
WAVE CHARACTERISTICS AROUND PERFORATED PILES IN A TWO ROWS ARRANGEMENT

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Abstract: An experimental study was performed to investigate the transmission response of a two-row perforated double ring pile (DP). The tests were conducted in unidirectional waves with different wave conditions and pile porosity that varied from 0.0625 to 0.48. From the experimental results, it was found that when the pile porosity increases, less wave energy was attenuated, resulting in higher wave transmission coefficient, K_t . Furthermore, K_t was found to be decreasing when the wave steepness increases for all porosity values. Moreover, higher water depth has higher K_t , especially at low relative depth range between 0.1 and 0.15 with K_t being more than 0.3 at a water depth $h \leq 0.27$ m and K_t was more than 0.60 when $h \geq 0.3$ m. Tests on spacing B and model width W were also investigated. Wider spacing ($B \geq 0.5D$) resulted in lower wave attenuation, whilst wider model of more than one row generally attenuated more wave energy as expected. However the percentage of attenuation of the model system with more than two-rows tends to be ineffective, thus indicating that the test model with a width $W > 2D$ has less influence in attenuating waves. An empirical equation to predict transmission coefficient was also derived based on statistical analyses using independent wave parameters namely relative depth (h/L), wave steepness (H/L), relative model spacing (B/L) and model porosity (ϵ). A multiple linear regression analysis was used to model the relationship of these variables. Comparisons of transmitted wave performance by other researchers were also analyzed.

Keywords: *perforated pile; experimental investigation; wave transmission; porosity; empirical formulae.*

1.0 Introduction

The shore is defined as a narrow strip of land in immediate contact with the sea, whilst, the shoreline is the intersection of a specified plane of water with the shore (U.S. Army Corps Engineers, 2002). Factors such as global climate changes that cause sea level changes, storm surges or tsunamis could trigger changes to a shoreline that is not protected. Also, waves especially are the element in determining the geometry and

composition of beaches. These waves, in combination with currents, tides and storm surges, are the main cause of coastal erosion problems; therefore, they significantly influence the planning and design of shore protection measures, coastal structures and waterways. The selection of structures to be used to protect the shoreline would depend on the wave characteristics and the morphology of the coastal region. Sheltering the harbour basins and harbour entrances against waves require the deployment of breakwaters.

Breakwaters can be installed shore-connected or detached. The setting up can be submerged or emerged and the position can be alongshore or oblique. According to Black and Mead (2000), submerged breakwaters have been the preferable choice over other coastal protection structures such as rubble-mound breakwaters or vertical wall breakwaters, to protect shorelines due to their low environmental impact. In the case of the sheltering of partially enclosed water bodies, submerged permeable type of structures acting as wave barriers were more favourable. These structures were considered popular alternatives in solving coastal engineering problems. Their submergence below the surface will not generally produce total reflection from the structure itself. Moreover, being porous or perforated they function to dissipate wave energy that passes through the structure and also control water tranquility conditions. And in this case, according to Pilarczyk (2003), large structures such as rubblemound breakwaters may not be the right choice. In this situation of controlling wave disturbances in partially enclosed water bodies, submerged permeable breakwaters are more preferred (Rao *et al.*, 1999).

With regard to laboratory experiments on perforated breakwaters, many related researches have been carried out since the mid 60's. One of them namely, the perforated pile breakwater has been considered as an alternative to obtain the needed tranquil water conditions in a harbour and to facilitate the exchange of water into and out of the harbour. A substantial amount of works on non-perforated pile breakwaters have been carried out by various researchers. They include Hayashi *et al.* (1966), Rao *et al.* (1999), Costello (1952), Nagai (1966), Van Weele and Herbich (1972), Khader and Rai (1981) and Mani and Pranesh (1986). Many of the above researchers mainly conducted laboratory investigations on the hydraulic performance of non-perforated pile breakwaters to attenuate waves. Results generated by their research works focused on evaluating wave transmission characteristics.

However, in later years an investigation on perforations effect on loss coefficient has been done by Rao *et al.* (2003) on single row suspended perforated pipe breakwaters. Their study reported that an increased in percentage of perforations from 0% to 25% has resulted in increment in loss coefficient from 0.7154 to 0.8385 or about 10% to 15%. Apart from pile breakwaters, other types of submerged breakwaters such as the vertical thin barriers by Wiegel (1961), vertical slotted walls by Grüne and Kohlhasse (1974),

vertical slit type breakwater by Kakuno (1983), and vertical and horizontal wave screens by Thomson (2000) have been used to test for wave attenuation characteristics.

In the literature, it was reported that porous submerged breakwaters have also been widely used as artificial reefs and mitigating measures for shore protection (Armono and Hall, 2000). The first parameter that was considered when investigating the performance of a porous submerged breakwater was the porosity; Dick and Brebner (1968) claimed that a porous submerged breakwater transmits less wave energy than a solid one over a certain frequency range (Twu *et al.*, 2001). Several types of porous structures have been investigated both theoretically and experimentally, namely the rubble mound breakwater type (Losada *et al.*, 1996) and submerged wave filter systems by Clauss and Habel (1999). Hattori (1972) conducted research on perforated wall and concluded that wave attenuation depended on three elements, namely the ratio of wall thickness, hole diameter and the porosity of the wall.

