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الخصائص الهيدرو–ديناميكية لكواسر الأمواج الفردية والمزدوجة تحت تأثير الأمواج المنتظمة والعشوائية

محمد الخالدي*، سابرامانيان نيلاماني، زهراء الزقاح*****

* قسم الهندسة المدنية، جامعة الكويت، ص. ب. 5969، الصفاة 13060، الكويت.

** برنامج الإدارة الساحلية، مركز أبحاث البيئة وعلوم الحياة، معهد الكويت للأبحاث العلمية، ص. ب. 24885، الصفاة 13109، الكويت.

***طالبة دراسات عليا في قسم الهندسة المدنية، جامعة الكويت.

* الاتصال بالمؤلف بالبريد الالكتروني: mohamad.alkhaldi@ku.edu.kw

الخـلاصــة

تم دراسة تفاعل كواسر الأمواج البحرية الفردية والمزدوجة مع موجات منتظمة وعشوائية من خلال تجارب مختبرية لتقييم خصائصها في الانعكاس ونقل الطاقة وتبديدها. كلا النوعين من نماذج كاسر الأمواج لها نفس الحجم الكلي. لكن المقطع العرضي لكاسر الأمواج الفردي هو شبه منحرف في حين كاسر الأمواج التوأم لها مقطع عرضي مثلث. تم النظر في مجموعات مختلفة من ارتفاعات الأمواج والفترات جنبا إلى جنب مع ثلاثة أعماق مختلفة للمياه. العوامل المحتملة التي تؤثر على كفاءة تخفيف الموجة لنماذج كاسر الأمواج هي عمق المياه النسبي (h / d)، وانحدار الموجة (Hi / L)، وارتفاع الموجة النسبي [(h-d) / Hi)]، وارتفاع الكسر النسبي، والتباعد النسبي (S / h) بين الحواجز المزدوجة. وتظهر نتائج الاختبار أن كواسر الأمواج الفردية والمزدوجة يستجيبان بشكل مختلف للتغيرات في ارتفاعهما النسبي وكذلك التغيرات في الارتفاع النسبي للموجات. تأثير عمق الماء النسبي على انعكاس الموجة، ونقل وتبديد الطاقة يتأثر بشدة من التغيرات في ارتفاع كاسر الأمواج النسبي، وارتفاع الأمواج النسبي والتباعد النسبي بين كاسر الأمواج. كما تشير النتائج إلى أنه ضمن نطاق أعماق المياه النسبية التي تم اختبارها تحت كل من الموجات المنتظمة والعشوائية، تسمح تحفز كواسر الأمواج الفردية على تبديد الطاقة بصورة أفضل من كواسر الأمواج المزدوجة وبالتالي تعطي أداء متميز بشكل عام.

Hydrodynamic characteristics of single and twin offshore rubble mound breakwaters under regular and random waves

Mohamad A. Alkhalidi*, S. Neelamani**, and Zahraa Al-Zagah***

** Civil Engineering Department, Kuwait University, P.O. Box 5969, Safat 13060, Kuwait*

*** Coastal Management Program, Environment and Life Sciences Research Centre, Kuwait Institute for Scientific Research, P.O. Box: 24885, Safat 13109, Kuwait*

**** Graduate Student at Civil Engineering Department, Kuwait University*

** Corresponding Author: mohamad.alkhaldi@ku.edu.kw*

ABSTRACT

The interaction of single and twin offshore rubble mound breakwaters with regular and random waves is investigated through physical modeling to assess the wave reflection, transmission, and energy dissipation characteristics. Various combinations of wave heights and wave periods were used in a series of experiments. Three different water depths are used to represent low tide, mean water level, and high tide conditions. Both models have the same total volume of rubbles; stones of same sizes are used for the model construction, which will help in reducing the construction cost. The single breakwater cross-section is trapezoidal, while the twin breakwaters have triangular cross-section. The possible factors affecting the wave attenuation efficiency of the breakwater models are the relative water depth, wave steepness, relative wave height, relative breakwater height, and relative spacing between the twin breakwaters. The results indicate that the single and double breakwaters respond differently to the change in their relative height as well as to the relative wave height. The effect of the relative water depth on wave reflection, transmission, and energy dissipation is highly influenced by the change in the relative breakwater height, the relative wave height, and the relative breakwater spacing. Within the range of the relative water depth tested in this study and under both regular and random waves, it is found that the single breakwater allows for lower wave transmission and shows higher energy dissipation effect than the twin breakwaters and hence has the best overall performance.

Keywords: Single breakwater; twin breakwater; wave reflection; wave transmission; wave energy dissipation.

INTRODUCTION

Protecting shorelines and coastal infrastructures against destructive wave attacks have been one of the most challenging tasks for coastal engineers and governmental planners. Many breakwater types were developed over the decades to serve this purpose. Rubble mound breakwaters are widely used around the world either for shore sheltering purposes or for the construction of harbors (Neelamani and Vedagiri, 2002). Offshore rubble mound breakwaters can be constructed as a single structure for localized shore protection, or as a segmented breakwater to protect a larger zone of the beach (Dally and Pope, 1986). To enhance the protection efficiency, multiple breakwaters may be used and placed in a parallel configuration. The use of multiple breakwaters was reported by many researchers. The behavior of partially immersed twin vertical walls under regular and random waves was investigated by Dally and Pope (1986) through a serious of physical experiments. They concluded that the double barrier breakwater generally works better in reducing wave transmission and increasing energy dissipation in the case of random waves. They also noticed that the transmission coefficient generally tends to increase as the relative depth of immersion increases, and the increase in the relative water depth causes a significant reduction in the transmission coefficient, while the increase in the wave steepness results in an increase in the coefficient of energy dissipation and a decrease in the coefficient of wave transmission. Koraim et al. (2011) investigated the hydrodynamic performance of double vertical wall with slotted lower part under normal regular waves. The physical model experiments along with a theoretical model were conducted to estimate the coefficients of wave transmission, reflection, and energy dissipation of the wall.

