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Experimental investigating on the reflected waves from the caisson-type vertical porous seawalls

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Abstract

The hydrodynamic efficiencies of caisson-type vertical porous seawalls used for protecting coastal areas were calculated in this study. Physical models were developed to compare the wave reflection from vertical plane, semi-porous, and porous seawalls caused by both regular and random waves. Tests were carried out for a wide range of wave heights, wave periods, and different water depths (d=0.165, 0.270 and 0.375 m). The performance regarding the reflected waves from porous and semi-porous seawalls showed improvement when compared with those from the plane seawall. The reflection coefficients of the porous and semi-porous seawalls were calculated as 0.6 and 0.75, respectively, while the coefficient for the fully reflecting plane vertical wall was significantly higher (0.9). It was also observed that the reflection coefficient decreases with increase in wave steepness and relative water depth. In addition, the reduction in the reflection coefficient of porous and semi-porous seawalls, as compared to that of a plane seawall, was observed for both regular and random waves. New equations were also proposed to calculate the reflection coefficient of different types of seawalls with the aid of laboratory experiments. By verifying the developed equations using some other experimental data, it was validated that the equations could be used for practical situations. The results of the present study can be applied to optimize the design of vertical seawalls and for coastal protecting schemes.

Key words: reflection coefficient, porous seawall, regular wave, random wave, flume

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1 Introduction

Seawalls are structures that can be used to protect shorelines. They are built to reduce the destructive effects of wave action, protect the shore from excessive erosion, and guard coastal structures against damage. Any seawall placed in a wave field reflects part of the incident wave energy away from the structure, which in turn creates steep and unstable waves. This can then lead to increasing wave disturbance and wave loads in adjacent areas and harbors. As a result, for harbor management and shore protection, it is extremely important to identify the cause and impact of wave reflections and discover preventive solutions.

Porous seawalls could be used as a solution to the problem associated with increasing wave disturbance. Porous seawalls are common shore protection structures around the world. They can dissipate the incident wave energy and reduce the reflected wave height. Vertical porous seawalls are considered as effective replacement for traditional impermeable seawalls, especially for the reduction of wave energy in harbors and fishing ports. The amount of wave energy dissipation depends on the porosity of the seawall (n). In addition, the shore side of the vertical porous seawall can be used for vessel berthing activities.

Many theoretical and experimental studies have been conducted on different hydrodynamic aspects of waves, such as reflection, transmission, and dissipation, and their effects on various seawall structures. For instance, Zhu (1999) examined the wave interactions of a porous seawall to estimate the reflection of waves by employing theoretical analyses, numerical modeling, and experimental investigations. Suh et al. (2001), using an analytical model, deduced that the reflection of irregular waves radiated normal to a caisson-type seawall. They conducted some laboratory tests to investigate the performance of the proposed model. In this regard, varying flume widths were employed. They showed that the frequency-averaged reflection coefficients derived from the measurement were in line with those obtained from calculations.

Zhu and Chwang (2001) analytically studied the interaction between waves by developing a linear wave, using a slotted seawall with a specific expansion function method. Their investigations indicated that the characteristics of the reflected waves mainly depend on the porosity of the seawall gap and height of the incident wave.

Neelamani and Sandhya (2003) conducted an experimental study to compare the reflection characteristics of vertical and sloped planes and dentate and serrated seawall models. In their research, they considered regular and random waves across a myriad of heights and periods. They measured the reflection of different waves to assess the dissipation effect of the seawalls. They claimed that the serrated seawall showed better efficiency, compared with the plane and dentate seawalls, for reduction of the reflection of waves. Based on their measurements and multiple regression analyses, they offered some equations to calcu-

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*Corresponding author, E-mail: maryamrahbani@yahoo.com late the reflection coefficient caused by regular and random waves.

Chen et al. (2006) proposed a numerical solution for the reflected waves from a submerged porous vertical seawall. They mentioned that the submerged porous structure with a trapezoidal shape has higher efficiency in the reduction of wave reflection than that with a triangular shape. Employing extensive experimental data, Zanuttigh and van der Meer (2008) analyzed the wave reflection for various types of seawalls and presented a new, simple formula for both permeable and impermeable seawalls.