Losada *et al.* (1997) in his study on submerged porous step breakwater (rectangular shape wood block) with porosities ranging between 0.521 and 0.62 reported that transmission was highly dependent upon porous material characteristics. The reduction of wave transmission decreased dramatically when porosity increased and vice versa. Clauss and Habel (1999) reported that if the porosity of the submerged structure was higher than 50%, nearly no reduction of wave height and energy was achieved. Wave transmission reduced to 26% when porosity was 5% and structure height at about 100% water depth. Thomson (2000) in his report used four different porosities in his wave screens; 0.2, 0.3, 0.4 and 0.5. He concluded that the transmission coefficient value, K_t , decreased as the porosity decreases. He recommended that the screen porosity be lowered by 20%, the ratio of b/t (where b was the width of individual screen slats, t was the thickness of slat) values be other than 2 and when using triple screens systems to utilize different gap spaces and porosities. Twu *et al.* (2001) reported that porosity affected the transmission coefficient particularly for thick (wide) structures. The larger porosity value would result in smaller transmission coefficient. This was because a structure with larger porosity would allow more wave energy to be dissipated when penetrating the structure before the waves finally passed through.

Rao *et al.* (1999) and Hayashi *et al.* (1966) reported that Wiegel (1961) provided results for transmission through vertical cylinder breakwaters. Thomson (2000) in his study reported that Hartmann (1969) used a wire mesh structure to dissipate wave energy. He showed that wave transmission was a function of wave steepness and porosity. Dattari *et al.* (1978) also experimentally studied porosity effect on wave transmission over permeable submerged breakwaters. However, the porosity was confined to a small range, namely, 0.35 to 0.42 and showed no significant effect on transmission coefficient. Ting *et al.* (2004) when using a frame-type rectangular structure, examined porosity ranging from 0.421 to 0.912. They reported that the breakwater porosity markedly affect the wave transmission coefficient. Their research observed that wave energy loss

decreased for the porosity above 0.75. Thus, they concluded that less porous models corresponded to larger wave reflection and smaller wave transmission.

Rao *et al.* (1999) studied the performance of two rows perforated hollow piles with a porosity of 0.065. They found that the perforated pile attenuated more wave energy than non-perforated piles. He concluded that the influence of porosity remained uncertain. Therefore, he recommended that further investigations be carried out to study the influence of the porosity of submerged pile breakwater on wave transmission coefficient by using porosity value greater than 0.065. The study carried out on perforated breakwaters by Jaffar Sidek and Abdul Wahab (2007) showed the influence of porosity on wave transmission. Their test on model porosities 0.40, 0.60 and 0.80 indicated a variance of K_r . Their investigations found that K_r increased from 0.60 to 0.71 when the porosity increased from 0.60 to 0.80 respectively.

The goal of the study described herein was to measure simultaneously, on a perforated pile structure, wave transmission for varied wave frequencies, water levels, structure porosity and configurations.

2.0 Test Setup

An experiment consisting of an extensive series of small scale physical model test was conducted at the Coastal and Offshore Engineering Institute (COEI) of Universiti Teknologi Malaysia International Campus (UTM). The experiments were performed in a wave flume with dimensions 18 m (length) x 0.95 m (width) x 0.9 m (height). Both sides of the wall boundary were encased by 5 mm thick glass and 5 mm thick plastic perspex panels fixed in steel frames. In order to reduce wave reflection, an L-shaped steel bar-screen was used to act as a wave absorber at one end of the flume. To generate waves, a piston wave generator was used. The test structure section was installed in the channel about 10.0 m from the wave generator board. A typical set-up of the flume layout and wave probe arrangement is shown in Figure 1 and Figure 2, respectively. Five capacitance-type wave probes were used to measure waves at various points along the channel. The distance of the wave gauge is shown in Figure 3.

