A Study of the Solitary Wave Energy Attenuation through Pervious Concrete Breakwater

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Abstract

Coastal erosion is a primary problem for coastal communities worldwide. Furthermore, the climate change impact and the resulting sea-level rise have reduced the sediment transportation along the coast, deteriorated infrastructure, and the natural coastal environment. These significant concerns lead to extensive innovations in coastal protection. Breakwaters are coastal structures typically applied for shorelines protection and sheltering harbours by providing wave energy attenuation and reflecting amounts of wave currents. In the present study, pervious concrete is utilised as a permeable breakwater considering the influence of permeability introduced to deliver the ecological friendliness defence for shorelines. A physical experimental model evaluated four models of structures that differed in porosity (15%, 20%, 25% and 30%) to study and analyse the performance of pervious concrete breakwater over the solitary wave impact. Subsequently, the hydrodynamic scattering coefficient (i.e., reflection, transmission, and dissipation coefficient) is analysed by considering changes in physical parameters such as the relative water depth and the wave period. In addition, the physical properties (i.e., void ratio test and permeability test) were also investigated. The experiments were conducted in the open channel flume (12 m. long, 0.6 m. wide, and 0.8 m. high) at KMUTT. The results were analysed and indicate that the introduction of pervious concrete breakwater improves wave transmission, reflection, and wave dissipation performance. As a result, a pervious concrete breakwater is a feasible alternative for a prospective coastal protection structure.

Keywords**:** Breakwater, Coastal erosion, Coastal protection, Pervious concrete, Wave attenuation

1. Introduction

Coastal zones have always been territories that influence humankind's settlement due to the significant number of resources with various natural ecospheres. Consequently, coastline areas have eventually been immensely inhabited and improved with more than 10 million population [1-3]. At present, the problem of coastal erosion is broadly realised since this affects the society living nearby the coastal area. In addition, the importance of economics from the coastal land use is also a problem that needs to be concerned, such as the travelling industry, agriculture, aquaculture, and fisheries. These are the dominant professions of the people living in the affected area and still be the significant income of their communities. By the influence of coastal erosion impact, rehabilitation and damage mitigation are the primary concerns that lead to extensive innovations in coastal protection. One of the typically used solutions is to construct coastal protection structures. These structural types mainly focus on coastal regions' protection and sheltering harbours from wave impacts.

A Breakwater is considered an offshore structure that protects structures along the shorelines by providing wave energy attenuation and reflecting amounts of wave currents. Besides, a seawall is an appealing method to alleviate the sea level rising impact. This significant onshore structure also prevents the detrimental influence of ocean wave actions and flooding driven by storms. However, these structures are still doubtful in the contradictions of the long-term applications. Though the protection structures provide sheltering for the rear features, the reflected wave tends to shift beside and beneath those structures, resulting in erosions spotted neighbouring. For those reasons, permeability has become a delightful option. By utilising a permeable structure for protection, some encountered waves are reflected in the ocean. In the meantime, some energies are demolished by the wave breaking and then transmitted the inward of the breakwater. Accordingly, a permeable structure has been introduced to deliver the ecological friendliness defence for shorelines by enabling the free seawater replacement between the sheltered and seaward sides through systems.

Pervious concrete is a distinctive type of concrete with different characteristics from conventional ones. This material does not contain fine or small aggregate in the mixture paste. Instead, there are interconnected pores inside the structure with the void fraction and the pore sizes of 15 - 30 % by volume and 2-4 mm, respectively. Generally, pervious concrete would have a permeability between 0.14 to 1.22 cm/sec with a compressive strength of 2.8 MPa to 28 MPa.

In this study, pervious concrete material is applied as a permeable breakwater to investigate the ability of wave transmission, wave reflection, and wave energy attenuation through the physical experiment. In addition, the configurations of material properties are compared and analysed to identify the most appropriate solution for coastal protection.

