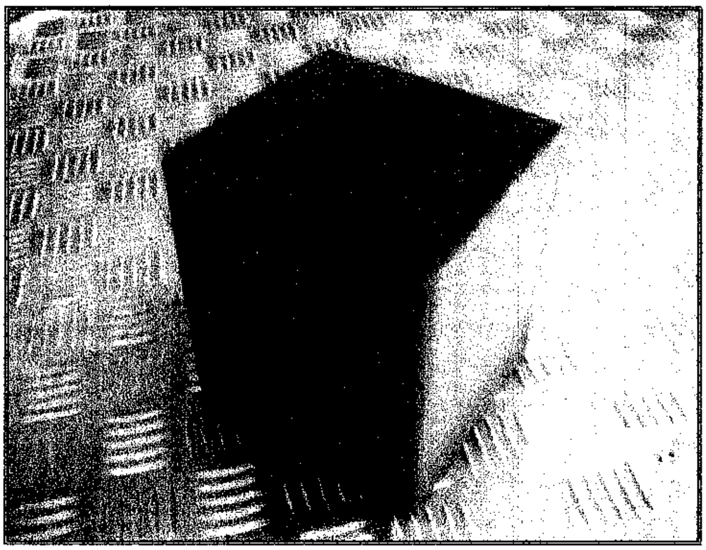


Figure 3.3: Rectangular unit of submerged breakwater

Then the second stage of model construction was carried out in UTP Concrete Laboratory. Four (4) units of triangular modules were fabricated using concrete as shown in Figure 3.4. As mentioned before, two stages of model constructed separately since there were limited time and budget provided.

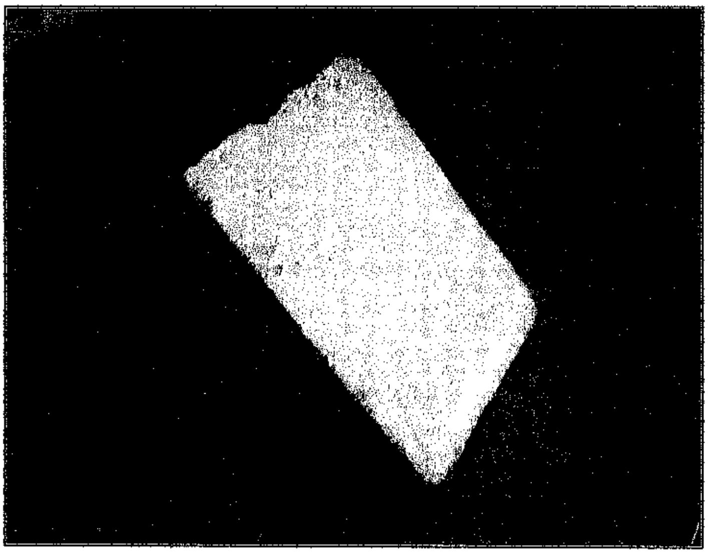


Figure 3.4: Triangular module of submerged breakwater

CHAPTER 4: EXPERIMENTAL SETUP AND PROCEDURES

4.1 General

Before running the experiments, all the equipments in the coastal engineering laboratory is being set up. The procedures of the experiment are arranged so that it can be carried out efficiently. Wave period is initially determined prior to others. Detailed information of the wave period determination test and the experimental study of proposed submerged breakwater will be discussed in Section 4.3.1 and Section 4.3.2 respectively.

4.2 Tools and Equipment

The most important equipment for the laboratory experiment is wave flume. For this case, a 1000cm (length) x 30cm (width) x 45cm (height) wave flume is available in the laboratory. The flume is made of a rigid steel bed, with glass panel sides for the purpose of observation of the wave performance during any laboratory test. Figure 4.1 shows the wave flume in the UTP Coastal and Offshore Engineering laboratory.

Figure 4.1: Wave flume

Besides, a wave generator is also important to generate various types of wave for the experiments. There is a flat type wave paddle that driven by a gear motor used in the laboratory, while the frequency of the wave paddle can be set at a control panel. The illustration of the wave generator and control panel are shown in Figure 4.2.

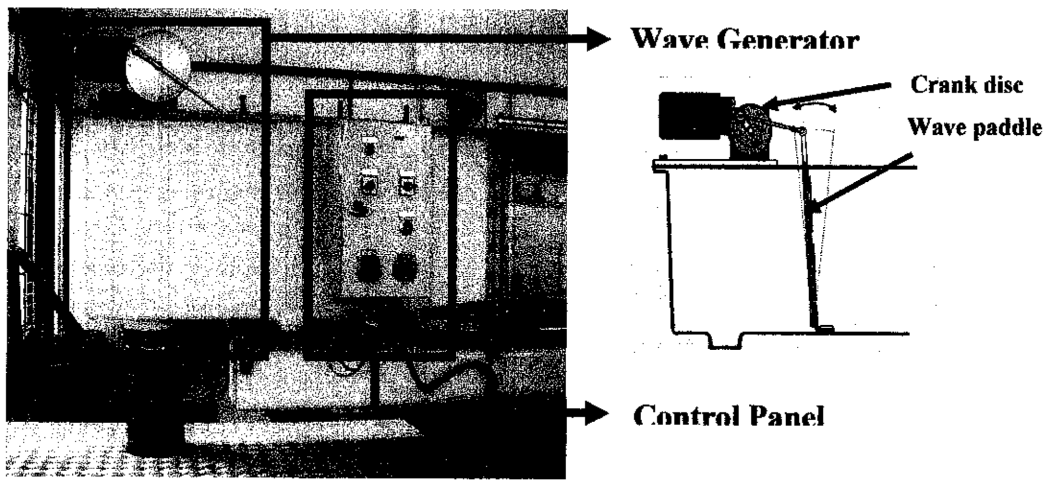


Figure 4.2: Wave generator and control panel

Other equipments such as hook and point gauges as well as wave absorber are also meant to assist the laboratory experiments. The hook and point gauges are able to measure water depth of the entire length of the flume with maximum water depth of 45cm. It can be moved back and forth on its carriage. While the wave absorber is absolutely act to further attenuate wave energy and prevent the wave from reflected back to the tested structure. It is 120cm (length) x 30cm (width) x 120cm (slope length) with wire mesh absorber and adjusted slope up to 90°. Figure 4.3 and 4.4 shows hook and point gauges and wave absorber respectively.

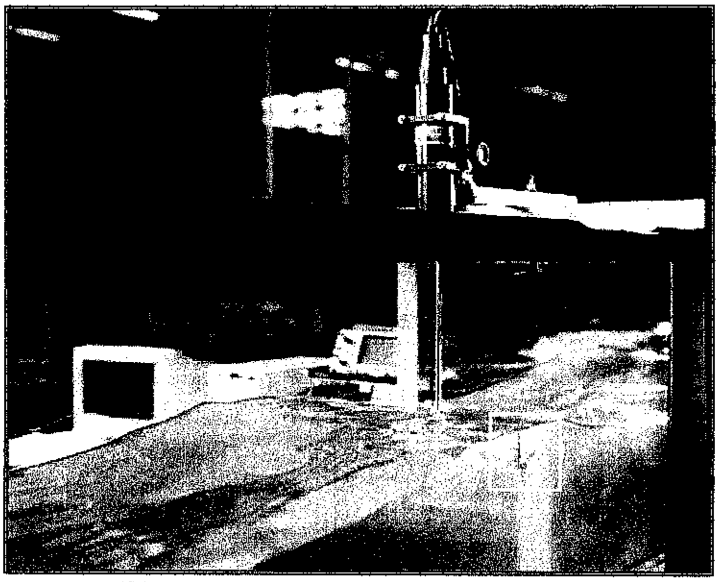


Figure 4.3: Hook and point gauges

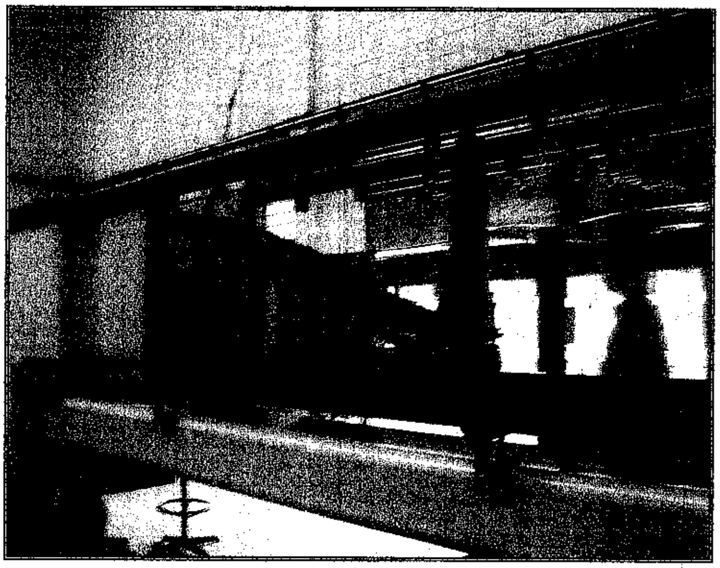


Figure 4.4: Wave absorber

Also required are the camera and video camera to record the laboratory experiment.