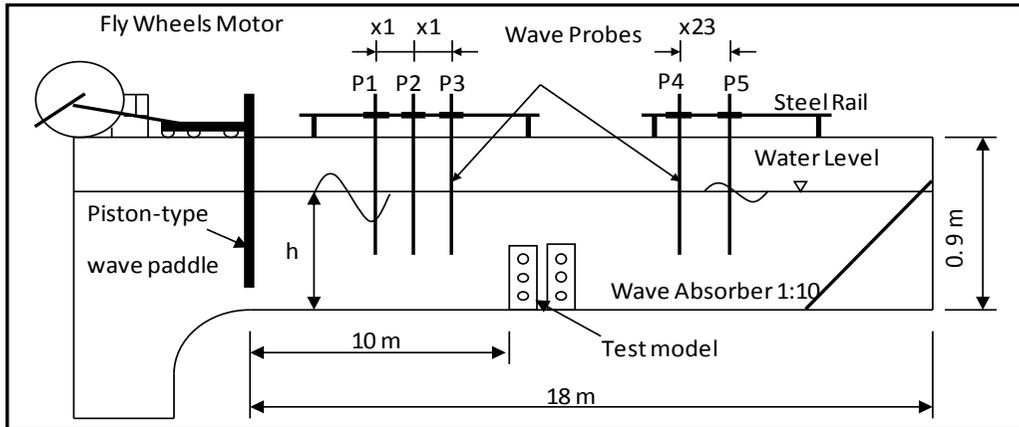


Figure 1: A schematic layout of the wave flume



Figure 2: Wave probe arrangement

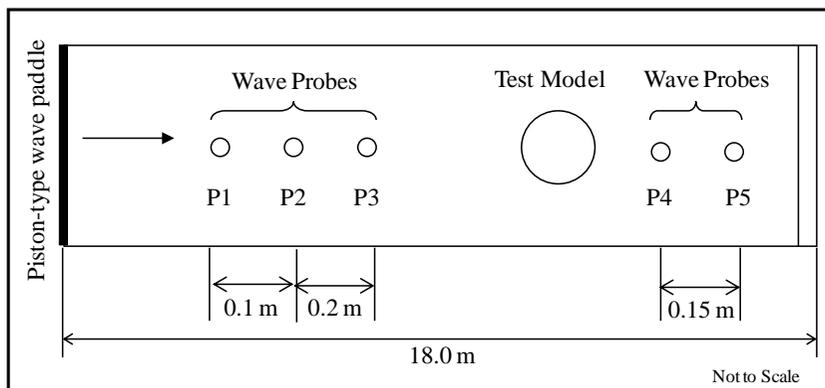


Figure 3: Distance between wave gauges

The pile model structures known as Double Ring Pile (DP) were constructed from PVC pipes of 250 mm height (d). Four different porosities were tested, $\varepsilon = 0.0625, 0.14, 0.28$ and 0.48 with outer pile diameter D being 200 mm and inner pile diameter $D' = 100$ mm, as shown in Figure 4 and a sketch of the model is illustrated in Figure 5. Figure 6 shows a typical layout of the two rows DP model arrangement used throughout the experiments.

Prior to conducting the experiments, each wave probe was calibrated. Incident and reflected waves were resolved using a linear wave theory by Mansard and Funke (1980). Wave trains were generated using different wave heights, wave periods and water depths combinations. The test program along with the range of parameters tested is shown in Table 1. Wave periods were selected from 0.85 s to 1.18 s and the experiments were conducted under no-breaking wave conditions. Five water depths were used in the experiments, namely, $h = 0.19$ m, 0.23 m, 0.27 m, 0.30 m and 0.35 m.

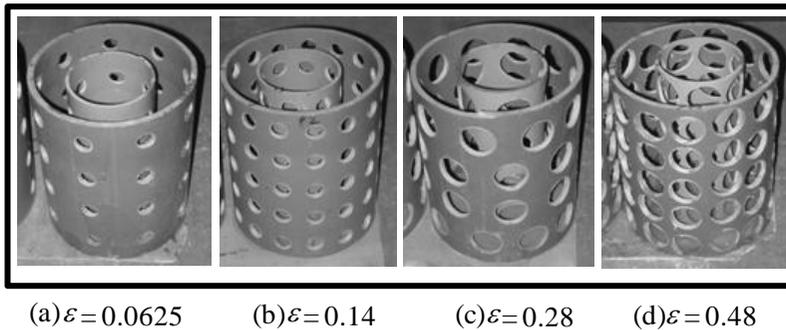


Figure 4: Double Ring Pile (DP) model with various porosities, ε

A total of 320 runs were carried out in the test series altogether. The mean transmitted wave height was determined by taking an average of at least 5 wave heights in the wave train of each individual wave periods.

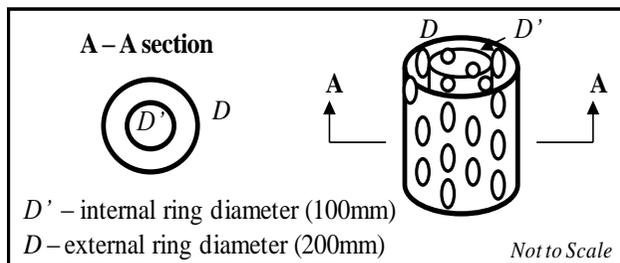


Figure 5: A sketch of the Double Ring Pile (DP) test model

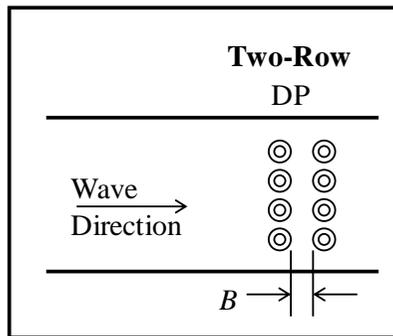


Figure 6: Typical layout of two-rows DP model arrangement

Table 1: Summary of test conditions for wave transmission measurements of two-row DP models

Geometry of Test Models		Hydraulic Parameters	
Porosity, ε	Spacing between rows, B	Water depth, h (m)	Wave period, T (s)
0.0625	0D, 0.5D, 0.75D	0.19	0.85, 0.90, 0.96, 1.03, 1.12, 1.18,
0.14		0.23	
0.28		0.27	
0.48		0.30	
		0.35	

3.0 Analysis of wave transmission

There are three main phenomena observed when a wave strikes the pile test model namely, wave transmission, wave reflection and loss of energy. The transmitted wave energies are described by general energy balance as given in the following equations:

$$E_i = E_r + E_t + E_l \quad (1)$$

where, E_i = Incident energy (kN/m^2)
 E_r = Reflected energy (kN/m^2)
 E_t = Transmitted energy (kN/m^2)
 E_l = Dissipated energy (kN/m^2), and

$$(\rho g H^2)_i / 8 = (\rho g H^2)_r / 8 + (\rho g H^2)_t / 8 + (\rho g H^2)_l / 8 \quad (2)$$

Since the density of water (ρ) and the acceleration due to gravity (g) is constant,

$$H_i^2 = H_r^2 + H_t^2 + H_l^2 \quad (3)$$

where, H_i = incident wave height (m)
 H_t = transmitted wave height (m)
 H_r = reflected wave height (m)
 H_l = dissipated wave height (m)

The equation can be redefined in terms of coefficients:

$$\begin{aligned} 1 &= (H_r/H_i)^2 + (H_t/H_i)^2 + (H_l/H_i)^2 \\ &= K_r^2 + K_t^2 + K_l^2 \end{aligned} \quad (4)$$

where K_l is the loss coefficient, K_r is the reflection coefficient and K_t is the transmission coefficient.