They observed that increasing the relative water depth, decreasing the lower part porosities, and increasing the relative upper part drafts decreased the coefficient of wave transmission and, in the meantime, increased the coefficient of wave reflection. Their theoretical results also showed that the performance of the double vertical wall is strongly affected by increasing the upper part draft of the first or both walls and by decreasing the lower part porosity of the first wall or both walls. Comparing their results with those of Rageh and Koraim (2010) for a single slotted vertical wall showed that the use of the second wall reduces transmission and reflection by almost 10-20% and 510%-, respectively, and increases the energy dissipation by about 1020%-. Zidan et al. (2012) studied experimentally the hydrodynamic interaction of regular waves with single and twin pontoons. They noticed that the transmission coefficient decreases with increasing the relative breakwater draft of single and double pontoons, increasing the relative breakwater width of single pontoon, and decreasing the relative distance between the twin pontoons, whereas the reflection coefficient increases with increasing the relative breakwater draft of single and double pontoons, the relative breakwater width of single pontoon, and the relative distance between the twin pontoons.

Liu et al. (2016) developed full linear analytical solutions to evaluate the reflection and transmission capabilities of multiple semi-circular breakwaters under oblique and normal waves as well as an experimental model to determine the reflection and transmission coefficients of single and twin breakwaters under normal waves. In comparison with the single semi-circular breakwater, they concluded that the use of twin breakwaters is more efficient as they can reflect more wave energy and hence allow lower wave transmission through the breakwater into the sheltered area. The analytical model results showed that increasing the number of breakwaters and increasing the breakwater radius can separately increase the peak reflection coefficient in a significant way. The interaction of water waves with multiple rubble mound structures was tackled by very few researchers. Cho et al. (2004) conducted a series of laboratory experiments and developed a numerical model to investigate the occurrence of Bragg reflection of regular waves due to multiple rectangular and trapezoidal submerged breakwaters, which were both permeable and impermeable. They noticed that increasing the number of impermeable trapezoidal and rectangular breakwaters strengthens the magnitude of reflection coefficients as well as the resonant reflection, and the reflection coefficients of the rectangular breakwater are slightly greater than those of the trapezoidal breakwater. Their results also showed that the reflection coefficients of permeable trapezoidal breakwaters were less than those of impermeable ones. A numerical model along with physical modeling experiments was also performed by Jeon and Cho (2006) to study the characteristics of the Bragg reflection of sinusoidal waves due to an array of porous and non-porous trapezoidal submerged breakwaters.

The porous and non-porous breakwaters were both installed in one array, two arrays, and three arrays, each at a time, with a fixed spacing between the adjacent breakwaters. Both physical and numerical models showed that the reflection coefficients increase as the number of breakwater arrays increases and the reflection coefficients of non-porous breakwaters were greater than those of porous breakwaters, whereas for relatively short waves, the number of arrays and permeability of submerged breakwaters influence neither the reflection coefficients nor the breakwater performance. A numerical study was carried out by Liang et al. (2015) to investigate the influence of changing the relative spacing between double trapezoidal submerged breakwaters on wave transmission. Based on the numerical simulations, the regular wave transmission and attenuation coefficients were affected by the change in the relative breakwater spacing, while the reflection coefficient remained almost constant.

The most appropriate relative breakwater spacing for practical use was identified, given certain values of wave height, period, and water depth, and certain breakwaters geometry. Cao et al. (2012) investigated experimentally the attenuation characteristics of linear and cnoidal incident waves interacting with double submerged trapezoidal breakwaters on a flat-bed. They studied the effect of wave steepness, relative wave height, relative submerged water depth, and relative spacing between the breakwaters on the coefficients of wave reflection, transmission, and attenuation and concluded that the wave attenuation efficiency of the breakwaters is strengthened as the waves become steeper, and the wave steepness has a weak influence on the coefficients of wave reflection and transmission when the spacing between the breakwaters is too large or too small. They also noticed that modifying the relative breakwater spacing had a significant effect on the reflection coefficient within a specific range.

In addition, they concluded that the increase in the relative wave height resulted in an increase in the reflection coefficient and a decrease in the transmission coefficient, while the increase in the relative wave height enhanced the attenuation effect of the double breakwaters. Offshore breakwaters could be emerged or submerged. Having their crests above the mean sea level, emerged breakwaters are more effective in the sheltering function as they can dissipate more wave energy and hence allow less wave transmission, which might decrease the water circulation between the lee side of the breakwater and the open sea, causing the water quality to deteriorate and affecting marine life. Emerged breakwaters might be non-preferable for communities as they block the aesthetic sea view. On the other hand, submerged breakwaters are more environmentally friendly as they prevent water pollution in the sheltered area by allowing more wave overtopping and water circulation. They can also function as natural reefs in attracting fish and other sea organisms. Due to their low crests, submerged breakwaters are more economical as they require less cost for construction and maintenance; however, their low crests can lower the degree of coastline protection in a significant way. Based on the literature review, it is found that there is no work reported in the literature that studied the assessment of wave transmission, reflection, and energy dissipation coefficients for offshore single trapezoidal and double triangular rubble mound breakwaters with the same sized materials all along the depth of the breakwater and under different submergence conditions. This is the main motivation for the present work. The advantage of using the same sized materials for core, inner layers and armor layer is ease of construction and saving in the overall cost.

The study is to experimentally investigate the wave transmission, reflection, and energy dissipation due to single and twin offshore rubble mound breakwaters for different wave climates and present recommendation for engineering applications. The volume of stones used for the single trapezoidal offshore breakwater is exactly divided into two equal portions to build the twin breakwaters of triangular cross section. In the next section, the experimental setup is presented followed by the model details. In Section 4, the hydrodynamic characteristics of the tested breakwaters are presented and followed by the conclusion and discussions of the results.

