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PROTECTING COASTS AGAINST PROBABLE SEA LEVEL RISE USING POROUS VERTICAL SEAWALL *

El-Sadek M. Heikal , Ayman S. Koraim, Ahmed A. Abo Zaid**

Water and Water Structure Engineering Dept., Faculty of Engineering, Zagazig University, Egypt

ABSTRACT

There are three main parameters affecting on seawall crest level determination: tidal range, wave run-up and sea level rising. In this paper, the hydrodynamic efficiency of a new type porous seawall is experimentally studied. This is by using physical models to minimize the run-up at the front of the wall. The seawall consists of front screen (steel screen suspended on nearly spaced piles), back solid wall and filled rock-core in between the two walls. The hydrodynamic efficiency of the seawall is presented as a function of the wave run-up, reflection, and energy dissipation coefficients. Different wave and structural parameters affecting the seawall efficiency are investigated. The results indicate that; the run-up and reflection coefficients decrease with increasing of relative wave length (h/L), wave steepness (H_i/L), relative porous media width (B/L) and porous media width-water depth ratio (B/h). The energy dissipation coefficient takes the opposite trend. The efficiency of the proposed porous seawall in reducing wave run-up and reflection coefficient is better than the impermeable type by about 10 to 25% and 20 to 40% respectively. In addition, it is better than the impermeable one in dissipating the incident wave energy by about 30 to 60%. The increasing of the porous media width helps in reducing the wave run-up and reflection coefficient and increasing the dissipated wave energy by about 5 to 10%, 10 to 20% and 5 to 20% respectively. The empirical equations are developed to estimate the run-up and reflection coefficients. The results of these equations compared with the experimental results and it give a reasonable agreement by about 80 to 90%.

KEY WORDS: Seawalls, Porous structures; Wave Run-up; Reflection; Energy dissipation.

PROTECTION DES CÔTES DE HAUSSE PROBABLE NIVEAU DE LA MER EN POREUX SEAWALL VERTICAL

RÉSUMÉ

Il existe trois principaux parametres qui affectent le niveau de determination digue de crete: niveau de l'amplitude des marees, des vagues run-up et des mers. Dans cet article, l'efficacite hydrodynamique d'une digue nouveau type poreux est etudiee experimentalement. C'est a l'aide de modeles physiques afin de minimiser la veille a l'avant du mur. La digue est constituee de l'ecran avant (ecran en acier suspendue sur pilotis pres espaces), mur arriere solide et remplie de roche-core entre les deux parois. L'efficacite hydrodynamique de la digue est presentee comme une fonction de l'onde run-up, la reflexion, et les coefficients de dissipation d'energie. D'onde differente et les parametres structurels qui affectent l'efficacite digue sont etudiees. Les resultats indiquent que, la veille et de reflexion coefficients diminuent avec l'augmentation de la longueur d'onde relative (h / l), cambrure (salut / l), largeur relative des milieux poreux (b / l) et poreux rapport des medias largeur profondeur d'eau (b / h). Le coefficient de dissipation de l'energie prend la tendance inverse. L'efficacite de la digue proposee poreuse dans la reduction des ondes run-up et le coefficient de reflexion est meilleur que le type impermeable d'environ 10 a 25% et de 20 a 40% respectivement. En outre, il est preferable que celui impermeable a dissiper l'energie onde incidente d'environ 30 a 60%. L'augmentation de la largeur de support poreux permet de reduire l'onde de lancement et le coefficient de reflexion et augmenter l'energie dissipee onde d'environ 5 a 10%, de 10 a 20% et de 5 a 20% respectivement. Les equations empiriques sont developpes pour estimer le run-up et des coefficients de reflexion. Les resultats de ces equations par rapport aux resultats experimentaux et de le donner a un accord raisonnable d'environ 80 a 90%.

MOTS CLÉS: digues, les structures poreuses; vague run-up, reflexion, dissipation d'energie.

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1. INTRODUCTION

Seawalls are onshore structures with the principal function of preventing or alleviating overtopping and flooding of the land and the structures behind due to storm surges and waves. Seawalls are built parallel to the shoreline as a reinforcement of a part of the coastal profile. Quite often seawalls are used to protect promenades, roads, and houses placed seaward of the crest edge of the natural beach profile. In these cases a seawall structure protruding from the natural beach profile must be built. In addition, seawalls are consider good methods to control the probable sea level rising due to the climate changes. Seawalls range from vertical face structures such as massive gravity concrete walls, tied walls using steel or concrete piling, and stone-filled cribwork to sloping structures with typical surfaces being reinforced concrete slabs, concrete armor units, or stone rubble. When vertical, they are labeled non-energy absorbing, whereas if with a sloping surface or rubble mound, they absorb some energy. The front face may also be curved or stepped to deflect wave run-up.

The key functional element in seawall design is the crest elevation to minimize the overtopping from storm surge and wave run-up. There are three main parameters affecting on seawall crest level: tidal range, wave run-up and sea level rising. The reflection and run-up characteristics of a seawall, in addition to its stability, are important parameters to be studied. The reflection from the vertical and slightly battered walls of impermeable type will be around 90 to 100%. The reflection from these structures causes standing waves which are accompanied by increased water particle velocities, leading to more erosion along the face of the wall and may lead to undermining the structure (Mallayachari and Sundar 1994).