Equation 4 can also be written as:

$$K_t = (1 - K_r^2 - K_l^2)^{0.5} \quad (5)$$

in which the transmission coefficient K_t can be expressed in terms of;

$$K_t = H_t/H_i \quad (6)$$

In the present paper, the results of the experimental investigations on two-row double ring pile are presented. Using the values of transmission coefficients computed for different cases and different pile configurations, the influence of the wave parameters are shown in graphical form and conclusions have been drawn by analyzing the graphs. An empirical equations derived based on multiple regression analyses were also developed.

3.1 Effects of relative depth (h/L)

To represent the influence of water depth on K_t for constant porosity ε , graphs of h/L against K_t have been plotted. From Figure 7, the plot shows that as depth of water increases the higher the wave transmission especially at lower relative depth (h/L range between 0.1 and 0.15). In this experiment, the height of the structure d is 0.25 m and the structure is considered fully submerged when water depth $h \geq 0.35$ m. Thus in its fully submerged state where $h \geq 0.35$ m (i.e. $h/d > 1.0$), overtopping occurs, more energy is transmitted and hence lower energy losses.

The plot also indicates that the fully submerged state shows higher wave transmissions than the partially submerged ($h \leq 0.27$ m). Thus, this indicate that partially submerged

conditions are better in attenuating waves than the fully submerged conditions. However, in terms of relative depth, as h/L increased from 0.2 to 0.35, the difference in wave transmission magnitude at given water depth is insignificant. Thus, this shows that the wave energy is effectively attenuated at longer waves (low frequency) compared to shorter wave length (high frequency) at a given water depth.

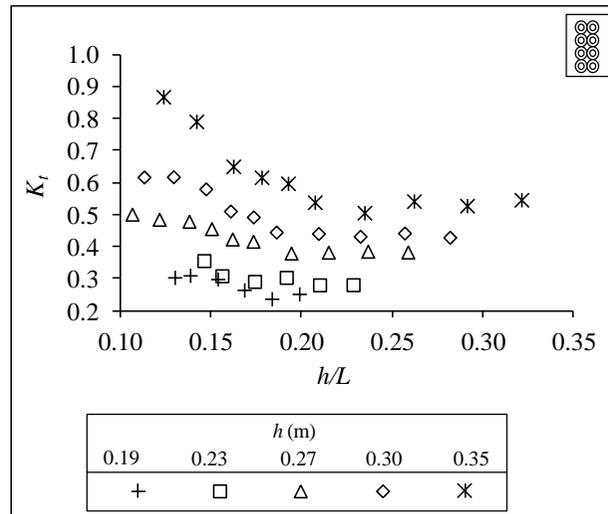


Figure 7: Influence of h on K_t at spacing $B = 0$ for porosity $\varepsilon = 0.0625$

3.2 Effects of wave steepness (H/L)

The wave steepness ranges from 0.008 to 0.037. In the present investigations, for all the experiments the wave steepness is taken from 0.008 to 0.04. Figures 8 and 9 show the plots of measured K_t versus wave steepness H/L at two different spacing (B) considered. The models were tested under wave length ranging from 0.96 m to 1.58 m.

The curve shows that as wave steepness increased, K_t decreased. As steeper waves impinged on the test model's surface at a larger frequency, greater reflection and thus lower transmission resulted. When the waves pass through the models, they created larger vortices on the leeward side of the model hence resulting in greater energy dissipation.

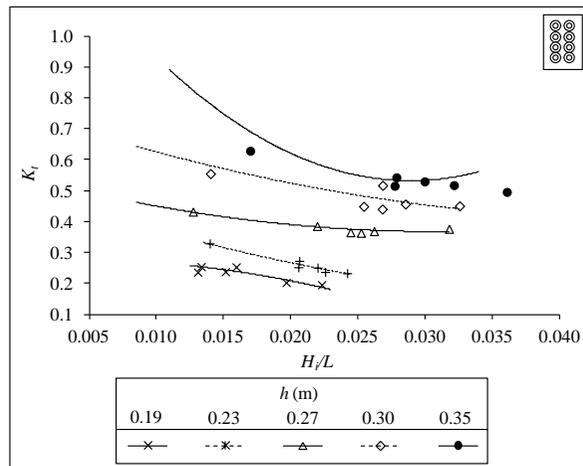


Figure 8: Influence of H_i/L on K_t at spacing $B = 0.5D$ for porosity $\varepsilon = 0.0625$

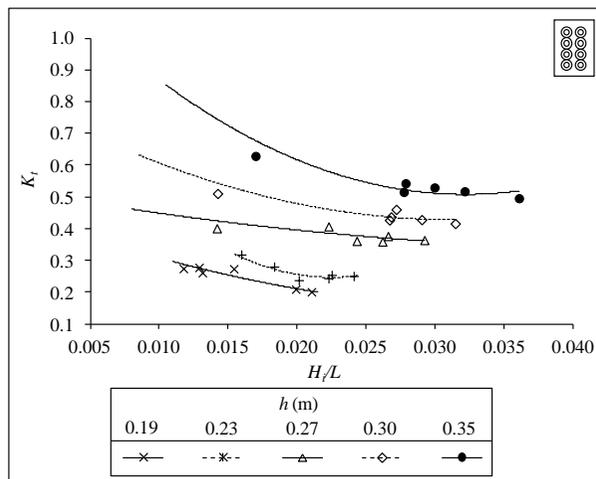


Figure 9: Influence of H_i/L on K_t at spacing $B = 0.75D$ for porosity $\varepsilon = 0.0625$

3.3 Effect of porosity, ε

For studying the effect of perforations on wave transmissions, plots of H_i/L against K_t were drawn with the perforations as a third variable. Here the performance of perforated piles with different porosities was compared. From Figure 10, it can be clearly noted that at higher wave steepness more porous pile caused more wave transmission. It shows that as the perforation increases from 0.0625 to 0.48, wave transmission increases from 0.29 to 0.69 at H_i/L range between 0.012 and 0.026. Hence, there is an increase in transmission coefficient of the order of 30% to 35%.

