Wave Hydrodynamic Characteristics of Vertical and Sloped Seawalls

خصائص الأمواج الهيدروديناميكية للحوائط البحرية الرأسية و المائلة

El-Alfy, K.S. [a] ;Rageh, O.S. [a]; and Nassar, K.A.[b]

[a] Prof., Irrigation & Hydraulics Dept, Fac. of Engrg, EL-Mansoura Univ. [b] Demonstrator, Irrigation & Hydraulics Dept., Fac. of Engrg., EL-Mansoura Univ.

الخلاصة

تم دراسة الأداء الهيدروديناميكي للحوائط البحرية الرأسية و المائلة معمليا تحت ظروف الأمواج المنتظمة وبمجال واسع من خصائص الأمواج كدالة في المعاملات الهيدروديناميكية للموجة والتي تتمثل في معامل الإرتداد ،معامل الصعود النسبي ،ومعامل الهبوط النسبي للموجة ،وذلك بإستخدام نماذج ذات أسطح ملساء وأخري ذات خشونة مستطيلة أو مثلثة الشكل. أوضحت الدراسة أن الحوائط ذات الخشونة المستطيلة تعطي نتائج افضل في تقليل المعاملات الهيدروديناميكية المذكورة أعلاه مقارنة بالحوائط ذات الخشونة المثلثة والحوائط الملساء ،كما أوضحت الدراسة أن استخدام مسافات بين قوالب الخشونة تساوي مرتين عرض القالب في حالة الحوائط ذات الخشونة المستطية أو المثلثة أفضل من إستخدام مسافات تساوي مرة واحدة أو ثلاث مرات عرض القالب، كما أظهرت النتائج أن رقم (إريبارين) ذو تأثير ضعيف نسبيا على المعاملات الهيدروديناميكية مقارنة بالإنحدار الموجي، العمق النسبي للموجة، والمسافات النسبية للخشونة المستخدمة. تم عمل تقييم كلي للنماذج المقترحة بإستخدام معامل الأداء الهيدروديناميكي للموجة، فوجد أن الحوائط مستطيلة الخشونة ذات كفاءة أفضل في تقليل قيم هذا المعامل عن الحوائط مثلثة الخشونة والحوائط الملساء حيث أن إضافة بلوكات مستطيلة أومثلثة تقلل هذا المعامل بنسب 37%، 28% على التوالي. تم رصد أفضل نتائج لهذا المعامل عند إستخدام الحوائط مستطيلة الخشونة بمسافات بين القوالب ما بين (2.21-2.27) من عرض القالب، وكذلك مابين (2.34-2.41) في حالة الحوائط مثلثة الخشونة، كما توصي الدراسة بتجنب إستخدام حوائط بميل 75^o حيث سجلت النتائج قيم عالية نسبيا لمعامل الأداء الهيدروديناميكي. باستخدام تحليل الانحدارالغير الخطى بواسطة برنامج SPSSالإحصائي تم إستنباط معادلات تقريبية لحساب معامل الارتداد، معامل الصعود النسبي ،معامل الهبوط النسبي للموجة.

Abstract

The hydrodynamic performance of vertical and sloped plane, rectangular serrated, and triangular serrated seawalls were investigated experimentally in terms of wave reflection coefficient, k_r, relative wave run-up, R_{up}/H_i, and relative wave run-down, R_{down}/H_i, using physical model studies. Regular waves of wide rang of heights, and periods were used. Tests were carried out for different inclinations of seawall (i.e. $\theta = 45, 60, 75, \text{and } 90^0$), relative dissipater blocks spacing (s/w =1.0, 2.0, 3.0), and a constant water depth of 0.4 m. It was observed that the rectangular serrated seawall was superior to the triangular serrated and plane seawall in reducing the hydrodynamic parameters mentioned above. As well it was found that the relative spacing of dissipater blocks, s/w, wave steepness, H_i/L_i, and the relative water depth, d/L_i were better influencing parameters compared to the surf similarity parameter (Iribarren N0), ξ in predicting the wave hydrodynamic parameters. Both rectangular and triangular serrated seawalls gives a good results for all hydrodynamic parameters when, s/w=2.0 compared to s/w equal to1.0 and 3.0. A total performance evaluation was done in terms of a single parameter called hydrodynamic performance parameter, and it was found that for s/w=2.0, both rectangular and triangular serrations reduces this parameter by about 37% and 28% respectively compared with the plane seawall. The worst results for performance parameter were observed when $\theta = 75^0$, while the optimum values occur when, s/w equal to (2.21-2.27), and (2.34-2.41) for the rectangular and triangular serrated seawalls respectively. Simple predictive equations were developed for estimating the wave reflection coefficients, relative run-up, and relative run-down by using non-linear regression analysis by SPSS.16 (SPSS Inc, 2006) software.

Keywords

Regular waves; Wave hydrodynamics; Wave breaking; Iribarren No; Seawalls.

Received: 8 December, 2014 – Accepted: 26 January, 2015

1. Introduction

Protection of coastal upland from erosion is one of the challenging problems. Different types of shore protection structures are in use around the world (e.g. seawalls, groins, offshore breakwaters) to stabilize the shore against wave-induced erosion. Each protective structure has its own merits and demerits. Selection of any suitable structure for shore protection is site specific. Vertical seawalls have been very widely used around the world as shore protection structures and as quay walls in harbors. But it has the disadvantage of increasing the water particle kinematics in front of the structure due to significant wave reflection, which results in increased wave loads on the seawall and increased toe scour. In order to overcome this difficulty, sloped seawalls had been introduced. Sloped seawalls are good energy dissipaters when compared to vertical seawalls, especially when the slope of the seawall is mild. Sloped seawalls cause phase lag of reflected waves and induce waves to break on the slope and hence dissipate a part of the incident wave energy. The amount of wave energy dissipation depends greatly on the slope provided. If the slope of the seawall is mild, then more number of waves breaks by spilling, which is beneficial from force and water particle kinematic reduction point of view (Fu¨hrbo¨ter, 1993). But milder the slope, the more expensive the structure is. Therefore, sloped seawalls of $\theta = 45$, 60, 75 and 90 with energy dissipaters in the form of rectangular and triangular serrated blocks were proposed. A steep sloped seawall with energy dissipaters distributed on its surface is expected to hydrodynamically replace the mild sloped seawall from dissipating the incident wave energy, and hence expected to reduce the wave reflection, wave load on the seawall, wave run-up, run-down, and toe scour. The hydrodynamic performance of these structures was investigated based on physical model study. The magnitudes of various hydrodynamic parameters will give an indication of the suitability of this structure as a coastal defense structure.

2. Literature review

A detailed review of the existing literature reveals that the present investigation is required for understanding and gaining knowledge on the sloped seawalls with energy dissipater blocks. Many studies on different hydrodynamic aspects on vertical as well as plane sloped seawalls is reported in the literature.

2.1. Predicting of wave reflection

Some of the studies related to wave reflection from sloped structures given by Moraes (1970), and Battjes (1974), they proposed empirical formula by using surf similarity parameter as the independent variable for plane and rough slopes. Seelig and Ahrens (1981) have experimentally and analytically studied wave energy dissipation and reflection characteristics for a variety of structures. Shuto (1982) proposed an approximate solution for standing waves in front of a sloping dike. Based on this, he proposed formula to estimate the reflection coefficient in front of the sloping dike. Stive (1984) suggested that the flow field of waves breaking on a gently sloping beach closely resembled that of hydraulic jumps which supports the use of hydraulic jump formulation for breaking wave energy dissipation. Kobayashi et al.(1990) carried out experimental investigations to estimate the irregular wave reflection on a 1:3 rough impermeable slope. Ahrens et al. (1993) gave an interpolation method for predicting smooth slope transitional wave reflection coefficients. An empirical formula was given by Seelig and Ahrens (1995) for regular wave conditions for the prediction of reflection due to breaking waves on a plane smooth slope. Twu and Liu (1999) developed a theory for sloping seawalls for the estimation of wave reflection. The hydrodynamic efficiency of a new type porous seawall is experimentally studied by using physical models by Heikal et al (2014).

