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THE USE OF PERFORATED PILE BEAKWATERS TO ATTENUATE WAVES

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Abstract: A laboratory investigation was conducted to compare the transmission characteristics of one-row and two-row submerged perforated pile breakwater models. The laboratory tests were conducted in unidirectional waves with different wave conditions and pile porosity that varied from 0.0625 to 0.48. The influences of water depth, incident wave steepness and porosities were studied. From the experimental results obtained, it was found that when the number of rows tested was increased, more wave energy was dissipated. This resulted in the decrease in transmitted wave heights. When the pile porosity was increased, less wave energy was attenuated, resulting in higher wave transmission coefficient, K_t and the transmission coefficient, K_t decreases as the wave steepness increases for all porosity values. It was also found that lower water depth has a significant influence on the transmission coefficient at higher wave steepness with K_t being less than 0.45 at a water depth below 0.23 m for partially submerged condition compared to K_t being more than 0.50 at water depth above 0.35 m for the submerged condition, for both the one-row and two-row piles respectively.

Keywords: *Perforated pile breakwater; Experimental investigation; Wave transmission; Wave attenuation; Porosity; Wave steepness*

1.0 Introduction

Preventing land erosion by wave attacks and minimizing their impacts on shorelines are important aspects to be considered in selecting proper and suitable defence structures. 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 they function to dissipate wave energy that passes through the structure.

Several types of submerged permeable structures have been tested and used by many researchers. 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 Kohlhase (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; ε. 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 to 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 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 indicates a variance of K_t. Their investigations found that K_t increased from 0.60 to 0.71 when the porosity increased from 0.60 to 0.80 respectively.

Extensive experimental studies have been undertaken at the Coastal and Offshore Engineering Institute (COEI) of Universiti Teknologi Malaysia International Campus (UTM) to evaluate the performance of a single ring perforated pile breakwaters to attenuate waves. The general responses to be expected when wave passes a pile breakwater is shown in Figure 1. Apart from water depth, h, incident wave height, H_i and porosity, ε are considered variables that have been shown to influence the magnitude of wave transmission. Figure 1 shows the incident wave, transmitted wave and reflected wave around the test model. These waves were varied accordingly in the test series in order to obtain an assessment of the efficiency of the porous breakwater to dissipate wave energy.

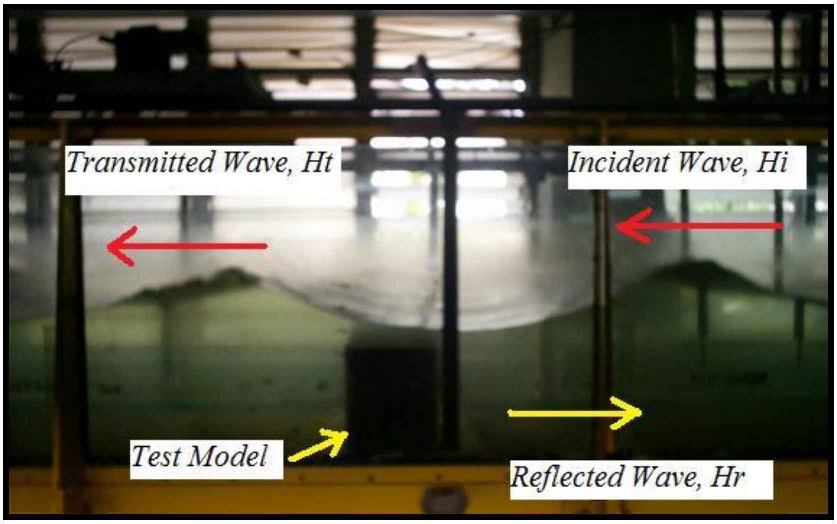


Figure 1: Laboratory test of SP model

2.0 Theoretical Considerations and Experimental Procedures

The experiments were conducted by generating regular waves in a two-dimensional wave flume available at COEI of UTM. The submerged single ring perforated pile 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. A typical set-up of the flume layout and wave probe arrangement is shown in Figure 2 and Figure 3, respectively.