Theocharis et al. (2011) proposed a new type of wave absorbing quay wall with a partial wave chamber containing a rock-armored slope. In the investigation, they employed a physical model and claimed that wave heights in front of the wall can be reduced by 20%–30%. Young and Testik (2011) studied the effects of submerged vertical and semicircular breakwaters on local waves and the characteristics of the reflected wave. In their research, the parameterization technique was used to obtain reflection coefficients.

Koraim and Rageh (2013) used a physical model to find the hydrodynamic efficiency of vertical porous structures under the effect of regular waves. In their study, empirical equations were developed to estimate their transmission and reflection coefficients. In another experiment, Koraim et al. (2014) investigated the wave reflection characteristics of a new type of porous seawall for the protection of coastal areas with a likely sea level rise. For this purpose, a physical model was used and they showed that the calculated reflection coefficients owing to the seawall decreased with increasing relative water depth, wave steepness, relative seawall width, and seawall porosity.

Lee and Shin (2014) carried out some laboratory tests in a wave flume with one and two gaps to obtain the reflection coefficient of a caisson-type partially perforated seawall. They presented different reflection coefficients for each seawall configuration of the structure.

Furthermore, Negm and Nassar (2016) investigated vertical and sloping seawalls, and determined the optimal characteristics of seawalls for reflection of waves under a variety of hydrodynamic conditions. In their experiments, both rectangular and triangular serrated blocks and slotted seawalls were considered. Using dimensional analysis and laboratory measurements, they proposed formulae to calculate the reflection coefficient of the seawalls employed in their experiment.

From the literature survey, it was concluded that nearly no investigation has been carried out on the mechanism of wave reflection from vertical caisson-type porous and semi-porous seawalls. The present study is based on experimental investigations on wave interactions with vertical porous and semi-porous seawalls in order to estimate the reflection coefficient of the wave against these seawalls. The aim of this research is to better understand the performance of vertical porous and semi-porous seawalls in front of sea waves and to increase the knowledge about this type of coastal structures.

To achieve this aim, some laboratory tests were conducted on vertical plane, semi-porous, and porous seawalls. The tests were carried out with regular and random waves for a wide range of hydrodynamic conditions and for different water depths. The exact experiments were conducted for plane, semi-porous, and porous seawalls in order to obtain the best performance with regard to the reflection coefficients and to determine an empirical formula for the reflection coefficient, K_r, of each type of seawall.

2 Experimental set-up and methods

2.1 *Wave flume*

In this experiment, a wave flume with dimensions of 33 m (length)×5.5 m (width)×1.5 m (height) was used. The wave flume was provided by the Soil Conservation and Watershed Management Research Institute, Tehran, Iran. It was equipped with a modern Danish Hydraulic Institute (DHI) wave generating system and included paddle, power pack, hardware, and software components.

To prevent the formation of cross waves, the flume was divided into three longitudinal distinct sections employing two 24.5 m long walls, 1 m from each other (Fig. 1). A piston-type wave maker was installed at one side of the flume to generate regular and random waves. At the other side of the flume, a rock slope absorber, with a slope of 1:8, was provided to effectively absorb the wave's energy (Fig. 2).

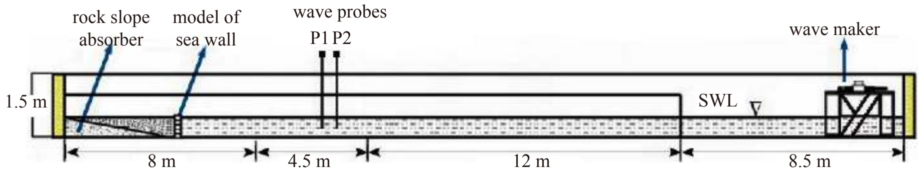


Fig. 1. Side view of the SCWMRI wave flume.

Fig. 2. A view of the SCWMRI wave flume.

2.2 *Seawall details*

A caisson is a hollow box that, when filled with the proper materials, can be sunk to a desired water depth to form a foundation. The use of caissons in the development of seawalls is gaining considerable attention, e.g., Yan et al. (2017) and Sassa et al. (2016). A caisson-type seawall prototype was used in the installation of the wave flume. The dimension of each caisson was 0.1 m × 0.1 m × 0.1 m, and it was made from a 1-cm thick Plexiglas sheet. To obtain a semicircular shape to reduce the reflection of the wave, a semi cylinder Plexiglas with an outer radius of 5 cm and inner radius of 1.5 cm was connected to one of the uncovered sides of the box (Fig. 3).