4.3 Experimental Procedures

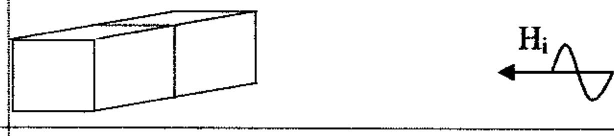
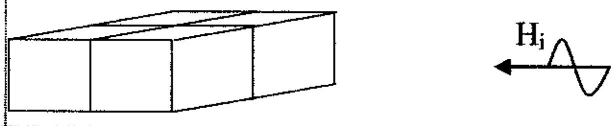
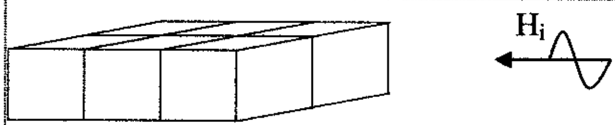
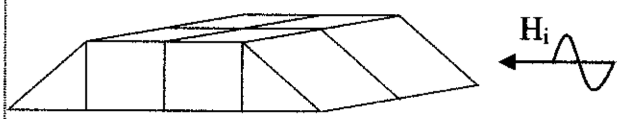
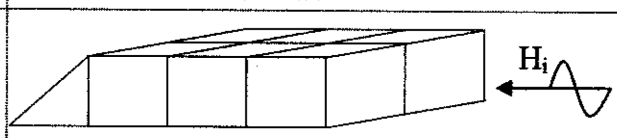
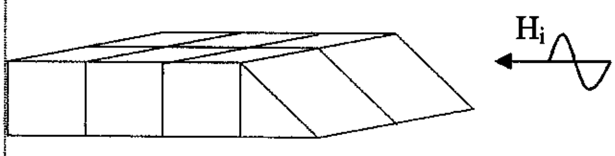
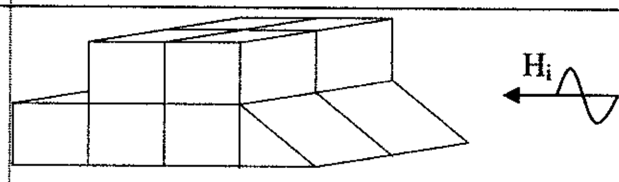
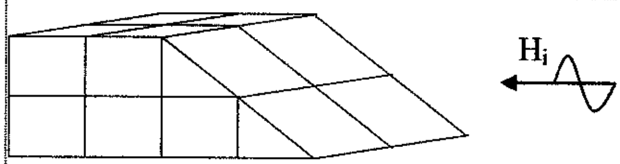
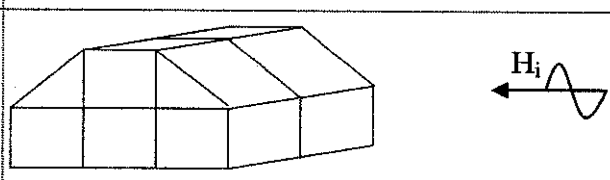
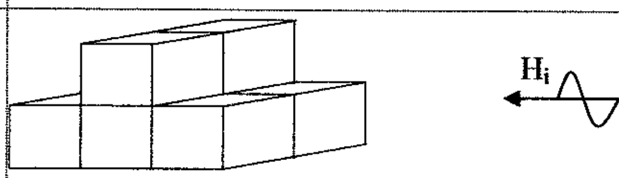
4.3.1 Wave Period Determination

The purpose of this test is to determine the wave period, T with respect to different stroke frequencies for calibration for the wave attenuation performance analysis. The wave period is measured by obtaining time taken by the crank disc to resolve 10 cycles. The measurement continues for a series of stroke frequencies. It is then repeated for another two times and the average values are calculated. The characteristic of wave period for three different stroke adjustments, for instance 80 mm, 140 mm and 200 mm are observed. Result of the experiment is shown in Section 5.2.

4.3.2 Experimental Studies on Submerged Breakwater

The most important part of this study is to run the experiments for the determination of transmission coefficient C_t. The experiments were carried out in three different transitional water depths of 20 cm, 25 cm and 30 cm. The study of this modular submerged breakwater consists of three (3) cases namely; (1) Effect of submerged breakwater width, (2) Effects of sloping / vertical faces and contact area, and (3) Effect of various submerged breakwater configurations. Summary of the configurations of those cases are tabulated in Table 4.1. Note that the incident wave H_i is from the right hand side.

Table 4.1: Modular submerged breakwater configurations

Case		Configuration
Case 1: Effect of submerged breakwater width	a)	
	b)	
	c)	
Case 2: Effect of sloping / vertical faces and contact areas	a)	
	b)	
	c)	
Case 3: Effect of various submerged breakwater configurations	a)	
	b)	
	c)	
	d)	

The example of an experiment setup for a configuration of modular submerged breakwater is shown in Figure 4.5. Both rectangular and triangular modules were arranged together in wave flume to form certain shape. The water was then fixed to a certain depth, and the wave generator was on to enable the wave paddle to move and create certain wave period. The required wave period can be adjusted by the frequency of the wave paddle on the control panel.

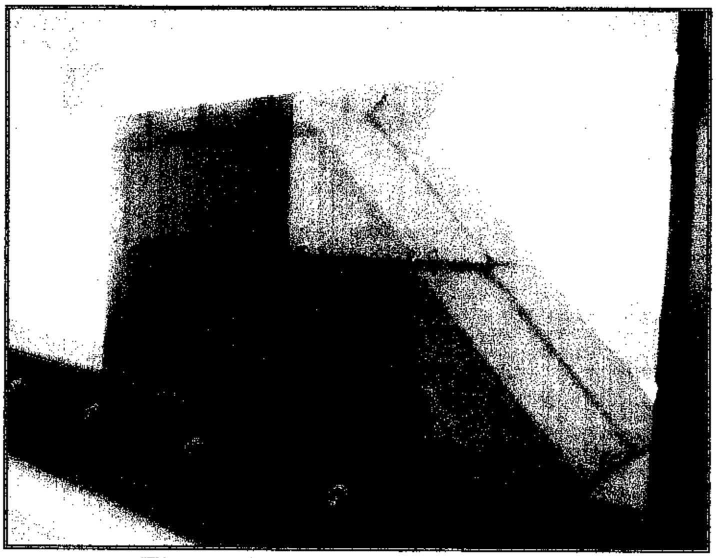


Figure 4.5: Experimental Setup

The wave period for 200 mm stroke adjustment is ranging from 0.5 seconds to 2.0 seconds. The significant parameters measured in the experiment are as follows:

i) Three (3) readings of incident wave height H_i measured prior the placement of submerged breakwater at the test section in the flume

$$H_i = \frac{\sum H_i}{3} \tag{4.1}$$

ii) Three (3) readings of transmitted wave heights, H_t at the lee side 0.5 m away from the submerged breakwater

$$H_t = \frac{\sum H_t}{3} \tag{4.2}$$

iii) From the wave heights obtained in the experiment, the transmission coefficient can be calculated using equation 2.1.

CHAPTER 5: RESULTS AND ANALYSIS

5.1 General

Sequentially after the laboratory experiment is done, the results obtained are analyzed. All the experiments were carried out in monochromatic wave condition, assuming there is no wave reflected from the shore and the front side of the structure, no wind velocity and no current. Summary of wave period and incident wave height determination, also the experimental studies on submerged breakwater results are discussed in the next two sections.

5.2 Wave Period Determination

Wave period is define as the time taken for a wave to successfully pass a point. As mentioned in the previous chapter, the average time taken for one complete cycle of the crank disc for a set of stroke is recorded. The result of wave period determination experiment is tabulated in the Table 5.1, and the chart of the average wave period is plotted in Figure 5.1.

Table 5.1: Observed Wave period for various stroke adjustments

Frequency, F (rpm)	Wave period, T (s)			
	S = 80	S = 140	S = 200	Average
108	0.488	0.497	0.488	0.491
88	0.600	0.603	0.596	0.600
74	0.705	0.709	0.707	0.707
64	0.829	0.842	0.829	0.834
56	1.008	1.000	1.004	1.004
50	0.982	1.023	1.021	1.008
44	1.253	1.253	1.252	1.253
40	1.269	1.262	1.264	1.265
37	1.663	1.654	1.664	1.661
34	1.681	1.685	1.688	1.685
31	1.697	1.696	1.697	1.697
29	2.448	2.424	2.423	2.432
27	2.470	2.452	2.460	2.461
25	2.515	2.496	2.498	2.503
24	2.494	2.499	2.498	2.497
23	2.546	2.497	2.483	2.509

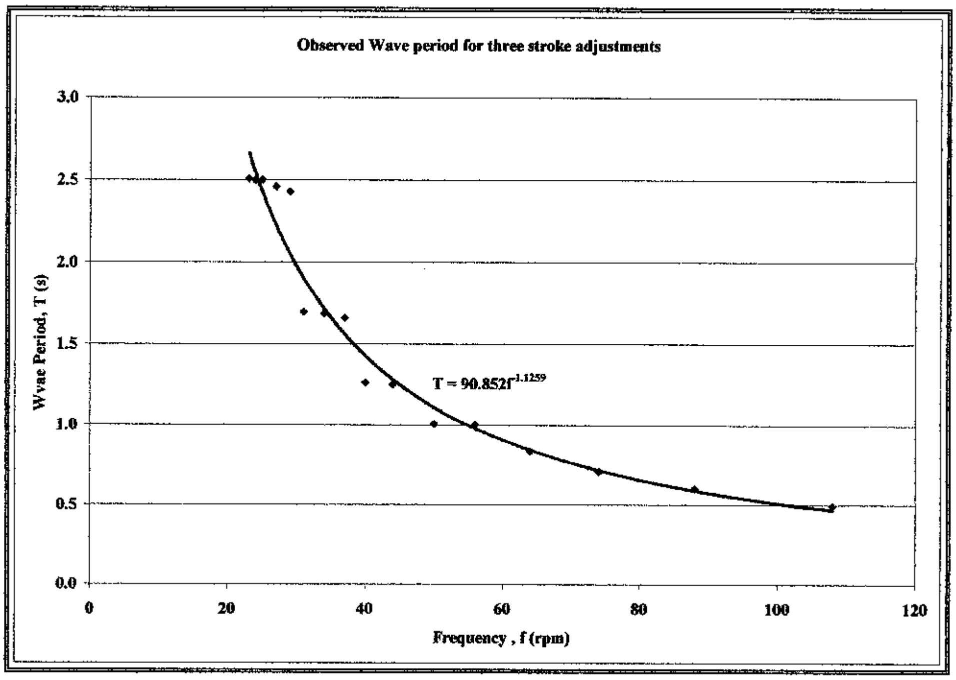


Figure 5.1: Wave period vs. frequency

The graph shows quadratic curve relates wave period T and frequency f by the equation 5.1.

$$T = 90.852f^{1.1259} \tag{5.1}$$

From the result, it can be concluded that different stroke adjustment for each frequency will produce similar values of wave period. Thus, the wave period is not depending on the stroke adjustment, but on the frequency of the wave generating system.