2.2. Predicting of wave run-up

Hunt (1959) derived a formula for wave run-up on smooth slopes. Ahrens and McCartney (1975) presented an empirical method based on the non-linear function of the surf similarity parameter for estimating the wave run-up on structures protected by various types of primary armor units. Chue (1980) adapted and combined a number of standard prediction formulas to produce a single equation of wider applicability for wave run-up. Ahrens and Titus (1985) proposed an empirical formulas characterized by the surf similarity parameter according to the wave–structure regimes for the wave run-up on smooth slopes. Van der Meer and Stam (1992) identified two regions of wave breaking on a smooth sloping structure and relationships were derived for 2% run-up level. Run-up on smooth and rough slopes of seawalls is studied by Shankar and Jayaratne (2003). Run-up in narrow bays is studied with respect to the Samoa tsunami of 29 September 2009 by Ira Didenkulova (2012).

2.3. Predicting of wave run-down

Van der Meer and Breteler (1990) presented a formula for estimating relative run-down on smooth sloped seawalls for $2 \prec \xi \prec 4.3$. Schu¨ttrumpf et al.(1994) estimated an empirical formula for relative run-down on smooth sloped wall for $0.5 \prec \xi \prec 2.0$. Ching-Piao Tsai, Jiann-Shyang Wang and Chang Lin (1998) investigated the characteristics of down-rush flow from breaking waves on sloping seawalls, which cause toe scour. Neelamani[a], and Sandhya (2005) presented an experimental investigations on wave reflections, run-up and run-down, and wave pressures on plane, dentated and serrated seawalls in random wave fields.

3. Problem selection

A review of the available literature concluded that no investigations have been carried out on wave reflection, run-up and run-down on different shapes of serrations on plane seawalls. Further it is decided to introduce a number of serrations (i.e. rectangular, and triangular) on a plane seawall to increase the wave energy dissipation character.

4. Experimental setup

4.1. Test assumptions

1. The seabed is horizontal and sediment motions don't interfere with the wave motion and don't affect the model performance.
2. Both incident wave height and length are the same in the absence and presence of seawall.
3. Only hydrodynamic performance in front of the test models is considered.
4. The density difference between fresh water and seawater is not considered.

4.2. Wave flume

Several experiments were carried out in a wave flume 15.1m long, 1.0m wide and 1.0m depth, in the irrigation and hydraulics laboratory at the Faculty of Engineering, El-Mansoura University. A flap type wave generator was used to displace the water in the flume to get the desired wave characteristics. This wave generator was installed at one end of the flume. Two wave absorbers was used to prevent the reflection of wave at the other end of the flume in order to increase the efficiency of experiments and to reduce the time required between runs while the water is calming down. The first absorber was placed in the front of the wave generator while the other absorber has a slope of 1:7 (after Van der Meer, 1992) was installed at the end of the flume. The experiments were carried out with a constant water depth, d, of 0.4 m. The flap is controlled by an induction motor of 11 kW. This motor is regulated by an inventor drive (0-50Hz) rotating in a speed range of 0-155 rpm. Regular waves of heights, H_i, (6.495-11.1cm) of periods, T, (0.669– 1.308s) have been generated with this facility.

4.3. Model description

The tested models were placed at the middle of the wave flume. The models were fixed inside the wave flume rigidly for the required angle of inclination by using supports and wedges driven between the model and flume wall. The model consists of a plane plate, rectangular, and triangular dissipater blocks. Plate made of hardwood of thick 3mm coated with water insulation material. Blocks were made of wood of sizes 99cm length, 5 cm width (parallel to wall slope), 4cm height (perpendicular on wall slope). They were fixed on the plate in a regular manner as shown in Figure (1).

4.4. Experimental conditions

The measured variables together with their possible range of application are listed in Table (1).

Table 1. Range of measured variables:

Variable	Range
Water depth (d) (cm)	40.0
Inventor frequency (Hz)	From 2.5 to 4.9
Wave periods (T) (sec)	From 0.669 to1.308
Wave heights (H_i) (cm)	From 6.495 to 11.1
deep zone wave height (H_o) (cm)	From 5.93 to 11.093
Incident wave length (L_i) (cm)	From 69.69 to 218.4
Deep zone wave length (L_o) (cm)	From 69.82 to 266.89
Angle of wave attack (β)	90^o
Seabed angle (α)	0^o
Dissipater blocks spacing (s) (cm)	5.0, 10, and 15
Dissipater block width in the direction of seawall slope (w) (cm)	5.0
Seawall angle with seabed (θ)	45, 60, 75, and 90^o

The hydrodynamic performance of seawall has been checked in response to non-dimensional seawall and wave characteristic listed in Table (2).

Table 2. Range of non-dimensional seawall and wave characteristics:

Parameter	Range
Relative wave depth (d/L_i)	From 0.183 to 0.574
Wave steepness (H_i/L_i)	From 0.0297 to 0.1593
Wave steepness in terms of wave period (H_i/gT^2)	From 0.0039 to 0.0253
Surf similarity parameter (ξ)	From 2.426 to 2.93 (plunging wave) From 3.394 to 23.924 (surging wave)
Relative dissipater blocks spacing (s/w)	1.0, 2.0, and 3.0
Cot θ	0, 0.267, 0.577, and 1.0

4.5. Measuring devices

Vertical scales fixed with the Perspex part of the flume were used to measure the wave characteristics. The accuracy of these scales was 1.0 mm. The vertical scale was selected to be in front of the seawall model (seaward side) to measure the hydrodynamic parameter of waves (i.e. wave reflection, wave run-up, and wave run-down). A digital camera, (auto focus 14 mega pixel, and optical zoom 5 x), was used for recording the wave characteristics. It was connected to a personal computer, in order to analyze the wave data.

4.6. Wave Height Measurement

The water level variation resulting from wave-structure interaction was recorded by using digital camera. The camera zoom was adjusted exactly perpendicular to the linear scales on the glass flume side at each recording position. The used camera was fixed on vertical stand to avoid the variations of video shots. By using a slow motion technique that divides the second into thirty fractions, the recorded waves taken by the camera can by analyzed. Then, a relation between the wave elevation and time can be drawn.

4.6.1. Wave Reflection Measurement

The vertical distance between wave crests and the lowest elevation (trough) represents the incident wave height, H_i, in case of model absence. While, to measure the reflected wave heights, H_r, two recording positions (P_2 and P_1) were positioned in front of the seawall model (seaward side) at distances $0.2L_i$ and $0.45L_i$ respectively measured from wall teo, based on the method of Dean, R. G., and Dalrymple, R. A. (1984). These two vertical scales were positioned to meet the upper and lower limits of the standing wave envelop.

After recording the water surface elevations at two vertical scales by using the camera, the following parameters could be computed:

H_{max} = max wave height at antinodes = max crest level - min through level (1)

H_{min} = min wave height at nodes = min crest level-max through level (2)

$$H_{max} = H_i + H_r \quad (3)$$

$$H_{min} = H_i - H_r \quad (4)$$

The reflection coefficient, K_r, is the ratio between reflected and incident wave heights, therefore:

$$K_r = H_r / H_i \quad (5)$$

Depending on the equations (3), (4) and (5)

$$K_r = \frac{H_{\max} - H_{\min}}{H_{\max} + H_{\min}} \quad (6)$$

Hence, the significant reflected wave height is computed using the following relationship:

$$H_r = K_r \times H_i \quad (7)$$

4.6.2. Wave run-up and run-down measurement

A set of vertical scales have been fixed at the model position to cover the run-up and run-down zones for different selected wall slopes, so run-up and run-down could be computed as follow:

Maximum wave run-up (Rup) = maximum wave elevation on the sloped face – still water level (SWL) (8)

Maximum wave run-down (Rdown) = minimum wave elevation on the sloped face – still water level (SWL) (9)

The details of wave flume, position of the tested seawall models, shapes of used models, and the location of wave recordings are shown in Figure (2).