2. Literature review

2.1 Coastal erosion

According to the abundance of natural resources in these areas, coastal zones have been extensively used. They are still increasing by human activities such as human settlement, agriculture, trading, or the existence of harbours for ocean transportation. Coastal erosion is a process of the coastal area changing that occurs over time by the impact of waves and wind. Sediment transportation from one region to another caused the coastline to reform. As a result, areas with less incoming sediment than the quantity of sediment departing are considered coastal erosion. Figures 1 and 2 reveal the coastline area where the coastal erosion is located. Figure 1 depicts the site investigation in Nakorn Si Thammarat Province, Thailand, and found that over 36 km of the sandy beach have been severely eroded, affecting the lives of local communities along shorelines [4]. From the significant concern about the damage from the erosion problem, some related departments have managed the land use in structural and non-structural methods. For example, from Figure 2, more vegetation has been planted. In addition, the vertical seawall has been constructed to absorb and reduce the damage from the wave energy, which is the primary cause of coastal erosion.

Figure 1 Erosion at Nakorn Si Thammarat province, Thailand [4]

Figure 2 Aerial photographs and beachfront view of Sattahip beach, Thailand

2.2 Breakwater

Breakwaters are the coastal protection structures and are generally applied globally. This structural type is typically installed to reduce the force of wave action. This structure is suitable for withstanding high wind and waves due to the breakwater's design. In addition, breakwaters can promote sediment accumulation and provide valuable habitats for plants and animals. Numerous types of breakwaters have been developed over many decades. Unique marine geology is the most critical factor in breakwater development. Offshore breakwaters can be constructed in the plan either individually or in multiple (in pieces). The pieced offshore breakwater is inexpensive due to less material usage; it also allows water exchange between the shore and offshore due to the spaces between the particular piece of the breakwater. This is advantageous for the shoreline where the offshore segmented breakwater will be applied. Breakwater located offshore can be submerged or emerged. According to the structure attributes, different types of breakwaters can be classified as mound types, monolithic types, composite types, and particular types as stated in Figure 3 [5].

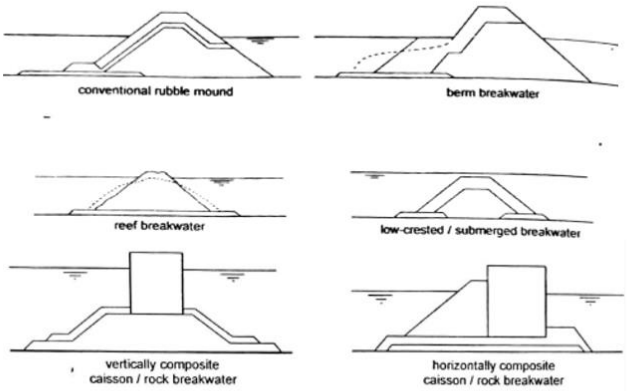

Figure 3 Various breakwater types classified by the structure attributes [5]

2.3 Pervious concrete

Typically, pervious concrete (PC) is a near-zero slump, open-graded material composed of Portland cement, coarse aggregate, little or no fine aggregate, admixtures, and water. Combining these components will produce a hardened material with interconnected pores (Figure 4), ranging from 2-8 mm, allowing water to flow through easily. Typically, the void content ranges from 15%-35%, with compressive and flexural strengths of 2.8 to 28 MPa and 1.5 to 5 MPa, respectively. The drainage rate of pervious concrete pavement will vary based on aggregate size and mixture density but will typically drop between 0.14 and 1.22 cm/s [6].

Figure 4 Pervious concrete texture [6]

The compressive strength of pervious concrete is strongly affected by the mixture proportion and compaction effort during placement. Therefore, investigations have been based primarily on laboratory tests, with some data from actual field installations obtained [7]. Figure 5 depicts the connection between porosity and compressive strength and found that although a general trend of increasing permeability with increasing porosity is observed, there is a large scatter and weak correlation, in contrast to the strength-porosity data. Permeability is the efficiency with which a porous medium transmits liquid under a hydraulic gradient. It is dependent on the pore structure, but the relationship between the two is complex. According to a comprehensive literature review, the permeability of permeable concrete ranges from 0.003 to 3.30 cm/s. In Figure 6, the compiled permeability data is plotted against porosity.