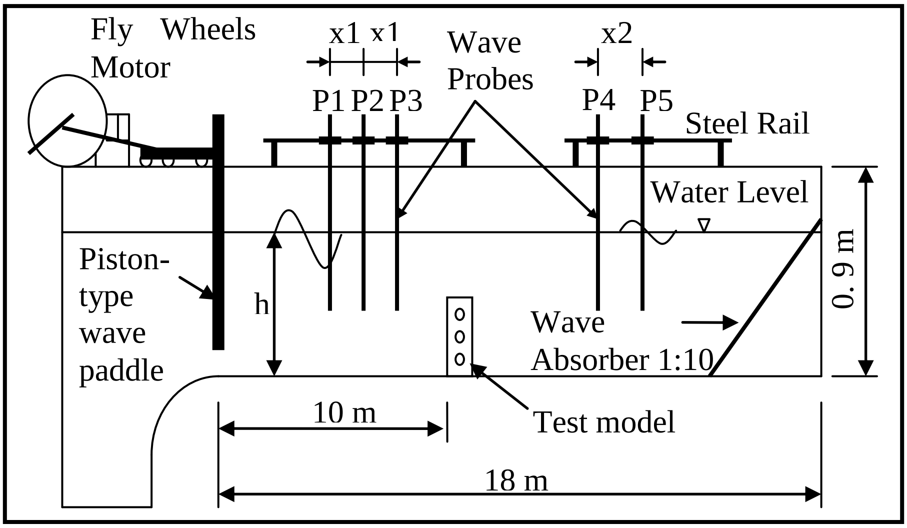


Figure 2 : A Schematic Layout of the Wave Flume

Figure 3 : Wave probe arrangement

The pile model structures known as Single Ring Pile (SP) were constructed from PVC pipes of 250 mm height. Four different porosities were tested, ε = 0.0625, 0.14, 0.28 and 0.48 with pile diameter D being 200 mm as shown in Figure 4. These piles were placed in the flume and glued to a base made of fiber glass and clamped down to the flume side wall so as to prevent any movement from wave action (Figure 5). Figure 6 illustrates a typical layout of the one row and two rows SP model arrangement used throughout the experiments.

(a) $\varepsilon = 0.0625$ (b) $\varepsilon = 0.14$ (c) $\varepsilon = 0.28$ (d) $\varepsilon = 0.48$

Figure 4 : Single Ring Pile (SP) Test Model with Various Porosities, ε

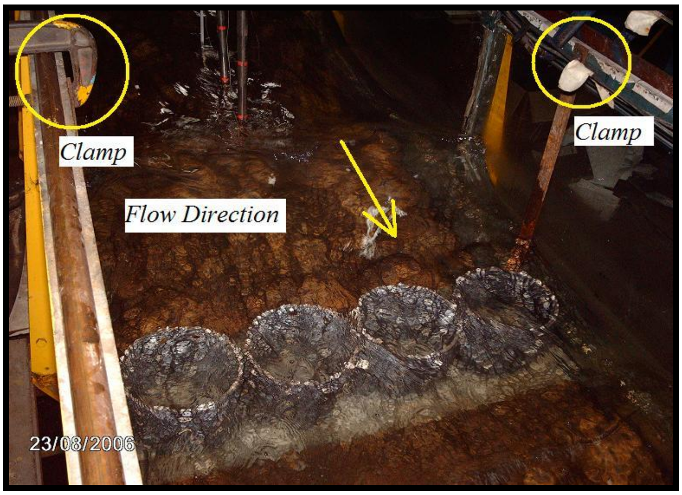


Figure 5 : SP test model installed in the flume

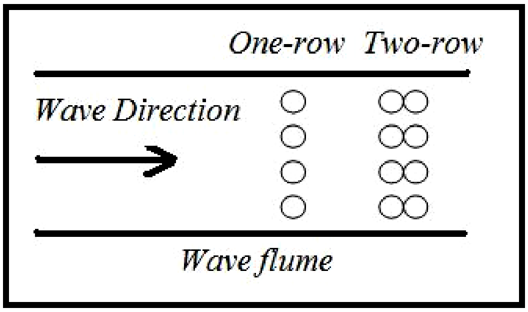


Figure 6 : Typical Layout of One-row and Two-rows SP Model Arrangement

Five capacitance-type wave probes were used to measure waves at various points along the channel. The wave probe applied system comprised a capacitance wave gauge, an electric amplifier, a DAS-800 cardboard and a DAS-801 electronic card. Prior to conducting the experiments, each wave probe was calibrated. Calibration of the probes was performed to determine the relationship between the output signal of the instrument and the value of the physical quantity being measured. The method of calculating the incident and reflected wave components is based on a linear wave theory by Mansard and Funke (1980). The probes were placed in two arrays, one array of two probes was set on the lee side of structure to measure the transmitted wave heights and the other array of three probes were positioned in front of the model to measure the incident and reflected wave heights. The location of wave probes is shown in Figure 2. Wave trains were generated using different wave heights, wave periods and water depths combinations.

A list of wave characteristics and experimental variables used in the experiment is shown in Table 1. Wave periods were selected from 0.85 s to 1.67 s and the experiments were conducted under no-breaking wave conditions. Two types of submergence conditions were used in the experiments, namely, partially (h = 0.19 m and 0.23 m) and fully (h = 0.27 m and 0.35 m) submerged conditions. 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.