The construction of sloping rubble mound walls will reduce the level of reflections to limit the problem of local scour when waves approach normal to the shore. These structures require large quantity of stones especially when the water depth and wave height increase. And to avoid this point, the vertical porous seawall can be used instead of the sloped one. The simplest form of the vertical porous seawall is rock-filled work. In which the seawall consists of front screen (steel screen suspended on nearly spaced piles), back solid wall and filled rock-core in between the two walls.

The present investigation with porous, vertical seawall has been carried out with the following objectives:

1. To propose a new type seawall helping in crest level reduction by dissipating the most of incident wave energy.
2. To investigate experimentally the wave run-up, reflection and energy dissipation characteristics of the proposed seawall.
3. To investigate the same characteristics for different wave climate and structure configurations.

2. PREVIOUS WORK

In recent decades, with porous structures being widely used in coastal areas, the phenomena of wave interaction with these structures have been studied theoretically and experimentally by many investigators. Straub et al 1957 reported the reflection characteristics of permeable wave absorbers of different porosities, lengths and configurations through an experimental program. Lean 1967 proposed a simplified analytical model for the evaluation of reflection characteristics of permeable wave absorbers due to long waves. Sollitt and Cross 1972 presented a summary of previous analytical approaches to the problem of predicting the transmission and the reflection characteristics of a porous structure. Madsen 1974 produced a simple solution for the reflection and the transmission coefficients based on the assumption of relative long normally incident waves on a rectangular homogeneous porous structure. Madsen 1983 presented a theoretical solution for the reflection of linear shallow water waves from a vertical homogeneous wave absorber on a horizontal bottom. Sulisz 1985 formulated a theory to predict the wave reflection and transmission at an infinite rubble mound breakwater under normal wave incidence.

Dalrymple et al 1991 adopted the Sollit and Cross 1972 approach to analyze the reflection and transmission of oblique incident waves from infinitely long porous structures.

Huang and Chao 1992 investigated a small-amplitude water wave acting on a vertical porous breakwater in an infinitely long channel. Losada et al 1993 extended this study to the case of an infinitely long, homogenous, vertical structure capped with an impervious element under oblique wave incidence. Mallayachari and Sundar 1994 determined the reflection characteristics of permeable vertical seawalls with a numerical model which based on Green's Identity formula. The variation of the reflection coefficients with the porosity of the wall, its friction factor and the relative wall width was studied. Yu 1995 presented a solution of the two-dimensional problem of wave reflection and transmission by a permeable vertical barrier. Liu et al 1999 presented a numerical model for simulating wave interaction with porous structures. The model calculates the mean flow outside of porous structures based on the Reynolds averaged Navier-Stokes equations.

Recently, Isaacson et al 2000 presented a theoretical analysis and an associated numerical model used to assess the performance of a breakwater consisting of a perforated front wall, an impermeable back wall, and a rock-filled core. The numerical method was based on an Eigenfunction Expansion and utilizes a boundary condition at the perforated wall that accounts for energy dissipation. Requejo et al 2002 proposed a mathematical model to solve the potential flow around and inside a porous breakwater. The reflection, transmission, dissipation, horizontal and vertical forces and overturning moment were solved. Twu and Liu 2004 developed a computational model to investigate the wave damping characteristics of a periodic array of porous bars. The transmission and reflection coefficients as well as the wave energy dissipation were evaluated relating to the physical properties and geometric factors of bars. Hsu et al 2005 derived an analytical solution of oblique water waves impacting on thin porous walls based on the concept that the wave direction remains unchanged as it permeates into the thin porous medium.

Lin and Karunarathna 2007 studied the solitary wave interaction with porous breakwaters by using a two-dimensional numerical model. The flows outside of porous media were described by Reynolds-averaged Navier-Stokes equations. Rageh 2009 experimentally studied the efficiency of the vertical thick submerged or emerged porous structures under normal and regular waves with wide ranges of wave heights and periods. Theocharis et al 2011 investigated experimentally a new type of wave absorbing quay-wall with a partial wave chamber containing a rock-armored slope. In addition to the basic design containing a wave chamber with an impermeable back wall, there were several alternative absorbing systems that use rock within the core of the wave chamber.

The detailed literature review reveals that there are some references available on similar models. There are little works, in particular experimental investigations, carried out for studying the vertical porous seawalls. So that, the efficiency of the vertical porous seawall that consists of front screen, back solid wall and crushed stone filled in between the two walls is experimentally studied using physical model. The seawall efficiency is presented as a function of run-up, reflection, and wave energy dissipation coefficients. The effect of different wave and structural parameters on the seawall efficiency is investigated such as; the incident wave length and height and the seawall permeability and width.

3. EXPERIMENTAL WORK

Several experiments are carried out in a wave flume 13.0m long, 0.45m deep, and 0.30m wide in the Hydraulics and Water Engineering Laboratory of the Faculty of Engineering, Zagazig University, Zagazig, Egypt. Its vertical sides are made from toughened glass of 0.012m thickness. A flap type wave generator with stroke distance of 0.22m is installed at one end of the flume. This wave generator is used to generate regular wave trains with different wave periods. A steel screen wave absorber with slope 3:1 is installed at the other end of the flume to absorb the transmitted waves. Froude scaling technique is adopted for physical modeling, which allows for the correct reproduction of gravitational and fluid inertial forces. A scale of 1:20 is chosen for the selection of model dimensions and wave properties in the present study.