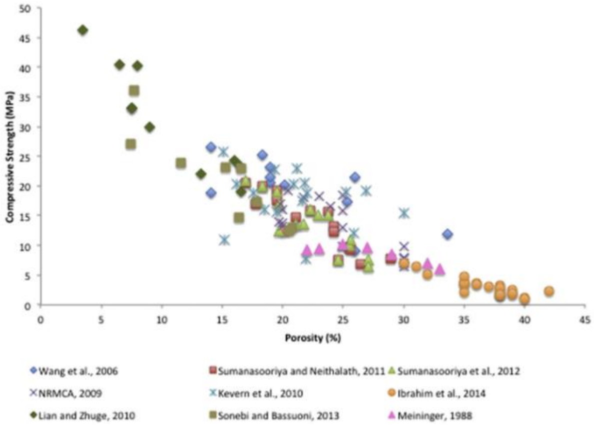

Figure 5 Correlation between compressive strength and porosity of permeable concretes [7]

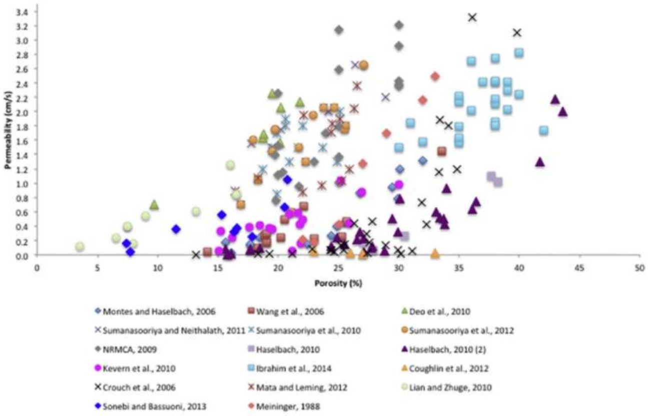

Figure 6 Correlation between permeability and porosity for permeable concretes [7]

3. Literature review

3.1 Studying the related research

The related studies were reviewed through the properties of pervious concrete, the breakwater as a coastal protection structure, and some background knowledge. In addition, experimental setup procedures with the information and behaviour of the wave energy through permeable breakwater were also studied.

Coastal erosion and shoreline management plans are often implemented on an action-reaction and post-disaster basis, resulting in the various mitigation strategies adapted for coastal protection, including installing hard engineering structures, such as groins, seawalls, revetments, gabions, and breakwaters. Permeable breakwaters offer an alternative to conventional solid breakwater to create a tranquil water basin for the berthing of vessels by dissipate the energy of incoming waves. The efficiency of the porous breakwaters is governed by their porosity and their depth of submergence.

3.2 Mix design

The volumetric method was used to design the mixtures. Four different porosities, 15%, 20%, 25%, and 30%, were designed with a fixed aggregate size of 4.75-9.5 mm, a water-cement ratio of 0.3 with 0.5% of superplasticiser. The mix ratio is illustrated in Table 1.

Table 1 Mix ratio of pervious concrete (PC)

Mix No.	Aggregate size (mm.)	Water-cement Ratio	Designed Porosity (%)	Mass of ingredient (kg/m^3)			
				Coase Aggregate	Water	Cement	SP
1	4.75-9.5	0.3	15	1565.83	118.11	393.69	1.968
2	4.75-9.5	0.3	20	1448.82	115.36	384.55	1.923
3	4.75-9.5	0.3	25	1359.97	108.29	360.96	1.805
4	4.75-9.5	0.3	30	1238.98	106.78	355.93	1.780

3.3 Physical properties testing method

3.3.1 Void ratio and porosity test

Based on ASTM C 1754/C1754M [8], a void ratio test for the pervious concrete can be performed. The connected void (V_c) refers to the interconnected pores inside the material. Meanwhile, the disconnected void (V_d) indicates the closed pores without a connection. Before conducting the test, the specimen must be submerged in the water for at least 24 hours. After removing it from the water, dry the specimen and weigh it to collect the air-dried mass (M_2). The submerged mass (M_1) can be determined by weighing the specimen under the water. Finally, place the specimen inside the oven at 110±5 °C to obtain the dried mass (M_3).