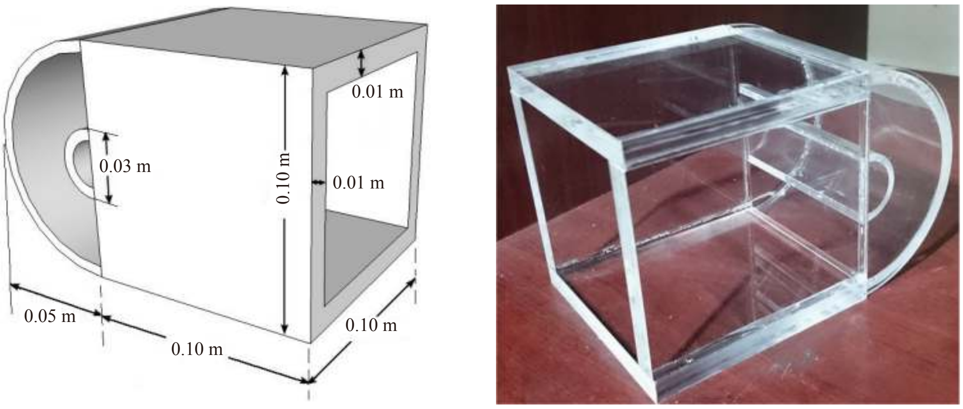
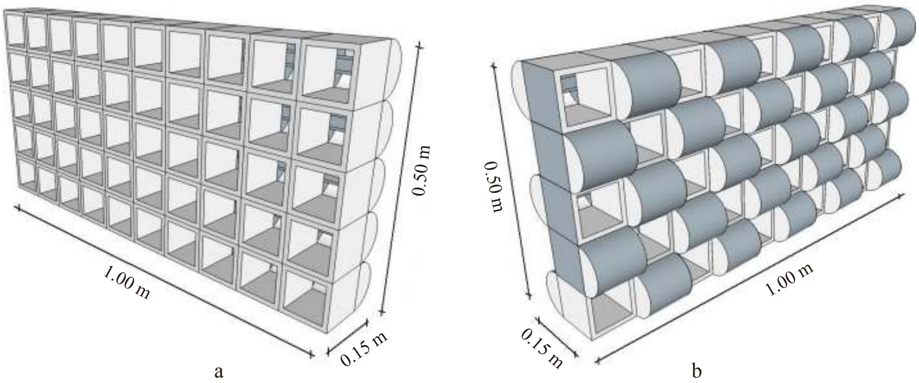


Fig. 3. The designated caisson for the seawall.

The next step involved affixing 50 blocks to a rigid frame in the flume in two formats; one as a totally porous seawall (Fig. 4a) and the other as a semi-porous seawall (Fig. 4b). The frame was fixed inside the main flume vertically and rigidly, 24 m away from the wave paddle. The wave probes were located 6 m and 6.35 m from the seawall model.



a

b

Fig. 4. A schematic view of the porous (a) and the semi-porous seawall (b).

The Froude scaling technique was considered to calculate the proper wave heights and wave periods in this experiment. Therefore, the dimensions of the seawall and the experimental wave height were considered based on a 1:10 scale; that is, considering a normal wave height of 0.3–1.5 m with wave period of 3–5 s inside the breakwater domain, the proper wave period and wave height were calculated. This principle was also used for the correct reproduction of the gravitational and fluid inertial forces.

2.3 *Characteristics of the waves*

This experiment involved the use of waves with heights ranging from 0.03–0.15 m and wave periods ranging from 1.6–2.8 s, which, according to the Froude scale, correspond in actual situations to wave heights of 0.3–1.5 m and wave periods of 5.05–8.85 s, respectively. Table 1 presents the ranges of the parameters that were used for the different experiments. Table 2 lists the non-dimensional parameters that were employed for the regular and random wave experiments.