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The tested seawall model is placed at the end of the wave flume. Two seawall models are tested. The first model is graffito impermeable wall with thickness of 0.02m. The second model is porous seawall consists of front screen wall, back solid wall and core-rock filled in between the two walls with width B=0.125, 0.25 and 0.375m. The height of the core-rock is enough to prevent the wave overtopping on the seawall. Details of the tested models and experimental setup ranges are shown in **Fig. 1** and **Table 1**. Also, the component of the tested model and the general view of the tested model are presented in **Figures 2 and 3.** in addition, the results of the sieve analysis of the core-rock is shown in **Fig. 4**.

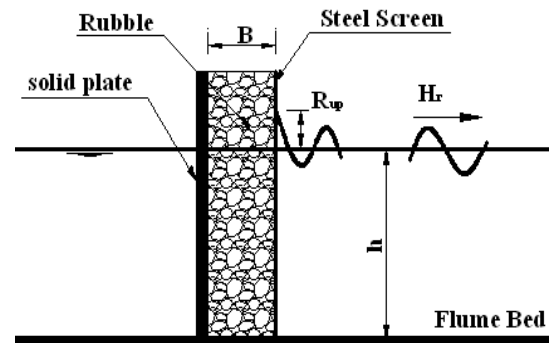| Parameter	Units	Ranges
Water depth (h)	m	0.20 and 0.25
Wave periods (T)	s	0.65 to 1.90
Wave length (L)	m	0.67 to 2.90
Seawall width (B)	m	0.125, 0.25 and 0.375
Rock mean diameter (d_{50})	m	0.017
Rock porosity (n)	-	45%
Rock weight (w)	t	$(11\text{-}18) \times 10^{-6}$
Relative wave length (h/L)	-	0.08–0.37
Wave steepness (H_i/L)	-	0.018–0.095
Relative seawall width(B/L)	-	0.045–0.863
Width-depth ratio (B/h)	-	0.5–1.875

Fig. 1. Details of the tested seawall mod

Table 1. Experimental setup parameters for the proposed seawall model.

(a) The used rock.   (b) The steel screen   (c) The solid back wall

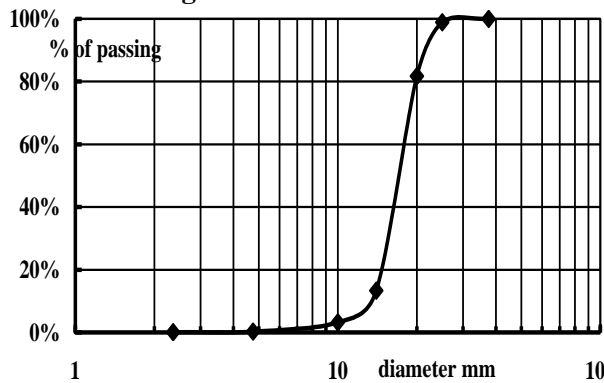**Fig. 2. General view of different components of the tested seawall model**

Fig. 3. Sieve analysis for the used rock.

(a) Elevation   (b) Side view

Fig. 4. General view of the tested seawall model.

Standard conductivity type wave probe is used to measure the wave elevations. The wave probe comprises of two thin parallel stainless steel electrodes. The probe consists of two 0.0015m diameter stainless steel wires spaced 0.0125m apart

and 0.30m long. The probe is connected to wave monitor module in the electronic console by a twin core flexible cable. This monitor provides output signals in form of voltage data. Static calibration of the wave probe is carried out every day and at the beginning and end of each set of experiments. The calibration constants are found to have a standard deviation of less than 1.0%. An electronic converter has been used for converting analogue signals to digital voltage data. These data are collected by the personal computer and converted to the wave elevation by simple computer program. Then the variation of water surface with time can be drawn.

To measure the incident (H_i) and reflected (H_r) wave heights, two recording positions P_3 and P_2 ($H_{max.}$ at location P_3, the quasi-antinodes, and $H_{min.}$ at location P_2, the quasi-nodes) are located in front of the seawall model (wave generator side). The positions P_3 and P_2 located at distances L and 1.25 L (L is the wave length and it is variable according to the wave period T) from the model face according to Dean and Dalrymple 1984. The incident (H_i) and the reflected (H_r) wave heights estimated by:

$$H_i = (H_{max.} + H_{min.}) / 2$$

$$(1)$$

$$H_r = (H_{max.} - H_{min.}) / 2$$

$$(2)$$

To measure the wave run-up (R_{up}), one additional recording position (P_4) is set at the front of the seawall. In addition, the recording position (P_1) is located at distance of 2.0m from the wave generator for measuring the incident wave height to inshore the calculated one from Eq. (1). Details of wave flume, position of the tested seawall models, and

locations of wave recording are shown in **Fig. 5**. The run-up (k_{rp}) and reflection (k_r) coefficients can be estimated by:

$$k_{rp} = R_{up} / H_i$$

$$(3)$$

$$k_r = H_r / H_i$$

$$(4)$$

The energy equilibrium of an incident wave attack the structure can be expressed as follows:

$$E_i = E_r + E_d$$

$$(5)$$

In which, E_i is the energy of incident wave ($E_i = \rho g\, H_i^2 / 8$, ρ is the water density and g is the acceleration of gravity), E_r is the energy of reflected wave ($E_r = \rho g\, H_r^2 / 8$), and E_d is the wave energy dissipation. Substituting in Eq. (5) by values of E_i and E_r and dividing by E_i, yields:

$$1 = \frac{H_r^2}{H_i^2} + \frac{E_d}{E_i}$$

$$(6)$$

Substituting by Eqs. (4) in Eq. (6), the wave energy dissipation coefficient $k_d = (E_d/E_i)^{1/2}$ can be estimated as follows:

$$k_d = \sqrt{1 - k_r^{\,2}}$$

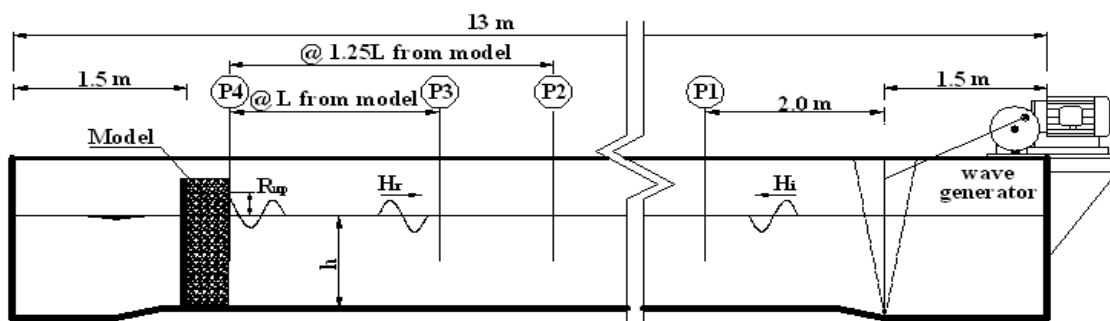$$(7)$$

Fig. 5. Details of wave flume, position of model and location of wave recordings.

4. RESULTS AND ANALYSIS

4.1. Dimensional Analysis

Many parameters affecting the seawall efficiency are studied such as incident wave

length and height (L, H_i), water depth (h), seawall porosity and width (n, B). The analysis presents the efficiency of the seawall in the form of relationships between run-up, reflection, and energy dissipation coefficients

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(Rup/Hi, kr, kd) and dimensionless parameters representing the wave and structure characteristics as following:

$$R_{up}/H_i, k_r, k_d = f (h/L , H_i/L , B/L, B/h, n) \quad (8)$$

Investigating the effect of h/L and Hi/L on Rup/Hi, kr and kd is essential to understand the hydrodynamic characteristics of the present seawall for coastal regions. Also, to understand the performance of the seawall for normal and extreme wave actions. In addition, investigating the effect of B/h, B/L, and n on Rup/Hi, kr and kd is required to select the appropriate structure configuration.

Using the above dimensionless parameters [Eq.(8)], the Regression analysis and 75% of the measured data, two simple empirical equations to estimate the run-up and reflection coefficients are developed as follows:

For impermeable case (n=0)

$$R_{up}/H_i = 1.06 \, (h/L)^{-0.28} \, (H_i/L)^{0.13}, \quad R^2=0.80 \quad (9)$$

$$k_r = 0.98 \, (h/L)^{-0.08} \, (H_i/L)^{0.07}, \quad R^2=0.85 \quad (10)$$

For porous case (n=45%)

$$R_{up}/H_i = 0.78 \, (h/L)^{0.36} \, (H_i/L)^{-0.44} \, (B/L)^{-0.56} \, (B/h)^{-0.03}, \, R^2=0.83 \quad (11)$$

$$k_r = 0.40 \, (h/L)^{-1.95} \, (H_i/L)^{1.79} \, (B/L)^{1.94} \, (B/h)^{-0.13}, \, R^2=0.88 \quad (12)$$

Then the wave energy dissipation coefficients k_d can be estimated from Eq. (7). The above equations are applicable for ranges shown in Table 1.

4.2. Experimental Measurements Analysis

Figures 6 and 7 show a sample of the analyzed data using the wave probe at the four wave recording positions P1, P2, P3 and P4 for the case of porous seawall and h=0.20m, B=0.25m when T=0.68 and 1.8s respectively. Figures 6a and 7a show that the first 2 to 5s, the wave travels from the wave generator to