Table 1: Dimensions of Test Models and Wave Characteristics

Geometry of Test Models		**Hydraulic Parameters**	
Nos. of row	Porosity, ε	Water depth, h (m)	Wave period, T (s)
1 2	0.0625 0.14 0.28 0.48	0.19 0.23 0.27 0.35	0.85 0.90 0.96 1.03 1.12 1.18 1.25 1.34 1.49 1.67

The expressions used to relate incident wave energy with the reflected, dissipated (if the percentage of energy dissipated by breaking and friction was taken into account) and transmitted wave energies were given by general energy balance as 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) was 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:

$$1 = (H_r/H_i)^2 + (H_t/H_i)^2 + (H_l/H_i)^2 = K_r^2 + K_t^2 + K_l^2 \quad (4)$$

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:

$$1 = (E_r/E_i)^2 + (E_t/E_i)^2 + (E_l/E_i)^2 = K_r^2 + K_t^2 + K_l^2$$

or

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

Therefore, the reflection coefficient K_r can be expressed in terms of;

$$K_r = H_r/H_i \quad (6)$$

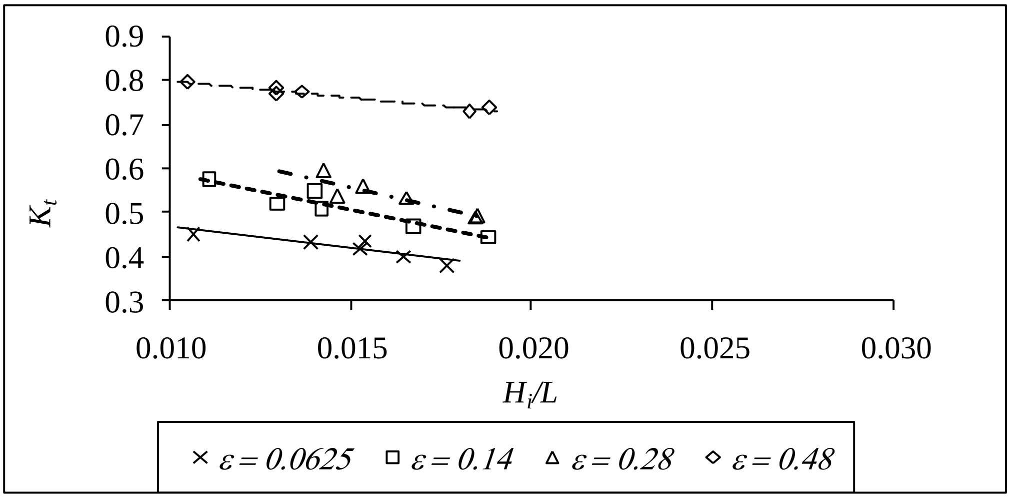
and since, H_t is transmitted wave height, thus the transmission coefficient can be expressed by;

$$K_t = H_t/H_i \quad (7)$$

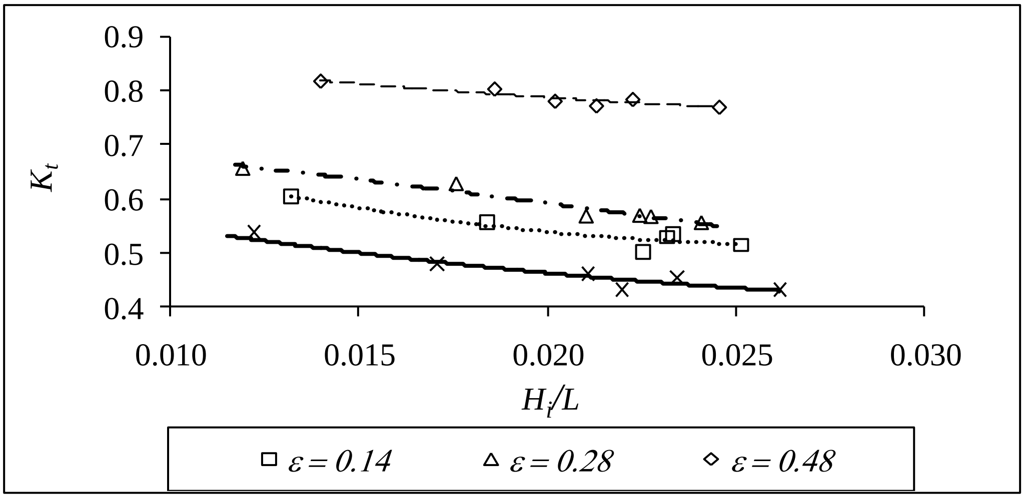
3.0 Results and discussion

The experimental data to evaluate the effect of porosity and characteristics of wave transmission for both the permeable submerged breakwater models in the one-row and two-row pile arrangements were presented herein in a graphical form (see Figure 7 to Figure 10). Figures 7 to 10 illustrate the experimental results obtained for wave transmission in partially (water depth, h = 0.19 m and

0.23 m) and fully submerged (water depth, h = 0.27 m and 0.35 m) conditions for both types of arrangements. The figures indicate the effect of wave steepness and porosities on wave transmission at various submergence depths.