EXPERIMENTAL SETUP

The experiments were carried out in the two-dimensional rectangular wave flume of the coastal engineering laboratory at Kuwait Institute for Scientific Research (KISR) in Kuwait. The glass-sided flume is 54.5 m long, 0.6 m wide, and 1.15 m deep. A piston type wave generator is at the upstream end of the flume. The wave maker has a single paddle and is operated with an electrical servo actuator. A parabolic wave dissipater filled with fishing nets that form a mesh was installed at the downstream end of the flume to absorb the waves transmitted from the tested breakwater. The breakwater models were placed at approximately 15 m from the wave maker. Figure 1 demonstrates the schematic diagrams of the experimental setup inside the wave flume. Wave probes of standard DHI capacitance type with a 60-cm range were positioned at six different locations to measure the water surface variations resulting from the wave-structure interaction simultaneously.

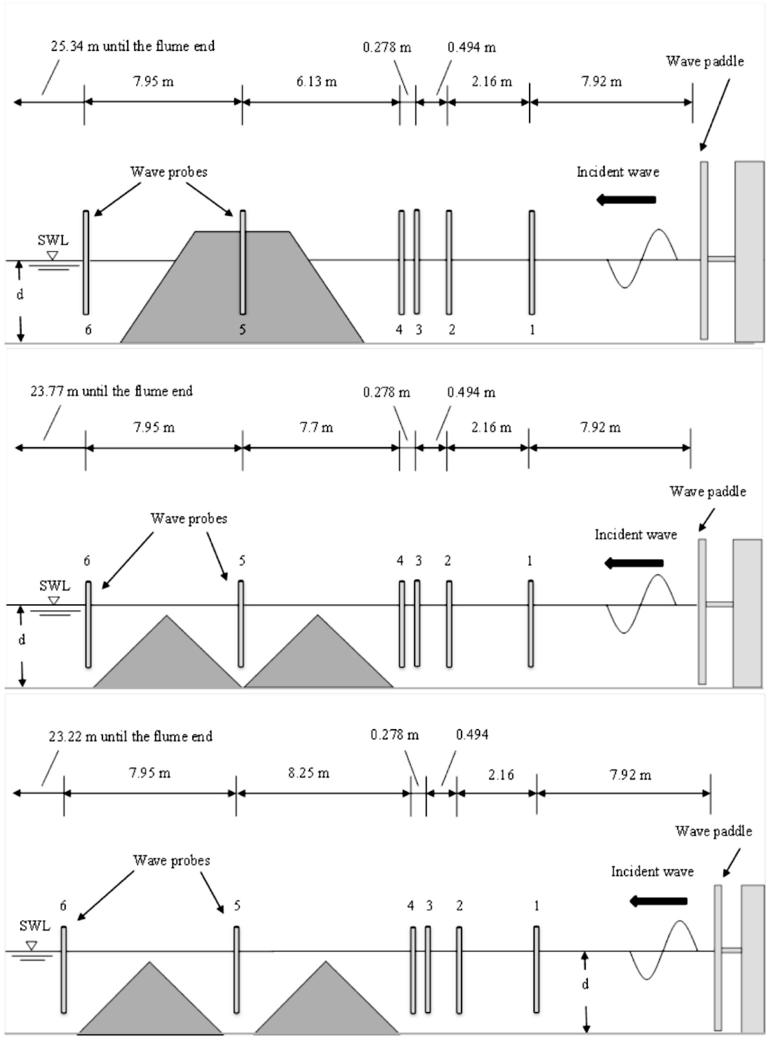

Figure 1. Details of flume, location of the model, and positions of wave probes. Top: single breakwater, middle: twin breakwaters with S = 0, and bottom: twin breakwaters with S = 1.04 m.

An A/D converter was used for converting analogue signals transmitted from the wave probes into digital data. The data collected by the wave gauges and represented as time series files was analyzed using the Wave Synthesizer (WS) Analysis Tools provided by DHI. WS Crossing Analysis, WS Reflection Analysis, and WS Linear Spectral Analysis modules were all used for data analysis. One wave probe (WP1) was placed in front of the wave maker at a distance equal to one wave length of the largest wave to be generated during the experiments to measure the incident wave heights. Three other wave probes (WP2, WP3, and WP4) were fixed in front of the breakwater model to measure the wave heights of the reflected waves and separate them from the incident ones. To avoid singularity in the incident and reflected wave height estimations as described by Goda and Suzuki (1967), the DHI Manual standards require that the distance between wave probes WP2 and WP4 (i.e. Δl24) should satisfy the following criterion:

$$\Delta l24 \geq \frac{L_{max}}{20} \tag{1}$$

where L_{max} is the maximum wave length to be generated during the model testing. In this study, a maximum wave length of 7.45 m is generated; however, a wave length of 10 m is utilized for calculating this formula to consider the generation of any long waves in random waves experiments. Thus, in the present work, the selected values for Δl24 and Δl34 were chosen as 0.772 m and 0.278 m, respectively, to meet the DHI manual requirements. The fifth wave probe (WP5) was partially immersed inside the breakwater model when a single structure was being tested, and in the middle between the breakwaters in the case of twin breakwaters, to measure the wave variations either inside the single structure or in the water pool formed in the area between the twin breakwaters. One additional wave probe (WP6) was placed in the lee side of the breakwater to measure the transmitted wave height. The input parameters used for regular and random wave tests are presented in Table 1, in which H_i is the incident wave height, H_{is} is the significant incident wave height, T is the wave period for regular waves and Tp is the peak period for random waves, d is the water depth, and S is the clear spacing between the bottoms of the twin breakwaters. Three water depths and two spacing conditions were considered for testing the single and twin breakwaters during the study. Ranges of the normalized parameters used in regular and random wave experiments are presented in Table 2 in which H_i/L is the wave steepness, d/L is the relative water depth, h/d is the relative height of the breakwater, $(h\text{-}d)/H_i$ is the relative wave height, and S/h is the relative spacing between the twin breakwaters. Three water depth conditions were used in the experiments. These conditions are submerged, water level at the breakwater crest, and emerged (Table 3). The indications of the used normalized parameters are shown in Table 4. The single and twin permeable breakwater models were both constructed with single sized rubbles. The use of single sized structure is the reduction of construction time and cost as well as simplifying the construction process. Details of the three tested models are provided in Table 5.