5. Results and discussions

5.1. General

The wave reflection characteristics will provide an indication of the wave energy dissipation characteristics of the various structures and wave field in front of the structure. Wave run-up information is required for selection of the minimum crest height of the structure for no overtopping. Wave run-down is an indirect input for understanding toe scour. The following parameters were studied such as: wave length, L_i; wave period, T; wave height, H_i; water depth, d; spacing between energy dissipater blocks, s; width of dissipater blocks, w; seawall slope angels, θ; and surf similarity parameter, ξ. The analysis presents the hydrodynamic performance in front of the seawall in terms of relationships between reflection coefficient, relative wave run-up, relative wave run-down (K_r, R_{up}/H_i, R_{down}/H_i), and the dimensionless parameters that represent the wave and structure characteristics as in the following equation:

$$K_r, \frac{R_{up}}{H_i}, \frac{R_{down}}{H_i} = f\left(\frac{H_i}{L_i}, \xi, \frac{d}{L_i}, \frac{s}{w}, \cot\theta\right) \quad (10)$$

5.2. Wave Reflection Characteristics

The effect of slope and seawall type (i.e. plane wall, rectangular serrated wall with s/w=2.0, and triangular serrated wall with, s/w=2.0) on the reflection coefficient for different wave periods (d/L_i) is given in Figure (3). For d/L_i varies from 0.183 to 0.574, it is found that the K_r value decreases with increased (cot θ) value due to wave breaking on the sloped surface by surging and plunging. The K_r value for the rectangular serrated seawall varies from 0.794 to 0.351 when cot θ is varied from 0.0 to 1.0. For the same range of cot θ, the K_r value for the plane seawall varies from

0.99 to 0.53. This clearly illustrates the better energy dissipation character of the rectangular serration. The performance of the triangular serrated seawall is in between the plane and rectangular serrated seawall, where the K_r value varies from 0.808 to 0.419 for the same range of wave periods and cot θ. The K_r reduction values in case of s/w=2.0 ranges from (32.8% - 38.3%) and (30.2%-36.8%) for rectangular and triangular serrated seawalls respectively. The effect of the slope of the seawall is more significant in K_r reduction for the shorter (d/L_i from 0.495 to 0.574) waves more than for the longer waves (d/L_i from 0.183 to 0.263).

The effect of wave steepness H_i/L_i on the K_r values incase of wall slope $\theta = 90^o$ for rectangular serrated wall with plane wall and triangular serrated wall with plane wall under different relative blocks spacing s/w (i.e. s/w=1.0, 2.0.and 3.0) was illustrated respectively in Figures (4a, 4b). It is noticed that for the case of rectangular and triangular serrated seawalls, the K_r values reduces with increase of H_i/L_i, due to excessive dissipation of energy for steeper waves. The K_r values for vertical plane are almost constant, whereas the K_r ranges from 0.955 to 0.587 for rectangular serrated, and from 0.93 to 0.62 for triangular serrated wall. This clearly brings out the benefit of vertical serrated seawall compared to plane wall for the applications in the construction of quay walls and berthing structures with vertical faces. It is to be recalled that wave reflection from the vertical walls inside the harbor is one of the main problems in the mooring of vessels. Among the three walls, the rectangular serrated seawall offers the least reflection and the reduction compared to the triangular serrated and plane seawall. A similar plots for $\theta = 45^o$ shown in Figures (4c, and 4d). It is noticed that the K_r values decreases with increase of wave steepness for all study cases, as well it is cleared that the values of K_r for the rectangular serrations are the same for s/w=1.0 ,and 3. Both rectangular and triangular serrated seawalls gives a good results for K_r when, s/w=2.0 compared to s/w equal to1.0 or 3.0 for all seawall slope angels under study.

Figure (5) is provided for illustrating the effect of surf similarity parameter ξ from the range of 3.394 to 23.924 both for plane, rectangular, and triangular serrated seawall. It can be seen in general that K_r value increases with increased ξ (the previous researchers also proved it). For the sloped plane wall, ξ is one of the important influencing parameters on K_r (Twu and Liu, 1999).

By using the above dimensionless parameters in equation (10), a non-linear regression analysis was carried out using SPSS.16 (SPSS Inc, 2006) software.

Empirical equation for estimating the reflection coefficient was developed as follow:

$$K_r = a_1\left(\frac{d}{L_i}\right)^{b_1}\left(\frac{H_i}{L_i}\right)^{c_1}(\xi)^{d_1}(\cot\theta)^{e_1}\left(\frac{s}{w}\right)^{f_1} \qquad (11)$$

The values of parameters, a_1, b_1, c_1, d_1, e_1 and f_1 for plane, rectangular serrated, and triangular serrated seawall in case of vertical and sloped wall faces are listed in Table (3).

Table 3. : Parameters of predicting reflection coefficient for different seawall types:

Vertical seawall (cot θ = 0.0)						
Wall type	a_1	b_1	c_1	d_1	e_1	f_1
Plane R^2= 0.91	0.92	0.05	-0.04	0.0	0.0	0.0
Rectangular Serrated R^2= 0.55	0.4	0.33	-.039	0.0	0.0	-0.03
Triangular serrated R^2= 0.5	0.48	0.17	-0.25	0.0	0.0	0.03
Sloped seawall (cot θ from 0.267 to 1.0)						
Plane R^2= 0.82	0.51	-0.09	-0.48	-0.76	-1.0	0.0
Rectangular Serrated R^2= 0.78	0.25	0.058	-0.82	-1.0	-1.3	-0.06
Triangular serrated R^2= 0.74	0.31	-0.07	-0.61	-0.8	-1.1	0.04

5.3. Relative Energy Dissipation

In practice, when a wave reaches the structure, some of the wave energy is dissipated by the structure itself. This dissipation part of the wave energy can be estimated in terms of non dimensional parameter called relative energy dissipation, (R_L). The value of R_L could be evaluated as a function of reflection coefficient as given by Reddy and Neelamanit (1992):

$$R_L = 1 - k_r^2 \qquad (12)$$

Figure (6) illustrates the relative energy dissipation for both plane, rectangular serrated, and triangular serrated seawalls (i.e. for s/w=2.0) versus wave steepness for wall slope angle $\theta = 60^o$. it is noticed that the plane seawall dissipates about(%8.35-40%), while the rectangular and triangular serrations dissipates about (%58-83%) and (%55-78%) respectively. This means that the rectangular and triangular blocks are good energy dissipaters.

5.4. Wave Run-up and Run-down

Relative wave run-up, R_{up}/H_i, and run-down, R_{down}/H_i were plotted for plane, rectangular and triangular serrated seawall (i.e. s/w =2.0) versus the wave steepness, H_i/L_i as provided in Figures (7a, and 7b) for wall slope angle $\theta=60^o$. It is evident that the values of relative run-up and run-down for the plane, rectangular, and triangular serrated seawalls decreases as the wave steepness increase. It is noticed that the shape of serration is not significant for the relative run-up when the wave steepness bigger than 0.1405, while the values of relative run-down always decreases when the wave steepness bigger than 0.0683.

The effect of slope on both relative run-up and run-down for the three wall types ((i.e. plane wall, rectangular serrated wall with ,s/w=2.0, and triangular serrated wall with, s/w=2.0) shown in Figures (8a,and 8b) with different wave periods, d/L_i, varies from 0.183 to 0.574 and cot θ from 0 to 1.0. it is cleared that the values of R_{up}/H_i increases with cot θ due the big disturbance sequenced by the wave breaking on the sloped faces, while the values of R_{down}/H_i decreases with cot θ. It is cleared that both rectangular and triangular serrations reduces the values of relative run-up by about(22%-28%) and (17%-22%) respectively, while the reduction values of relative run-down are (27%-43%) and(21%-33%), where adding of the serrations makes blocking for the flow on the surface of the seawall.

Figures (9a, and 9b) represents a comparison between the plane and rectangular serrated seawall (i.e. s/w =1.0, 2.0, and 3.0) for wall slope angle $\theta=60^o$ to show its effect on relative wave run-up, R_{up}/H_i, and run-down, R_{down}/H_i for different wave periods, d/L_i. The Figures show that the best values for R_{up}/H_i, and, R_{down}/H_i occur when s/w=2.0. As well, it is noticed that the effect of both dissipater blocks and relative spacing on the values of R_{up}/H_i, are not significant for short wave periods (i.e. d/L_i= 0.495 to 0.574), it is also cleared in Figure (8a). A similar plot for the triangular serrated seawall is shown in Figures (9c, and 9d). It is illustrated that for d/L_i less than 0.45, the effect of s/w on the values of R_{up}/H_i is not significant. The effect of s/w =1.0 and s/w=3.0 is almost the same for reducing the values of R_{up}/H_i, and, R_{down}/H_i.

