

THE PERFORMANCE OF NARROW AND BROAD-CRESTED SUBMERGED BREAKWATERS IN DISSIPATING WAVE HEIGHTS

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Graphical abstract



Abstract

The main objective of this paper is to determine the wave transmission coefficient of an improved submerged breakwater called WABCORE. The objective is further explored to assess the effect of various parameters such as wave steepness, H_i/L , relative freeboard, R/d , and relative width of the top crest, B/L on wave transmission coefficient, K_T . In general, as wave steepness increases, the wave transmissions decrease. Moreover wave transmission increases as relative freeboard increases. This is due to the fact that higher relative freeboard contains greater wave energy and hard to dissipate. As B/L increases, K_T decreases. The effect of relative top crest width is insignificant as the freeboard increases. The transmission coefficient, K_T derived from this study can be equated as $K_T = -2.143 \left(\frac{H_i}{L} \right) + 1.36 \left(\frac{R}{d} \right) - 1.932 \left(\frac{B}{L} \right) + 0.514$, valid for certain ranges. This study concludes that WABCORE is capable to dissipate wave energy.

Keywords: Submerged breakwaters, WABCORE, wave transmission coefficient, wave steepness, relative freeboard, relative top crest width

Abstrak

Objektif utama kajian ini adalah untuk menentukan pekali penghantaran ombak bagi pemecah ombak tenggelam dipanggil WABCORE yang telah ditambah baik. Kemudian, objektif dilihat secara mendalam untuk mengkaji pelbagai pemboleh ubah seperti kecurangan ombak, lambung bebas, ketebalan puncak stuktur ke atas pekali ombak. Secara amnya, semakin curam ombak, semakin rendah penghantaran ombak. Semakin tinggi lambung bebas, semakin tinggi penghantaran ombak. Ini oleh kerana lambung bebas yang tinggi mengandungi tenaga ombak yang lebih besar dan sukar untuk dipecahkan. Selain itu, apabila ketebalan puncak stuktur meningkat, penghantaran ombak juga meningkat. Ketebalan puncak stuktur tidak memberi kesan apabila lambung bebas meningkat. Pekali bebas penghantaran ombak dapat yang diperolehi dari kajian ini boleh didapati dalam bentuk $K_T = -2.143 \left(\frac{H_i}{L} \right) + 1.36 \left(\frac{R}{d} \right) - 1.932 \left(\frac{B}{L} \right) + 0.514$, di mana ianya boleh digunakan bagi sesetengah jarak. Kajian ini mendapati bahawa WABCORE berupaya untuk mengurangkan tenaga ombak yang dihantar.

Kata kunci: Pemecah ombak tenggelam, WABCORE, pekali penghantaran ombak, kecurangan ombak, lambung bebas, ketebalan puncak stuktur

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1.0 INTRODUCTION

Breakwaters are known to be one of the coastal protection structures that protect beach from the direct wave attack. Rubble mound breakwaters are widely used in the early introduction of the breakwaters. Takahashi (1996) stated that the stone masonry breakwaters are constructed as early as in 2000 BC in Alexandria, Egypt [1]. As time goes by, breakwaters have been undergoing few changes to suit various needs. For example, submerged breakwaters are introduced to resorts and tourist attraction areas to maintain the aesthetic value of the beach [2].

Erosion has been acknowledged as one of the major problems along beaches even though the process of erosion and accretion is part of a natural cycle. This erosion problem is unavoidable. The National Coastal Erosion Study (NCES) that was conducted in 2015 (previously conducted in 1985) showed that 15% of Malaysia's coastline with the length of 8,840km is facing erosion covering areas that are vulnerable to erosion such as the east coast of Malay Peninsular. Million ringgit Malaysia were invested to protect the coasts from continuously being eroded [3]. Back in 2016, the federal government of Malaysia spent RM 90 million to counter erosion in Pantai Mengabang Telipot, Terengganu after the beach was slammed by 2.8m height of wave [4]. Since then, studies and researches were successfully done in details to prevent the beach erosion even after the sand reclamation were done on that particular beach.

The purpose of this study is to explore the performance of a new type submerged breakwater called WABCORE, an acronym of Wave Breaker and Coastal Restoration breakwater. The main objective is to determine the wave transmission coefficient of an improved submerged breakwater called WABCORE. The objective is further explored to various parameters such as wave steepness, H_i/L , dimensionless freeboard, R/d , and width of the top crest, B . The details of WABCORE is explained in Section 1.2.