Figure 5.1 shows wave period decreases exponentially as the stroke frequency increases. For the determination of frequency, Equation 5.1 is used to determine the corresponding stroke frequency for a range of wave period (0.5 – 2.0 second).

5.3 Experimental Studies on Submerged Breakwater

Incident wave height H_i and transmitted wave height H_t, were obtained from the experiment, while transmission coefficient, C_t was calculated using Equation 2.1. The result of each case; (1) Effect of submerged breakwater width, (2) Effects of sloping / vertical faces and contact area, and (3) Effect of various submerged breakwater configurations will be discussed in the next four sections.

All the design graphs were plotted for transmission coefficient, C_t against wave steepness, H_i/gT^2. This dimensionless wave parameter is a widely used parameter to study the wave attenuation of submerged breakwaters. It is also used to physically characterize waves as it incorporates incident wave height, H_i and wave period, T. Besides that, breakwater width to depth of water ratio, b/d is used to show the relative width of submerged breakwater with respect to water depth.

5.3.1 Case 1: Effect of Width

This section shows the experimental results of wave attenuation performance of submerged breakwater due to width effect. The C_t of one row, two rows and three rows of rectangular modules with the width of 12.5 cm, 25.0 cm and 37.5 cm respectively are graphically presented in Figure 5.2.

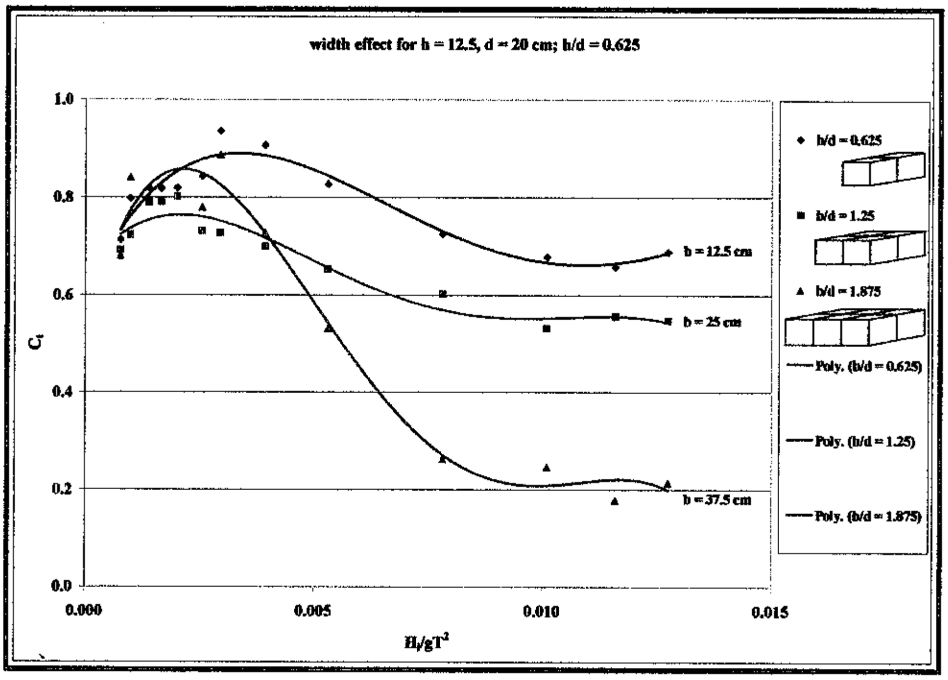


Figure 5.2: Performance of submerged breakwater of Case 1

Almost all C_t plots decrease with the increasing of H_i/gT^2. For $H_i/gT^2 < 0.003$, C_t is less dependent on the width effect. But for $0.003 < H_i/gT^2 < 0.010$, wave attenuation of submerged breakwater is greatly effected by the breakwater width. The greater the width of submerged breakwater, the better will be the wave attenuation. However for $H_i/gT^2 > 0.010$, the plots of C_t are somewhat stable. The wider the structure, the greater will be the wave energy dissipation. This is due to the additional surface area resulted from extension of breakwater width help to interfere the motion of the water particles, thereby reducing wave energy through friction.

5.3.2 Case 2: Effect of sloping / vertical faces and contact areas

Case 1 as illustrated in Table 4.1 shows a single layer of submerged breakwater which consists of combination of triangular and rectangular modules. The height of the structure is 12.5 cm. The water depths tested were 20 cm and 25 cm subsequently yielding *h/d* of 0.500 and 0.625, respectively.

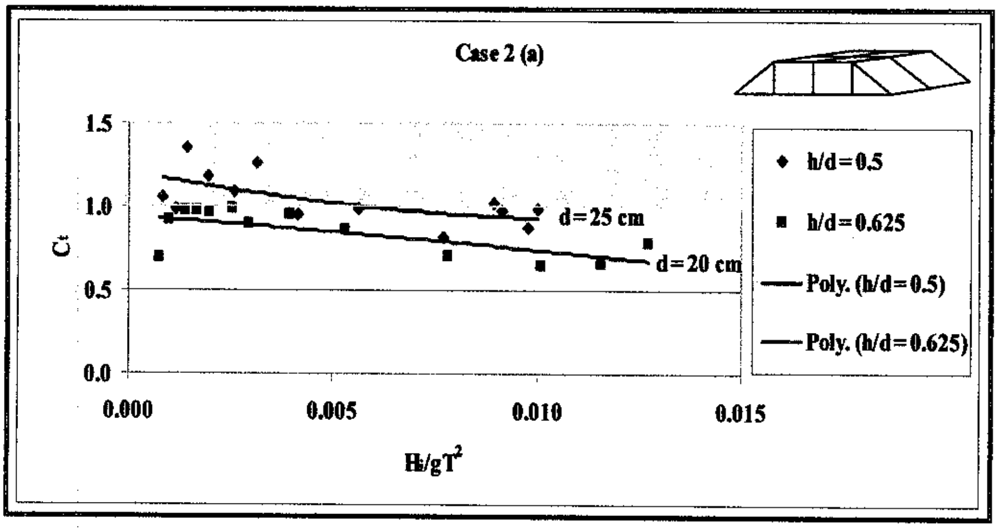


Figure 5.3: Performance of submerged breakwater for Case 2 (a)

Figure 5.3 shows C_t plots relating to H_i/gT^2 and *h/d*. Generally, both plots are slightly decline with H_i/gT^2. Noted that shadowed region is the value of $C_t > 1.0$, where the structure is no longer effective due to $H_t > H_i$. It is not advised to design the height of the structure to be lesser than half of the depth of water at the construction site because the structure is ineffective in attenuating wave energy for $H_i/gT^2 < 0.010$. It is observed that placing the submerged breakwater at site having condition of $h/d = 0.625$ would give improved results; $C_t \approx 1.0$ for low steepness wave and $C_t \approx 0.7$ for $H_i/gT^2 > 0.010$.

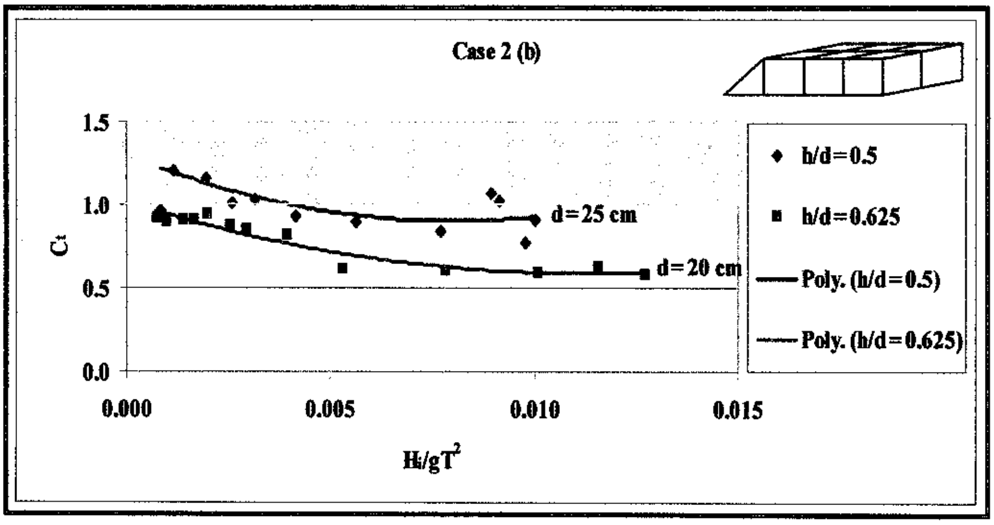


Figure 5.4: Performance of submerged breakwater for Case 2 (b)

Figure 5.4 shows the comparison of C_t with respect to *h/d* for case 2 (b) arrangement. Again, wave attenuation performance improves with *h/d*. The shallower the water depth, the greater the damping of wave energy. Similar to the previous configuration, the value of C_t decreases as H_i increases. At $h/d = 0.5$, $C_t > 1.0$ as $H_i/gT^2 < 0.004$. This means that the structure fails to reduce the incident wave height, but increases as the wave passes over the structure.

Generally, the performance of submerged breakwater with case 2 (b) is better than case 2 (a). This is because some of the wave energy are intercepted by the vertical impermeable surface of the seaward rectangular modules and get reflected, apart from wave breaking and dissipate on the structure.