Connected void, disconnected void and the total void ratio can be calculated using equations 1–3.

$$V_c = \frac{M_2 - M_1}{V\rho_w} x\,100 \tag{1}$$

$$V_d = \frac{M_3 - M_1}{V\rho_w} x\,100 \tag{2}$$

$$n = \left(1 - \left(\frac{M_2 - M_1}{V\rho_w}\right)\right) x100 \tag{3}$$

where:

V = Volume of the specimen (m^3)

V_c = Connected void

V_d = Disconnected void

n = Porosity (%)

ρ_w = Water density (kg/m^3)

M_1 = Submerged mass of specimen (kg)

M_2 = Air-dried mass of specimen (kg)

M_3 = Oven-dried mass of specimen (kg)

3.3.2 Permeability test

Permeability coefficient (*K*), also known as hydraulic conductivity, measures the ease of passage of fluid to flow through the material. Therefore, permeability is one of the most crucial parameters for pervious concrete's hydrological design. By Darcy's Law theory, the laminar flow through pervious concrete assumptions, including the standard of ASTM D5084-03 [9], the property of permeability could be determined. The permeability coefficient is conducted by using the falling head equipment. From Figure 7, the lateral surface of the specimen is covered by rubber. To begin the test, pour water into the tube with the specified water amount. The time for water flow through the specimen can be recorded with the specified water amount. The coefficient of permeability can be determined using the equation 4.

$$K = \frac{aL}{At} ln \frac{h_1}{h_2} \tag{4}$$

where:

K = Coefficient of permeability (mm/s)
L = Specimen Length (mm)
A = Cross sectional area of the specimen (mm^2)
α = Cross sectional area of the water tank (mm^2)
t = Time recorded for water to flow through specimen (s)
h_1 = Initial water level (mm)
h_2 = Final water level (mm)

Figure 7 Permeability test equipment

3.4 Wave energy attenuation

3.4.1 Test specimen design

Pervious concrete specimens examined in this experiment differ in 15%, 20%, 25%, and 30% of porosities. For the experimental test, six prismatic beam specimens (0.1 meters wide, 0.1 meters deep, and 0.4 meters long) were required for each desired porosity; therefore, 24 pervious concrete specimens were cast in this project. In addition, two specimens of each %porosity were cut into half to be able to apply for the entire length of the flume width.

Figure 8 Hydraulic wave flume with the equipment setup for wave energy attenuation test

3.4.2 Experimental procedure

The experiments were conducted in an open channel wave flume (12 m. long, 0.6 m. wide, and 0.8 m. high) at the Hydraulics Laboratory of civil engineering department at King Mongkut's University of Technology Thonburi as illustrated in Figure 8. The wave attenuation, and reflection performance of pervious concrete breakwater (PCB) were investigated through the experiments. In addition, physical parameters such as the relative water depth, wave period, structural dimensions and four different porosities were conducted to find the most effective solution for coastal protection.

3.4.3 Model test setup

For laboratory experiments, rectangular-shaped concrete breakwaters were installed 4 meters away from the wave generator. The breakwater length is the same as the width of the flume. The height of the breakwater (h_b) was fixed as 0.2 m with the varying width as B_w = 0.1 m, 0.2 m for single-layered (SG) and double layered (DB), respectively (as illustrated in Figure 9). Four different porosities of 15%, 20%, 25%, and 30% were applied to construct the permeable breakwaters. The tailgate flap-type wave generator installed at the end of the wave flume is applied to generate regular waves with two sets of different wave periods (T), as $T1$ and $T2$. In addition, three still water depths (h), 0.25 m, 0.2 m, and 0.15 m, with three relative submergences (h_b/h), 0.8 (submerged), 1 (submerged), and 1.33 (emerged) were performed for the different hydraulic parameters. A watergate is installed 7 meters from the end of the flume, as stated in Figure 10.