1.1 Submerged Breakwaters

Submerged breakwaters can be defined as a breakwater that is fully submerged inside the body of the water and the top crest of the structure is below the lower mean sea level. Parameters governing the submerged breakwater can be referred in Figure 1.

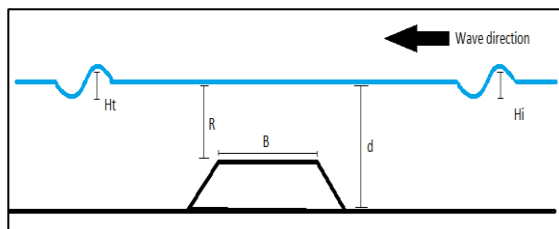


Figure 1 Governing parameters related to submerged breakwater

Incident wave height, H_i is the wave height propagating before reaching the submerged breakwater while, transmitted wave height, H_t is the wave height that is propagated after the submerged breakwater. Water depth, d is the depth of water measured from the bed to the surface water level. Freeboard, R is the distance from top crest of the submerged breakwater to the surface water level. Top crest width, B is the top crest width of the submerged breakwater.

There are several wave transmission variables that are associated with wave transmission over submerged breakwaters. Friebel (2000) identified five correlation of variables derived from data obtained from study by Seelig (1980), Daemrich and Kahle (1985), Van der Meer (1988), Daemen (1991), and Seabrook (1997) [5]. Those correlations are h/d_s , F/H_{m0i} , F/B , B/d_s , and B/L where h is the height of structure from seabed, F is the freeboard, B is crest width of breakwater, and L is wavelength at local depth. Friebel (2000) came out with an equation with R-squared (RSQ) value of 0.9402 and standard deviation of 0.0510 as depicted in Equation 1.

$$K_T = -0.4969 \exp\left(\frac{F}{H_{m0i}}\right) - 0.0292 \left(\frac{B}{d_s}\right) - 0.4257 \left(\frac{h}{d_s}\right) - 0.0696 \log\left(\frac{B}{L}\right) + 0.1359 \left(\frac{F}{B}\right) + 1.0905 \quad (1)$$

1.2 Previous Study on Submerged Breakwater

There have been a lot of studies covering the topic of submerged breakwaters in the past decades. Some of the most notably studies are by Dattatari *et al.* (1978) whose showed that wave transmission is mainly affected by the structure crest width (B) and the freeboard of the structure below the sea surface (R); the studies by Van der Meer (2005), d'Angremond *et al.* (1996) and Seabrook and Hall (1998) have resulted in some experimental formula for the wave transmission coefficient [6], [7], [8], [9]. These studies focus on the wave transmission over conventional breakwater which is the rubblemound type breakwater. However, submerged breakwater has long been innovated in terms of materials, composition, functionality, and others to fill the requirements needed. For example, Liao *et al.* (2013), studied on wave breaking criteria and energy loss caused by a submerged porous breakwater on horizontal bottom, Armono and Hall (2004) studied on the wave transmission on hollow hemispherical shape artificial reefs (HSAR) and Hamdani *et al.* (2015) experimented on wave transmission on submerged breakwater with interlocking D-Block Armor [10], [11], [12].

1.3 Wave Breaker Coral Restoration (WABCORE)

Wave Breaker Coral Restoration (WABCORE) is a composite system unit developed by National Hydraulics Research Institute Malaysia (NAHRIM). The

invention of WABCORE was patented under *Reka bentuk Industri dengan Perbadanan Harta Intelekt Malaysia (MyIPO)*, reference number 12-00200-101. WABCORE has a characteristic of submerged breakwater that acts as an erosion control structure and beach stabilization with wave breaking as well as an artificial concrete reef, a luxury home for aquatic life. Pre-fabricated concrete structures are positioned together to form a simple trapezoidal design (pyramid shape) which formed out as one unit. The WABCORE model is arranged in a way where the base with wide bottom and narrow crest of 4, 3, 2 and 1 units respectively from the bottom, second and third middle layers followed by the top crest and in narrow crested shape. Complying to the Froude scaling for mass weight of $1 : x^3$, the mass weight of the prototype structure is 371.4 kg, hence the model weight has to be at 5.8kg for scale 1:4. The first prototype model was successfully installed at Pulau Tioman in Endau-Rompin, Pahang and Pulau Tinggi in Johor as seen in Figure 2 [13], [14].