the wave gauge at location P1. Some disturbance appears in the shape of the wave for few seconds then, the wave seems to be very stable for some time (t=5 to 15s) which is the suitable period to measure the incident wave height. After this time, the reflected waves from the seawall model affecting on the incident waves.
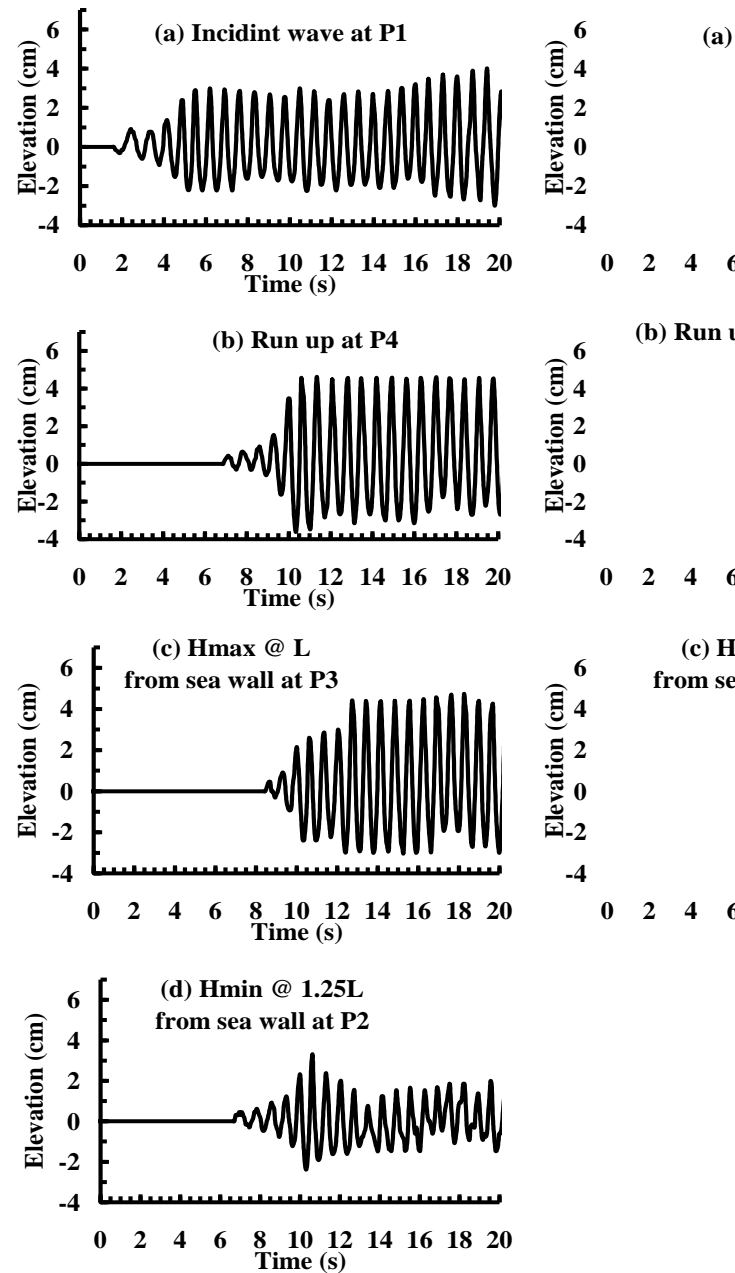

Fig. 6. Variation of wave elevation with time at the different wave recording positions for the case of porous seawall when h=0.20m, B=0.25m, and T=0.68s.

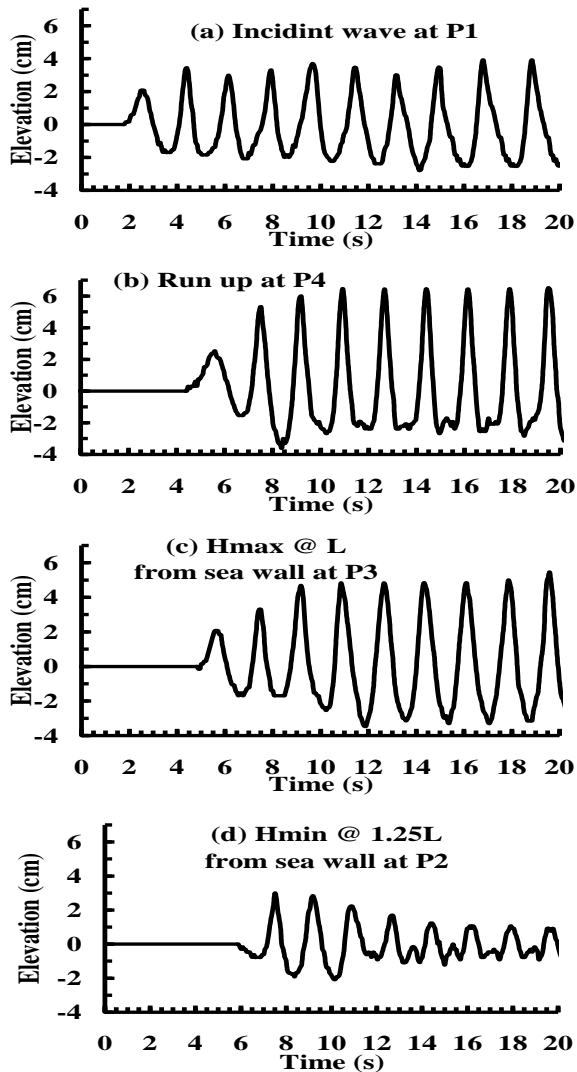**Fig. 7. Variation of wave elevation with time at the different wave recording positions for the case of porous seawall when h=0.20m, B=0.25m, and T=1.8s**

Figures 6b, c, d and 7b, c, d show that the first 8 to 12s, the wave travels from the wave generator to the wave gauges at location P2, P3, P4 and reflects from the seawall model and the partial standing wave begins to build its shape. After that, the wave tends to be stable for some time (t=10 to 15s) which is the period of the suitable zone to estimate the run-up and reflection coefficients. After this time, the form of the partial standing wave changes due to the new reflection of the wave from the wave generator, which generates a new incident wave

with different characteristics. The reflection coefficients are estimated from the data obtained by wave gauge at locations P2 and P3 while the run-up coefficients are estimated from the data obtained by wave gauge at location P4. In addition, the figures show that, the wave of T=1.9s seems not uniform than the wave of T=0.68s. This is attributed to the effect of the shoaling on the wave profile in which the wave of T=1.9s is longer than the wave of T=0.68s.