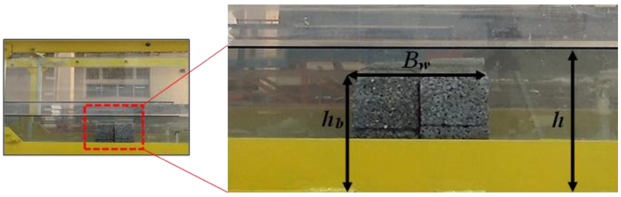

Figure 9 Pervious concrete breakwater with double layered (B_w = 0.2 m)

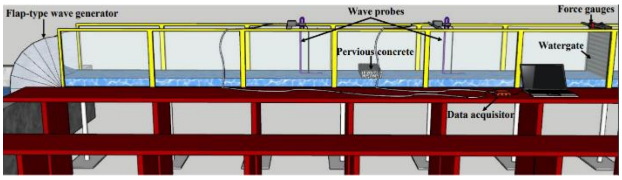

Figure 10 Model test setup in detail by SketchUp

3.3.4 Void ratio and porosity test

In order to indicate the accuracy of the designed porosity, the measured porosity was taken according to equations 1-3. Figure 11 represents the relationship between experimentally measured porosity and designed porosity. Also, values are similarly closed to one another with a correlation factor of 0.9915.

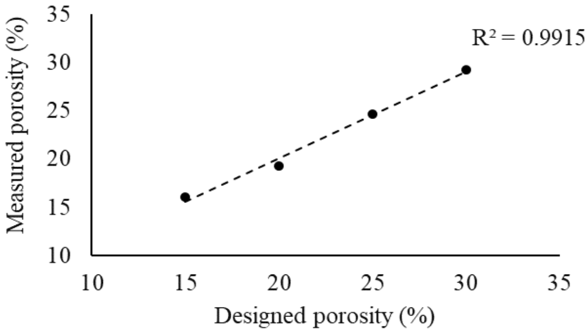

Figure 11 The relationship between the designed porosity and measured porosity of pervious concrete

3.3.5 Performance characteristics

The transmission (K_t), reflection (K_r), and dissipation (K_d) coefficients are regarded as breakwater performance characteristics because they play a significant role in determining the efficiency of any breakwater. The breakwater typically becomes optimal when wave transmission and reflection are minimised and maximises the dissipation. In this experiment, the performance of PCB is studied in terms of these performance characteristics. These performances can be determined using equations 5-8 [10].

$$K_t = \frac{H_t}{H_i} \tag{5}$$

$$K_r = \frac{H_r}{H_i} \tag{6}$$

The wave energy dissipation coefficient (K_d) is determined using the law of energy conservation and is given by

$$1 = K_r^2 + K_t^2 + K_d^2 \tag{7}$$

$$K_d = \sqrt{1-(K_r^2 + K_t^2)} \tag{8}$$

where:

K_t = Coefficient of transmission
K_r = Coefficient of reflection
K_d = Coefficient of dissipation

4. Result and discussion

This chapter presents experimental results from testing, the physical and hydraulic properties were observed and collected. Results were analysed and presented in many aspects. The impact of various factors on these properties are discussed as follows.

4.1 Permeability

Permeability is typically a significant factor in PC categorisation. The interconnected void space allows stormwater to percolate and thus reduce the amount of run-off. In addition, the permeability or the saturated hydraulic conductivity of the pervious concrete signifies its capacity to allow the water to transmit within the specimen. From Figure 12, the permeability coefficient increases as the void or porosity within the sample increases, with a correlation coefficient of 0.9702. The equation relating porosity and permeability of pervious concrete is applicable as $y = 0.0881e^{0.00642x}$

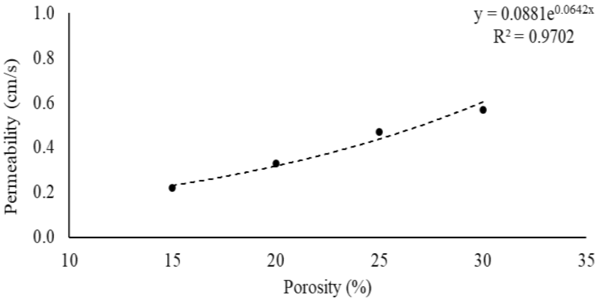

Figure 12 The relationship between porosity and permeability of pervious concrete

The pervious concrete system and its corresponding strength are as important as its permeability characteristics. In this project, the effect of the porosity through permeability would be aimed. For coastal structure, permeability is a significant factor that can be implied to the influence of the dissipated wave, resulting from the combination between the reflection and transmission of the wave energy at which the impacted waves interact through the porous media at the seaward face of the structure [11]. The more permeability would allow the more penetrated wave to be transmitted into the lee side and then interact with the coastal zone behind. In contrast, less permeability would influence more waves to be reflected and interact with the lateral zone without the protection. Hence, the preliminary results of this study are valuable and serve as a helpful reference for the optimum in designing and constructing pervious concrete in the future.