Figure 2 Original WABCORE prototype before being deployed in 2014 [5]

In this study, the WABCORE model that was used is an innovated version from the original model. The new WABCORE has similar geometry but different composition of materials as shown in Figure 3. The obvious difference between these two WABCORE models is their weight and interlocking system. The model dimension is kept the same but the new WABCORE's weight was reduced to 3.5 kg with a density of 1600 kg/m^3 . This was achieved by substituting some of aggregates with recycled materials such as rubber crumbs, polystyrene, pvc pipe and mesh fibre that have lighter density. Their interlocking system is improved by providing a concrete bars on top crest instead of steel bar as can be seen in Figure 3.

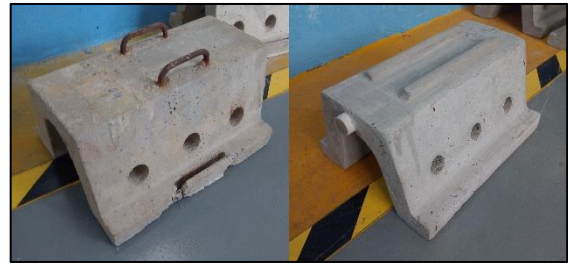


Figure 3 Original model of WABCORE (left) and new model of WABCORE (right)

Apart from the density and weight, the interlocking system in the new model of WABCORE is improved. The new WABCORE has additional interlocking system at the side of the model to connect with the adjacent model. The metal rod is substituted with a strip of concrete as shown in Figure 3. Geometrically, the dimension of both models is remain unchanged.

2.0 METHODOLOGY

In this section, the setup of the experiment, procedure and method of data analyzing are briefly explained.

2.2 Experiment Setup

A series of experiment was conducted in the Hydraulic Lab of Civil Engineering Department, UPM. The WABCORE model was fabricated and supplied by NAHRIM. Two type of WABCORE models were studied which are narrow crested WABCORE model and wide crested WABCORE model. For the narrow crested model, it was positioned in the trapezoidal shape where the width base is arranged in three units followed by two units in the middle, and one unit on the top crest. For the broad crested WABCORE model, the base was setup with four units, followed by three units in the middle and two units on the top. The model was placed in the middle of the wave flume as shown in Figure 4.

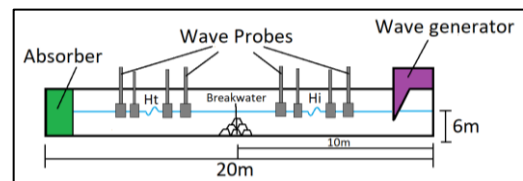


Figure 4 Experimental setup of WABCORE inside the wave flume

Eight wave probes, which four of them were positioned in front of the submerged breakwater model while the remaining four were placed behind the model. The distance between the probes is set at 0.45m. The wave probes were used to capture the incident, H_i and transmitted wave heights, H_t . At the far end of the wave flume, a wave absorber was placed to damp the transmitted waves so that wave energy is dissipated and reflection can be minimized due to transmitted waves. The generation of a series of regular waves with specified heights and periods was done using a wave generator equipped within the wave flume. Calibration setup prior to model testing was also conducted.

To determine the wave coefficient transmissions, six waves with different heights ($H_s=0.05$ m, 0.10 m, 0.15 m, 0.20 m, 0.25 m, 0.30 m) were generated and the freeboard were varied up to five heights ($R = 0.02$ m, 0.07 m, 0.12 m, 0.17 m, 0.22 m). Three wave periods (1.43 s, 1.68 s, 2.0 s) were tested together with other parameters. Overall, 180 number of tests were simulated.

For the effect of top crest width on K_T , two type of crested widths are used namely narrow crest (9.5 cm) and broad crest (24 cm). Throughout this paper, these two types of top crest widths are referred as narrow and broad crested WABCORE, respectively. In addition, the WABCORE model is strengthened with cable ties as shown in Figure 5 to replicate the prototype which was bolted to each other and fixed with a metal plate at the base. This was to ensure that the structure is stable.