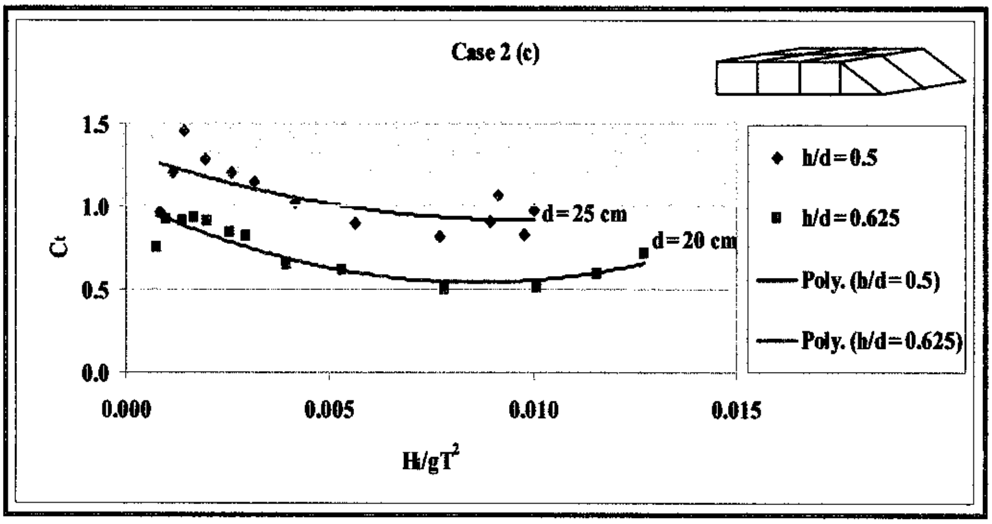


Figure 5.5: Performance of submerged breakwater for Case 2 (c)

Figure 5.5 illustrate the performance of submerged breakwater for configuration 2 (c). The performance of wave attenuation is pretty similar to the submerged breakwater of case 2 (b). However, the wave energy dissipation mechanisms are mainly due to wave breaking at the inclined surface and friction between the flowing water and the surface of the structure. It is believed that wave reflection is minimal and insignificant in this case.

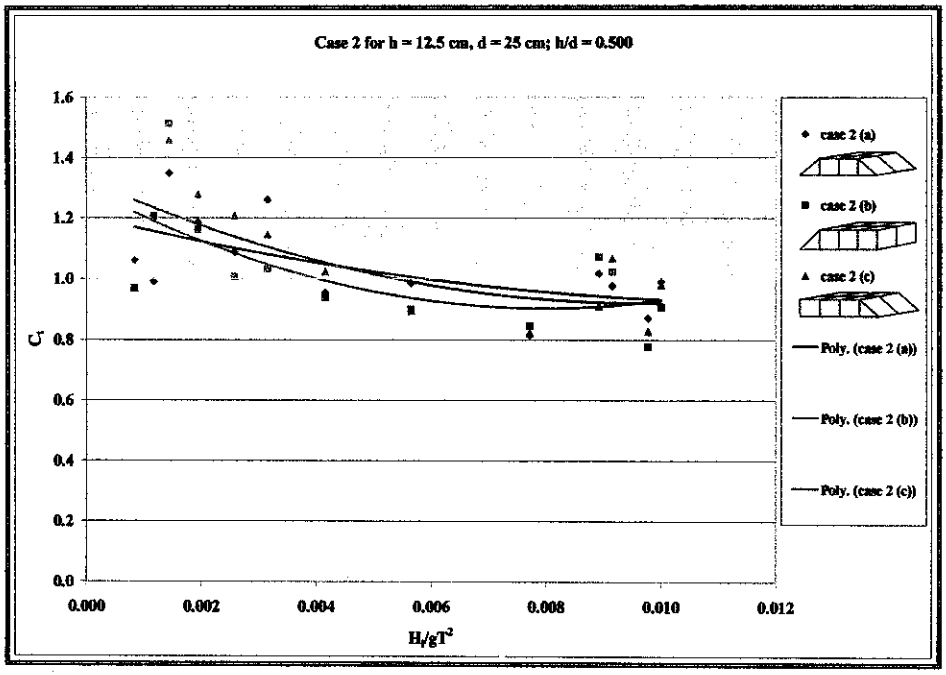


Figure 5.6: Performance of submerged breakwater of Case 2 for *h/d* = 0.500

Figure 5.6 compares the performance of configuration 2 (a), 2 (b) and 2 (c) for $h/d = 0.500$. The design graph is only applicable for $H_i/gT^2 > 0.005$, because smaller H_i will produce higher value of C_t. The reason is because of the small relative breakwater height ratio as known as relative depth submergence that enable the wave to develop its height even after it passes the structure.

At $h/d = 0.500$, implementation of any of the submerged breakwater is strictly prohibited because the incident wave height will be amplified if $H_i/gT^2 < 0.004$. As these low steepness waves propagate across these structure, they are slowed and steepened due to waves do not break, conversely the height of waves are amplified and causes enhancement of wave energy at the lee side of the submerged breakwater. At $H_i/gT^2 > 0.004$, improvement of wave attenuation can be observed from the figure. However, the C_t variations of the three arrangements of submerged breakwaters are somewhat small and closely related to each other.

From the overall observation and graphical result shown in Figure 5.6, case 2 (b) gives the best performance as it gains the least value of C_t especially within $0.004 < H_i/gT^2 < 0.010$. This is happened due to vertical faces of the structure, where reflection is governed. As a result, the wave passed at the lee side of the submerged breakwater will be lesser in height than those with sloping faces.

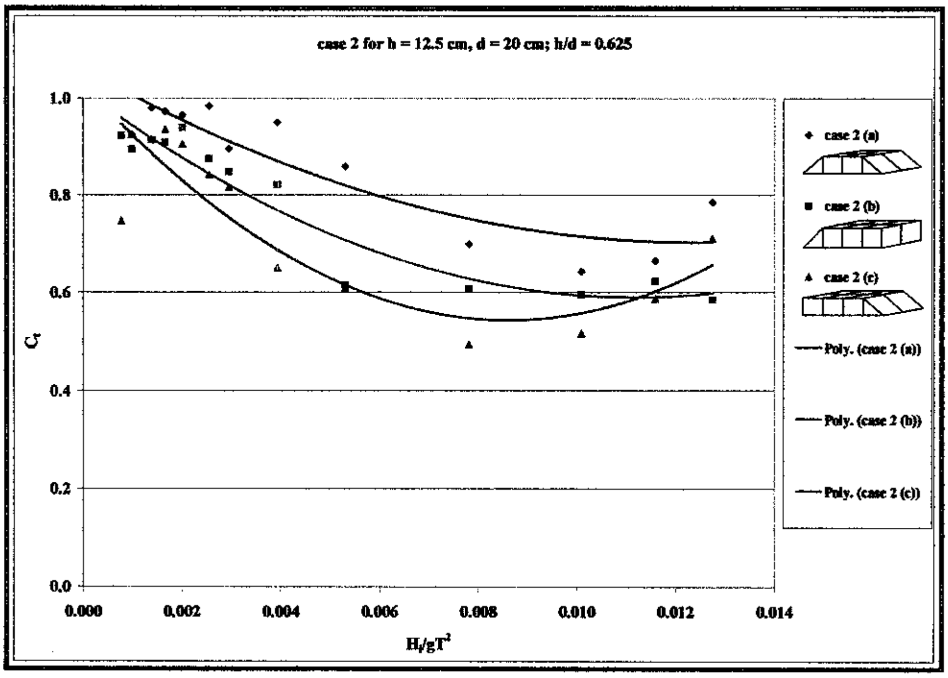


Figure 5.7: Performance of submerged breakwater of Case 2 for *h/d* = 0.625

Figure 5.7 shows the variation of C_t with H_i/gT^2 for different breakwater arrangements. At *h/d* = 0.625, C_t values of the three arrangement of submerged breakwater are greatly improved. It proves that submerged breakwater become more effective in attenuating wave energy if it is located at shallower waters. Apparently, arrangement of case 2 (c) gives the best performance due to its unique feature. Wave breaks and energy lost through heat, sound and turbulence while propagating above the inclined surface of the structure. The remaining wave energy is further being dissipated through friction between the running water and the total surface area of the structure. As for 2 (a) and 2 (b), the water depth develops gradually at the last row of the breakwater causes lesser dissipation of wave energy due to less interaction between the water particles and the surface of the structure as compared to 2 (c).

Therefore, inclined surface at the front row of submerged breakwater is needed to maximize the energy reduction of waves. Plus, it is important to maximize the surface area of the submerged breakwater to ensure effective wave energy dissipation.

5.3.3 Case 3: Effect of various configurations

Case 3 refers to breakwater arrangement that involves double layers of modules (triangular and rectangular) laid across the wave flume as indicated in Table 4.1. The structures with these arrangements were tested in 25 cm and 30 cm water depths. Owing to the total height of these double-layer breakwaters are 25 cm, the *h/d* values happen to be 0.833 and 1.000.