Table 1. Input parameters for regular and random wave tests.

Incident waves	H_i (m)	T (s)	d (m)	S (m)
Regular	0.1, 0.2	1, 1.2, 1.4, 1.6, 1.8, 2, 2.5, 3	0.5, 0.6, 0.7	0, 1.04
Incident waves	H_{is} (m)	Tp (s)	d (m)	S (m)
Random	0.1	1, 2, 3	0.5, 0.6, 0.7	0, 1.04

Table 2. Ranges of normalized parameters for regular and random wave tests.

Normalized parameter	H_i/L	d/L	$(h\text{-}d)/H_i$	S/h	h/d
Regular waves	0.0134 – 0.1322	0.0782 – 0.451	-0.5 – 1	0 – 1.73	0.857 – 1.2
Normalized parameter	H_{is}/L_p	d/L_p	$(h\text{-}d)/H_{is}$	S/h	h/d
Random waves	0.0134 – 0.0661	0.0782 – 0.451	-1 – 1	0 – 1.73	0.857 – 1.2

Table 3. Submergence conditions of breakwaters.

Water depth, *d* (m)	Water level condition	Breakwater submergence condition
0.7	High water level (HWL)	Submerged
0.6	Mean water level (MWL)	Water level at breakwater crest
0.5	Low water level (LWL)	Emerged

Table 4. Normalized parameters used in the study.

	Normalized parameters		
Water level and wave height condition	h/d	$(h\text{-}d)/H_i$	S/h
HWL, H_i= 0.1m	0.857	-1	• S/h= 0 for twin breakwaters with no clear spacing, S=0 • S/h=1.73 for twin breakwaters with clear spacing, S=1.04m
HWL, H_i= 0.2m	0.857	-0.5	
MWL, H_i= 0.1 or 0.2 m	1	0	
LWL, H_i= 0.1m	1.2	1	
LWL, H_i= 0.2 m	1.2	0.5	

Table 5. Model details for single and twin breakwaters.

Model Properties	Single Breakwater	Twin Breakwater (Case A)	Twin Breakwater (Case B)
Shape	Trapezoidal	Triangular	Triangular
Crest height, h (m)	0.6	0.6	0.6
Crest width (m)	1.04	0	0
Base width (m)	3.12	2.08	2.08
Sea side slope	15/26	15/26	15/26
Lee side slope	15/26	15/26	15/26
Clear spacing, S (m)	-	0	1.04

The horizontal distance between the peaks of the twin breakwater is 2.08 m, when S=0.0 m, and is 3.12 m, when S=1.04 m. The horizontal distance between peaks is important, since when this distance is equal to nL/2, where n=1,2,3, and so on, it will induce resonance in the pool of water between the breakwater, which will substantially affect the wave transmission, reflection, and energy dissipation.

The interaction between the incident waves and the breakwater causes simultaneous variations in the wave profile. Some of these waves are reflected backward and some are transmitted through the porous media of the breakwater and by wave overtopping, while some wave energy is dissipated during the process. If the porosity of the breakwater is high and the breakwater is emerged, then most of the wave transmissions are by flow through porous media. On the other hand, if the breakwater is submerged and the porosity is less, then the transmission will be mainly by wave overtopping. Using the wave height data recorded by wave gauges WP2, WP3, and WP4 during the physical modeling experiments, the coefficient of wave reflection, K_r, is estimated by the reflection analysis tool, where

$$K_r = \frac{H_r}{H_i} \tag{2}$$

The transmitted wave height, H_t, was recorded by WP6. The coefficient of wave transmission, K_t, is defined as

$$K_t = \frac{H_t}{H_i} \tag{3}$$

Based on the law of energy conservation, the coefficient of energy dissipation, K_l, is estimated from the following relationship:

$$K_t^2 + K_r^2 + K_l^2 = 1 \tag{4}$$

Hence,

$$K_l = \sqrt{1 - K_t^2 - K_r^2} \tag{5}$$

For a multi-parameter problem, carrying out a dimensional analysis can be of great advantage to identify the governing parameters, which control the model performance during the test studies. When a rubble mound structure is subjected to a train of water waves that propagate in a normal direction, the variables that affect the breakwater efficiency and influence the nature of the obtained results for reflection, transmission, and energy dissipation coefficients include wave length and height (*L* and *H*), water depth (*d*), crest height of the breakwater (*h*), and spacing between double breakwaters (*S*). Thus, the reflection, transmission, and energy dissipation coefficients can be expressed in terms of dimensional parameters representing the wave and structure characteristics as follows:

$$K_r, K_t, and\ K_l = f\left(\frac{d}{L}, \frac{H_i}{L}, \frac{h}{d}, \frac{h-d}{H_i}\right) \tag{6}$$

In the case of twin breakwaters, the relative spacing between the breakwaters (*S/h*) is added; thus:

$$K_r, K_t, and\ K_l = f\left(\frac{d}{L}, \frac{H_i}{L}, \frac{h}{d}, \frac{S}{h}, \frac{h-d}{H_i}\right) \tag{7}$$

Thus, the possible factors affecting the wave attenuation efficiency of the breakwater models are the relative water depth (*d/L*), wave steepness (*Hi/L*), relative wave height, (*h-d)/Hi*), relative height of the breakwater, (*h/d*), and relative clear spacing between the twin breakwaters, (*S/h*). The influence of all these parameters on the coefficients of wave transmission, reflection, and energy dissipation is discussed in the following section.