Figure 5 WABCORE model tied with cable ties

2.3 Analysis Method

The general transmission coefficient can be determined using the following equation referred from the Shore Protection Manual [15].

$$K_T = \frac{H_t}{H_i} \quad (2)$$

In this study, the analysis of incident and transmitted wave heights is mainly based on the study done by Safari (2016) who had been referred to the study conducted by Isaacson (1991) [12]. The

values of H_i and H_t were obtained from the equation as follows:

$$H^2_i = \frac{H^2_{moav}}{(1 + C_r^2)} \quad (3)$$

To obtain C_r , reflection analysis was conducted to separate between incident wave and reflected wave. There are previous studies on methods of separating those two waves such as Least Square Method by Mansard and Funke (1980), a time domain method by Frigaard and Brorsen (1995), and separation of cross modes by Gronbech *et al.* (1996) [16], [17], [18]. In this study, the C_r values were obtained from the software WaveLab3 in which the analysis is based on study by Lin and Huang (2004) for linear waves [19].

3.0 RESULTS AND DISCUSSION

In this section, the results of this study are discussed. Discussions cover the effect of wave steepness, H_i/L on K_T , effect of dimensionless freeboard, R/d on K_T and effect of dimensionless top crest width, B/L on K_T , and the performance of the WABCORE.

3.1 Effect of Wave Steepness, H_i/L on K_T

Figure 6(a) shows the relationship between the wave steepness, H_i/L and K_T for $T_m=1.43$ s followed by $T_m = 1.68$ s (Figure 6(b)) and $T_m = 2.0$ s (Figure 6(c)) for the narrow crested WABCORE. For $T_m = 2.0$ s, the highest K_T is 1.07 when H_i/L is 0.048 and $R = 0.22$ m. The lowest K_T is 0.38 when H_i/L is 0.008 and $R = 0.02$ m. For $T_m = 1.68$ s, the highest K_T is 1.08 when H_i/L is 0.011 and $R = 0.22$ m while the lowest K_T is 0.39 when H_i/L is 0.056 and $R = 0.02$ m. For $T_m = 1.43$ s, the highest K_T is 1.08 when H_i/L is 0.02 and $R = 0.22$ m while the lowest K_T is 0.39 when H_i/L is 0.08 and $R = 0.02$ m. In general, as wave steepness increases, the wave transmissions decrease. This is because of the higher wave steepness possess lower wave energy compared to lower wave steepness. Thus, the wave energy is easily dissipated when wave is steepened.

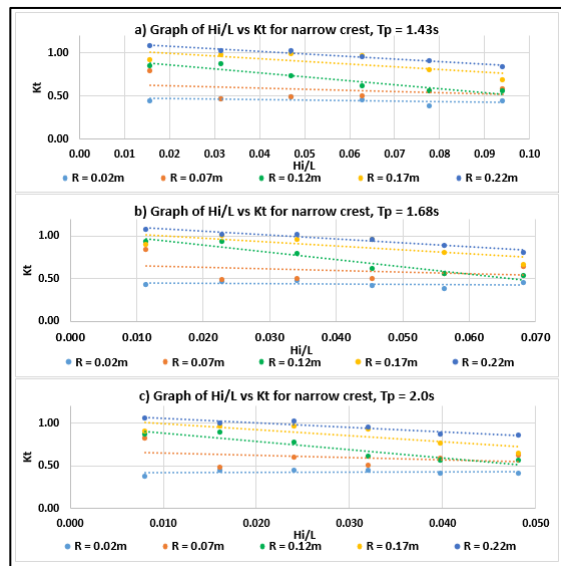


Figure 6 The graph of H_i/L vs K_T for narrow crested WABCORE

Figure 7(a) shows the relationship between the wave steepness and K_T for $T_m = 1.43$ s followed by $T_m = 1.68$ s (Figure 7(b)) and $T_m = 2.0$ s (Figure 7(c)) for the broad crested WABCORE. For $T_m = 2.0$ s, the highest K_T is 0.9 when H_i/L is 0.016 and $R = 0.22$ m. The lowest K_T is 0.33 when H_i/L is 0.016 and $R = 0.02$ m. For $T_m = 1.68$ s, the highest K_T is 0.82 when H_i/L is 0.011 and $R = 0.22$ m while the lowest K_T is 0.37 when H_i/L is 0.023 and $R = 0.02$ m. For $T_m = 1.43$ s, the highest K_T is 0.96 when H_i/L is 0.02 and $R = 0.22$ m while the lowest K_T is 0.27 when H_i/L is 0.08 and $R = 0.02$ m. Similar to the narrow crested WABCORE, broad crested WABCORE results in the decrease of wave transmission coefficient when the wave steepness increases.