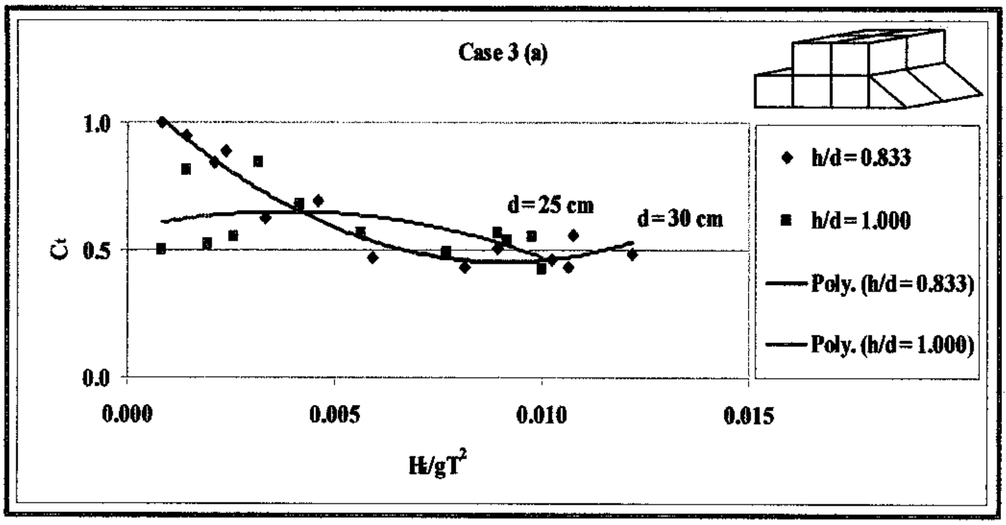


Figure 5.8: Performance of submerged breakwater for Case 3 (a)

Submerged breakwater with configuration 3 (a) as shown in the Figure 5.8 consists of 10 rectangular modules and two triangular modules. It is found to perform well in both water depths as it is able to dissipate wave energy and reduce the incident wave height for all wave conditions as the value of C_t is always less than 1.00. It is seen that *h/d* = 1.000 performs better when $H_i/gT^2 < 0.004$. However, the wave dissipation performance of breakwater having *h/d* = 0.833 is slightly better than the submerged breakwater with *h/d* = 1.000.

At *h/d* = 0.833, waves with low steepness (small wave amplitude) will pass through the submerged breakwater with ease. As it develop gradually portion of the energy of waves is reflected by the seaward vertical surface of the submerged breakwater. The triangular block placed at the forefront of the structure does not contribute much in dissipating the energy of the small amplitude waves. Nonetheless, the triangular clock begins to secure its purpose as steeper waves approaching the submerged breakwater. It helps to break the waves with greater amplitude before it is subsequently reflected by the vertical surface of the rectangular block. Finally, it reaches an optimum C_t of 0.5 when $H_i/gT^2 > 0.007$.

When the crest of the submerged breakwater having the same elevation as the depth of water, the small amplitude waves are brought closer to the structure hence having more interactive with the structure. Reflection and breaking of waves become more evident in a limited depth. As it grows to be steeper, C_t continue to drop gradually until it reaches am optimum C_t of 0.5 when $H_i/gT^2 > 0.007$. It is worthwhile to note that the C_t of the submerged breakwater is slightly higher than the one with h/d = 0.833. The agitation of the transmitted waves is resulted from the effect of splashing during breaking.

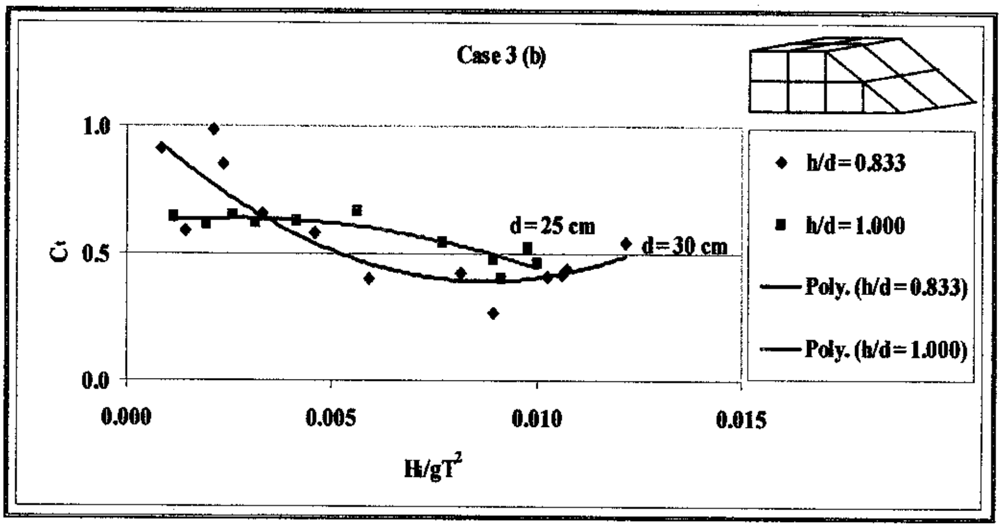


Figure 5.9: Performance of submerged breakwater for Case 3 (b)

Figure 5.9 presents C_t performance of another layout of four-row double-layer submerged breakwater where consists of eight (8) rectangular modules and four (4) triangular modules. It is arranged such that a slope of (gradient) fronting the structure. When $H_i/gT^2 < 0.004$, C_t of submerged breakwater with h/d = 1.000 is lower than the one with h/d = 0.833. Waves with small amplitude breaks and dissipates energy directly on the inclined slope of the submerged breakwater when h/d = 1.000. At h/d = 0.833, most of the waves transmit through the submerged breakwater with ease.

When $H_i/gT^2 > 0.004$, C_t of submerged breakwater with $h/d = 0.833$ is lower than the other one. This may be attributed to the steeper waves closely interacting to the inclined structure causing substantial breaking and turbulence in front of the submerged breakwater. The remaining waves are continuously fractioned with the surface of the structure before reaching the lee side of the submerged breakwater. As for the submerged breakwater with $h/d = 1.000$, the rate of energy dissipation is not as significant as the former one. This may be attributed to the bores / splash from the breaking waves, that form at the lee of the submerged breakwater.

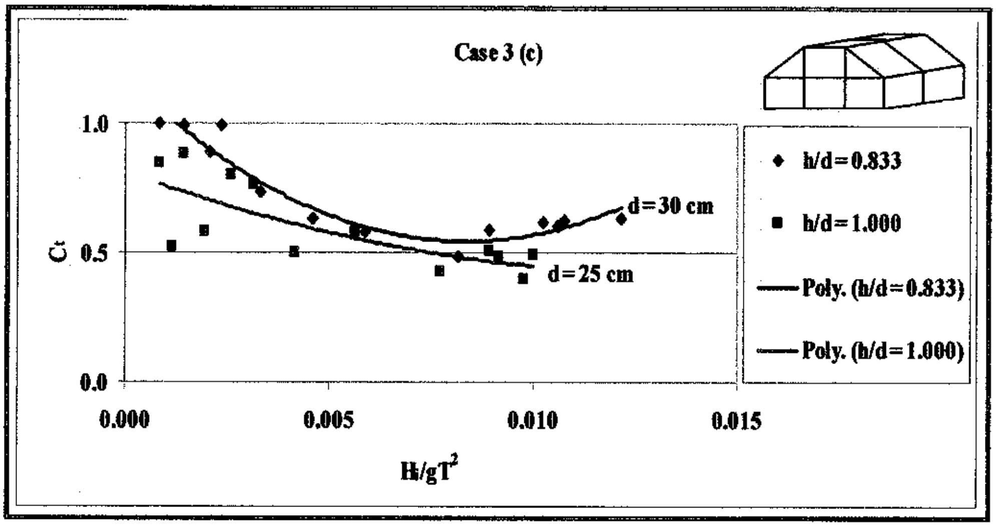


Figure 5.10: Performance of submerged breakwater for Case 3 (c)

Submerged breakwater with 3 (c) configuration is practically an elevated trapezoidal structure built up from eight (8) units of rectangular modules and four (4) units of triangular modules. Both sides of the structure consist of sloping faces. These sloping faces somehow help to facilitate wave breaking process. Figure 5.10 shows the wave dampening performance of submerged breakwater with case 3 (c) configuration. The performance is governed by $h/d = 1.000$. The shallower the water depth, the greater will be the attenuation of waves. But again, C_t reduces as H_i/gT^2 increases for both curves.

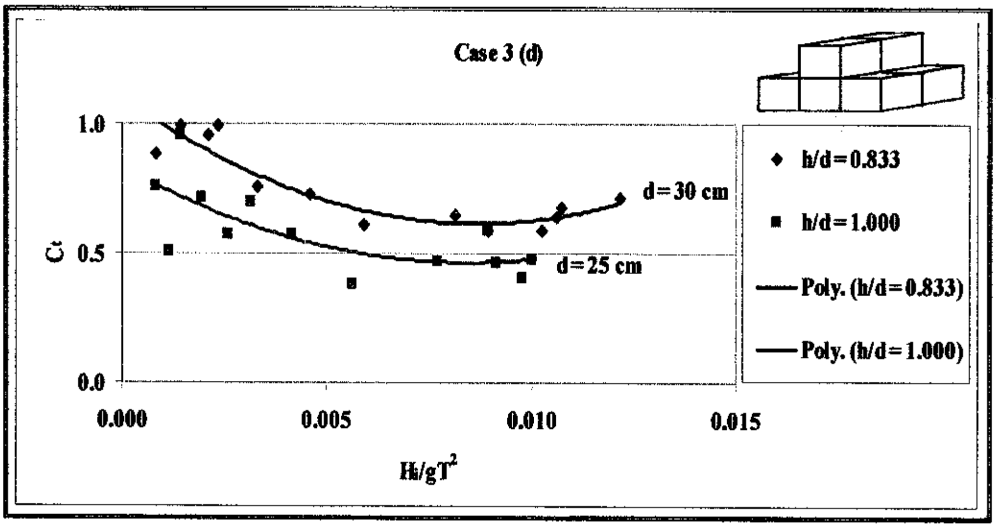


Figure 5.11: Performance of submerged breakwater for Case 3 (d)

Submerged breakwater with case 3 (d) configuration was also tested in the similar testing environment. Eight (8) rectangular modules were used to form up the submerged breakwater. It is expected that the principal wave energy dissipation mechanisms is wave reflection from the impermeable vertical surface of the submerged breakwater. From the results shown in Figure 5.11, the theory is proven to be true. The greater the water depth, wave energy reduction becomes smaller. Smaller water depth poses evident wave reflection as the energy carried by waves is greatly redirected to seaward as reflected waves.