Figures (10a,and 10b) show the effect of surf similarity parameter ξ from the range of 3.394 to 23.924 for both rectangular, and triangular serrated seawall on the values of R_{up}/H_i, and, R_{down}/H_i. It is cleared that ξ is not significant for the values of R_{up}/H_i, while the values of R_{down}/H_i increases with increased ξ.

The predictive equations for relative run-up and run-down for the seawalls based on a non linear regression analysis are given are given as follow:

$$\left(\frac{R_{up}}{H_i}, \frac{R_{down}}{H_i}\right) = a_2\left(\frac{d}{L_i}\right)^{b_2} \left(\frac{H_i}{L_i}\right)^{c_2} (\xi)^{d_2} (\cot\theta)^{e_2} \left(\frac{s}{w}\right)^{f_2} \quad (13)$$

The values of parameters, a_2, b_2, c_2, d_2, e_2 and f_2 for plane, rectangular serrated, and triangular serrated seawall in case of sloped wall faces are listed in Table (4).

Table 4. : Parameters of predicting relative run-up and relative run-down for different seawall types:

Relative run-up (R_{up}/H_i)						
Wall type	a_2	b_2	c_2	d_2	e_2	f_2
Plane R^2= 0.99	0.48	-0.49	-2.09	-3.64	-3.6	0.0
Rectangular Serrated R^2= 0.72	0.81	-0.48	-1.21	-2.41	-2.3	-0.09
Triangular serrated R^2= 0.87	0.62	-0.51	-1.59	-2.95	-2.84	-0.05
Relative run-down (R_{down}/H_i)						
Plane R^2= 0.94	0.72	-0.49	0.48	0.83	0.78	0.0
Rectangular Serrated R^2= 0.74	0.67	-0.77	0.57	0.59	0.46	-0.19
Triangular serrated R^2= 0.8	0.63	-0.77	0.46	0.46	0.37	-0.06

5.5. Hydrodynamic Performance Parameter

A total performance evaluation was done in terms of a single parameter (called wave hydrodynamic performance parameter) which represents the sum of all observed hydrodynamic parameters with the same weight values, so:

Performance parameter = $w_t*K_r+w_t*R_{up}/H_i+w_t*R_{down}/H_i$ (14)

Where: w_t, is a weight factor.

The effect of slope and seawall type (i.e. plane wall, rectangular serrated wall with s/w=2.0, and triangular serrated wall with, s/w=2.0) on the performance parameter is given in Figure (11). It was found that the values of this parameters varies from (3.28-3.47), (2.18-2.39), and (2.43-2.56) for plane, rectangular serrated, and triangular serrated seawalls respectively. This is means that the rectangular and triangular blocks reduces this parameter by about 37% and 28% respectively.

A sample of data selected for showing the mechanism of calculating of wave hydrodynamic performance parameter for plane wall with different slope angles listed in Table (5).

It was recorded that the biggest values of performance parameter occur when wall slope angle equal to 75^o (i.e. cot θ=0.2679) compared to other wall slopes under study, as shown in table (5) for plane wall as an example.

Figures (12a, 12b) show a relationship between the performance parameter versus the relative spacing between blocks, s/w, for both rectangular and triangular serrations to estimate the optimum relative spacing between dissipater blocks. It was found that the optimum relative spacing varies from (2.21-2.27), and (2.34-2.41) for the rectangular and triangular serrated seawalls respectively for all slope angles θ.

parameter	Weight (wt)	Plane wall							
		$\theta = 90^0$		$\theta = 75^0$		$\theta = 60^0$		$\theta = 45^0$	
		V	V*Wt	V	V*Wt	V	V*Wt	V	V*Wt
k_r	1.0	0.982	0.982	0.967	0.967	0.866	0.866	0.695	0.695
R_{up}/H_i	1.0	1.149	1.149	1.379	1.379	1.461	1.461	1.544	1.544
R_{down}/H_i	1.0	1.151	1.151	1.131	1.131	1.121	1.121	1.062	1.062
Cumulative marking			3.282		**3.477**		3.448		3.301

Table 5. Mechanism of calculating of wave hydrodynamic performance parameter for plane wall with different slope angles for (d/L_i = 0.183 - 0.574):

5.6. Comparison with Models Presented by Neelamani (2005)

Figure (13) shows the effect of dentated and serrated seawalls which presented by Neelamani (2005), and the present work (i.e rectangular and triangular serrated seawall, with s/w =2.0) on the reduction of both reflection coefficient, relative wave run-up, and relative wave run-down for wall slope angle $\theta=60^{o}$, and range of wave periods (d/L_i) from 0.183 to 0.574. The figure was plotted as a relationship between the values of, Kr, R_{up}/Hi, and R_{down}/Hi versus the wave steepness parameter in terms of wave period, Hi/gT^2. The figure shows a good agreement between the present study and the study presented by Neelamani (2005), where the values of K_r, R_{up}/H_i, and R_{down}/H_i decreases as Hi/gT^2 increases for all models. In addition, the figure shows that the suggested rectangular and triangular serrated seawalls of the present study are most efficient in reducing the values of K_r compared to the dentated and serrated seawalls presented by Neelamani (2005), while the serrated seawall of Neelamani (2005) gives a good reduction for the values of R_{up}/H_i, and R_{down}/H_i compared with the results of the present study.

6. Conclusions

Based on the experimental investigations, the following conclusions are obtained:

1- In general, rectangular serrated seawall is superior compared to plane and triangular serrated seawall in reducing wave hydrodynamic parameters (i.e. reflection coefficient, K_r, relative wave run-up, R_{up}/H_i, and relative wave run-down, R_{down}/H_i).

2- The relative spacing of dissipater blocks, s/w, wave steepness, H_i/L_i, and the relative water depth, d/L_i were better influencing parameters compared to the surf similarity parameter (Iribarren N0), ξ in predicting the wave hydrodynamic parameters.

3- Both rectangular and triangular serrated seawalls gives a good results for all hydrodynamic parameters when, s/w =2.0 compared to s/w equal to1.0 and 3.0.

4- Shape of serration is not significant for reducing the relative wave run-up in short wave periods (i.e. d/L_i more than 0.45).

5- Based on the measurements, predictive formulas are proposed to predict the reflection coefficient, relative wave run-up, and relative wave run-down due to regular waves for vertical and sloped plane, rectangular and triangular serrated seawalls.

6- A total performance evaluation was done in terms of a single parameter called hydrodynamic performance parameter, and it was found that both rectangular and triangular serrations reduces this parameter by about 37% and 28% respectively relative to the plane seawall for s/w = 2.0.

7- The worst results for performance parameter were observed when $\theta = 75^0$, while the optimum values occur when, s/w equal to (2.21-2.27), and (2.34-2.41) for the rectangular and triangular serrated seawalls respectively.

8- The proposed rectangular and triangular serrated seawalls gives good results for reflection coefficient compared with other models presented by Neelamani, and Sandhya (2005).

References:

[1] Ahrens, J.P., and McCartney, B.L. (1975) "Wave Period Effect on the Stability of Riprap" Proc. Civil Engineering in the Oceans III, American Society of Civil Engineers, pp. 1019–1034.

[2] Ahrens, J.P., and Titus, M.F. (1985) "Wave Run-Up Formulas for Smooth Slopes" Journal of Waterway, Port, Coastal and Ocean Engineering, American Society of Civil Engineers III (I), pp. 128–133.

[3] Ahrens, J.P., Seelig, W.N., Ward, D.L., and Allsop, W. (1993) "Wave Run-Up and Wave Reflection from

Coastal Structures" In: ASCE, Proceedings, Waves 1993, pp. 489–502.

[4] Battjes, J.A., (1974) "Surf Similarity" Proc. of 14th Coastal Engineering Conference, Copenhagen, pp. 466–480.

[5] Chue, S.H. (1980) "Wave Run-Up Formula of Universal Applicability". Proc. ICE Pt 2, Vol. 69, TN 274.

[6] Dean, R. G., and Dalrymple, R. A. (1984). "Water wave mechanics for engineers and scientists" Prentice-Hall Englewood Cliffs, NJ, 353.