For regular wave tests, waves were generated for a total duration of 90 s for each run. The utilized wave heights were 10 and 20 cm, and the wave periods ranged from 1 to 3s. Data collection from all channels was initiated at least 20s after the start of wave generation with a total duration of 30s to guarantee the beginning of the repeatability of the same wave heights at the model location and consider the short period waves (*T=1s*), which travel slower than the long period waves. After the completion of each run, the resulting real time series for water surface elevations measured by wave gauges (which results from multiplying the time series in volts by the calibration constants) were initially checked for the data collection accuracy. The adopted starting time for data collection was based on trial runs with different wave periods, while the data collection duration and ending time were appropriately selected in a way that prevents any re-reflected waves from the wave maker or the wave dissipater from affecting the measurements around the test section. For the random wave tests, waves were generated using a predefined JONSWAP spectrum for a total duration of 270s in each run. A total of 27 runs were performed with a significant wave height of 10 cm and peak wave periods ranging from 1 to 3s with an increment of 1s. Data collection from all channels was initiated at 20s after the start of wave generation with a total duration of 250s.

RESULTS AND DISCUSSIONS

Since 8 different wave periods are used, there are eight different *d/L* values. Other normalized input parameters are either two (two different breakwaters, two different relative spacing, two different wave heights, etc.) or three (three different water depths, etc.). Hence, the relative water depth (*d/L*) is considered on the x-axis of plots to understand how other normalized parameters affect *Kr*, *Kt*, and *Kl*.

Regular wave tests

For the case of LWL (i.e., emerged breakwater) and $(h\text{-}d)/H_i = 1$ (i.e., the incident wave height is equal to the depth of emergence of the breakwater), the results show that as the *d/L* increases, the value of K_t decreases. The maximum value for K_t is 0.25 for all types of breakwaters and is close to zero as *d/L* exceeds approximately 0.19 (Figure 2(a)). For single breakwater, K_t is smaller than those for twin breakwaters when *d/L* is relatively small (relatively long waves). The results indicate good performance for all breakwaters in blocking the wave transmission for this condition. This is expected to occur as the increase in *d/L* corresponds to relatively short waves, which tend to dissipate more energy through breaking and hence experience less transmission.

All breakwater types show the same trend in K_r with the increase in *d/L*. The values of K_r keep oscillating from peak to minimum due to the occurrence of wave resonance at wave lengths of 3.57 and 2.05 m. At LWL condition, the incident waves mostly interact with the seaward side of either the single breakwater or the first twin breakwater with minimum wave overtopping; hence, the energy dissipation mechanism is mostly due to the flow of water through the porous media of the structure, which induces turbulence and shear friction between the water waves and the rubbles of the breakwater. K_l takes the opposite trend to K_r. The points where waves are resonating show minimum energy dissipation values, while the peak values of energy loss occur when *Kr* takes minimum values. This is expected as the occurrence of the resonance phenomenon pushes more water volumes away from the breakwater and hence decreases the energy loss.

Similar phenomena for K_r, K_t, and K_l are observed when the value of $(h\text{-}d)/H_i = 0.5$ (Figure 2(b)).

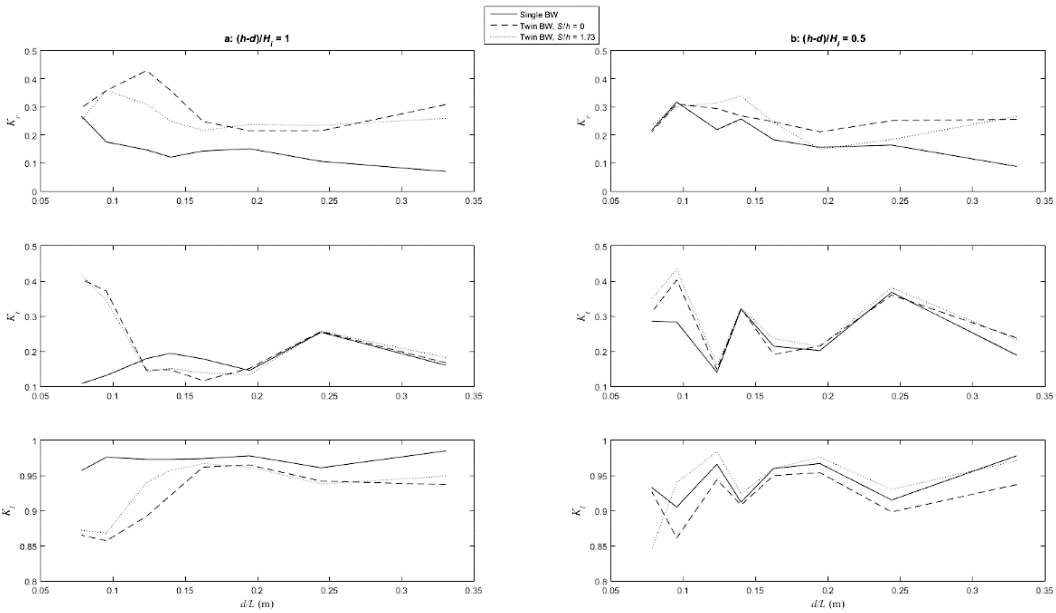

Figure 2. K_r, K_t, and *Kl* versus *d/L* for regular waves at LWL.