4.2 Wave energy attenuation

This project investigates the widths of the single-layered (SG) and double-layered (DB) breakwater as B_w = 0.1 and 0.2 m. Two sets of wave period (T) are stated as T1 and T2. Different relative submergences (h_b/h) are indicated as A = 0.8, B = 1, and C = 1.33, respectively. According to the different relative submergence (initial water depths), flap-type breakwater could generate the sets of wave periods as stated in Table 2.

Table 2 Abbreviation of the wave periods for the experiment

Abbreviation	Relative submergence case		
	A	B	C
	Wave period, T (s)		
T1	0.96	1.04	1.22
T2	0.92	1.00	1.18

4.2.1 Influence of pervious concrete breakwater on wave transmission

According to the experimental results, Figures 13-15 present the relationship between the transmission coefficient (K_t) and porosity of PCB for three different relative submergence depths (h_b/h) of 0.8, 1, and 1.33, respectively. In each case, a total of 16 points was plotted to classify the effect of the breakwater width and wave period on the wave transmission.

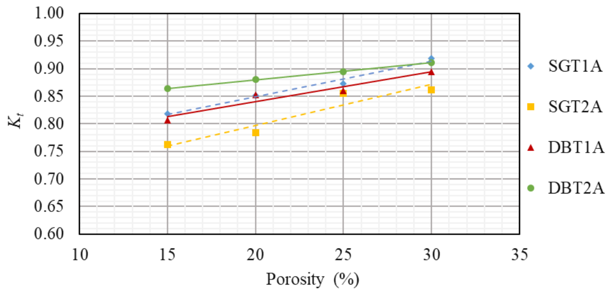

Figure 13 The relationship between porosity and transmission coefficient at h_b/h = 0.8

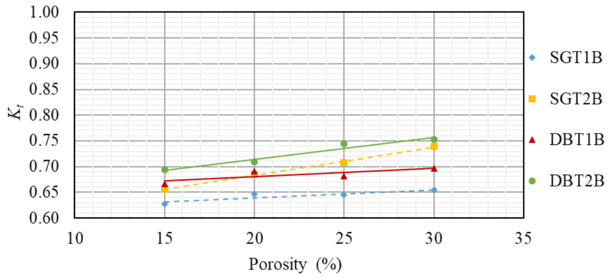

Figure 14 The relationship between porosity and transmission coefficient at h_b/h = 1

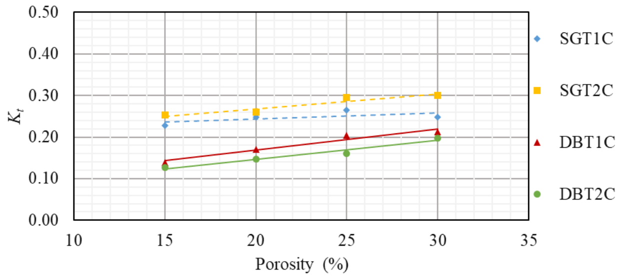

Figure 15 The relationship between porosity and transmission coefficient at h_b/h = 1.33

It is observed that the transmission coefficient (K_t) increases as the PCB's porosity increases for all cases and exposing that the porosity influences the damping of the transmitted wave. From the tendency, the porosity n = 15% shows the minimum transmission value in most cases due to the least allowable wave energy transferring compared to others. Generally, a wave has small transmission through the breakwater with a low relative submergence depth. On the other hand, the breakwater structure becomes more ineffective in damping the wave transmission when submerged ($h_b/h \leq 1$). Larger breakwater width (B_w) effectively damps the transmitted wave with a higher relative submergence depth (K_t = 0.12-0.21) but becomes less effective when being deeper submerged (K_t = 0.81-0.956), as displayed through Figures 13-15. This aspect may result from the decreased friction between the breakwater's surface and the transmitted wave, which causes a minor significant reduction in wave energy.