[7] Didenkulova, I. (2012) "Tsunami Run-Up in Narrow Bays: the Case of Samoa 2009 Tsunami" Nat Hazards, Vol. 65. pp. 1629–1636.

[8] Fu¨hrbo¨ter, A. (1993) "Wave Loads on Sea-Dikes and Seawalls" In: Abbott, M.B., Price, W.A. (Eds.), Coastal, Estuarial and Harbor Engineer's Reference Book, pp. 351–367.

[9] Heikal, E. M., Koraim, A. S. and Abozaid, A. A. (2014) "Protecting coasts against probable sea level rise by using porous vertical seawall" the Egyptian Int. J. of Sci. and Technology, Vol. 15, No. 3, pp:1233-1243.

[10] Hunt, I.A. (1959) "Design of Seawalls and Breakwaters" Jour. Waterways Div., ASCE, pp. 123–152.

[11] Kobayashi, N., Cox, D.T., and Wurjanto, A. (1990) "Irregular Wave Reflection and Run-Up on Rough Impermeable Slopes" J. of Waterway, Port, Coastal and Ocean Engineering, Vol. 116, pp. 708–726.

[12] Moraes, C.D. (1970) "Experiment of Wave Reflection on Impermeable Shores" Proc. of the 12th Conf. on Coastal Engineering, ASCE. 1. pp. 509–521.

[13] Neelamani, S. and Sandhya, N. (2005) "Surface Roughness Effect of Vertical and Slopped Seawalls in Incident Random Wave Fields" Ocean Engineering, Vol. 32, pp. 395-416.

[14] Reddy,M., and Neelamani, S. (1992) "Wave Transmission and Reflection Characteristics of a Partially Immersed Rigid Vertical Barrier" J. of Ocean Engineering, Vol. 19, No. 3, pp 313-325.

[15] Schu¨ttrumpf, H., Bergmann, H., and Dette, H.H. (1994) "The Concept of Residence Time for the Description of Wave Run-Up, Wave Setup and Wave Run-Down". Proc. 24th Int. Conf. Coastal Engineering, Kobe, Japan, pp. 553–564.

[16] Seelig, W.N., and Ahrens, J.P. (1981) "Estimation of Wave Reflection and Energy Dissipation Coefficients for Beaches, Revetments and Breakwaters" US Army Corps of Engineers, CERC, USA. pp. 81-140.

[17] Seelig, W.N., and Ahrens, J.P. (1995) "Wave Reflection and Energy Dissipation by Coastal Structures" In: Wave Forces on Inclined and Vertical Wall Structures. Task Committee on Forces on Inclined and Vertical Wall Structures, ASCE., pp. 28–51.

[18] Shankar, N.J., and Jayaratne, M.P.R. (2003) "Wave Run-Up and Overtopping on Smooth and Rough Slopes of Coastal Structures" Ocean Engineering, Vol. 30, pp. 221-238.

[19] Shuto, N. (1982) "Standing Waves in Front of Sloping Dike". In: Proceedings of the 13th Coastal Engineering Conference, Vancouver, BC, Canada., pp. 1629–1647.

[20] Stive, M.J.F. (1984) "Energy Dissipation in Waves Breaking on Gentle Slopes" Coastal Engineering, Vol. 8, pp. 99–127.

[21] Tsai, C.P., Wang, J.S., and Lin, C.(1998) "Down-Rush Flow from Waves on Sloping Seawalls" Ocean Engineering, Vol. 25, pp 295–308.

[22] Twu, S.W., and Liu, C.C. (1999) "The reflection Coefficient of Sloping Walls" Ocean Engineering, Vol. 26, pp. 1085–1094.

[23] Van der Meer, J.W., and Breteler, M.K. (1990) "Measurements and Computation of Wave Induced Velocities on a Smooth Slope" Proc. 22nd Conf. on Coastal Engineering, Delft, pp. 191–204.

[24] Van der Meer, J.W., and Stam, C.M. (1992) " Wave Run-Up on Smooth and Rock Slopes of Coastal Structures". Jour. Waterway, Port, Coastal and Ocean Eng. ASCE. Vol.118, No. 5, pp. 534–550.

Notation & abbreviations:

Notation:

The following symbols are used in this paper:

D : Still water depth;
G : Gravitational acceleration;
H_i : Incident wave height;
H_o : Deep zone wave height;
H_r : Reflected wave height;
K_r : Reflection coefficient;
L_i : Incident wave length;
L_o : Deep zone wave length;
P_1, P_2 : Wave recorders;
R_{down} : Maximum wave run-down;
R_L : Relative energy dissipation;
R_{up} : Maximum wave run-up;
S : Net spacing between dissipater blocks;
T : Wave period;
W : Width of dissipater blocks in the direction of wall slope;
w_t : Weight factor, equal to 1.0; and
V : Value of wave hydrodynamic parameters.

Greek letters

Θ : Slope angle between seawall and seabed;
A : Seabed angle;
Β : Angle of wave attack; and
Ξ : Surf similarity parameter (Iribarren number).

Abbreviations:

SPSS: Statistical Package for Social Science.
SWL: Still Water Level.

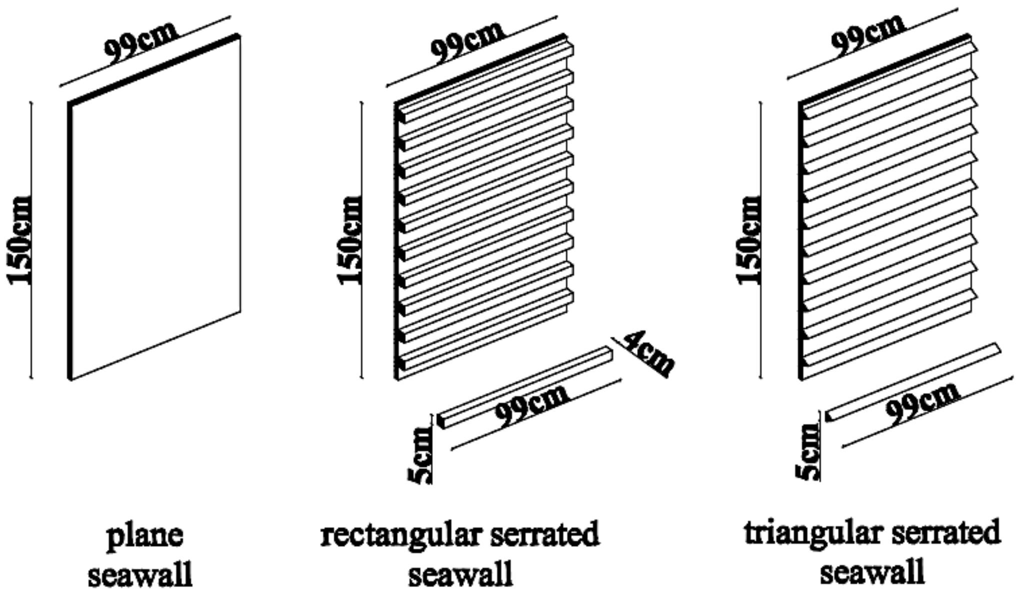

Fig. 1. Isometric views for the tested models, and blocks arrangement.