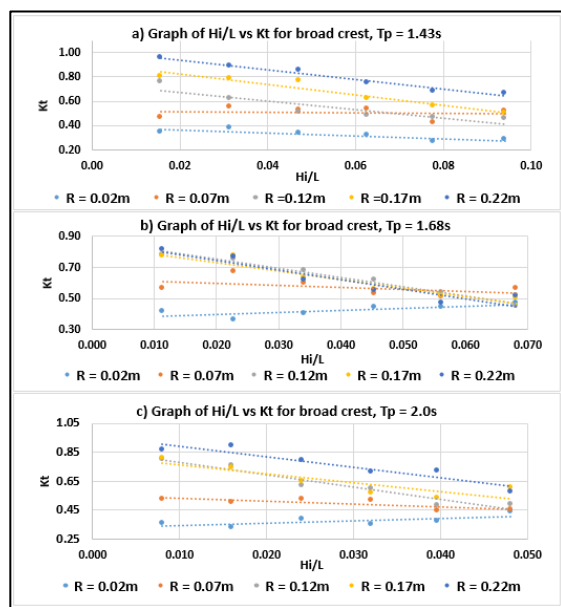


Figure 7 The graph of H_i/L vs K_T for broad crested WABCORE

The results from the study by Dattatri *et al.* (1978) [6] possess similar trend compared to the results of H_i/L against K_T . In their study, the effect of wave steepness on K_T is inconsequential for the range of higher wave steepness due to the fact that higher wave steepness seems to combine into one point. This interference is in line with our observations as can be seen in Figure 7(b) for H_i/L versus K_T for $T_m = 1.68$ s, where the points are close together. Apart from that, study by Hamdani *et al.* (2015) [12] on wave transmission on submerged breakwater with interlocking D-block armor also shows similar trend for the effect of wave steepness on K_T . Authors concluded that the higher the value of wave steepness, the lower the K_T is. Moreover, there is also a study on the wave transmission on submerged breakwaters made of hollow hemispherical shape artificial by Armono and Hall (2003) [11]. A qualitative parametric analysis was conducted to find the effects of the external and dimensional variables on the wave transmission through hemispherical shape artificial reefs (HSAR) breakwaters. For the relationship between K_T and wave steepness, Armono and Hall (2003) concluded that the higher the wave steepness, the lower the K_T . Based on those studies, it can be concluded that our experimental results are in agreement with the results obtained from those studies. In comparison to Figure 6 and Figure 7, the broad crested WABCORE has lower K_T compared to the narrow crested WABCORE.

3.2 Effect of Relative Freeboard, R/d on K_T

Figure 8(a) shows the relationship between the relative freeboard (R/d) and K_T for $T_m = 1.43$ s followed by 1.68 s (Figure 8(b)) and 2.0 s (Figure 8(c)) for narrow crested WABCORE. For $T_m = 1.43$ s, the highest K_T is 1.08 when R/d is 0.367 and $H_i = 0.05$ m. The lowest K_T is 0.39 when R/d is 0.05 and $H_i = 0.25$ m. For $T_m = 1.68$ s, the highest K_T is 1.08 when R/d is 0.367 and $H_i = 0.05$ m while the lowest K_T is 0.39 when R/d is 0.05 and $H_i = 0.25$ m. For $T_m = 2.0$ s, the highest K_T is 1.07 when R/d is 0.367 and $H_i = 0.05$ m while the lowest K_T is 0.38 when R/d is 0.05 and $H_i = 0.05$ m. Generally, K_T increases as the R/d increase. This is because of higher R/d contains more wave energy and harder to dissipate. This is the reason why wave energy in lower R/d is easily dissipated.