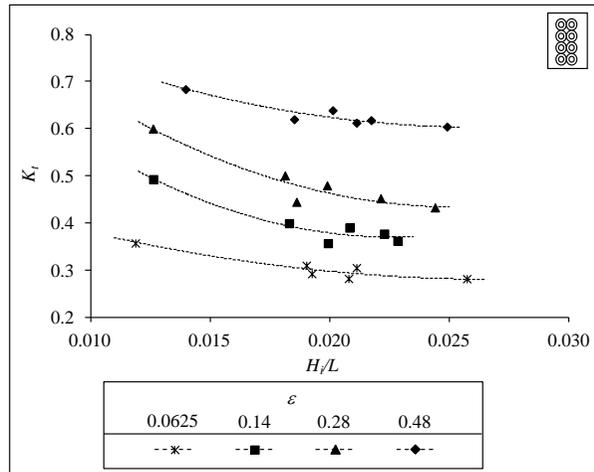


Figure 10: Influence of porosity ε on K_t at spacing $B = 0$ for $h = 0.23$ m

3.4 Effect of relative spacing B/L

Figures 11 to 14 illustrate the effect of relative spacing B/L on wave transmission under various water depth conditions. From observations of K_t results, the plots shown in Figures 11 to 14 indicated that as the relative spacing B/L increased, wave transmission coefficient K_t decreased but the reduction of K_t is less significant in higher wave frequency (shorter wave period). Thus, the influence of relative spacing, B/L on wave transmission K_t is more when $T > 1.03$ s or B/L between range 0.03 and 0.07 especially for $B = 0.5D$. However, for spacing $B = 0.75D$ the influence of B/L on K_t is significance when B/L between range 0.05 and 0.10.

The effect analyses on individual test model with different spacing indicated not so clearly the influence of B/L on K_t . Thus, by comparing both the spacing of the 0.48 test model porosity the influence of B/L on K_t is significant (shown in Figure 15). The spacing between the rows of tested models has been found to be an important parameter in attenuating waves. The test models with model spacing $B = 0.5D$ provides higher K_t compared to the $B = 0.75D$ system. This observation can be explained by the fact that larger T produces longer waves (lower B/L , 0.03 – 0.07) and spans to a considerable portion of wave length, thus allowing the two test models to act as a continuous structure functioning like a single unit than when they were smaller spaced ($B = 0.5D$). Whereas, for smaller T , a shorter wave length is produced ($B/L > 0.07$), thus the test models with wider spacing tended to act independently to perform as two separate wave attenuators in series.

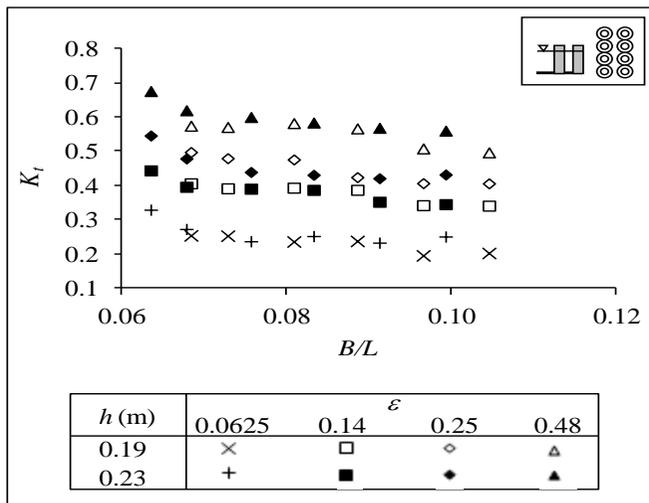


Figure 11: Influence of model spacing $B = 0.5D$ on K_t at water depths $h = 0.19$ m and 0.23 m.

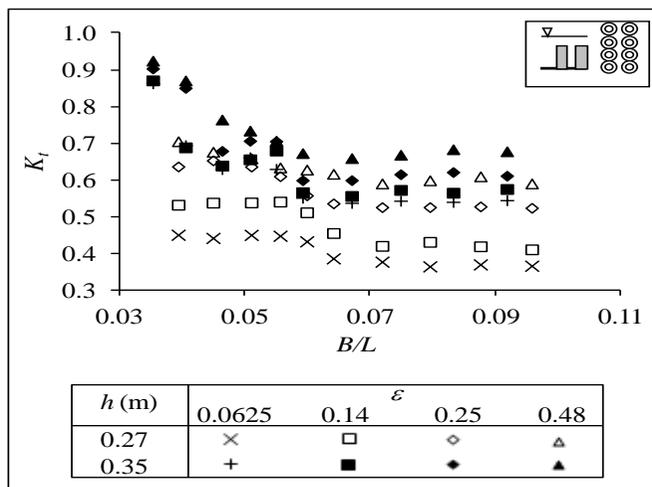


Figure 12: Influence of model spacing $B = 0.5D$ on K_t at water depths $h = 0.27$ m and 0.35 m.