For the case of MWL, two conditions were tested: (1) $(h\text{-}d)/H_i = 0$ and $H_i = 0.1$ m and (2) $(h\text{-}d)/H_i = 0$ and $H_i = 0.2$ m. For the first case (Figure 3(a)), the single breakwater seems to reduce the wave transmission more effectively as the increase in d/L results in a reduction in K_t past the structure, while wave resonance is observed between the twin breakwaters with *S/h*=1.73 at a wave length of 5.67m, and between the twin breakwaters with *S/h*=0 at a wave length of 4.36m. When d/L is relatively small, the twin breakwaters reflect more wave energy when compared to the single breakwater, while the reflecting capabilities of all breakwater types are the same for relatively high d/L values ($d/L \geq 0.222$). The reflected waves are resonating at a wave length of 3.82 m when a single breakwater is being tested and at a wave length of 2.12 m for both types of twin breakwaters. Figure 3(a) shows that, for small wave heights (H_i=0.1 m), the energy dissipation is generally good for all breakwaters; however; the single breakwater shows stronger wave attenuation effect, maintaining high dissipation values ($K_l > 0.95$) for all tested relative water depths.

For the second case (Figure 3(b)), the maximum value of Kt is limited to 0.35 for all breakwater types; however; it seems that the single breakwater reduces wave transmission more effectively, especially for steeper waves (when *d/L* is relatively large), despite the occurrence of wave resonance at wave lengths of 5.67 and 3.82 m. It can be noticed that the general performance of all breakwater types in reflecting wave energy is similar for high waves (H_i=0.2 m); however; when compared to the single breakwater, the twin breakwaters reflect more wave energy when *d/L* is relatively small ($d/L \leq 0.137$) or relatively large ($d/L > 0.32$). The values of K_r keep oscillating from peak to minimum due to wave resonance, which occurs at wave lengths of 5.67, 3.82, and 2.12 m for both types of twin breakwaters, and at wave lengths of 3.82 and 2.12 m for the single breakwater. The dissipation mechanism at MWL condition is mostly due to wave breaking at the first structure. More energy loss can occur due to the flow of water inside the porous structures, which induces turbulence and shear friction and the oscillation of water in between the twin breakwaters. Figure 3b shows that K_l takes the opposite trend to K_r for all breakwaters. The points where the reflected waves are resonating show minimum energy dissipation values, whereas the peak values of energy loss occur when K_r takes minimum values. All breakwaters show good energy dissipation ($K_l \geq 0.85$); however; the wave energy loss due to single breakwater is slightly higher.

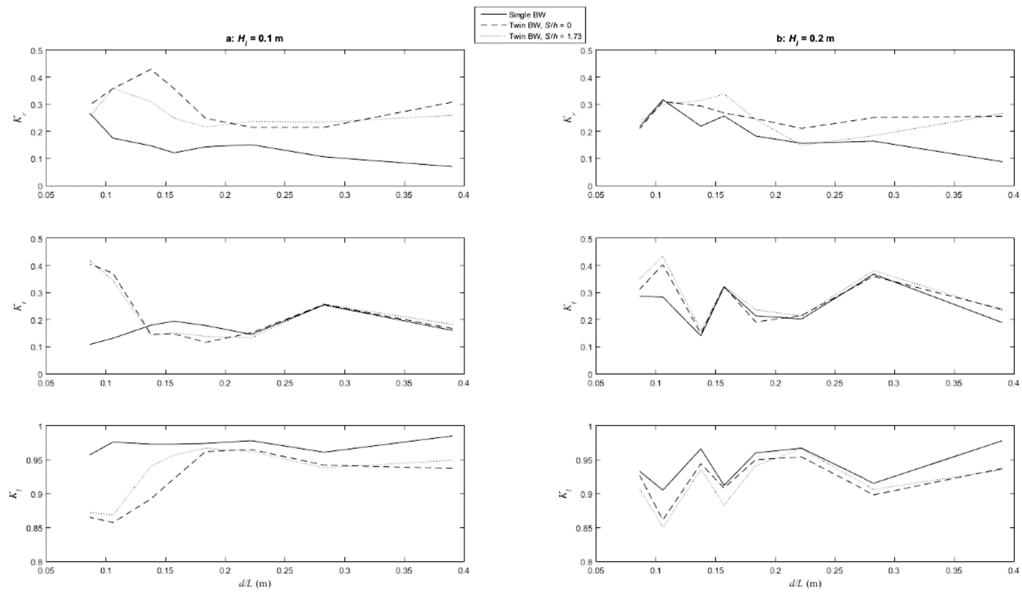

Figure 3. K_r, K_t, and K_l versus to *d/L* for regular waves at MWL.

For the case of HWL, two conditions were tested (1) $(h\text{-}d)/H_i$ = -1 and (2) $(h\text{-}d)/H_i$ = -0.5. For the first case (Figure 4(a)), the values of K_t are relatively high, and this is expected due to the increase in the wave overtopping, and the three breakwater models show different performance in blocking wave transmission. In general, the single breakwater allows for less wave transmission when compared to the twin breakwaters. Wave resonance occurs at wave lengths of 6.06 and 4.03 m for double breakwaters with *S/h*=0 and at wave lengths of 6.06 and 3.43 m for double breakwaters with *S/h*=1.73, whereas for single breakwater, the waves resonate at a wave length of 4.03 m. When *d/L* is relatively small, both types of twin breakwaters show higher reflecting capabilities than the single breakwater. On the other hand, when *d/L* is relatively large (*d/L*≥0.25), all breakwaters reflect the incident waves in a similar way. The double breakwaters with *S/h*=0 cause the reflected waves to resonate at a wave length of 6.06 m, while the single breakwater causes wave resonance at a wave length of 4.62 m. The three breakwater models show different trends in dissipating incident wave energy; however; the coefficient of energy loss corresponding to the single breakwater is always greater than 0.8, which indicates a better wave attenuation effect.