4.3. Empirical Equations Verification

Figures 8 and 9 present the comparison between the measured and calculated run-up and reflection coefficients for solid and porous cases respectively. It can be observed from the figures that a good agreement is obtained between the experimental and the calculated hydrodynamic coefficients. The equations somewhat over-predict and under-predict the hydrodynamic coefficients by values not more than 10%. The scatter between the experimental and calculated reflection coefficients is almost smaller than the scatter in run-up coefficients. In which the coefficient of determination R^2 (determined from the regression analysis) for run-up ($R^2=0.83$ and 0.85) is smaller than for the reflection ($R^2=0.88$ and 0.91). This is may be due to the high turbulence caused by the multiple wave reflections between the seawall and the wave generator.
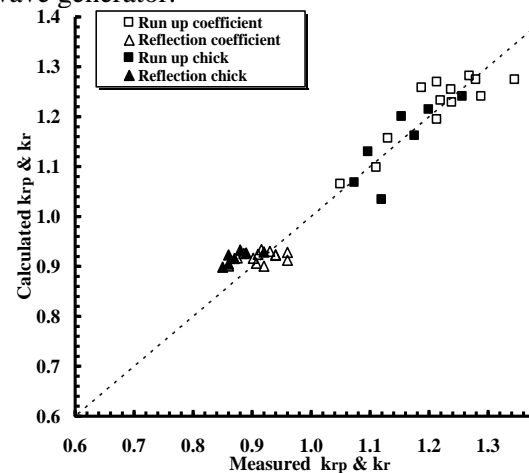

Fig. 8. Comparison between measured and calculated hydrodynamic coefficients for solid seawall.
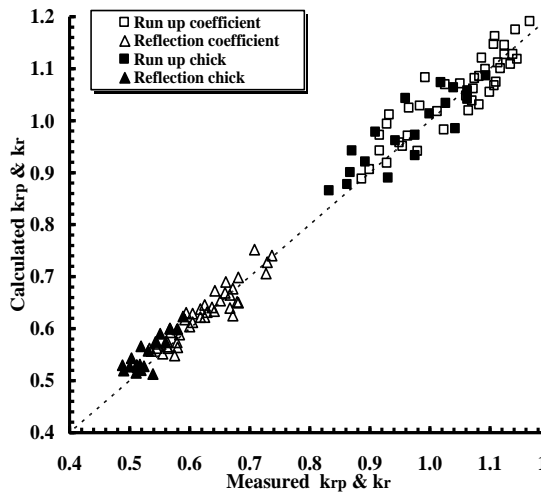
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Fig. 9. Comparison between measured and calculated hydrodynamic coefficients for porous seawall.

4.4. Experimental Results Analysis

Fig. 10 presents the relationship between the calculated and measured different hydrodynamic coefficients and the relative wave length (h/L=0.08-0.37) for different structural parameters (impermeable and porous cases). The figure presents the effect of the relative wave length (h/L), the seawall porosity and the porous seawall width-water depth ratio (B/h) on the seawall hydrodynamic efficiency. The figure shows that, all calculated and measured run-up (Rup/Hi) and reflection (kr) coefficients decrease with increasing values of h/L for all cases while the dissipation coefficient (kd) takes the opposite trend e.g., calculated Rup/Hi and kr decrease from 1.27 to 1.05 and from 0.92 to 0.86 and calculated kd increases from 0.4 to 0.5 with h/L increasing from 0.09 to 0.36 for the solid case. This can be explained by considering the water particle motions. When the wave strikes the model, the water particle velocity and acceleration suddenly change and the turbulence caused due to this sudden change in the particle motion causes the dissipation of wave energy.