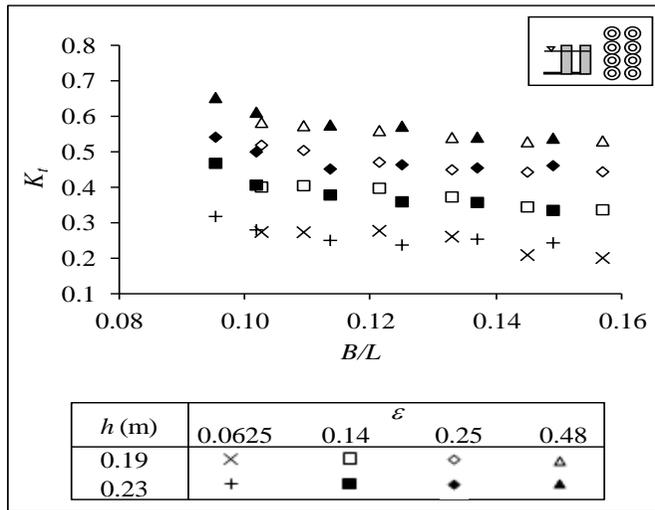


Figure 13: Influence of model spacing $B = 0.75D$ on K_t at water depths $h = 0.19$ m and 0.23 m.

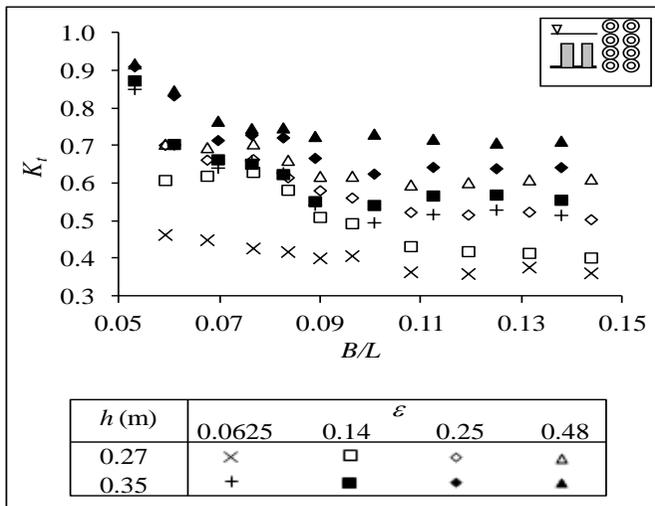


Figure 14: Influence of model spacing $B = 0.75D$ on K_t at water depths $h = 0.27$ m and 0.35 m.

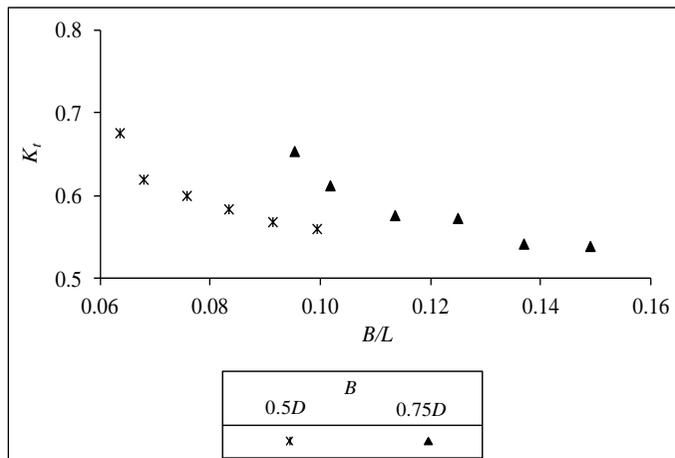


Figure 15: Influence of model spacing B on K_t at water depths $h = 0.23$ m and porosity $\varepsilon = 0.48$

4.0 Effect of Model Width, W

Apart from different spacing between pile rows, another factor considered in the present investigations was the width of model, W , i.e. width of two-row DP model, equivalent to twice the test model diameter ($W = 2D$). Figure 16 shows the K_t for a one, two and three-row model in relation to H/L . It was observed that to some extent the wider the width of the DP model, the better it performed to attenuate waves. The plots show good performance of the DP model to attenuate waves with one-row and two-row test models but much less influence was noted as the model rows increased to the three-row arrangements. In general, it can be concluded that the DP model with increased number of rows from one to two would show better wave attenuation characteristics that is, K_t decreased by 15% to 20% at H/L ranging between 0.015 -0.02, when compared with the three-rows model where K_t decreased by 7% to 10% at a similar range of H/L . Hence, in the derivation of the equation for K_t the parameter W has been excluded since W played an insignificant role in wave transmission.

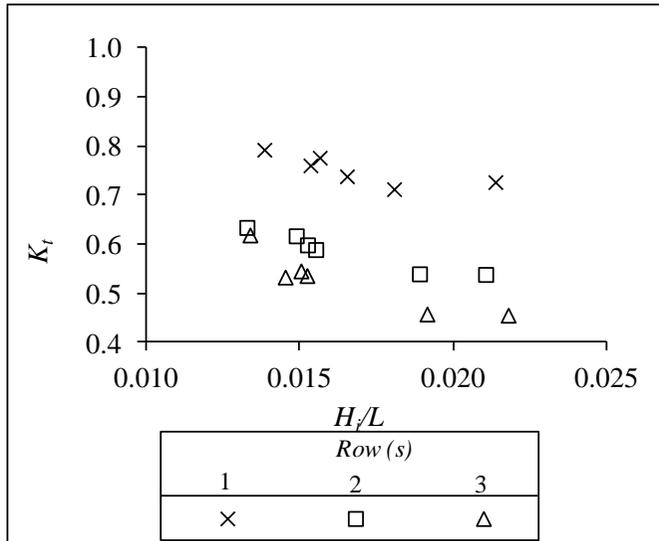


Figure 16: Influence of numbers of rows of model on K_t at water depths $h = 0.23$ m and porosity $\varepsilon = 0.48$

5.0 Comparison with other studies

Comparison of the results from the present investigation was made with the results obtained by Ting *et al.* (2004) and also Truitt and Herbich (1987). The plots in Figure 17 show that output from the present investigations are seen to be in reasonably good agreement with findings by other researchers whereby similarity has been observed in the trend of the curves yielded.