For the second case (Figure 4(b)), when interacting with high water waves and under high water level condition, all breakwaters take the same trend in K_t as *d/L* increases. For the three tested breakwaters, wave resonance occurs at a wave length of 6.06 m and a wave length of 3.43 m. It can be noticed that the single breakwater allows for the lowest wave transmission, while the double breakwater with *S/h*=0 has the highest K_t values. When d/L is relatively small (*d/L*< 0.25), the tested breakwaters show different trends in reflecting wave energy, and the single breakwater has the lowest K_r values among all as observed from Figure 4b. For relatively larger *d/L* (when $d/L \geq 0.25$), all breakwaters perform in a similar way with very close K_r values. As for energy dissipation, the same trend is noticed for all tested breakwaters, and the single breakwater performs best in dissipating incident wave energy, maintaining high values for the energy dissipation coefficient (K_l>0.85), for all tested *d/L* values.

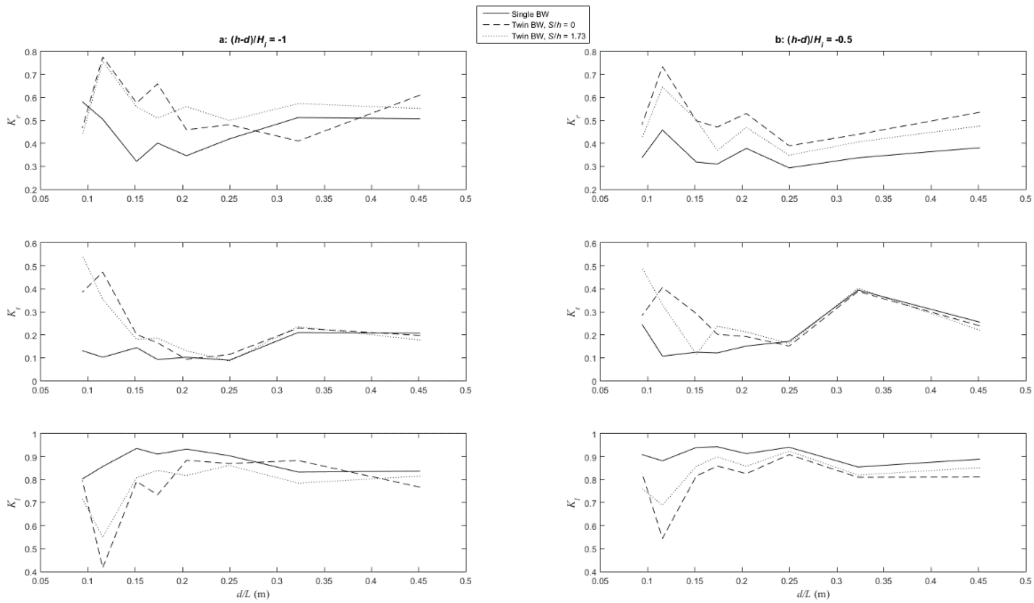

Figure 4. K_r, K_t, and K_l versus to *d/L* for regular waves at LWL.

Random wave tests

a) LWL tests

The results of random wave tests for the condition of LWL (Figure 5(a)) show that the coefficient of wave transmission, K_t, decreases with the increase in the relative water depth, *d/L*p. The values of K_t corresponding to the single breakwater are slightly smaller when compared to the twin. The resulting K_t values from the single breakwater range from 0.019 to 0.097, while the values of K_t for double breakwaters with *S/h* =0 and *S/h*=1.73 range from 0.039 to 0.179 and from 0.028 to 0.179, respectively. The increase in *d/L*p causes a decrease in K_r values for the single breakwater, whereas for double breakwaters, the increase in relative water depth causes K_t to decrease between d/Lp = 0.078 and *d/L*p = 0.12, and it maintains constant values until *d/L*p = 0.33. Moreover, the single breakwater reflects more wave energy than the double breakwaters, as observed from Figure 5(a). As for the coefficient of energy dissipation, the increase in *d/L*p causes a slight increase in K_l for all breakwaters, and the high values of K_l indicate good energy dissipation.

b) MWL tests

When testing wave transmission, the increase in water depth from 0.5 to 0.6 m (LWL to MWL) does not change the way of performance for all breakwaters. Figure 5(b) shows that K_t decreases with the increase in *d/L*p for all breakwaters, and the single breakwater has the lowest values of K_t. The three tested models show different trends in reflecting wave energy. The increase in d/Lp causes a linear increase in K_r for single breakwater. For double breakwater with *S/h*=0, the value of K_r decreases from 0.401 to 0.207 with the increase in *d/L*p, whereas for double breakwater with *S/h*=1.73, K_t decreases from 0.428 to 0.19 with the increase in *d/L*p and then increases slightly reaching a value of 0.223 at *d/L*p= 0.39. For all tested breakwaters, the coefficient of energy loss K_l increases with the increase in *d/L*p. Between *d/L*p =0.087 to 0.138, the increase in K_l is noticeable, while it is very slight between *d/L*p = 0.138 and 0.39.

c) HWL tests

At this condition, the increase in *d/L*p causes a decrease in wave transmission due to single breakwater from 0.59 at *d/L*p = 0.094 to 0.511 at *d/L*p = 0.451, whereas for double breakwaters with *S/h*=0, the increase in relative water depth causes K_t to decrease between *d/L*p= 0.094 and *d/L*p= 0.151 and increase again unit *d/L*p= 0.451, and for double breakwaters with *S/h*=1.73, the increase in *d/L*p results in a linear increase in K_t from 0.612 at *d/L*p= 0.094 to 0.653 at *d/L*p= 0.451. Different trends in wave reflection are observed for the three tested models. The increase in d/Lp causes a decrease in K_r from 0.39 at *d/L*p= 0.094 to 0.213 at *d/L*p= 0.451 for double breakwaters with S/h=0. For single breakwater, the value of K_r decreases between *d/L*p= 0.094 and *d/L*p= 0.151 and increases again until *d/L*p= 0.451. As for the double breakwaters with *S/h*=1.73, the value of K_r decreases significantly from 0.472 at *d/L*p= 0.094 to 0.187 at *d/L*p= 0.151 and then starts increasing again, reaching a value of 0.208 at *d/L*p= 0.451. Figure 5(c) demonstrates that all breakwaters show the same performance in dissipating incident wave energy. As *d/L*p increases, the coefficient of energy loss, K_l, starts increasing between *d/L*p= 0.094 and *d/L*p= 0.151 and decreases slightly afterwards. The figure also shows that the single breakwater has the highest K_l values and hence performs best in dissipating incident wave energy.