The figure shows also, all Rup/Hi and kr caused by the porous model are smaller than those caused by solid model while kd follows the opposite trend e.g. calculated Rup/Hi and kr decrease from 1.16 to 1.04 and from 0.89 to 0.62 and calculated kd increases from 0.45 to 0.78 when the porous model of B/h=0.5 instead of solid model for h/L=0.2.
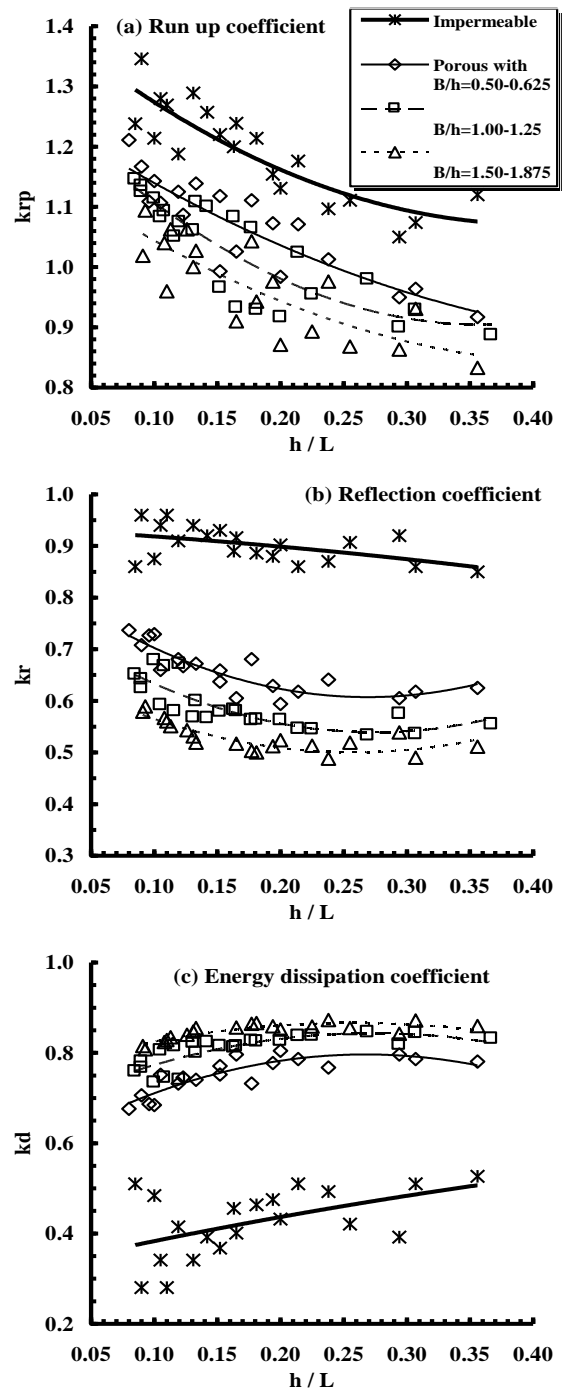

Fig. 10. Effect of h/L and B/h on the different hydrodynamic coefficients.

This is due to the dissipated wave energy through the porous media of the seawall and then the reflected waves decrease. The figure shows also, when B/h increases Rup/Hi and kr decrease and kd increases e.g. calculated Rup/Hi and kr decrease from 1.04 to 0.93 and from 0.62 to 0.51 and calculated kd increases from 0.78 to 0.86 when B/h increases from

B/h=0.5 to 1.5 for h/L=0.2. This can be attributed to the increase of the friction between the seawall porous media and the waves. As B/h increases, the width of the porous media that becomes subjected to the waves increases. Then the friction length increases causing more wave energy dissipation. In addition, the figure shows that, a reasonable agreement is obtained between the calculated and the measured hydrodynamic coefficients.
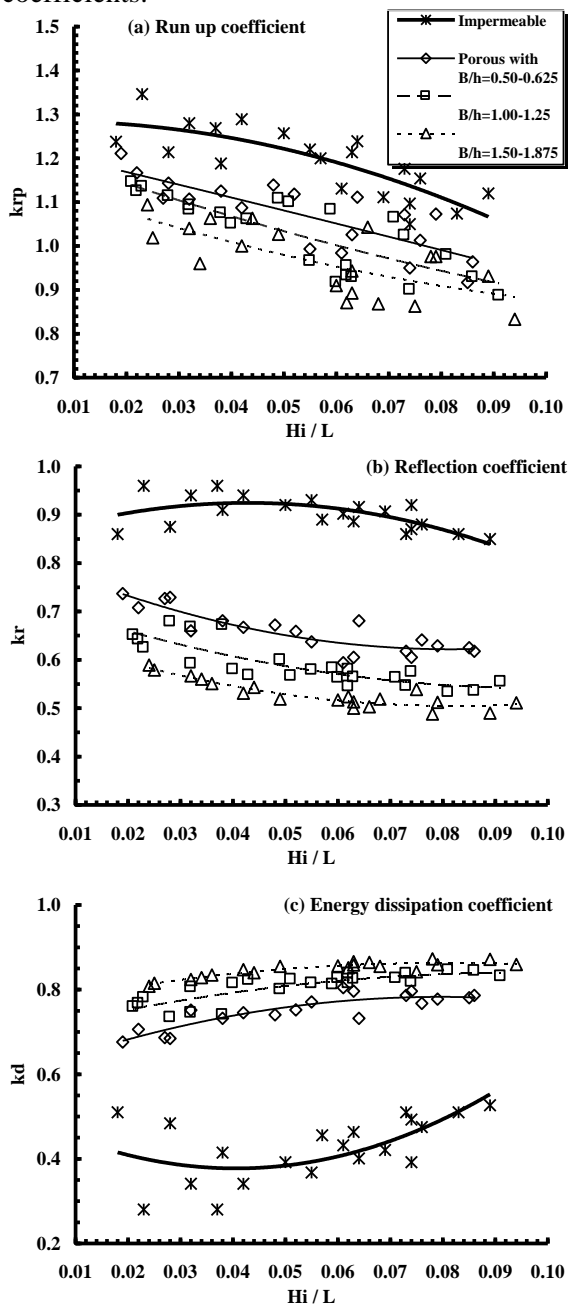

Fig. 11. Effect of H_i/L and B/h on the different hydrodynamic coefficients.