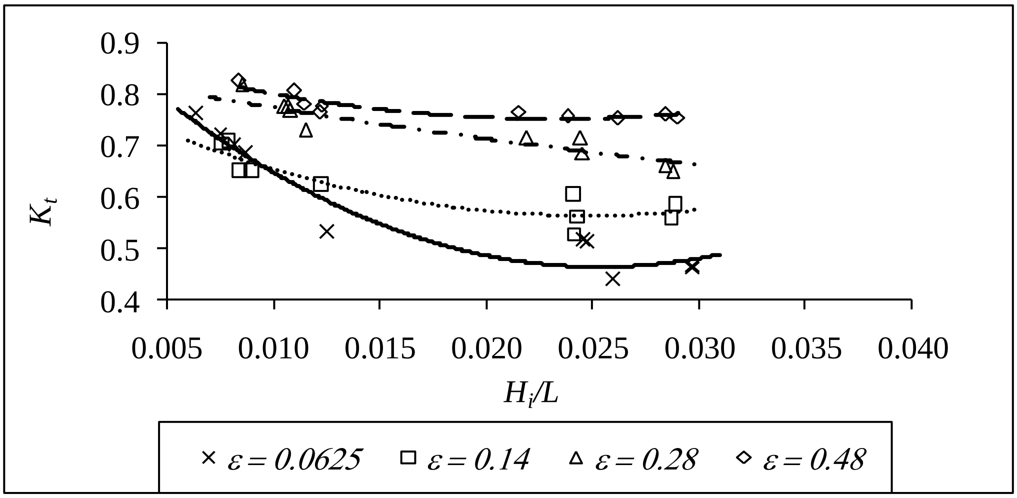
(a) Water depth, h = 0.19 m



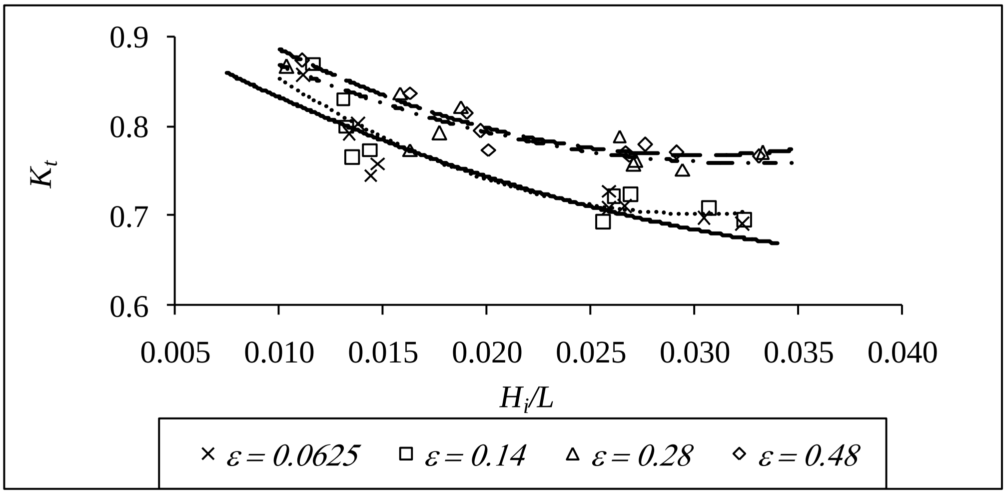
(b) Water depth, h = 0.23 m

Figure 7 : K_t vs. H_i/L for Various Porosities for the Partially Submerged One-row SP

As shown in Figures 7 to 10, the wave transmission magnitude becomes apparent as the porosity declines and higher porosity, ε = 0.48, results in higher K_t at lower wave steepness. Shorter wave period (wave period, T less than 1 s) will result in steeper waves and when the waves penetrate the tested model, it creates greater reflection and apparently will reduce wave transmission.