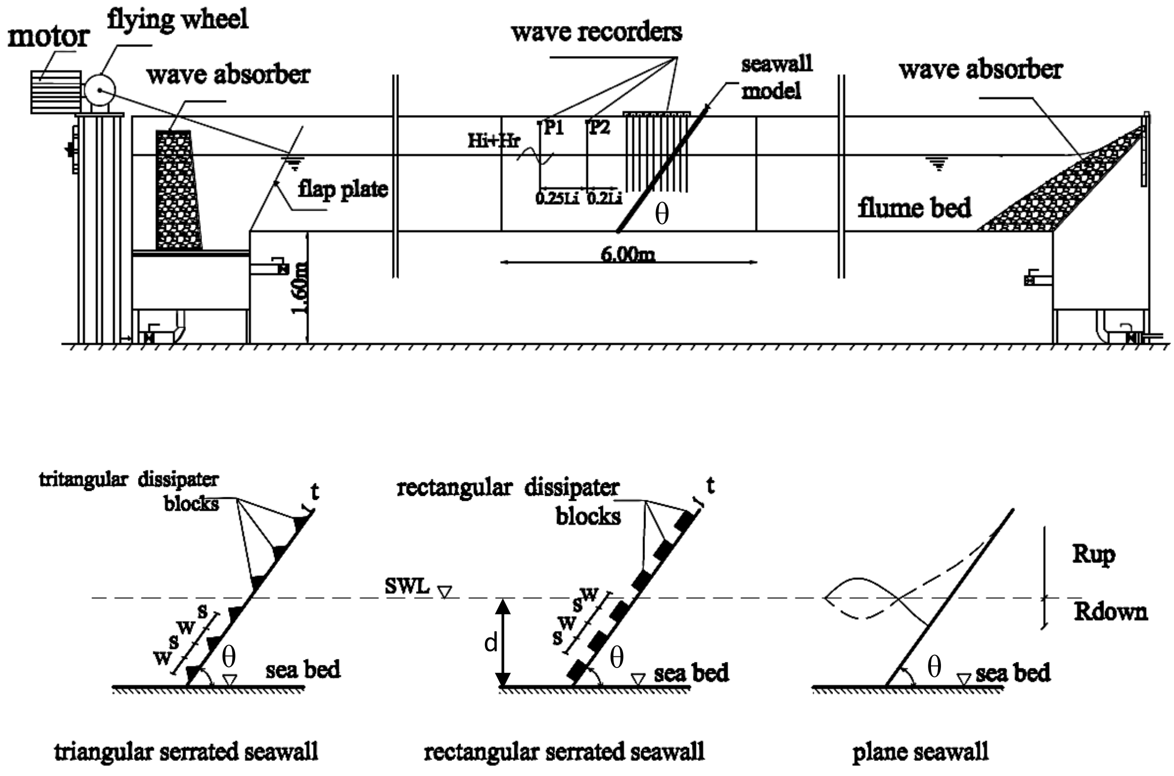

Fig. 2. Details of wave flume, position of model, shape of models, and location of wave recorder.

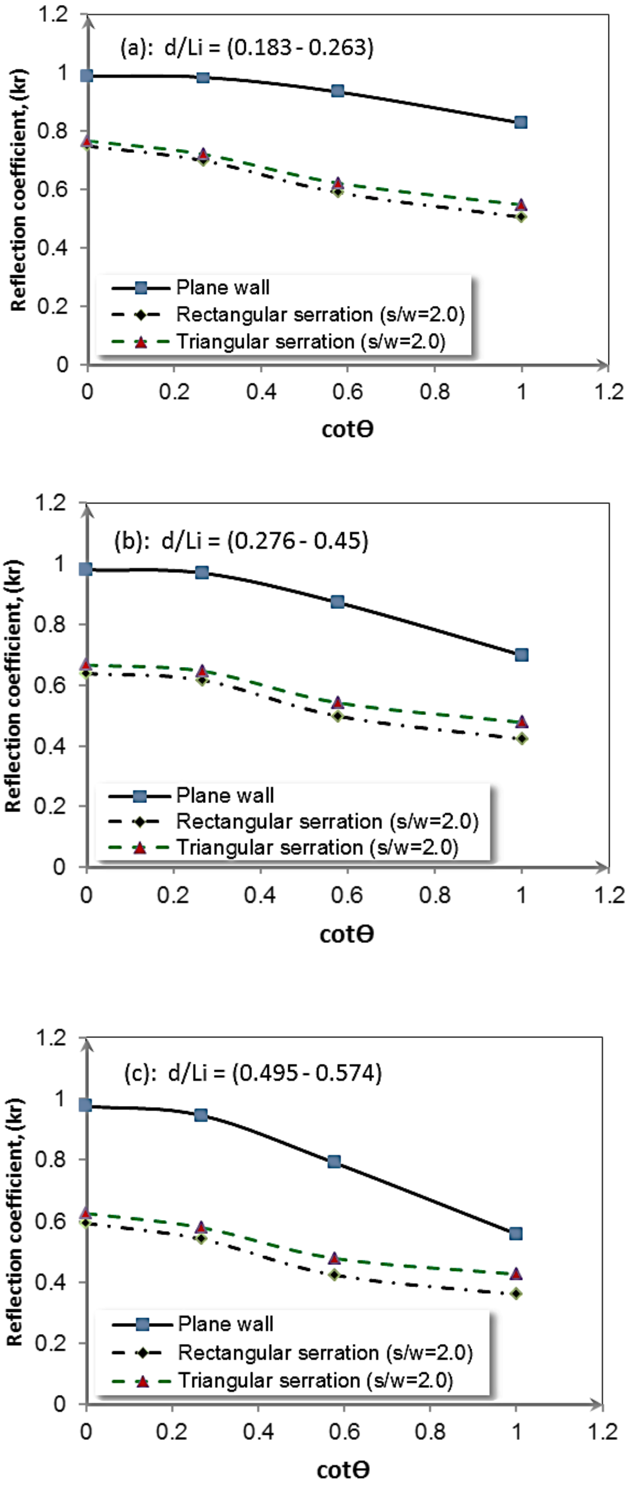

Fig. 3. Effect of seawall slope (cotθ) on (Kr) for plane wall, rectangular, and triangular serrated seawall with (s/w=2.0) at different wave periods.

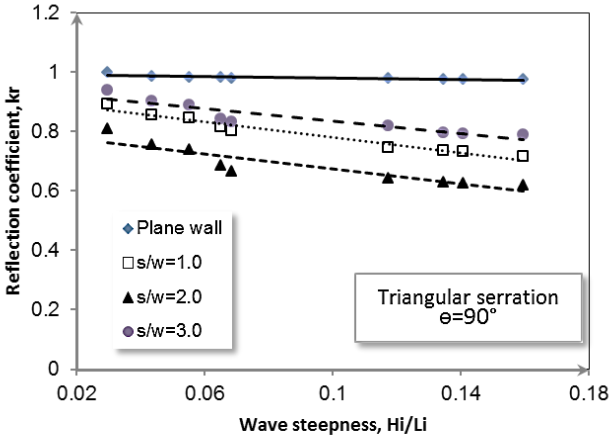

Fig. 4.a. Effect of wave steepness (H_i/L_i) on (Kr) for plane wall, and rectangular serrated seawall with different s/w ($\theta=90^o$).

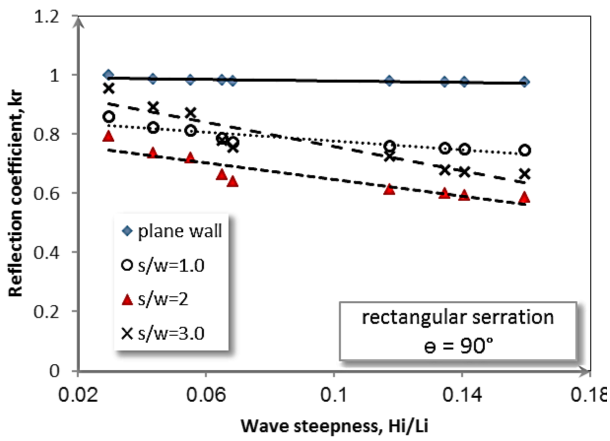

Fig. 4.b. Effect of wave steepness (H_i/L_i) on (Kr) for plane wall, and triangular serrated seawall with different s/w ($\theta=90^o$).

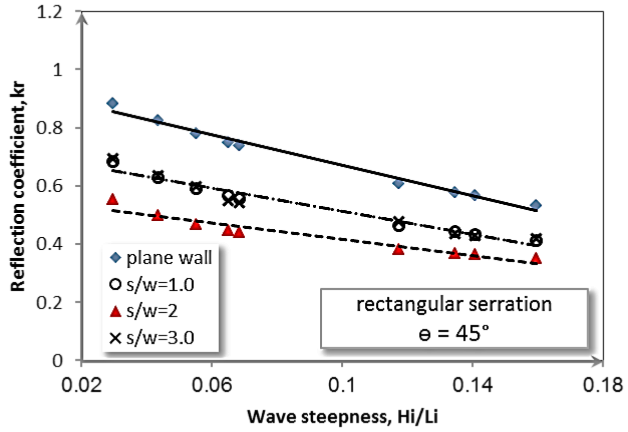

Fig. 4.c. Effect of wave steepness (H_i/L_i) on (Kr) for plane wall, and rectangular serrated seawall with different s/w (θ=45^o).