A total of 144 and 120 tests were conducted to measure the reflection coefficient of the regular and random waves, respectively, and they were conducted using plane, semi-porous, and porous seawalls. The amount of wave reflection is described by the reflection coefficient K_r, defined in terms of incident and reflected wave heights, H_i and H_r, respectively:

$$K_{\rm r} = H_{\rm r}/H_{\rm i}. \tag{1}$$

Table 1. Ranges of parameters used to setup the experimental tests

Parameter	Range
Wave period (T)	1.6–2.8 s
Wave length (L)	1.95–5.22 m
Incident wave height (H)	0.03–0.15 m
Water depth (d)	0.165, 0.270 and 0.370 m
Seawall porosity (n)	32% and 64 %

Two embedded wave probes were used to measure the hydrodynamic parameter of waves (i.e., incident and reflected wave heights). The representation of the probes' measurements was recorded as water-level variations owing to the incident and reflected waves' interactions. The wave synthesizer (WS) software provided by the Danish Hydraulic Institute was used to convert the resulted water-level time series into the incident and reflected waves. This was done to calculate the wave reflection. The software analyzes both regular and random waves with a desired wave height and period. The WS software uses the basic principle of a two-wave probe method described by Goda and Suzuki (1976) to calculate the reflection coefficient. To conduct their research, $0.05 < \Delta l/L < 0.45$ was considered, where Δl and L represent the distance between the two wave probes and the incident wavelength, respectively.

Table 2. Definitions and ranges of non-dimensional parameters for regular and random waves

Type of wave	Parameter	Definition	Range	Number of tests
Regular	H_i/L	incident wave steepness	0.007–0.054	144
	d/L	relative water depth	0.047–0.135	
	H_i/d	relative wave height	0.087–0.543	
Random	H_s/L_p	incident wave steepness	0.007–0.042	120
	d/L_p	relative water depth	0.047–0.135	
	H_s/d	relative wave height	0.093–0.475	

In accordance with the wave-probe separation distance criterion, the value of $\Delta l < 0.35$ m was chosen for all the experimental measurements in this research. The incident wave profiles were established by the generated waves without using the seawall model inside the main flume.

3 Results and discussion

3.1 *Reflection of regular waves*

The effect of wave height, in terms of wave steepness (H_i/L), and wave period, in terms of relative water depth (d/L), on the K_r was investigated for plane, semi-porous, and porous seawalls. A set of tests were carried out for three different depths: 0.375 m, 0.270 m, and 0.165 m. As the results were quite similar for the different depths, the results relevant to the depth of 0.270 m are presented here. Figure 5 represents the effect of wave height on the reflection coefficient for different wave periods on the vertical plane, semi-porous, and porous seawalls.

The reflection coefficients of the waves reflected from the plane seawall, for all H_i/L and d/L, were higher than 0.92. Under the same hydrodynamic conditions, the semi-porous and porous seawalls alternatively provided a K_r in the range of 0.7–0.94, and 0.57–0.89, respectively. These results clearly indicate the superiority of the vertical porous seawall compared to the plane wall.

Considering the average value for each seawall, the reflection coefficient for the porous and semi-porous seawalls showed 30% and 17% improvement, respectively. In fact, during these tests, it was observed that the porous seawall offered the least reflection for the regular waves. Figure 5 also shows that for vertical, semi-porous, and porous seawalls, the K_r value decreases with increasing H_i/L, owing to larger dissipation of energy for steeper waves. Figure 6 illustrates the effect of d/L on K_r for a constant value of H_i/d in different water depths. For a constant value of depth, it can be concluded that the variation in the parameter d/L represents the variation in period.

The increase in relative water depth, namely the decrease in period, leads to the reduction of K_r on semi-porous and porous seawalls. For the case of the plane seawall, however, an increase in d/L has much less influence in reducing K_r.

These tests also indicated that the vertical porous seawall obviously improved the reflection of waves when compared with the plane and semi-porous seawalls. That is, the value of K_r in the porous seawall was reduced by about 22%–41% when compared with the plane seawall, under the same input conditions. The K_r reduction of the semi-porous seawall in comparison with the plane seawall was about 14%–22%.

In general, for the regular waves, the reflection coefficient decreased with increasing wave steepness and relative water depth. This is in agreement with the results obtained by Neelamani and Sandhya (2003), Koraim and Rageh (2013), and Koraim et al. (2014).