(a) Water depth, h = 0.27 m



(b) Water depth, h = 0.35 m

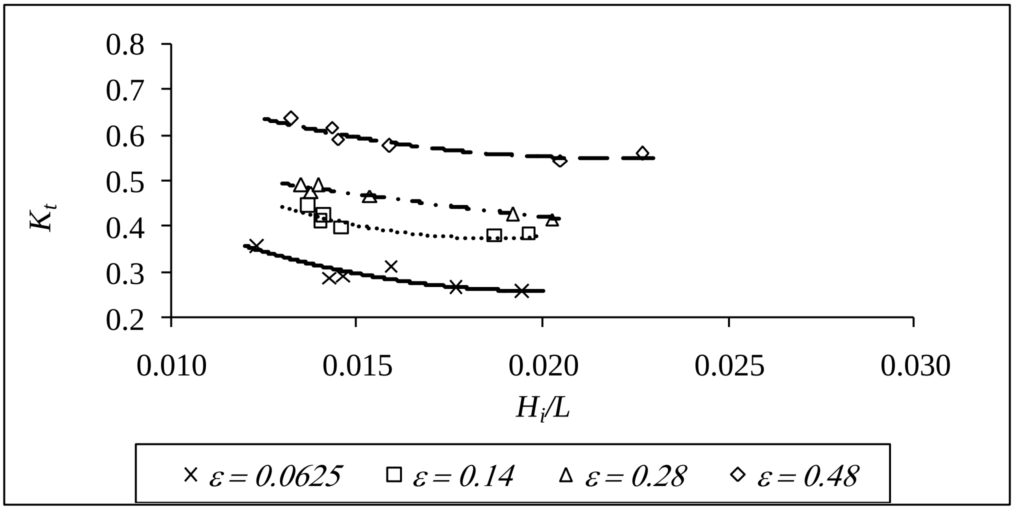
Figure 8 : K_t vs. H_i/L for Various Porosities for the Fully Submerged One-row SP

Furthermore, when steeper waves passed through the models, larger vortices on the leeward side were created due to a larger elevation head difference and flatter waves, resulting in greater energy dissipation. The effect of wave steepness was greater in partially submerged condition rather than fully submerged. This was due to more wave energy being dissipated when the water depth decreases and the effect on K_t was found to be greater as porosity decreases.

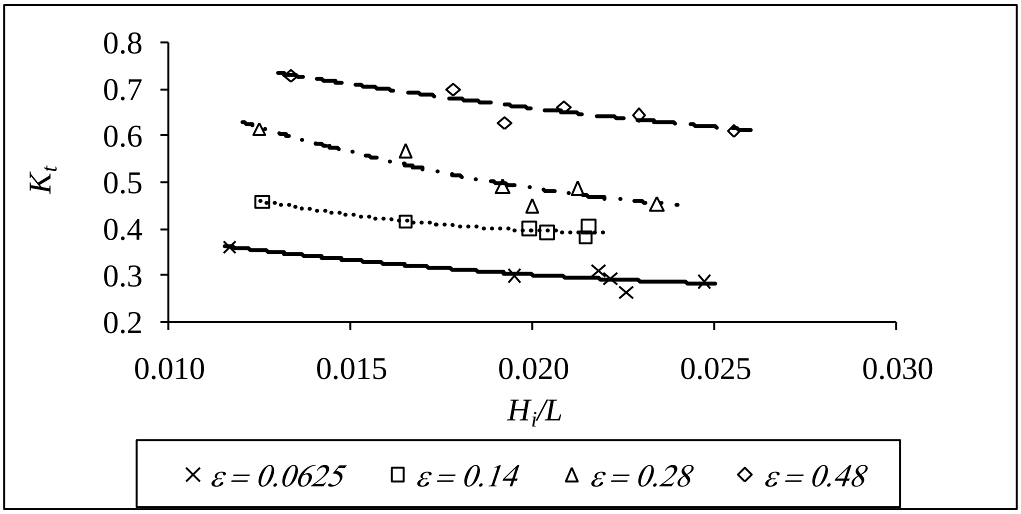
In Figure 7, when porosity of the model was 0.48 and H_i/L at 0.011 for h = 0.19 m and H_i/L at 0.014 for h = 0.23 m, K_t reached 0.79 and 0.82, respectively. Most K_t values for ε = 0.48 varied from 0.73 to 0.79 for h = 0.19 m, and varied from 0.77 to 0.82 for h = 0.23 m. When the porosity reduced to 0.28, K_t varied around 0.48 to 0.59 for h = 0.19 m, and K_t varied from 0.56 to 0.66 for h = 0.23 m. The K_t values ranged from 0.38 to 0.47 and 0.43 to 0.54 for h = 0.19 m and h = 0.23 m when the porosity decreased further to 0.0625. Furthermore, in a fully submerged condition (Figure 8), K_t values for ε = 0.48 varied from 0.75 to 0.82 for h = 0.27 m, and this varied from 0.77 to 0.87 for h = 0.35 m, respectively. The K_t values decreased from 0.44 to 0.71 and 0.69 to 0.86 for h = 0.27 m and h = 0.35 m when the porosity decreased further to 0.0625. The variation in transmission coefficient, K_t with wave steepness, H_i/L for the one-row SP results at various porosities, ε was apparent for partially submerged condition and marginal for fully submerged condition. This illustrated that porosity played a significant role whereby, K_t increased when porosity increased.