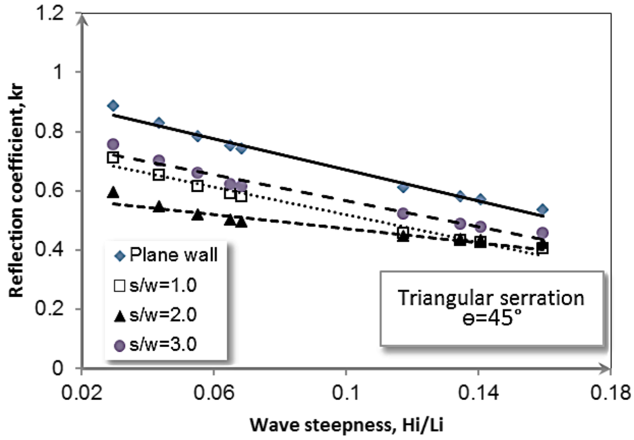

Fig. 4.d. Effect of wave steepness (H_i/L_i) on (Kr) for plane wall, and triangular serrated seawall with different s/w (θ=45^o).

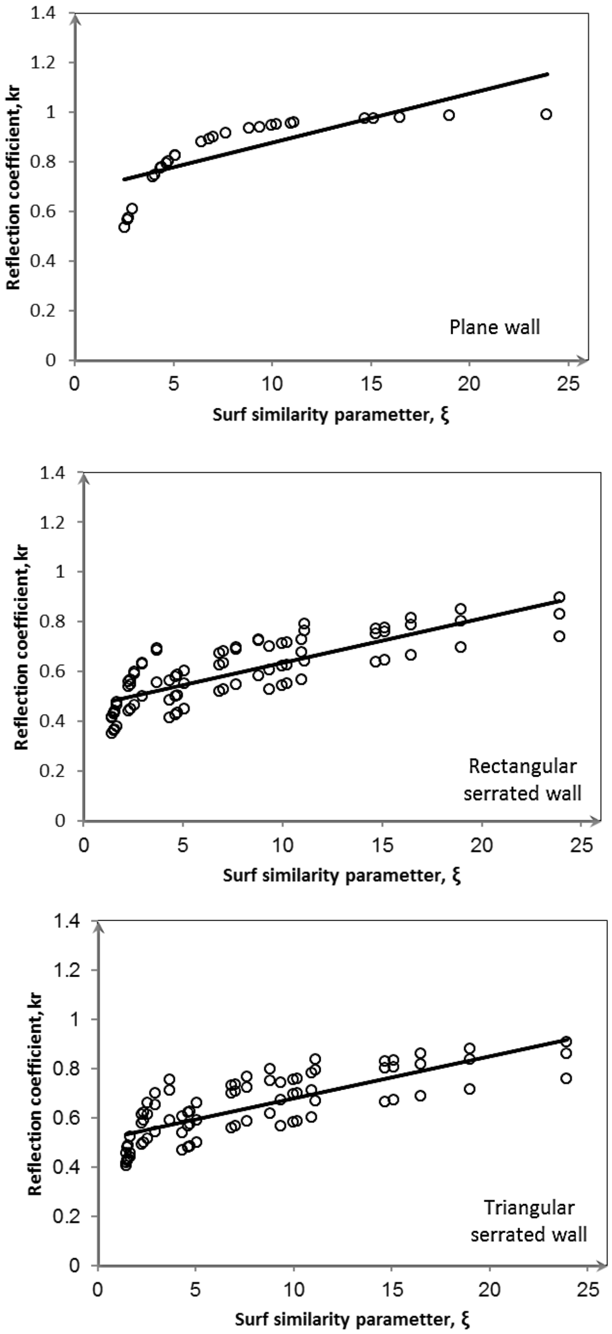

Fig. 5. Effect of surf similarity parameter (ξ) on (Kr) for plane, rectangular serrated and triangular serrated seawall.

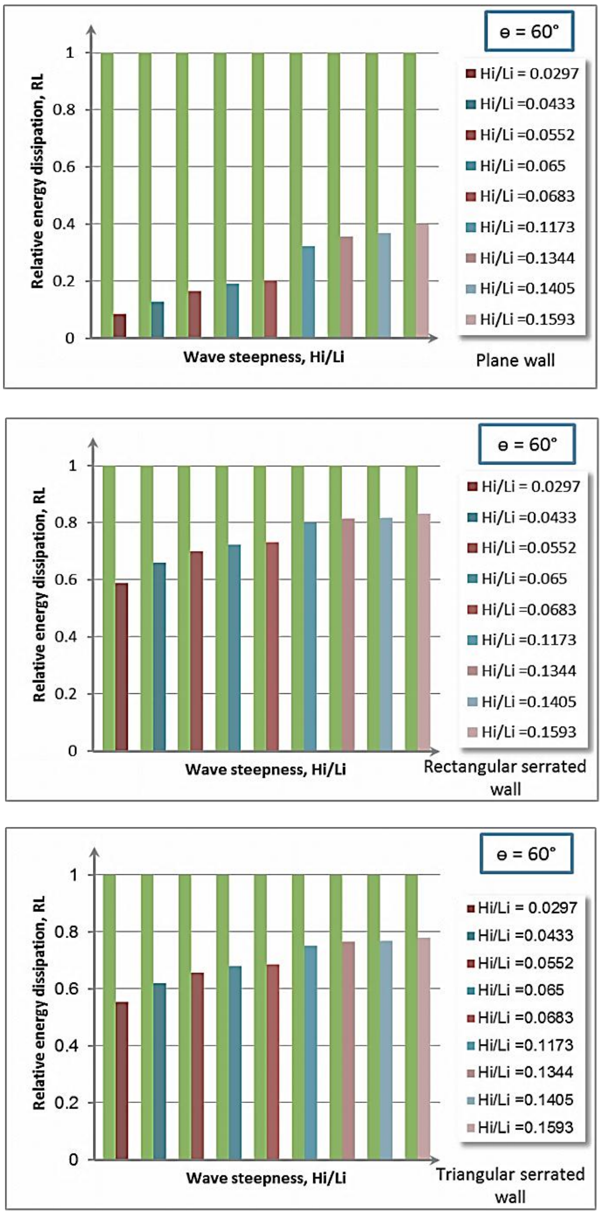

Fig. 6. Relative energy loss (R_L) versus wave steepness (H_i/L_i) for plane, rectangular serrated and triangular serrated seawall at (s/w=2.0, $\theta=60^o$).

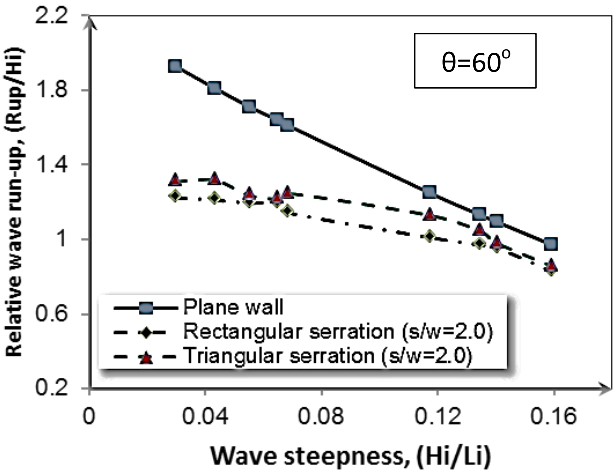

Fig. 7.a. Effect of wave steepness (H_i/L_i) on (R_{up}/H_i) for plane wall, rectangular, and triangular serrated seawall with different (s/w), ($\theta=60^o$).

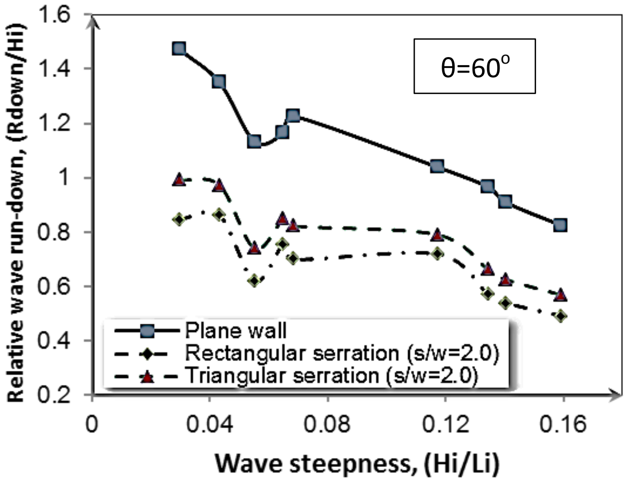

Fig. 7.b. Effect of wave steepness (H_i/L_i) on (R_{down}/H_i) for plane wall, rectangular, and triangular serrated seawall with different (s/w), ($\theta=60^o$).