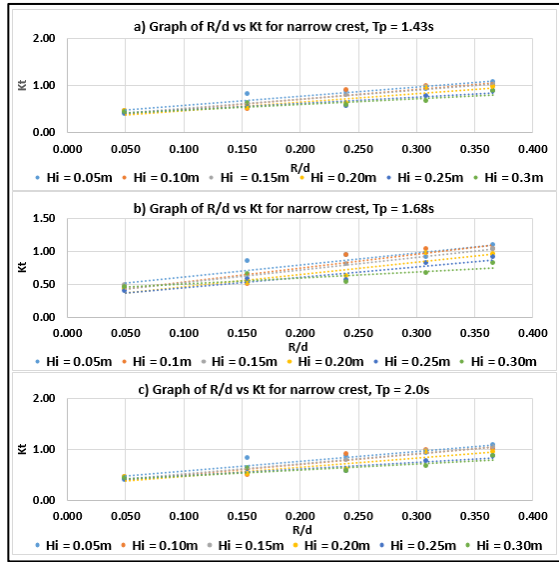


Figure 8 Graph of R/d vs K_T for narrow crested WABCORE

Figure 9(a) shows the relationship between the relative freeboard and K_T for $T_m = 1.43.s$ followed by 1.68 s (Figure 9(b)) and 2.0 s (Figure 9(c)) for broad crested WABCORE. For $T_m = 1.43 s$, the highest K_T is 0.96 when R/d is 0.367 and $H_i = 0.05 m$. The lowest K_T is 0.27 when R/d is 0.05 and $H_i = 0.25 m$. For $T_m = 1.68 s$, the highest K_T is 0.82 when R/d is 0.367 and $H_i = 0.05 m$ while the lowest K_T is 0.37 when R/d is 0.05 and $H_i = 0.10 m$. For $T_m = 2.0s$, the highest K_T is 0.90 when R/d is 0.367 and $H_i = 0.10 m$ while the lowest K_T is 0.33 when R/d is 0.05 and $H_i = 0.10 m$. Similar to the narrow crested WABCORE, K_T in broad crest WABCORE is also increases as the R/d increase.

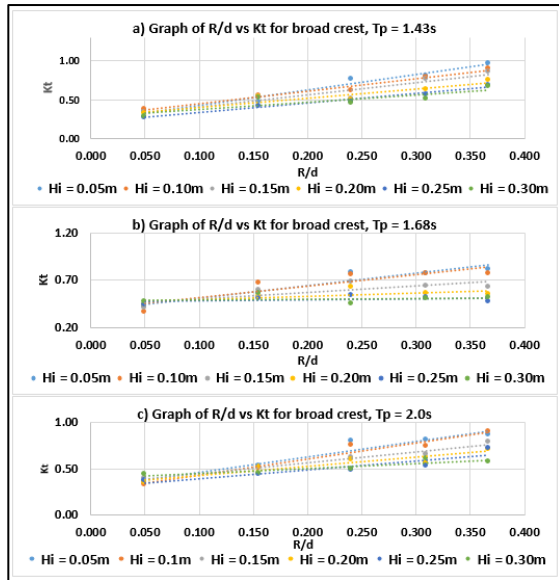


Figure 9 Graph of R/d vs K_T for broad crested WABCORE

Based on the previous study by Seabrook and Hall (1998), the variables that highly affecting the K_T are R (freeboard), incident wave height (H_i) and crest width (B) [9]. The results on the relationship between K_T and showed that the higher the freeboard (R), the higher the K_T . In addition, study by Yuliasuti and Hashim (2015) on wave transmission over submerged rubble mound breakwater using L-blocks which showed the relationship between freeboard and wave transmission has similar results [20]. The higher the freeboard, the higher the wave transmission. Authors added that when the relative freeboard is greater than 40%, the influence of freeboard on the wave transmission coefficient becomes insignificant.

3.3 Effect of Relative Top Crest Width, B/L on K_T

Figure 10 (a) shows the relationship between relative top crest width and K_T for $R = 0.02 m$ followed by $R = 0.07 m$ (Figure 10(b)), $R = 0.12 m$ (Figure 10(c)), $R = 0.17 m$ (Figure 10(d)), and $R = 0.22 m$ (Figure 10e)) for narrow crested WABCORE. Based on these figures, it can be seen that as B/L increases, K_T decreases except for the case when freeboard is the lowest at 0.02m. As R increases, it can be observed that the trend line is prone to form a horizontal line. This indicates that the increasing of R causes B/L effect on K_T is insignificant.