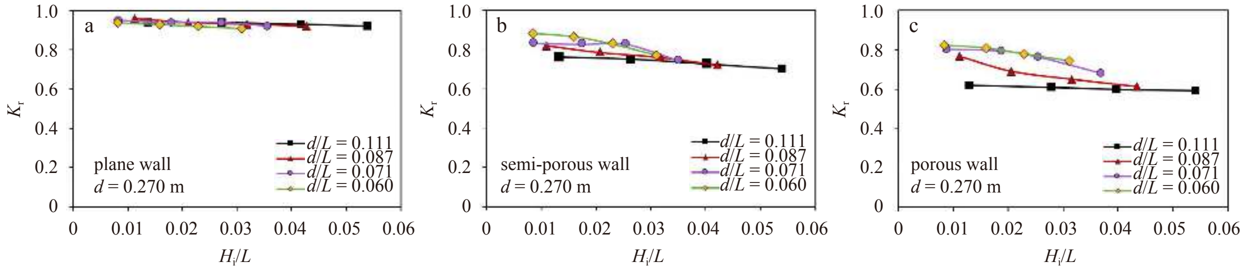


Fig. 5. K_r versus H_i/L in regular waves for plane (a), semi-porous (b) and porous seawall (c) in different wave periods.

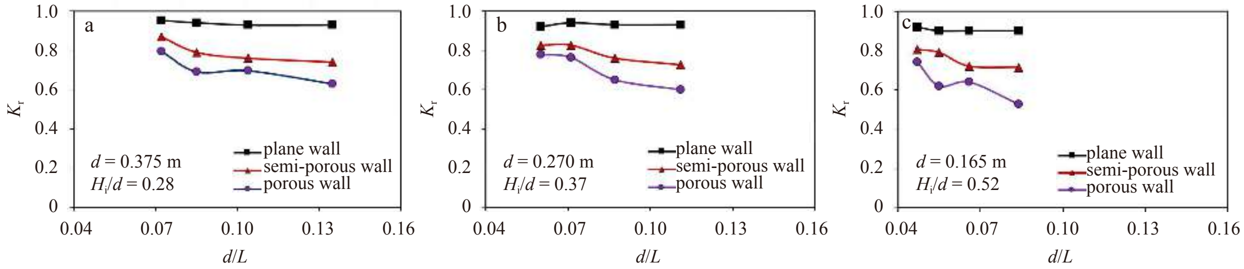


Fig. 6. K_r versus d/L in regular waves for plane, semi-porous and porous seawall in water depths of 0.375 m (a), 0.270 m (b) and 0.165 m (c).

3.2 *Reflection of random waves*

As in the case of regular waves, the effect of wave height in terms of wave steepness ($H_{\rm s}/L_{\rm p}$), and wave period in terms of relative water depth ($d/L_{\rm p}$), on $K_{\rm r}$ for the random waves is discussed here. For the set of random waves, $H_{\rm s}$ and $L_{\rm p}$ are alternately considered as the significant wave height and wave length corresponding to the peak period.

Figure 7 presents the variation of the reflection coefficient with wave steepness for the plane, semi-porous, and porous seawalls. These tests were again carried out for three different depths, and the results corresponding to the depth of 0.375 m are presented. In a similar manner to the case of regular waves, in this case, the wave reflection from the plane seawall is relatively high for all $d/L_{\rm p}$ and $H_{\rm s}/L_{\rm p}$, with values over 0.89. This value for the semi-porous seawall ranged from 0.66 to 0.90, whereas for the porous seawall, it ranged from 0.53 to 0.86. These sets of tests show that in the case of random waves, the porous and semi-porous seawalls cause a decrease in wave reflection of about 33% and 21%, respectively, in comparison with that for the plane seawall. The reduction in $K_{\rm r}$ value with increase in $H_{\rm s}/L_{\rm p}$ is obvious for the steeper waves because of higher energy dissipation.

Figure 8 shows the variation of $K_{\rm r}$ with $d/L_{\rm p}$ on the plane, semi-porous, and porous seawalls in water depths of 0.375 m, 0.270 m, and 0.165 m. As shown in the figure, the $K_{\rm r}$ decreases with increasing relative water depth for all the plane, semi-porous, and porous seawalls, for all the depths considered. There is appreciable reduction in $K_{\rm r}$ on semi-porous and porous seawalls for all $d/L_{\rm p}$ values. A comparison of the results for identical input conditions shows that the reduction in $K_{\rm r}$ for the porous seawall is about 30%–42%, and for the semi-porous seawall, it is about 20%–25%, when compared with the plane seawall. It is obvious from the plots that porous and semi-porous seawalls are better in reducing the wave reflection in comparison to the plane seawall. In addition, the porous seawall offers less reflection as compared to the semi-porous seawall.

The results derived from the experimental tests involving random waves confirmed that the value of $K_{\rm r}$ decreases with increasing $H_{\rm s}/L_{\rm p}$ and $d/L_{\rm p}$, which is in consistent with the results presented by Neelamani and Sandhya (2003) and Koraim et al. (2014).