Similar results were found for the two-row SP model, the reduction of K_t values was more apparent when rows of piles are increased as shown in Figures 9 and 10. The data points were scattered, but the trends were almost well defined. All the plots indicated a decreasing K_t with increasing wave steepness, especially for porosity, ε = 0.0625 at water depth, h = 0.35 m. The results in Figure 9 shows that when porosity, ε = 0.48 and H_i/L at 0.013, K_t reached 0.64 and 0.73 for h = 0.19 m and h = 0.23 m, respectively. When the porosity reduced to 0.0625, K_t varied around 0.26 to 0.36 for both h = 0.19 m and 0.23 m water depths. This indicates that for two-row models the effect of water depth increment is marginal on wave transmission. In fully submerged condition (Figure 10) however, K_t values for ε = 0.48 varied from 0.68 to 0.76 for h = 0.27 m, and varied from 0.70 to 0.92 for h = 0.35 m, respectively. The K_t values decreased from 0.43 to 0.59 and 0.54 to 0.89 for h = 0.27 m and h = 0.35 m when the porosity decreased further to 0.0625. The reduction of K_t values were more pronounced with the increment of H_i/L in fully submerged condition, as the surface water particles were more free to move rather than in the partially submerged condition. It was also observed from both Figures 9 and 10 that less porous models correspond to smaller K_t and vice versa.

Identical findings can also be found in studies by Grüne and Kohlhase (1974) using wave screens as wave dissipators. Their results showed that when the wall element ratio (the ratio of the impermeable screen area to the total screen area) was increased, wave transmission was found to decrease and reflection increased. The results of their experiments are illustrated in Figure 11.