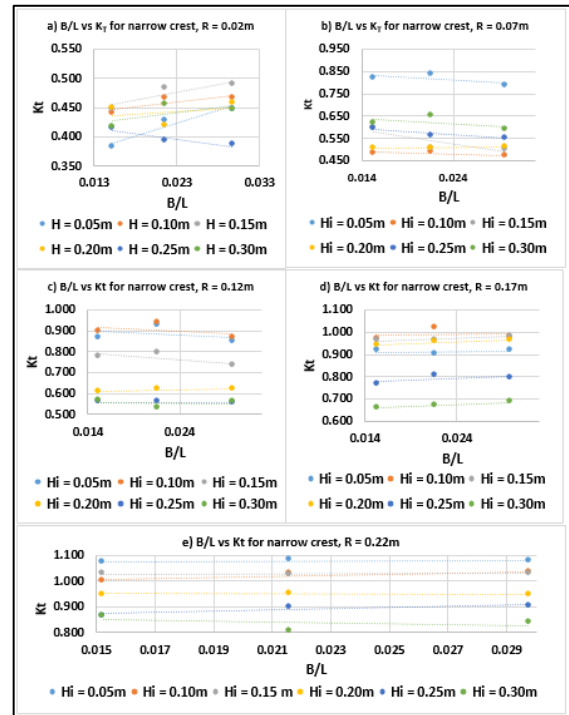


Figure 10 Graph of B/L vs K_T for narrow crested WABCORE

Figure 11 (a) shows the relationship between relative top crest width and K_T for $R = 0.02$ m followed by $R = 0.07$ m (Figure 11(b)), $R = 0.12$ m (Figure 11(c)), $R = 0.17$ m (Figure 11(d)), and $R = 0.22$ m (Figure 11e) for broad crested WABCORE. As B/L increases, K_T also increases. Similar to the narrow-crested breakwater, regardless the value of R , there is insignificant changes of K_T . This indicates B/L has no effect on the wave transmission coefficient.

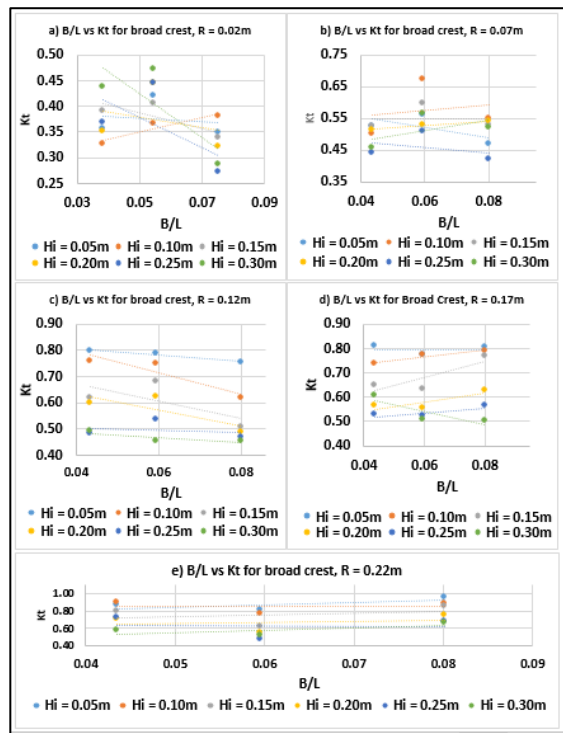


Figure 11 Graph of B/L vs K_T for broad crested WABCORE

The differences between the narrow crested and the broad crested WABCORE in dissipating waves energy can be seen in Figure 10 and Figure 11. The highest K_T for the narrow crested WABCORE is 1.08 while for the broad crested WABCORE, the maximum K_T is 0.90. A submerged breakwater depends on the crest width for wave breaking when the wave passes through the structures compared to an emerged breakwater where the waves are breaking at the face of the structure. Based on Dattatri *et al.* (1978), relative crest width plays a role in wave transformation over the breakwater [6]. When the crest width is small, the wave steepens as it is ready to break but revert as it reenters the relatively deeper waters as soon the wave passed through the crest width. In contrast, when the crest width is sufficient, the wave breaks and resulting in lesser transmission. An increase in the top crest width above the minimum value necessary to trigger wave breaking is insignificant to the wave transmission. Armono and Hall (2004), concluded that when the water depth increases, the relative crest width is insignificant as a

wave does not 'touch' the crest which resulting in inefficient wave dissipation [11].

3.4 Performance of the WABCORE

Figure 12 (a) shows the relationship between H_i/L and K_T followed by R/d and K_T (Figure 12(b)) and B/L and K_T (Figure 12(c)). The data is separated into two series which are data for narrow crested and broad crested WABCORE.