The graph illustrated in Figure 17 reveals that the relationship between K_t versus h/L achieved from the experiment conformed with studies carried out by other researchers. The results of the experiments concluded that K_t decreases proportionately with increased relative depth. This is due to less wave energy being dissipated in longer waves compared to waves with shorter wave length irrespective of the water depth.

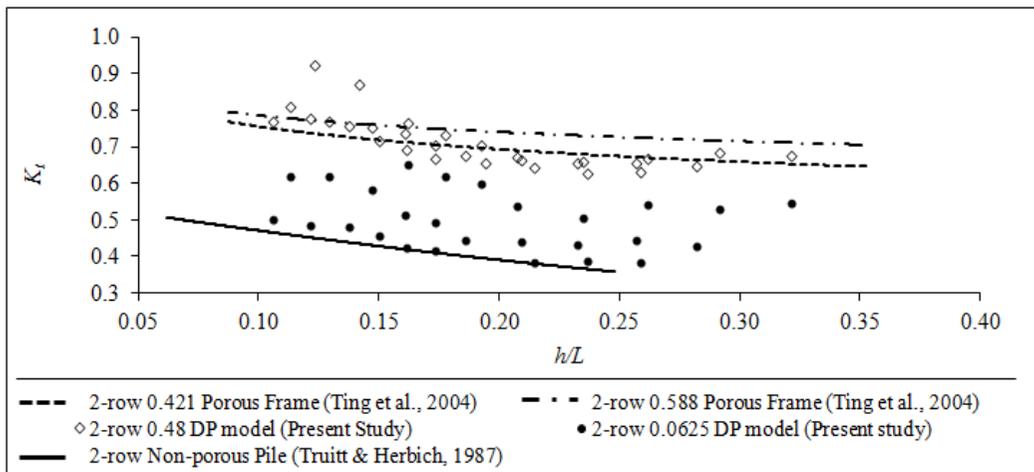


Figure 17 : Comparison of wave transmission coefficient obtained from the present investigations with values from works by other researchers

6.0 Analytical functions

A commercial statistical software package, SPSS Clementine Client V10.1 for Windows (SPSS Inc., 2006) has been used to speed up analytical and equation derivation process. The statistical analyses were performed to develop the simplest and most viable equation to aid in the evaluation of a practical DP test model design. Multiple linear regression analysis was used to model the relationship of the independent non-dimensional variable with the dependent variable K_t . Equation 8 illustrates that each of the predictor terms have a linear relationship with dependent variable K_t as given below:

$$K_t = a_0 + a_1(H/L) + a_2(h/L)^2 + a_3(B/L) + a_4\varepsilon \quad (8)$$

where h/L , H/L , B/L and ε are the independent non-dimensional variables.

The developed empirical equations to predict the wave transmission for the DP test model are given in Tables 2 and 3.

Table 2 : Summary of Equations Derived for the DP Models for $h \leq 0.23 m$

Equations	
Without Spacing ($B/D \approx 0$)	$K_t = 0.473 - 5.116(H_i/L) + 1.244(h/L) - 1.007(B/L) + 0.724\varepsilon$
With Spacing ($B/D > 0.1$)	$K_t = 0.389 - 2.678(H_i/L) - 0.380(h/L) - 0.281(B/L) + 0.715\varepsilon$

Table 3 : Summary of Equations Derived for the DP Models for $h > 0.23 m$

Equations	
Without Spacing ($B/D \approx 0$)	$K_t = 0.655 - 3.326(H_i/L) + 2.302(h/L) - 2.194(B/L) + 0.517\varepsilon$
With Spacing ($B/D > 0.1$)	$K_t = 0.607 - 3.479(H_i/L) + 0.294(h/L) - 1.315(B/L) + 0.448\varepsilon$

7.0 Conclusions

The size of perforations of the test models has been found to have a significant effect on wave transmission. The increase in the coefficient of wave transmission, K_t for the porous pile means that more energy is allowed to penetrate through the pile resulting in the increased height of the transmitted wave. A porosity value of $\varepsilon = 0.48$ was found to indicate the highest wave transmission characteristics.

The height of transmitted wave was also governed by water depth and wave steepness. The wave transmission coefficient was found to increase with the increment of water depth. With increasing wave steepness, the wave transmission tended to decrease for a given water depth for all porosity values tested.

The increase in spacing (B) resulted in a decrease in wave transmission. Thus, this indicated that model spacing B has an influence on wave transmission coefficient. However, the effect of the number of rows is significant only when the rows were increased from one to two-rows which resulted in higher wave energy being dissipated. However the increase of an additional row as illustrated by the three-row model showed a lesser reduction of wave energy dissipation compared with the two-row model. Thus the increase in the number of rows W to attenuate waves was shown to be insignificant. Hence, the equations derived for K_t as summarised in Tables 2 and 3 have been generated based on four variables namely h/L , H_i/L , B/L and ε .