4.2.2 Influence of pervious concrete breakwater on wave reflection

Figures 16-18 show the relationship between the wave reflection characteristics and the specimen's porosity on the relative submergence depths (h_b/h). The trend of reflection coefficient (K_r) appears to decrease with the increase of the specimen's porosity throughout most scenarios. As stated in Figure 16, the different wave period shows no noticeable wave reflection for a double-layered case with low relative submergence. However, by comparing with the single-layered case, it could be noticed that the double-layered breakwater would provide a considerably smaller amount of wave reflection as the wave moves overtopped the structure instead of transmitting inside. This observation shows how the double-layered could provide more wave transmission than the single-layered shown in Figure 13. However, in all cases, PCB with a porosity of 25% and 30% would provide a more wave reflection corresponding to the tendency for the single-layered case with a slight wave period. This significant result would influence the factor of erosion in the actual situation. For example, suppose that a particular location is experiencing wave energy with a mild wave period. Then, a single-layered PCB installed with 25% and 30% porosity will allow the wave energy to interact and then be transmitted inside compared to other cases with the same porosity. The lower relative submergence enhances the property of wave reflection over the structure as 0.217-0.385, 0.171-0.344, and 0.146-0.341 for h_b/h = 0.8, 1, and 1.33, respectively.

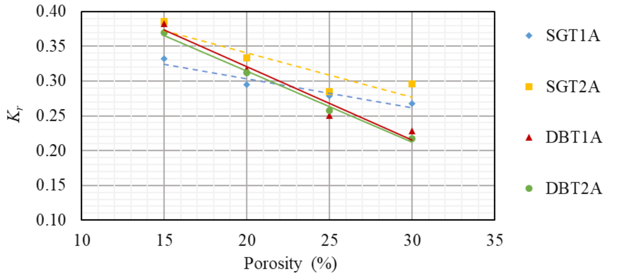

Figure 16 The relationship between porosity and reflection coefficient at h_b/h = 0.8

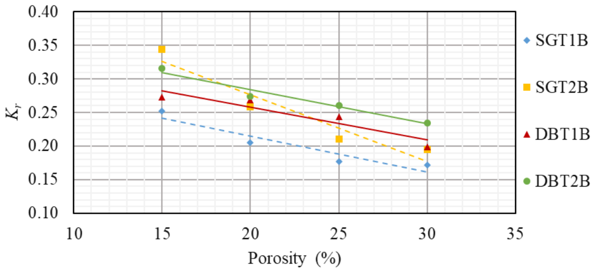

Figure 17 The relationship between porosity and reflection coefficient at h_b/h = 1

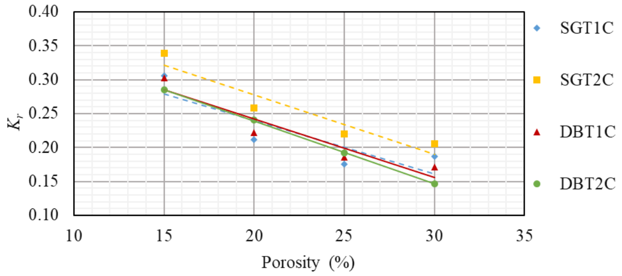

Figure 18 The relationship between porosity and reflection coefficient at h_b/h = 1.33

4.2.3 Influence of pervious concrete breakwater on wave energy dissipation

The expression for the energy dissipation factor is derived in conjunction with the wave energy balance equation as stated in equation 8. Consequently, both wave reflection and transmission coefficient play an essential part in determining this property.