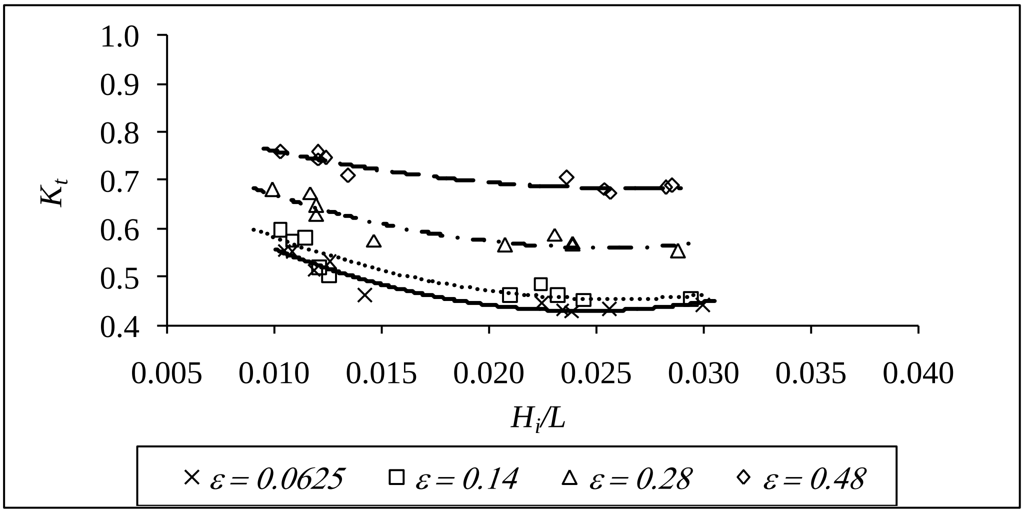


(a) Water depth, h = 0.19 m

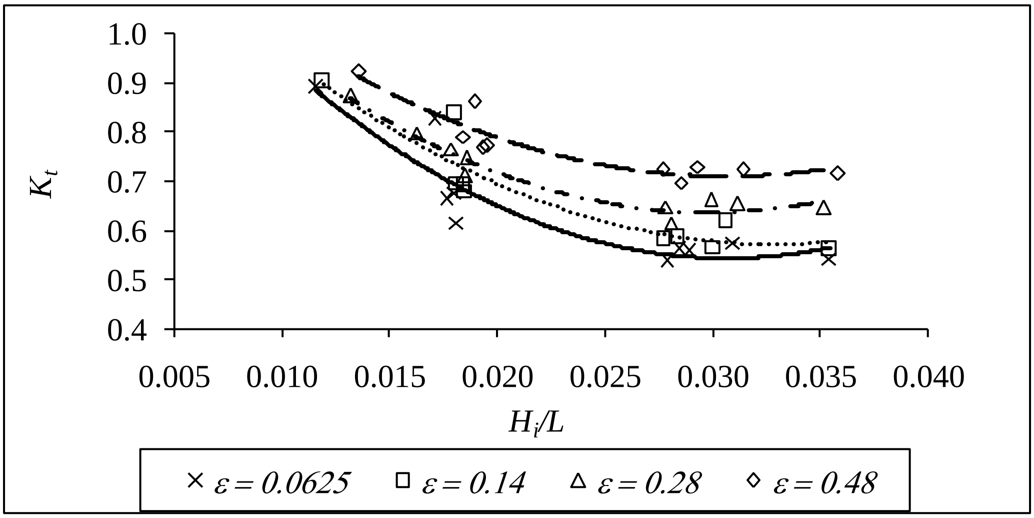


(b) Water depth, h = 0.23 m

Figure 9 : K_t vs. H_i/L for Various Porosity of Partially Submerged Two-row SP



(a) Water depth, *h* = 0.27 m



(b) Water depth, h = 0.35 m

Figure 10 : K_t vs. H_i/L for Various Porosity of Fully Submerged Two-row SP

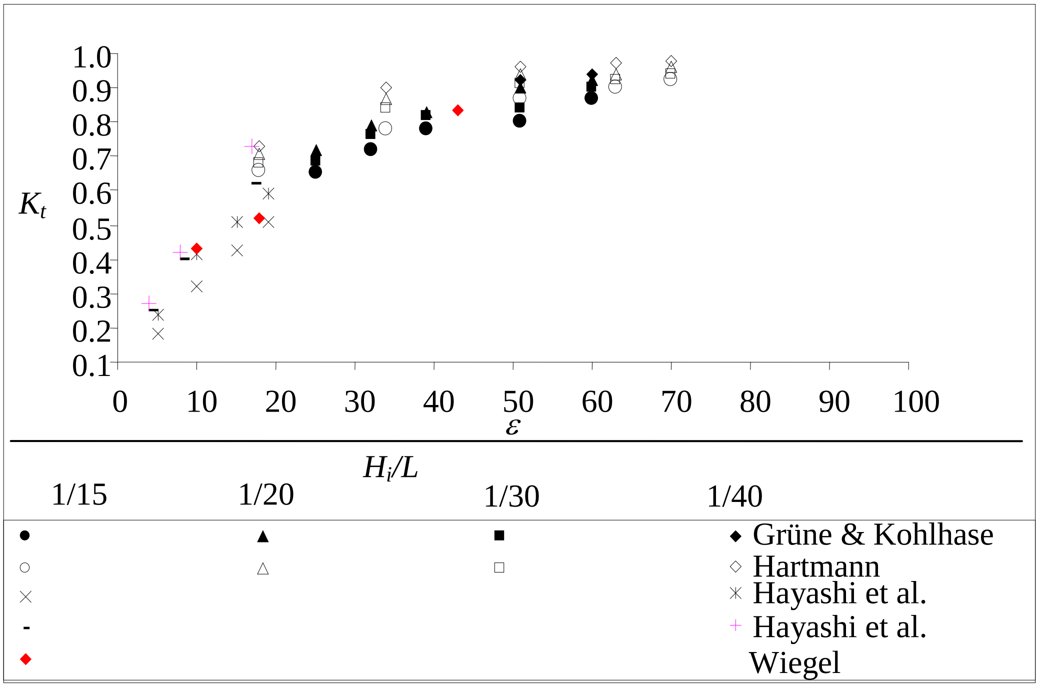


Figure 11 : Graph of K_t vs. ε (Source : Grüne and Kohlhase (1974)

Figures 12 and 13 show the comparison of K_t between the one-row and two-row pile arrangements at ε = 0.48 for the partially and fully submerged conditions respectively. It is evident that porosity has a significant influence on K_t with a lower porosity model resulting in lower K_t values. The maximum differences in K_t values were 0.35, 0.31, 0.14 and 0.14 for water depths at 0.19 m, 0.23 m, 0.27 m and 0.35 m, respectively. The differences in K_t values between each water depth were almost constant, with slightly higher difference of K_t for the partially submerged condition. K_t increased as porosity increased in parallel to water depth increment. Transmitted waves decreased further when the number of pile row tested was increased.