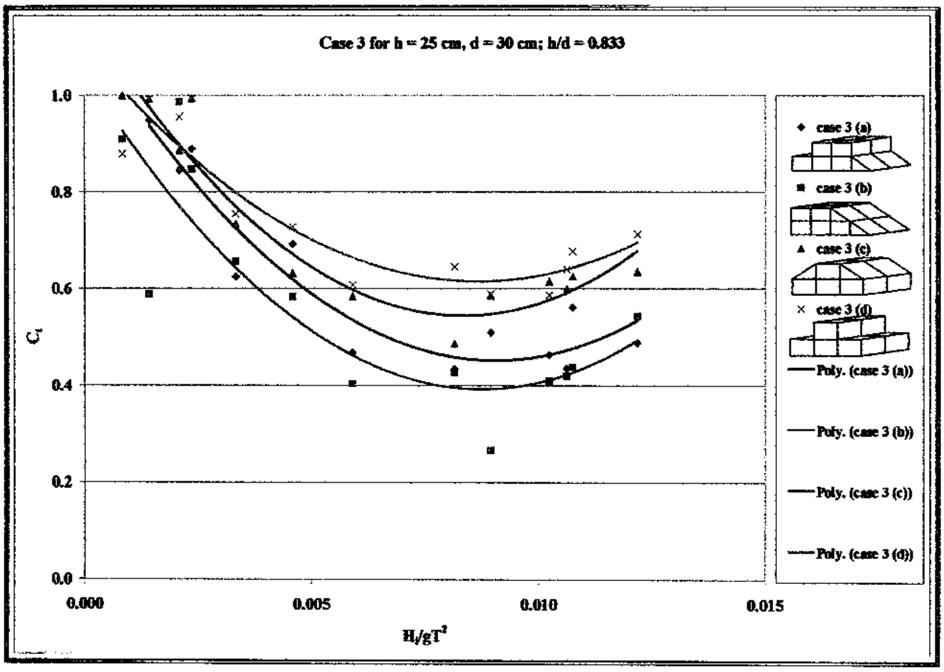


Figure 5.12: Performance of submerged breakwater of Case 3 for *h/d* = 0.833

Figure 5.12 exhibits the comparison of C_t of the four-row double-layer submerged breakwater with different arrangements, for $h/d = 0.833$. All C_t curves are agreeable with each other by having a similar trend where C_t diminishes with the increasing H_i/gT^2.

Apparently, it can be observed that the pink curve representing the wave attenuation performance of submerged breakwater with case 3 (b) arrangement performs to be the best submerged breakwater compared to the other breakwater arrangements. It is capable in reducing the wave height up to 70% when $H_i/gT^2 = 0.009$. There is mainly attributed to the wave dissipation mechanism inhibited by this breakwater arrangement. The sloping face at the structure front triggers wave breaking and a little wave reflection. The broken wave reaches the crest of the structure and water particles orbits are interfered by the surface of the structure. Sudden drop of structure height at the back of configuration 3 (a) create lesser surface contact with the water particle. Therefore the amount of energy dissipated is lesser than 3 (b).

As for breakwater with case 3 (a) arrangement, incident waves with low steepness travel across the submerged breakwater with a little breaking at the structure top. The breaking of waves become more significant if the breakwater is exposed to steeper waves, reducing greater amount of wave energy. It is believed that the single rectangular modules at the back of the structure does not contribute much on energy dissipation due to substantial depth of water above it.

The width of the submerged breakwater does play an important role in affecting the wave attenuation performance. It can be seen from the figure that the submerged breakwaters with four rows perform more efficiently than those of three rows. The greater the width of the submerged breakwater, the larger will be the contact area with the oscillating waves.

Breakwater with 3 (c) configuration is more efficient than the 3 (d) in reducing the incoming wave energy when $h/d = 0.833$. As previously mentioned, sloping face of a submerged breakwater is more capable in damping the energy of waves than vertical face when $d > h$. The governing dissipation mechanism is due to breaking of waves.

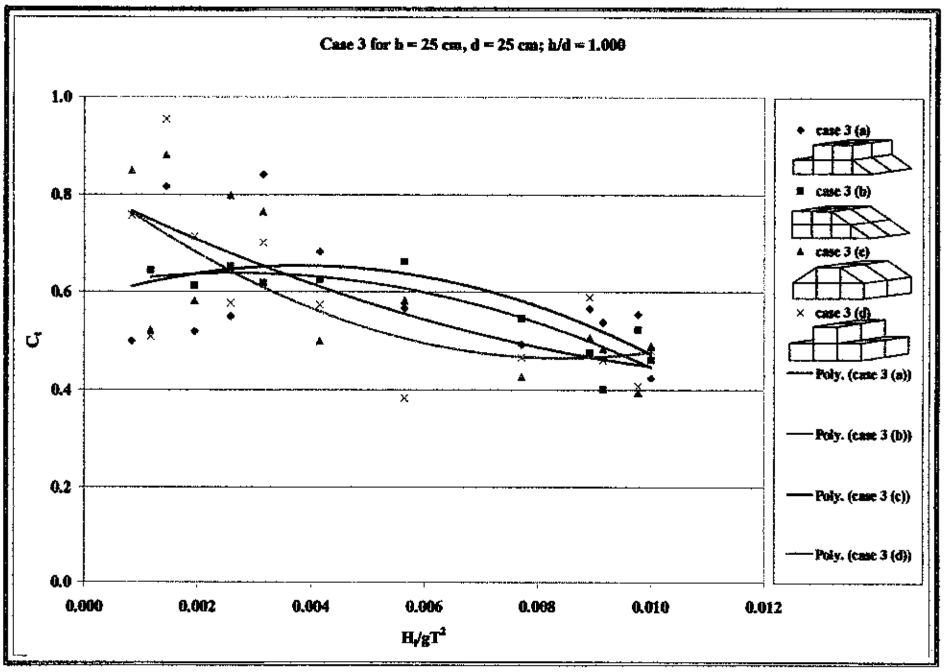


Figure 5.13: Performance of submerged breakwater of Case 3 for h/d = 1.000

There are two different trends split four rows and three rows of double-layer submerged breakwater proving the significance of width in submerged breakwater design. Though, the wave attenuation characteristics of both 3 (a) and 3 (b) configurations are almost homogeneous when $h/d = 1.000$, and so do the 3 (c) and 3 (d). As shown in Figure 5.13, configuration 3 (b) performs slightly better than configuration 3 (a), and 3 (d) performs better than 3 (c). Comparing those four (4) configurations, 3 (d) is governed, followed by 3 (c), 3 (b) and 3 (a).

As h/d = 1.000, the height of the submerged breakwater and the depth of water are identical. Again, wave dissipation mechanism is governing by reflection, breaking and surface friction. For configuration with vertical face such as case 3 (a), reflection takes place the most but lesser in sloping submerged breakwater like 3 (b). However, breaking will be the major wave dissipation mechanism in sloping structure where substantial breaking and turbulence in front of the submerged breakwater happens. The remaining waves of both configurations are further fractioned with the surface of the structure before passing the lee side of the submerged breakwater.

In shallower water, it seems that case 3 (d) configuration is a better submerged breakwater. This is because when $h = d$, incoming waves tend to break upon reaching the seaward most rectangular modules. The broken waves are further reflected by the vertical face at the top front of the structure, while the rest of waves will be dissipated on the crest of the submerged breakwater. As for breakwater with 3 (c) configuration, wave breaking and a little reflection take place on the structure's slope. That is why C_t of case 3 (d) is slightly better than case 3 (c).

5.3.4 General Performance

Figure 5.14 summarizes the performances of modular submerged breakwater with $h/d = 0.625$.

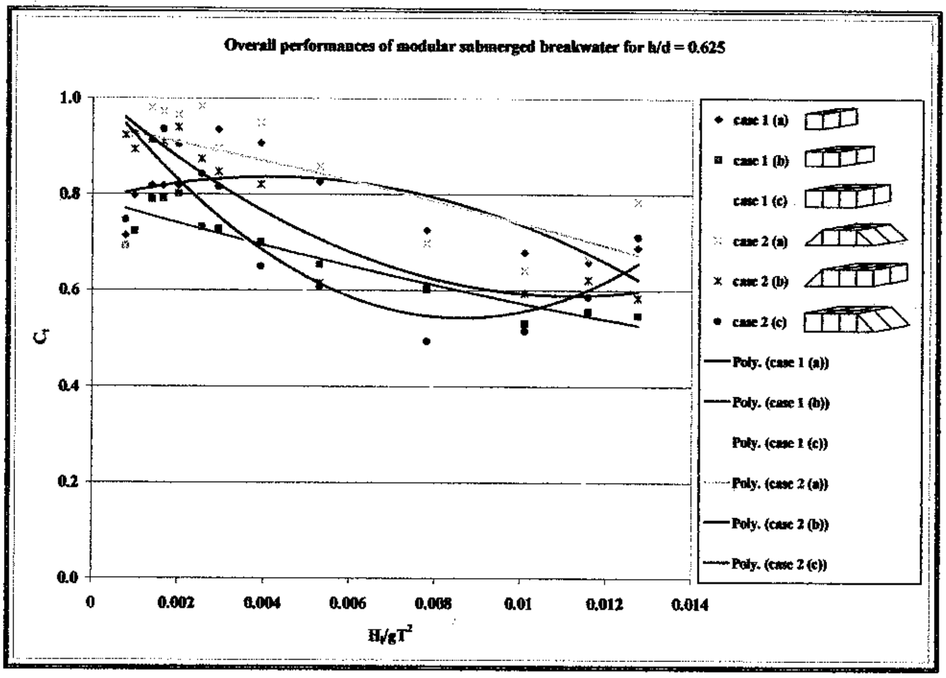


Figure 5.14: Submerged breakwaters performances for h/d = 0.625

Figure 5.14 shows the performances of modular submerged breakwater configurations for case 1 and case 2 for $h/d = 0.625$. Comparing those arrangements shows in the figure, it is found that case 1 (c) arrangement performs the best followed by 2 (c), 1 (b) and 2 (b). As the H_i/gT^2 gets larger, the value of C_t is reducing.