Besides, in a porous or semi-porous seawall environment, the tests involving random waves resulted in about 5% decrease in wave reflection when compared with that of regular waves. The reduction in the wave reflection in this case could be due to the mutual interaction of the random waves. No significant deviation was found in the case of regular and random wave reflection against a vertical plane seawall.

3.3 *Proposed equations*

Using the Buckingham *Pi* theorem, an equation for the reflection coefficient in terms of hydraulic characteristics of the proposed seawall was derived. The analysis indicated the hydrodynamic performance of the seawall in terms of the relation between $K_{\rm r}$ and the dimensionless parameters. Employing wave steepness $\left(\dfrac{H}{L}\right)$ and relative water depth $\left(\dfrac{d}{L}\right)$ as dimensionless parameters, a multiple regression analysis for about 70% of the test results was carried out using the Negm and Nassar (2016) concept. For this purpose, the SPSS (Statistical Package for Social Science) software was used. The general equation applied in the software is

$$K_{\rm r}=a\left(\frac{d}{L}\right)^{b}\left(\frac{H}{L}\right)^{c}, \tag{2}$$

where d/L *is* relative water depth; H/L is incident wave steepness; and *a*, *b* and *c* are constant coefficients.

The proposed equations for the plane, semi-porous, and porous seawalls for regular and random waves are listed in Table 3.

The rest of the test results (the remaining 30%) were used to verify the proposed equations for $K_{\rm r}$. The scatter diagram for correlation coefficient was prepared for regular (Fig. 9a) and ran-

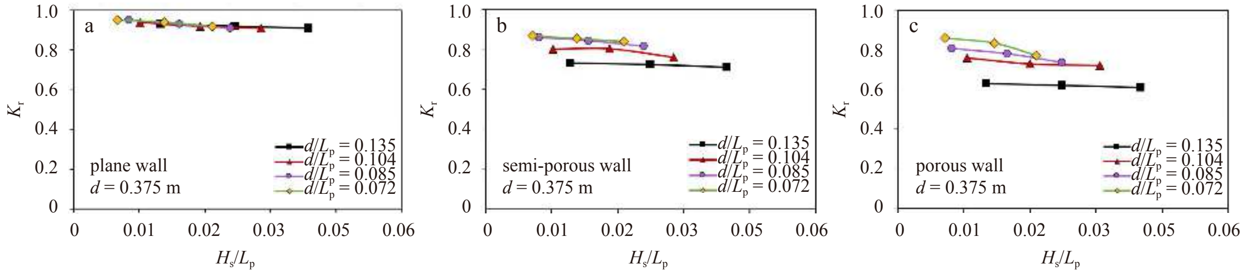


Fig. 7. $K_{\rm r}$ versus $H_{\rm s}/L_{\rm p}$ in random waves for plane (a), semi-porous (b) and porous seawall (c) for different relative water depth.

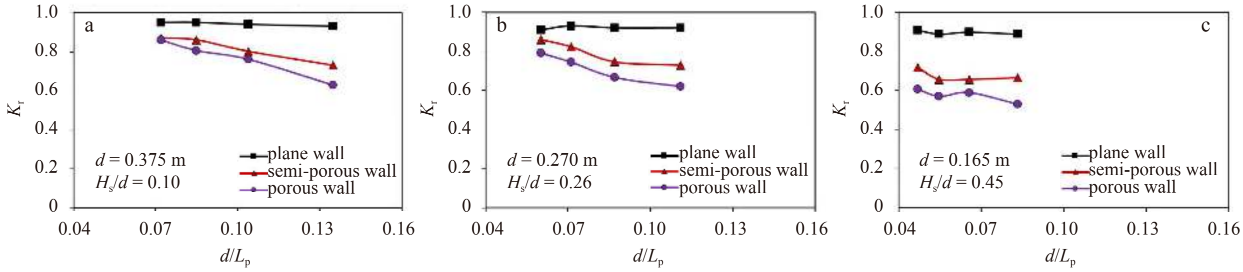


Fig. 8. $K_{\rm r}$ versus $d/L_{\rm p}$ in random waves for plane, semi-porous, and porous seawall in water depths of 0.375 m (a), 0.270 m (b) and 0.165 m (c).