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References

- Armono, H. D. and Hall, K. R. (2000). Wave Transmission on Submerged Breakwaters Made of Hollow Hemispherical Shape Artificial Reefs. *Canadian Coastal Conf.* Victoria, Canada. 1-13.
- Black, K., and Mead, S. (2000) Submerged Structures for Coastal Protection: A short summary of what they were, why we need them and how they work. *Summary Report*, ASR Ltd., Hamilton, New Zealand, pp. 1-7.
- Clauss, G. F., and Habel, R. (1999) Hydrodynamic Characteristics of Underwater Filter Systems for Coastal Protection. *Canadian Coastal Conf. 1999*, Victoria, Canada, pp. 139-154.
- Costello, R.D. (1952) Damping of Water Waves by Vertical Circular Cylinders. *Trans. Am. Geophys. Union* 33 (4), pp. 513-519.
- Dattari, J., Rahman, H., and Shakar, N. J. (1978) Performance Characteristics of Submerged Breakwaters. *Proc. 16th Coastal Eng. Int. Conf.*, ASCE, New York, N. Y., pp. 2152-2171.
- Dick, T. M., and Brebner, A. (1968) Solid and Permeable Submerged. *Proc. 11th Int. Conf. on Coastal Eng.* 1968: pp. 1141-1158.
- Grüne, J. and Kohlase, J. (1974) Wave Transmission through Vertical Slotted Walls. *Proc. 14th Coastal Eng. Conf.*, Copenhagen, Denmark. ASCE, New York, N. Y., pp. 1906-1923.
- Hartmann (1969) Das Stabgitter in Instationärer Stromungsbewegung. *Mitt. Des Instituts für Wasserbau und Wasserwirtschaft*, TU Berlin, Heft 69.
- Hayashi, T., Hattori, M., and Kano, T., and Shirai, M. (1966) Hydraulic Research on the Closely Spaced Pile Breakwaters. *Coastal Engineering in Japan*, Vol. 9, 1966, pp. 107 – 117.
- Hattori, M. (1972) Transmission of Water Waves through Perforated Wall. *Coastal Engineering in Japan*, Vol. 15, 1972, pp. 69 – 79.
- Jaffar Sidek, F., and Abdul Wahab, M. A. (2007) The Effect of Porosity of Submerged Breakwater Structures on Non-Breaking Wave Transformations. *Malaysian Journal of Civil Engineering*. 19(1), pp. 17-25.
- Kakuno, S. (1983) Reflection and Transmission of Waves Through Vertical Slit Type Structures. *Proceedings of a specialty conference on the Design, Construction and Maintenance and Performance of Coastal Structures*. Virginia, pp.939-952.
- Khader, M. H. A., and Rai, S. P. (1981) Wave Attenuation due to Closely Spaced Circular Cylinders. *International Association for Hydraulic Research XIX Congress*, New Delhi, India, pp.95-102.
- Losada, I. J., Silva, R., and Losada, M. A. (1996) 3-D Non-breaking Wave Interaction with Submerged Breakwaters. *Coastal Engineering* 28, pp.229-248.
- Losada, I. J., Patterson, M. D., and Losada, M. A. (1997) Harmonic Generation past a Submerged Porous Step. *Coastal Eng.* 31, pp.281-304.

- Mani, J. S., and Pranesh, M. R. (1986) Pile Breakwater Floating Barrier Interaction. *Proc. 3rd Indian National Conf. on Ocean Eng.*, Dept. of Civil Engineering, IIT, Bombay, India, pp. B217-B228.
- Mansard, E. P. D., and Funke, E. R. (1980) The Measurement of Incident and Reflected Spectra Using a Least Square Method. *Proc. 17th Coastal Eng. Conf.*, Sydney, Australia, vol. 1, pp. 154-172.
- Nagai, S. (1966) Research on Steel Pile Breakwaters. *Proc. 10th Coastal Eng. Conf.*, Tokyo, Japan., ASCE, New York, N. Y., pp. 850-872.
- Pilarczyk K. W. (2003) Design of low-crested (submerged) structures. *Proceedings of the 6th International Conference on Coastal and Port Engineering in Developing Countries*, Colombo, Sri Lanka, pp 1-19.
- Rao, Rao, N. B. S., Sathyanarayana, V. S. (1999). Laboratory Investigation on Wave Transmission through Two Rows of Perforated Hollow Piles. *Ocean Eng.* 26, pp. 675-699.
- Rao, S., and Rao, N. B. S. (2003). Energy Dissipation at Single Row of Suspended Perforated Pipes Breakwaters. *Journal of the Institution of Engineers (I)*, pt CV, vol. 84, pp. 77-81.
- Thomson, G. G. (2000) Wave Transmission through Multi-layered Wave Screens. Master Dissertation, Dept. of Civil Eng., Queen's University, Kingston, Ontario, Canada.
- Ting, C. H., Lin, M. C., and Cheng, C.Y. (2004) Porosity Effects on Non-breaking Surface Waves over Permeable Submerged Breakwaters. *Coastal Engineering* 50, pp. 213-224.
- Truitt, C. L., and Herbich, J. B. (1987). Transmission of Random Waves Through Pile Breakwaters. *Proc. 20th Coastal Engineering Conference*, ASCE. 3(169). 2303-2313.
- Twu, S-W., Liu, C-C., and Hsu, W-H. (2001) Wave Damping Characteristics of Deeply Submerged Breakwaters. *Journal of Waterways, Port, Coastal and Ocean Eng.*, 127 (2), pp. 97-105.
- U.S. Army Corps of Engineers (2002). *Coastal Engineering Manual* (CEM). Vicksburg, Mississippi. EM 1110-2-1100.
- Van Weele, J., and Herbich, J. B. (1972) Wave Reflection and Transmission for Pile Arrays. *Proc. 13th Coastal Eng. Conf.*, Vancouver, B. C., Canada. ASCE. New York, N. Y., pp. 1935-1953.
- Wiegel, R. L. (1961) Closely Spaced Piles as a Breakwater. *Dock and Harbour Authority*, Vol. 41, No. 491.