From the observation, the performance of 1 (c) arrangement is a lot depending on the crest width and its vertical front face. As discussed in Section 5.3.1; the wider the crest, the better will be the performance of the submerged breakwater. However when compare this arrangement with others with similar width; 2 (b) and 2 (c) it is found that both are having sloping faces which is subjected to lesser reflection. Thus the C_t value is much higher than configuration 1 (c).

The other two configurations; 1 (a) and 2 (a) are having a different trend and found to be the worst among all. However the value of C_t is also decreasing with the increasing of H_i/gT^2. Again, the small width of configuration 1 (a) gives smaller reduction of wave energy and vertical faces tend to reflect the incoming wave back to the seaward.

The summary of relative depth submergence, *h/d* and relative width of submerged breakwater with respect to water depth ratio *b/d* of various configurations are tabulated in Table 5.2 and 5.3 respectively.

Table 5.2: Summary of relative depth submergence, *h/d*

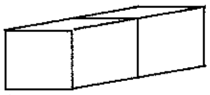
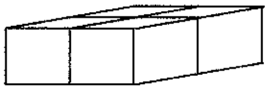
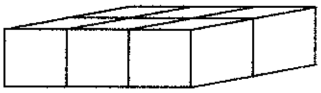
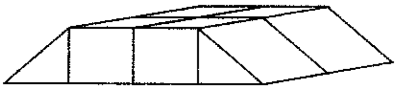
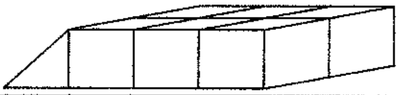
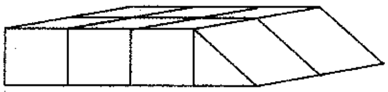
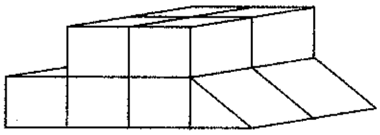
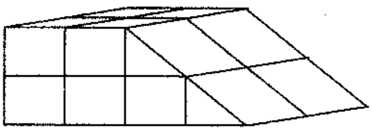
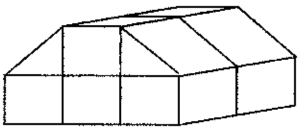
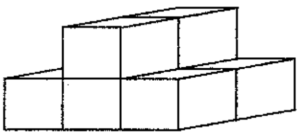
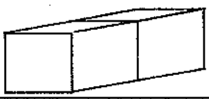
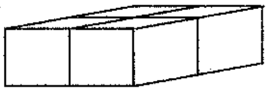
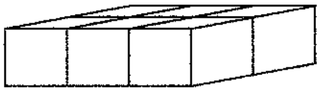
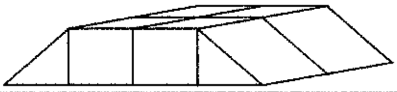
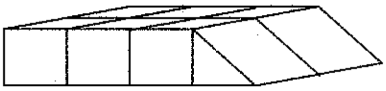
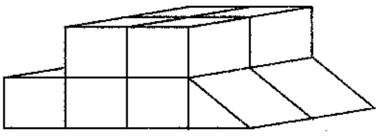
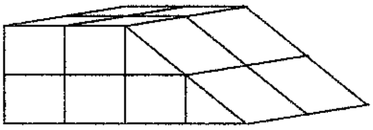
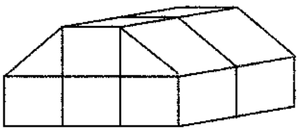
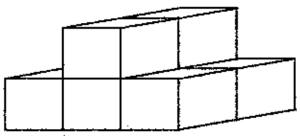
Case	Configurations	Relative crest width ratio, *h/d*		
		$d = 30$ cm	$d = 25$ cm	$d = 20$ cm
1 (a)		-	-	0.625
1 (b)		-	-	0.625
1 (c)		-	-	0.625
2 (a)		-	0.500	0.625
2 (b)		-	0.500	0.625
2 (c)		-	0.500	0.625
3 (a)		0.833	1.000	-
3 (b)		0.833	1.000	-
3 (c)		0.833	1.000	-
3 (d)		0.833	1.000	-

Table 5.3: Summary of relative width to water depth ratio, *b/d*

Case	Configurations	Relative crest width ratio, *b/d*		
		$d = 30$ cm	$d = 25$ cm	$d = 20$ cm
1 (a)		-	-	0.625
1 (b)		-	-	1.250
1 (c)		-	-	1.875
2 (a)		-	1.000	1.250
2 (b)		-	1.500	1.875
2 (c)		-	1.500	1.875
3 (a)		0.833	1.000	-
3 (b)		0.833	1.000	-
3 (c)		0.417	0.500	-
3 (d)		0.417	0.500	-

5.3.5 Comparison of C_t with other Submerged Breakwater Designs

Previously three cases of modular submerged breakwater performances namely; (1) Effect of submerged breakwater width, (2) Effects of sloping / vertical faces and contact area, and (3) Effect of various submerged breakwater configurations have been discussed. This section will be comparing the results obtained from the experimental studies of the proposed modular submerged breakwater with other homogeneous existing submerged breakwaters. Table 5.4 shows the value of relative depth submergence, *h/d* and submerged breakwater proportion, *h/B* for the selected submerged breakwaters.

Table 5.4: Relative depth submergence, *h/d* and SB proportion, *h/B*

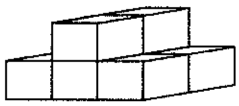
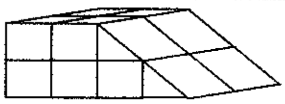
Type of submerged breakwater		*h/d*	*h/B*
Reef Ball		1.000	0.350
		0.799	0.583
		0.700	0.583
Modular Submerged Breakwater (MBS)		1.000	0.333
		0.833	0.500
		0.625	0.500

Figure 5.15, 5.16 and 5.17 will be discussing the comparison between both Reef Ball and modular submerged breakwater as medium to dissipate energy by transmission of wave, represent by transmission coefficient C_t.

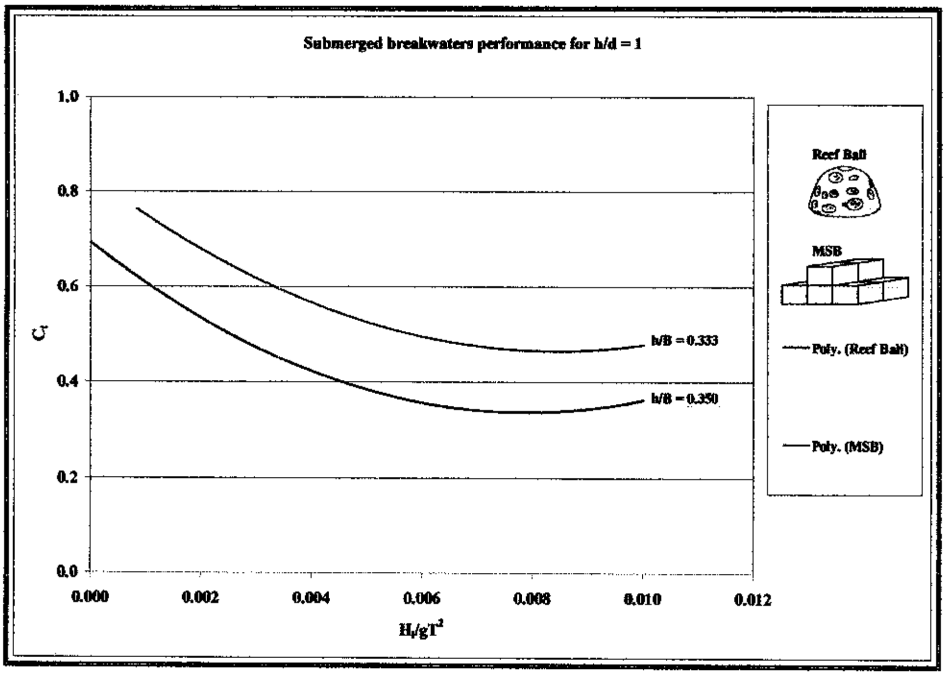


Figure 5.15: Comparison of MSB with other designs for *h/d* = 1

Figure 5.15 shows the performances of modular submerged breakwater (MSB) and Reef Ball in terms of transmission coefficient, C_t. Noted that configuration 3 (d) is taken into consideration because it performs better than others with similar *h/d* and covers almost similar value of *h/B* of Reef Ball. Both submerged breakwaters are having a similar trend of plot where C_t decreases as H_i/gT^2 increases.