Figures 19-21 show the variation of the dissipating wave energy on three relative submergence depths (h_b/h). With the increase of relative submergence, the trend of energy dissipation gradually increases and reaches a peak when h_b/h > 1 (emerged). Wave energy dissipation can be enhanced by increasing both frictions inside the porous media and vortex strength outside the breakwater. In addition, the emerged breakwater could also introduce wave breaking and enhance the energy dissipation. For the submerged breakwater, the influence of increasing porosity would markedly reduce the wave dissipation. The wave overtopping would reduce the effect of the specimen's porosity, which could dissipate the wave energy due to the internal friction of the pervious structure. On the contrary, the more significant porosity could provide more energy dissipation in the emerged case attributable to the increased interaction between the wave impact and the porous media, as illustrated in Figure 19.

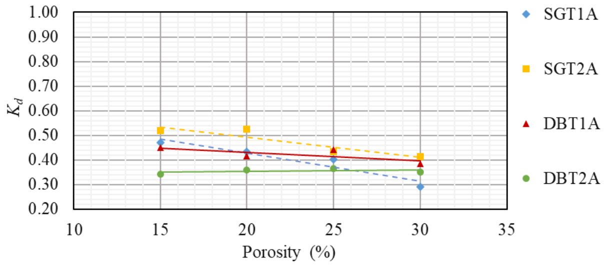

Figure 19 The relationship between porosity and dissipation coefficient at h_b/h = 0.88

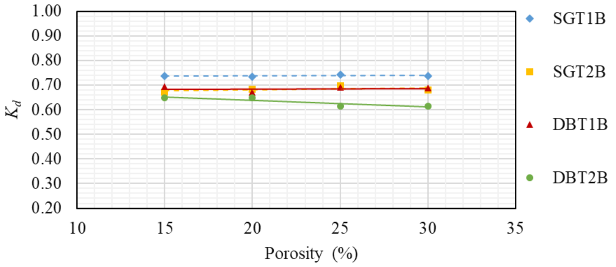

Figure 20 The relationship between porosity and dissipation coefficient at h_b/h = 1

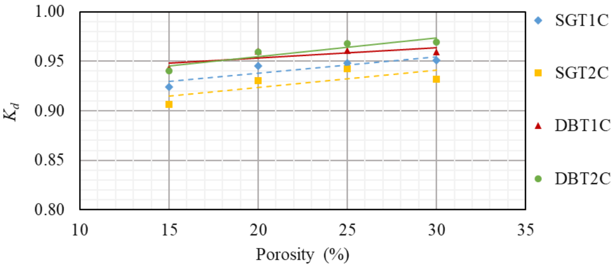

Figure 21 The relationship between porosity and dissipation coefficient at h_b/h = 1.33

5. Conclusions

This research introduces the innovation of pervious concrete as a permeable breakwater as an alternative solution to the potential coastal protection structure by comparing the structural properties, dimensions, and wave characteristics. First, the hydrodynamic scattering coefficient (wave reflection, wave transmission, and wave dissipation) is investigated and analysed the performance of pervious concrete breakwater over the solitary wave impact. In addition, the relative submergence depth, breakwater width, and porosity were discussed, respectively. The conclusions of pervious concrete breakwater characteristics can be noted as follows:

1. Due to the net reduction of aggregate volume, the increases in total porosity directly influence the pervious concrete's permeability to increase. The more permeability would allow the more penetrated wave to be transmitted into the lee side and then interact with the coastal zone behind. In contrast, less permeability would influence more waves to be reflected and interact with the lateral zone without the protection.
2. Experimental results reveal the minimum transmission coefficient for the PCB with the lowest porosity (*n* = 15%) with the emerged condition (h_b/h = 1.33).
3. The minimum reflection coefficient is obtained for the PCB with the highest porosity (*n* = 30%) and minimum submergence depth (h_b/h = 0.8).
4. According to the dissipation coefficient, the PCB specimen could attenuate the wave energy most effectively under the emerged condition (h_b/h = 1.33). The increases in porosity (*n*) tend to dissipate more wave energy attributable to the increased interaction between the wave impact and the porous media.

Since the wider breakwater would still reduce the wave transmission through the interaction among the wave and interconnected pores, the PCB would be an attractive alternative structure applied for the area with a massive structural requirement. For example, a breakwater application at a harbour with a docking system. This type of breakwater is still suitable in the installation process as a concrete, designable shape with a smooth surface requirement.

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