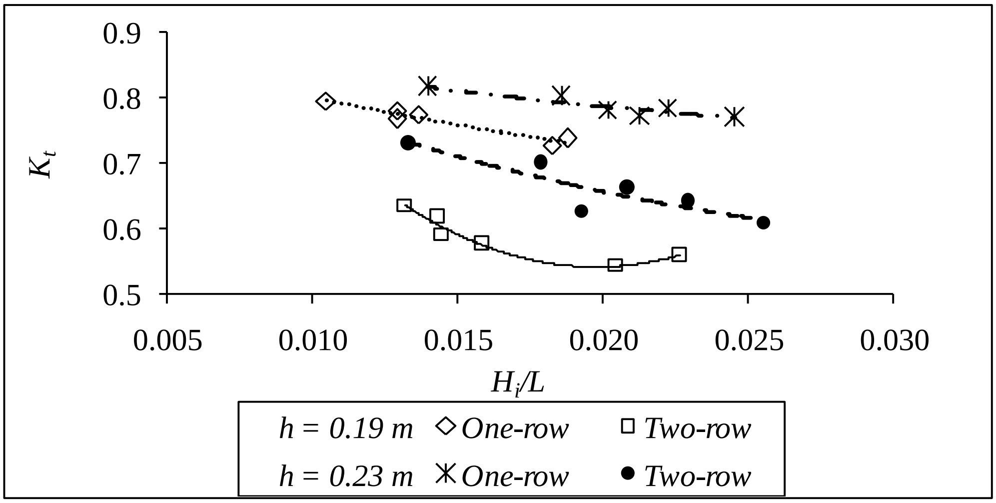


Figure 12 : Comparison of K_t between One-row and Two-row SP at $\varepsilon = 0.48$ for the Partially Submerged Condition

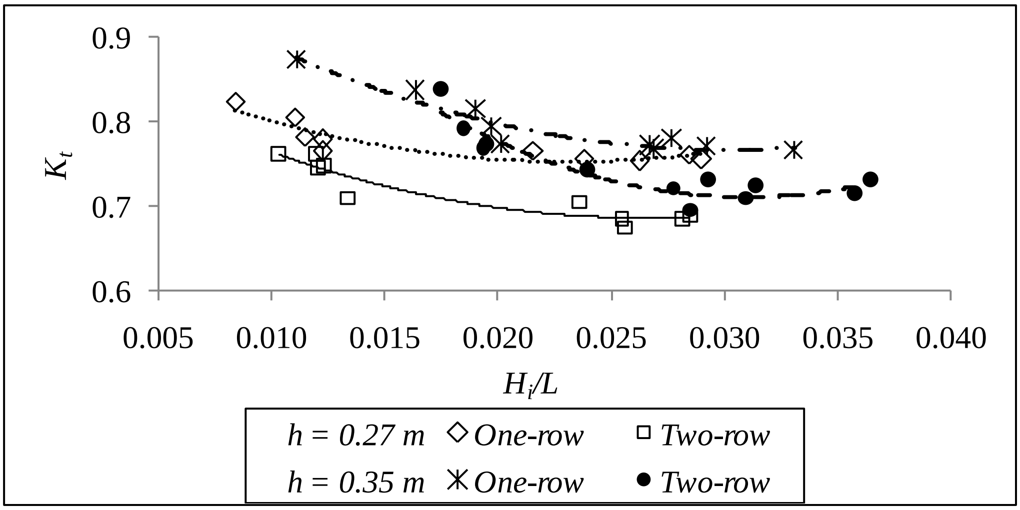


Figure 13 : Comparison of K_t between One-row and Two-row SP at $\varepsilon = 0.48$ for the Fully Submerged Condition

4.0 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 result in giving 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.

When the number of rows to be tested was increased, transmitted wave heights were also found to be decreased. This was because more wave energy was being dissipated as waves were transmitted through the test models. This happened for all the porosity values used in the study.

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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. 16^h Coastal Eng. Int. Conf.,* ASCE, New York, N. Y., pp. 2152-2171.

Dick, T. M., and Brebner, A. (1968) Solid and Permeable Submerged. *Proc. 11^th Int. Conf. on Coastal Eng.* 1968: pp. 1141-1158.

Grüne, J. and Kohlase, J. (1974) Wave Transmission through Vertical Slotted Walls. *Proc. 14^th Coastal Eng. Conf.,* Copenhagen, Denmark. ASCE, New York, N. Y., pp. 1906-1923.

Hartmann (1969) Das Stabgitter in Instationarer Stromungsbewegung. Mitt. Des Instituts fur 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.

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. 3^rd 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. 17^th Coastal Eng. Conf.,* Sydney, Australia, vol. **1**, pp. 154-172.

Mohd Anuar, N. (2008) *Performance of Perforated Piles as a Wave Attenuator,* Master of Eng. (Coastal & Maritime) Thesis, Faculty of Civil Engineering, Universiti Teknologi Malaysia.

Nagai, S. (1966) Research on Steel Pile Breakwaters. *Proc. 10^th Coastal Eng. Conf.,* Tokyo, Japan., ASCE, New York, N. Y., pp. 850-872.

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.

Sidek, F. J., 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.

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.

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.

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.