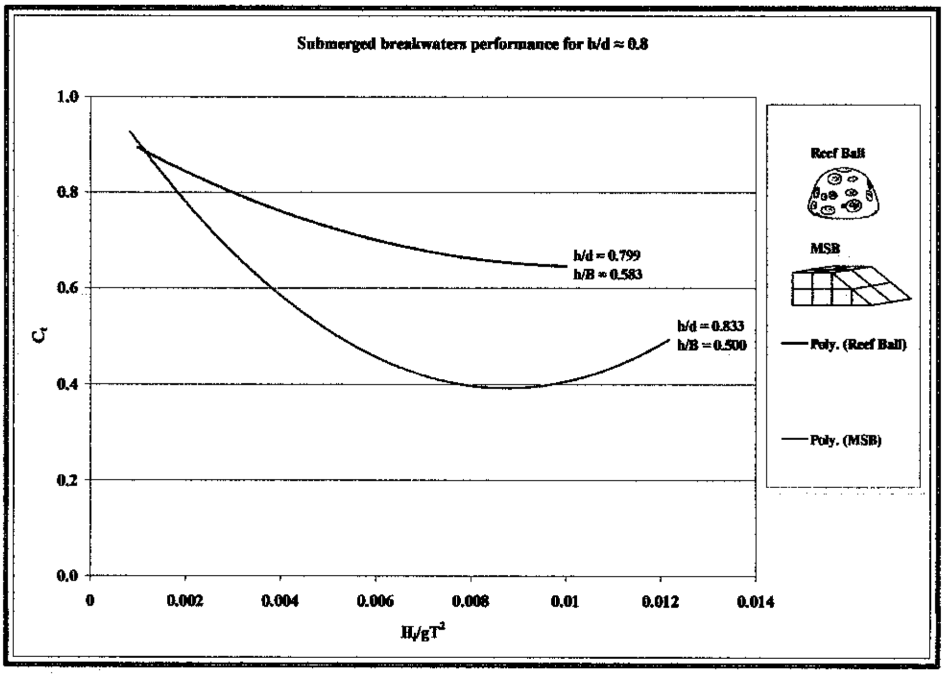


Figure 5.16: Comparison of MSB with other designs for *h/d* ≈ 0.8

Figure 5.16 shows the result of performances of both Reef Ball and modular submerged breakwater (MSB) with $h/d \approx 0.8$ and $h/B \approx 0.5$. From the laboratory experiment, the modular submerged breakwater with $h/d = 0.833$ is found to be better than Reef Ball of $h/d = 0.799$, with lesser value of C_t. It is able to reduce the wave height even more than 50% as compared to Reef Ball with less than 40%. However, this comparison cannot be considered since both studies are conducted in two different environments and limitations.

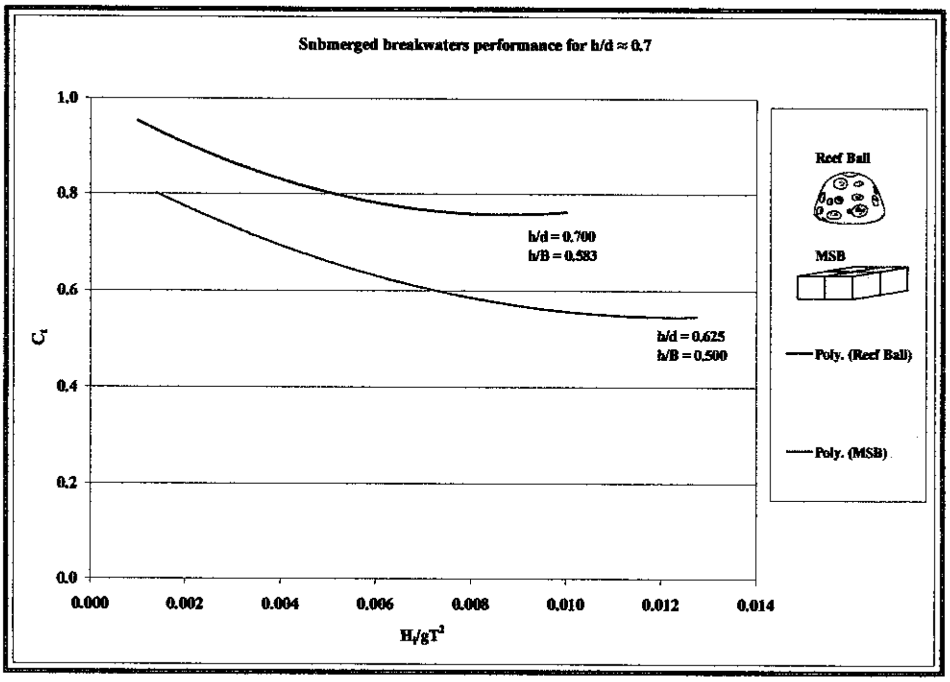


Figure 5.17: Comparison of MSB with other designs for *h/d* ≈ 0.7

Figure 5.17 represents the performances of both breakwaters in terms of C_t. Configuration 1 (b) is chose to represent the modular submerged breakwater (MSB) as its *h/d* and *h/B* are closely comparable to the Reef Ball's. As for $h/d \approx 0.7$, the proposed design of modular submerged breakwater is much better than Reef Ball. This is happening due to reflection causes by the vertical face of the structure.

From Figure 5.15, 5.16 and 5.17, it is proven that the modular submerged breakwater is able to perform as far as Reef Ball could. But these comparisons are less accurate since the value of *h/B* and *h/d* are slightly differs from each of the submerged breakwater. In additional, the surrounding factors during the results were obtained are a little different. The Reef Ball have been tested two dimensionally in flume tank with bigger size of model and totally covered by glass windows. While modular submerged breakwater with smaller size of model was tested in wave flume with uncovered roof, in only one dimensional. Another important thing is the dissimilarity of material of the submerged breakwaters that is not taken into consideration in this project.

CHAPTER 6: CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The conclusions of the present study are listed below.

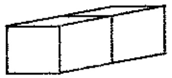
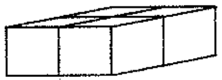
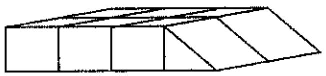
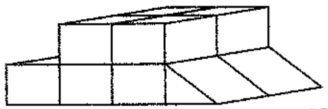
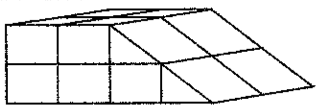
1. Two designs of modular submerged breakwater have been proposed and successfully fabricated. Since the scope of study does not cover the material of the model, the rectangular modules are made of mild steel filled with concrete, while the triangular modules are made of concrete. Both modules are designed in such a way to be arranged together to form certain configurations which can be submerged into the water and dissipate wave energy.

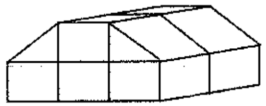
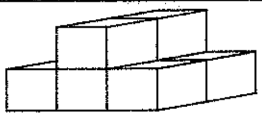
2. Those designs and its configurations have been tested in UTP Coastal and Offshore Laboratory. The outputs of the experiments are:
   i) The optimum number of row for an effective modular submerged breakwater is three (3). The wider the crest of the submerged breakwater, the lesser will be the C_t.
   ii) A sloping submerged breakwater is better than a vertical face one especially at the upper layer of the modular submerged breakwater to channel up the flowing water to the other side of the structure, to increase the total surface area for the purpose of friction, also to reduce reflection of wave back to the offshore.
   iii) The tendency of the breakwater to reflect the incident wave back to offshore is higher when $h = d$. but, smaller relative depth submergence, h/d will produce greater transmission coefficient, C_t as compared to a greater one since the collision between water particles and the structure is significant to reduce the wave height. Greater freeboard, F saves the higher water particles from collision with the structure and consequently maintains the height of the wave.

iv) The overall performance of the modular submerged breakwater shows that it is effective in reducing wave height in terms of wave transmission.

v) The design values obtained by the experimental studies are tabulated in Table 6.1.

Table 6.1: Suggested H_i/gT^2 and C_t range for modular submerged breakwaters

Case	Configurations	crest width, b (cm)		Relative breakwater height, h/d 0.500	0.625	0.833	1.000
Case 1 (a)		12.5	H_i/gT^2		0.008 – 0.013		
			C_t		0.73 – 0.66		
Case 1 (b)		25.0	H_i/gT^2		0.004 – 0.013		
			C_t		0.55 – 0.70		
Case 1 (c)		37.5	H_i/gT^2		0.004 – 0.013		
			C_t		0.20 – 0.70		
Case 2 (a)		25.0	H_i/gT^2	0.006 – 0.010	0.006 – 0.012		
			C_t	0.90 – 1.00	0.70 – 0.80		
Case 2 (b)		37.5	H_i/gT^2	0.004 – 0.010	0.003 – 0.012		
			C_t	0.90 – 1.00	0.60 – 0.80		
Case 2 (c)		37.5	H_i/gT^2	0.006 – 0.010	0.004 – 0.012		
			C_t	0.90 – 1.00	0.55 – 0.65		
Case 3 (a)		25.0	H_i/gT^2			0.005 – 0.012	0.005 – 0.010
			C_t			0.45 – 0.60	0.48 – 0.65
Case 3 (b)		25.0	H_i/gT^2			0.004 – 0.012	0.004 – 0.010
			C_t			0.40 – 0.60	0.45 -0.63

Case	Configurations	crest width, b (cm)		Relative breakwater height, *h/d*			
				0.500	**0.625**	**0.833**	**1.000**
Case 3 (c)		12.5	H_i/gT^2			0.004 – 0.012	0.001 – 0.010
			C_t			0.55 – 0.70	0.63 – 0.76
Case 3 (d)		12.5	H_i/gT^2			0.005 – 0.012	0.001 – 0.010
			C_t			0.61 – 0.70	0.65 – 0.76

3. As compared to the existing submerged breakwater (i.e. Reef Ball), the modular submerged breakwater is an effective breakwater that is able to reduce wave height in terms of wave transmission. Sometimes, the performance of the modular submerged breakwater is even better than Reef Ball.

6.2 Recommendation

Throughout the study of various types of submerged breakwaters also experience of the experiment in the laboratory, there are few things need to be considered and apply to improve the performance of the modular submerged breakwater. The recommendations are;

1. Further investigation should be carried out to study other wave attenuation mechanisms of this modular submerged breakwater such as reflection and energy loss to ensure better accuracy of the result.
2. The experiments should be carried out using wave probe instead of observation method to obtain more accurate result.
3. A suitable material for the modular submerged breakwater should be investigated for further improvement of its performance.
4. In the real situation, interlocking system should be introduced to the modules to maintain the connection between submerged breakwater units.
5. For a prototype submerged breakwater, it is suggested to install anchoring system as well for the penetration into the seabed that will provide more stability
6. A prototype submerged breakwater also needs to be deployed on a thin geotextile fabric for scour protection

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