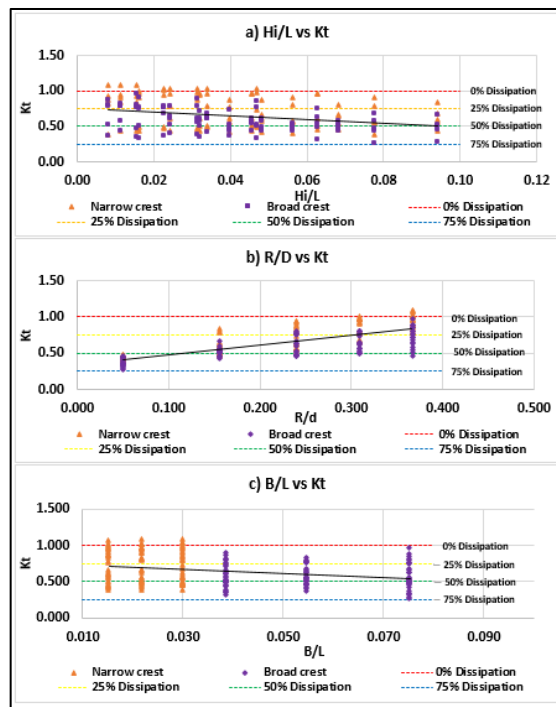


Figure 12 Graph of the relationship of various parameters on K_T

The graph is separated into five sections which in terms of the percentage of dissipation as presented in Figure 12. The data then are grouped in their respective sections and the results are tabulated in Table 1.

Table 1 Table of percentage of wave dissipation

Section	Count (N)	Count (%)
<0% Dissipation (Negative)	10	5.56
0% - 25% Dissipation	53	29.44
25% - 50% Dissipation	67	37.22
50% - 75% Dissipation	50	27.78
75% - 100% Dissipation	0	0

From Table 1, the highest percentage of wave dissipation due to WABCORE is between 25% and 50% followed by 0% - 25% dissipation and 50% - 75% dissipation. Approximately 5% of WABCORE failed to functionally dissipate the wave.

From the collected data, an empirical equation for a single submerged WABCORE was derived. Multiple regression analysis was applied using SPSS software to derive the linear equation. 70% sets of data were used in the analysis and another 30% sets of data were reserved for validation. Equation 4 shows the empirical equation developed using the multiple regression analysis.

$$K_T = -2.143 \left(\frac{H_i}{L} \right) + 1.36 \left(\frac{R}{d} \right) - 1.932 \left(\frac{B}{L} \right) + 0.514 \quad (4)$$

The statistical analysis gives the value of $R^2 = 0.621$ for the developed equation while the validation result between measured and calculated K_T gives the value of $R^2 = 0.9553$ as can be seen in Figure 13.

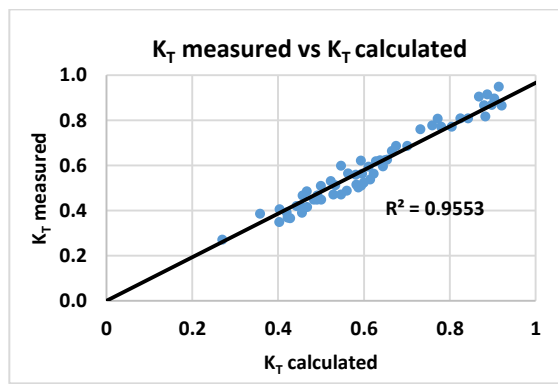


Figure 13 Graph of the K_T measured vs K_T calculated for validation

In general, WABCORE is capable to dissipate wave for certain range of parameters which are tested in this study. Based on the Equation 4, K_T can be derived as the incident wave height over transmitted wave height and the equation is valid for ranges An equation of K_T can be derived as

$$\begin{aligned} 0.011 &\geq \frac{H_i}{L} \leq 0.09 \\ 0.05 &\geq \frac{R}{d} \leq 0.367 \\ 0.015 &\geq \frac{B}{L} \leq 0.08 \end{aligned}$$

and only applicable to the case when single WABCORE submerged breakwater is applied.

4.0 CONCLUSION

Several conclusions are drawn based on the results obtained from the experimental study. In general, WABCORE is capable to dissipate wave energy as a submerged breakwater. Wave steepness, H_i/L influences the wave transmission over submerged breakwater. Furthermore, as wave steepness increases, wave transmission decreases due to wave

that is leaning to break. Moreover, small relative freeboard, R/d results in decreasing wave transmission coefficient. As relative top crest width, B/L increases, the K_T decreases but limited to a point where the effect of B/L becomes ineffective as the value of R increases. The equation derived from the result of this study can be written as $K_T = -2.143(H_i/L) + 1.36(R/d) - 1.932(B/L) + 0.514$ for certain ranges.

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