Table 3. Proposed equations to calculate wave reflection for different seawall types

Type of wave	Type of seawall	Proposed equation	R^2	Range of applicability	Eq. No.
Regular	plane	$K_r = 0.86(d/L)^{0.026} (H_i/L)^{-0.039}$	0.78	$0.047 < d/L < 0.135$; $0.007 < H_i/L < 0.054$	(3)
	semi-porous	$K_r = 0.45(d/L)^{-0.075} (H_i/L)^{-0.101}$	0.74		(4)
	porous	$K_r = 0.29 (d/L)^{-0.088} (H_i/L)^{-0.176}$	0.76		(5)
Random	plane	$K_r = 0.81 (d/L_p)^{0.010} (H_s/L_p)^{-0.039}$	0.87	$0.047 < d/L_p < 0.135$; $0.007 < H_s/L_p < 0.042$	(6)
	semi-porous	$K_r = 0.39 (d/L_p)^{-0.182} (H_s/L_p)^{-0.068}$	0.79		(7)
	porous	$K_r = 0.25 (d/L_p)^{-0.276} (H_s/L_p)^{-0.098}$	0.81		(8)

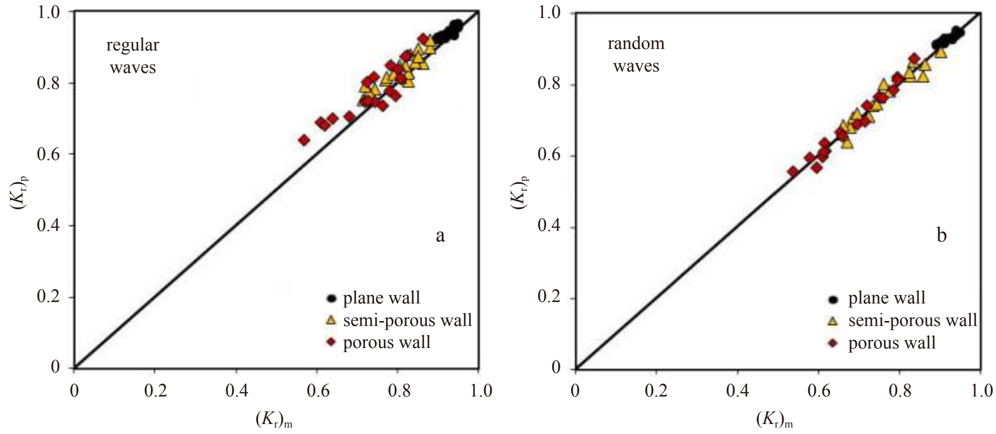


Fig. 9. Reflection coefficient scatter diagram for vertical plane, semi-porous and porous seawall; measured versus calculated using proposed equations for regular (a) and random (b) waves.

dom waves (Fig. 9a). The correlation between the measured ($(K_r)_p$) and predicted ($(K_r)_m$) values of K_r is rather good for the two cases, with correlation coefficients of 0.92 and 0.95, respectively, for regular and random waves. In other words, the coefficient of determination, R^2, for regular waves is slightly lower than for random waves. This may be due to greater turbulence caused by the occurrence of multiple wave reflections between the seawall and wave paddle in the experiments involving regular waves.

To validate the empirical equations, the results were compared with previous investigations for limited cases of vertical seawalls. Figure 10 illustrates the difference in the wave reflection coefficient derived from the present study and those from other research works. It can be seen that, for vertical impermeable seawalls, the effect of relative water depth is negligible on the values of K_r. This is the same outcome obtained by the present study and the study by Negm and Nassar (2016). Table 4 shows the formula proposed in this study and those proposed by other studies to calculate the reflection coefficient of regular waves against vertical plane, semi-porous, and porous seawalls.

As it can be seen, the offered equations according to various studies are quite different. However, the data presented in Fig. 10 shows similarity and acceptable agreement between the results derived from the present study and those collected from other research works.