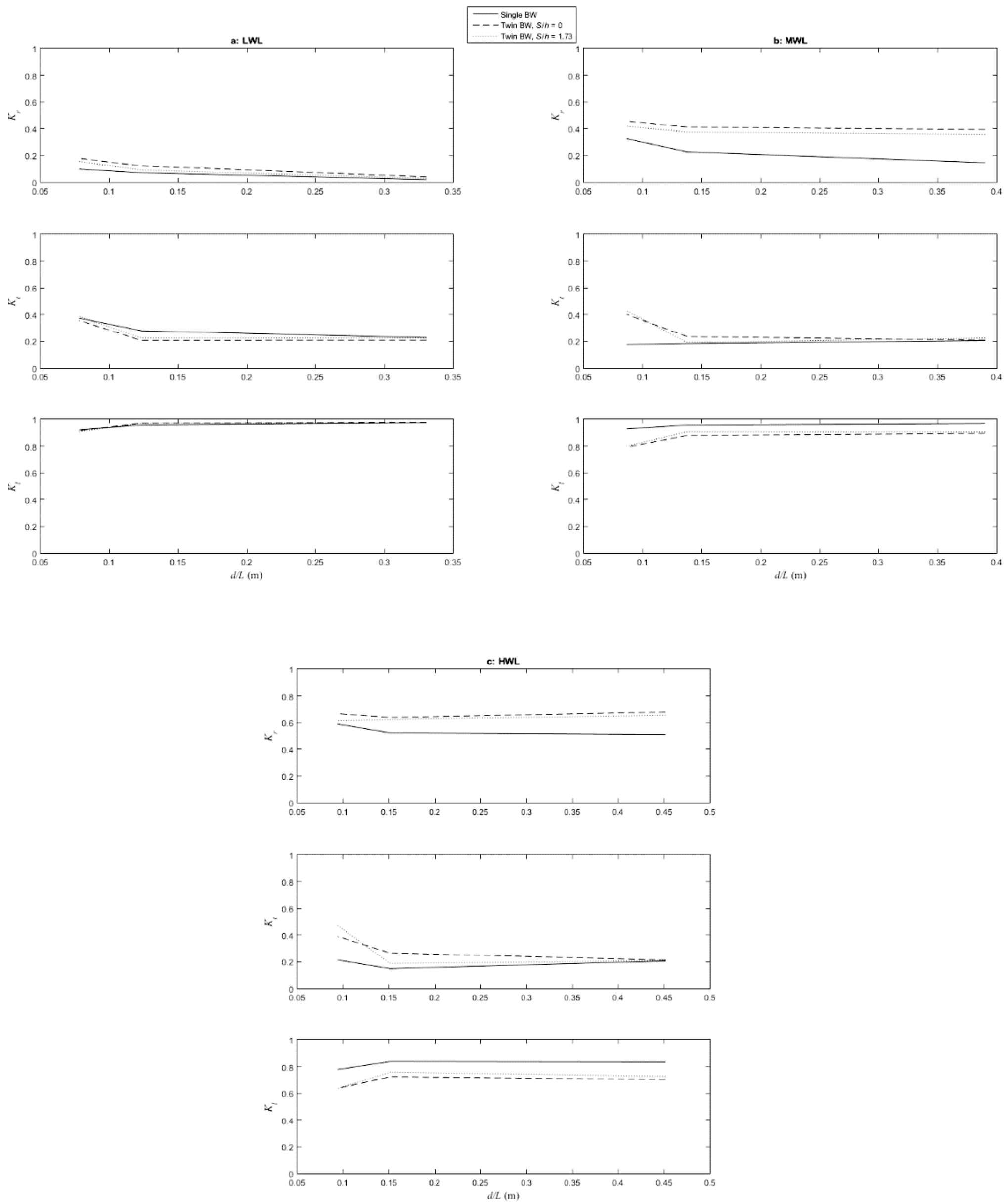

Figure 5. K_r, K_t, and K_l versus to *d/L* for random waves at (a) LWL, (b) MWL, and (c) HWL.

CONCLUSIONS

By keeping the volume of the breakwater material constant, a single trapezoidal shaped offshore breakwater is better than twin triangular shaped offshore breakwater for reducing the wave transmission. In comparison with the results reported in the literature, the results obtained in this study are quite different, as the single breakwater showed better hydrodynamic performance than the twin breakwaters, and this is due to the triangular design shape chosen for the twin breakwaters, which causes a significant reduction in their protection efficiency.

For twin triangular shaped offshore breakwater, increasing the relative spacing S/h from 0.0 to 1.73 helps reduce the wave transmission to a maximum extent of 20%.

In general, the increase in the relative water depth decreases the coefficient of wave transmission at LWL condition, regardless of the wave height, whereas for MWL and HWL conditions, it causes an oscillating response for all tested breakwater types.

The increase in the incident wave height generally leads to an increase in the reflection coefficients for all tested breakwaters under regular waves, regardless of the relative breakwater height. For twin breakwater during resonance condition, the wave energy dissipation reduces considerably.

The results for regular waves show very significant fluctuations due to the change in the relative water depth, while such fluctuations are not observed for random waves. This major difference in the response to the interaction with single and double breakwaters is due to wave resonance, which does not occur when random waves are acting on the structure, whereas it is predominant in regular waves.

This study with twin trapezoidal offshore breakwater and a study by more numbers of relative spacing between the twin breakwaters are to investigate the influence of changing the relative breakwater spacing on the occurrence of wave resonance and its effect on transmission, reflection, and dissipation.

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