Fig. 11 illustrates the effect of the wave steepness (Hi/L), porosity and B/h on the measured and calculated seawall hydrodynamic efficiency. The figure shows that, all Rup/Hi and kr decrease and all kd increase with Hi/L increasing e.g. calculated Rup/Hi and kr decrease from 1.27 to 1.05 and from 0.92 to 0.86 and calculated kd increases from 0.4 to 0.5 with Hi/L increasing from 0.018 to 0.09 for the solid case. Also, all Rup/Hi and kr caused by the porous model are smaller than those caused by solid model while kd follows the opposite trend e.g. calculated Rup/Hi and kr decrease from 1.23 to 1.09 and from 0.91 to 0.65 and calculated kd increases from 0.41 to 0.76 when the porous model of B/h=0.5 instead of solid model for Hi/L=0.05. In addition, when B/h increases Rup/Hi and kr decrease and kd increases e.g. calculated Rup/Hi and kr decrease from 1.09 to 1.01 and from 0.65 to 0.54 and calculated kd increases from 0.76 to 0.84 when B/h increases from B/h=0.5 to 1.5 for Hi/L = 0.05. In addition, the figure shows that, a reasonable agreement is obtained between the calculated and the measured hydrodynamic coefficients.

Fig. 12 shows the effect of the relative porous seawall width (B/L) on the measured and calculated Rup/Hi, kr and kd. The figure shows that, all Rup/Hi and kr decrease with B/L increasing and kd takes the opposite trend e.g. calculated Rup/Hi and kr decrease from 1.18 to 0.86 and from 0.74 to 0.50 and calculated kd increases from 0.68 to 0.87 when B/L increases from 0.045 to 0.55. In addition, the figure shows that, a reasonable agreement is obtained between the calculated and the measured hydrodynamic coefficients.
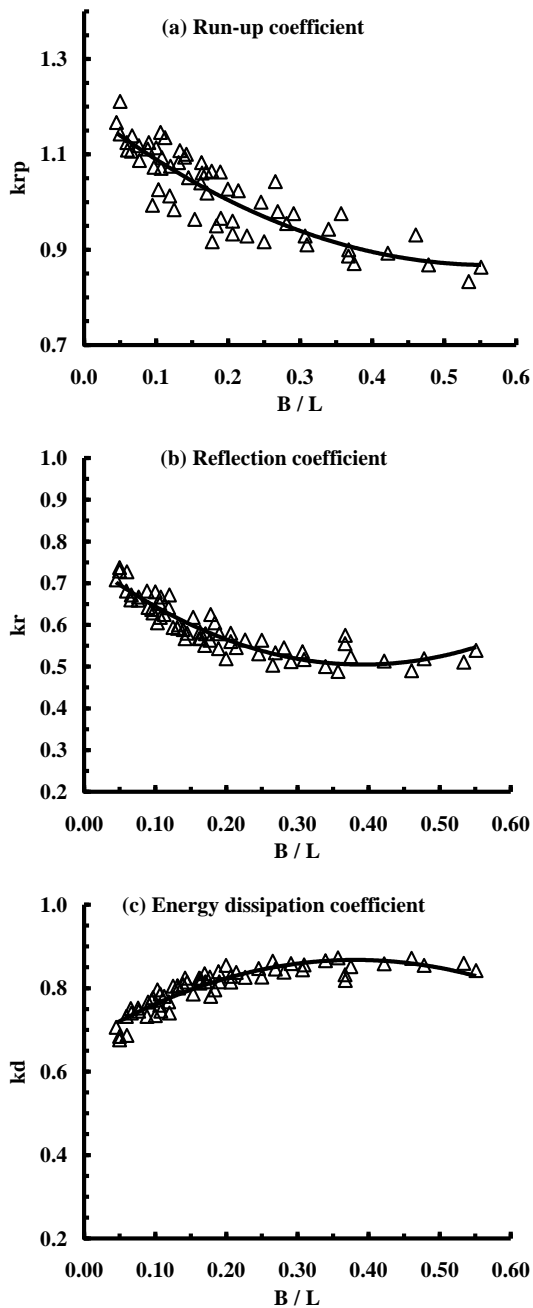
Fig. 12. Effect of B/L on the different hydrodynamic coefficients.

5. CONCLUSIONS

The efficiency of a new type seawall, which consists of front screen wall (steel screen suspended on nearly spaced piles), back solid wall and crushed stone filled in between the two walls. The wave run-up, reflection, and energy dissipation characteristics are studied for regular waves of different wave heights and periods. The salient conclusions are given below.

1- In general, the run-up and reflection coefficients decreases with relative wave length (h/L), wave steepness (H$_i$/L), relative seawall width (B/L) and porous media width (B/h) increasing while the dissipation coefficient takes the opposite trend.

2- The efficiency of the proposed porous seawall in reducing wave run-up and reflection coefficients is better than the solid type by about 10 to 25% and 20 to 40% respectively. Also, it is better than the impermeable one in dissipating the incident wave energy by about 30 to 60%.

3- The increasing of the porous media width, reducing the wave run-up and reflection coefficient and increasing the dissipated wave energy by about 5 to 10%, 10 to 20% and 5 to 20% respectively.

4- The empirical equations used for estimating the run-up and reflection coefficients are developed by using the Regression analysis. The results of these equations compared with the experimental results and it give a reasonable efficiency.

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