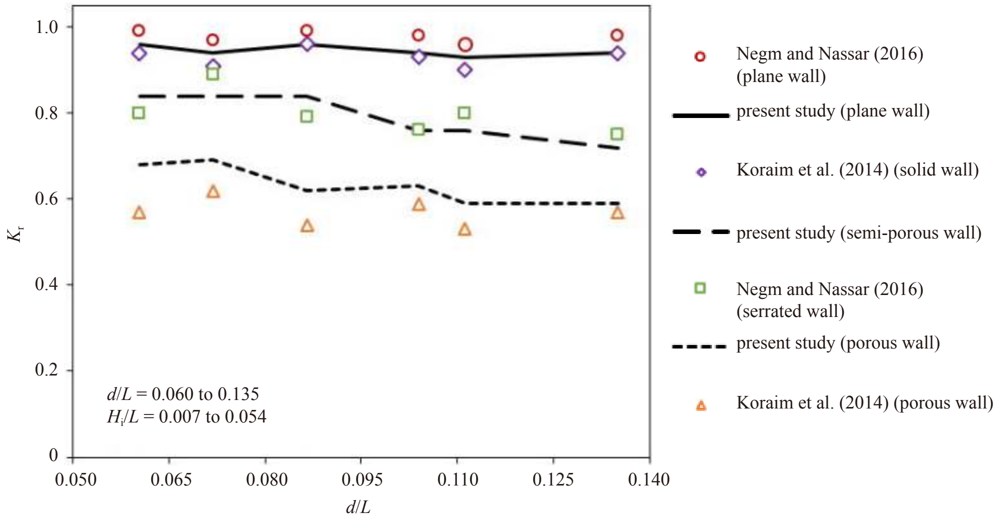


Fig. 10. A comparison between finding of the present study with those of the previous research works: K_r versus relative water depth for regular waves.

Table 4. Reflection coefficient equations for regular waves against different seawall types (proposed in this study and other research works)

Type of seawall	Plane	Semi-porous	Porous
This study	$K_r = 0.86(d/L)^{0.026}\,(H_i/L)^{-0.039}$	$K_r = 0.45(d/L)^{-0.075}\,(H_i/L)^{-0.101}$	$K_r = 0.29(d/L)^{-0.088}\,(H_i/L)^{-0.176}$
Eq. No.	(3)	(4)	(5)
Koraim et al. (2014)	$K_r = 0.83\,(d/L)^{0.16}\,(H_i/L)^{-0.12}$		$K_r = 0.24(d/L)^{-0.01}\,(H_i/L)^{-0.14}\,(b/d)^{-0.20}\,(n)^{-0.53}$
Eq. No.	(9)		(10)
Det.			*b:* seawall width; *n:* porosity of the wall
Negm and Nassar (2016)	$K_r = 0.92(d/L)^{0.054}\,(H_i/L)^{-0.049}$	$K_r = 0.40(d/L)^{0.334}\,(H_i/L)^{-0.389}(s/w)^{-0.027}$	
Eq. No.	(11)	(12)	
Det.		*s:* net spacing between dissipater blocks; *w:* width of blocks	

However, it should be mentioned that, for the case of semi-porous or porous seawalls, the amount of porosity was one of the main concerns in other studies, including Koraim et al. (2014) and Negm and Nassar (2016). They introduced some parameters, such as n in Eq. (10) and s and w in Eq. (12), to configure different porosities of the seawall. In this research however, the main concern was to determine the reflection coefficient of the pre-designated seawall, which is shown in Fig. 4. As can be seen, the configuration and dimensions of both seawalls are fixed. Thus, the variation of porosity was not a concern in this research.

4 Conclusions

The reflections of regular and random waves from plane, semi-porous, and porous seawalls were studied using a physical wave flume. The employed seawalls in this study were pre-designed with a fixed structure, which means that the value of porosity was not variable. The influence of wave height and period, and water depth on the reflection coefficient was examined. Employing regression analyses and dimensionless parameters, some equations were proposed to predict the reflection coefficient for regular and random waves.

The results of this study are summarized as follows:

(1) The reflection coefficient decreases with increasing relative water depth and wave steepness, for both regular and random waves.

(2) The reflection coefficient of the plane seawall, for all H_s/L_p and d/L_p, is over 0.89. Under the same input and hydrodynamic conditions, the semi-porous and porous seawalls provide a K_r ranging from 0.66 to 0.90 and 0.53 to 0.86, respectively. This clearly shows that the porous seawall is more effective than the plane or semi-porous seawalls.

(3) For these three seawalls, the trends of variation in the reflection coefficient, in terms of wave steepness and relative water depth, are quite similar for the regular and random waves.

(4) Empirical equations to estimate the reflection coefficient for regular and random waves are proposed using multiple regression analyses. The results derived from the proposed equations show reasonable agreement with similar tests performed by other researchers.

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