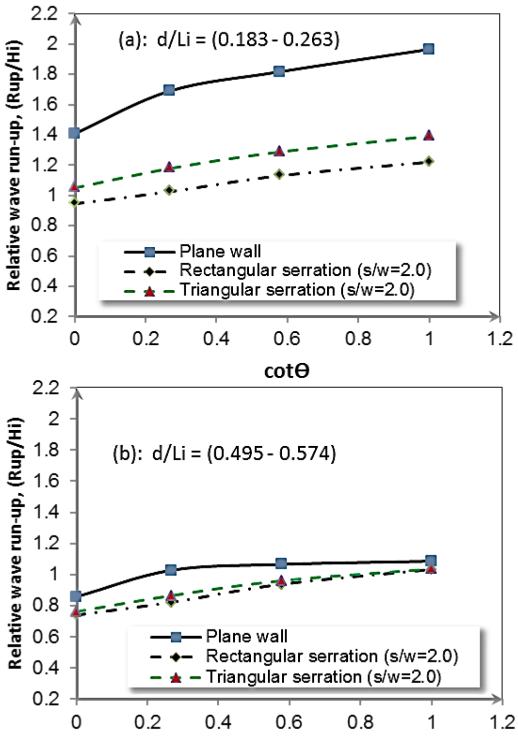

Fig. 8.a. Effect of seawall slope (cotθ) on (R_{up}/H_i) for plane wall, rectangular, and triangular serrated seawall with (s/w=2.0) at different wave periods.

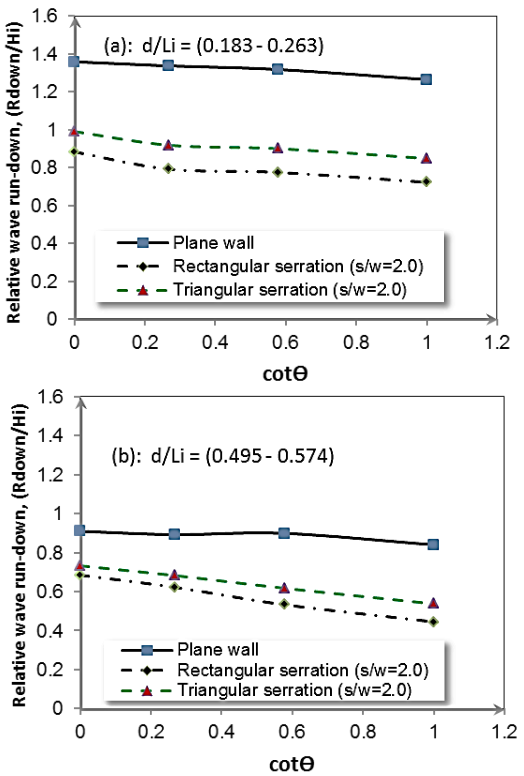

Fig. 8.b. Effect of seawall slope (cotθ) on(R_{down}/H_i) for plane wall, rectangular, and triangular serrated seawall with (s/w=2.0) at different wave periods.

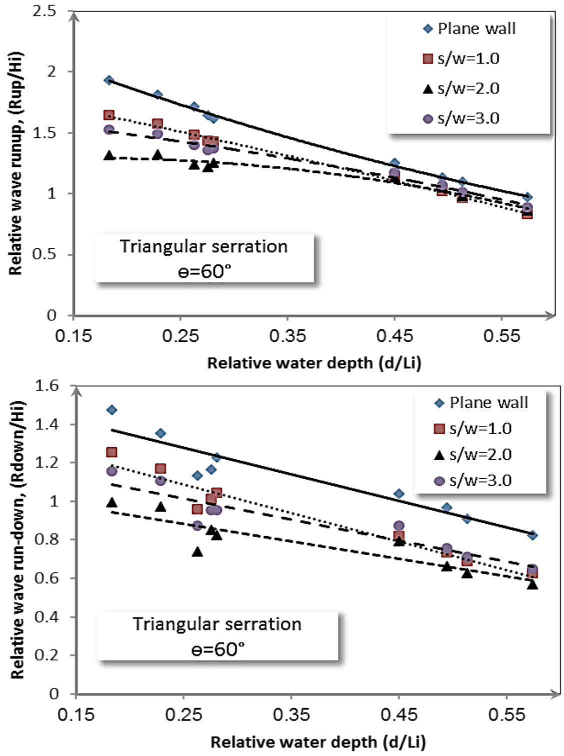

Fig. 9.a. Effect of relative depth (d/L_i) on (R_{up}/H_i),and (R_{down}/H_i) for plane wall, and rectangular serrated seawall with different s/w ($\theta=60^o$).

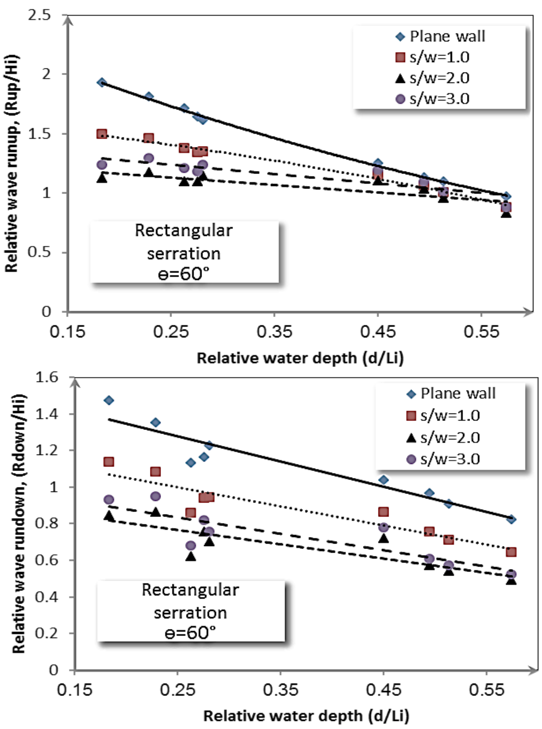

Fig. 9.b. Effect of relative depth (d/L_i) on (R_{up}/H_i),and (R_{down}/H_i) for plane wall, and triangular serrated seawall with different s/w ($\theta=60^o$).

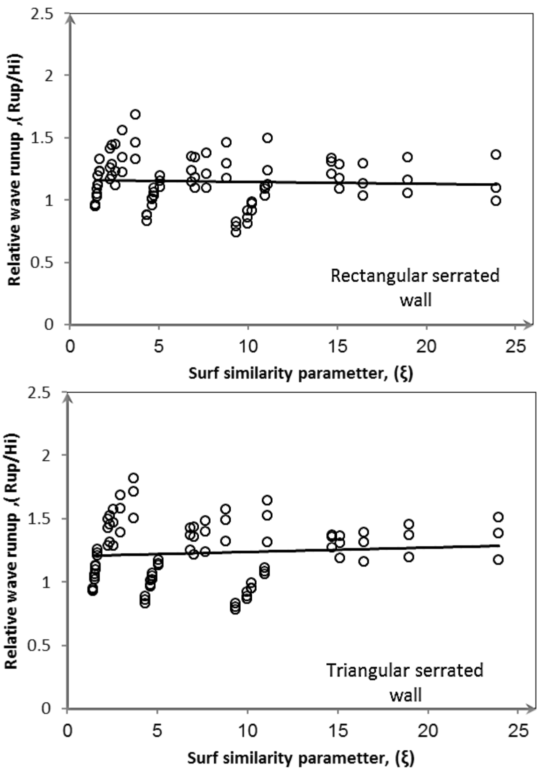

Fig. 10.a. Effect of surf similarity (ξ) parameter on (R_{up}/H_i) for rectangular and triangular serrated seawall.

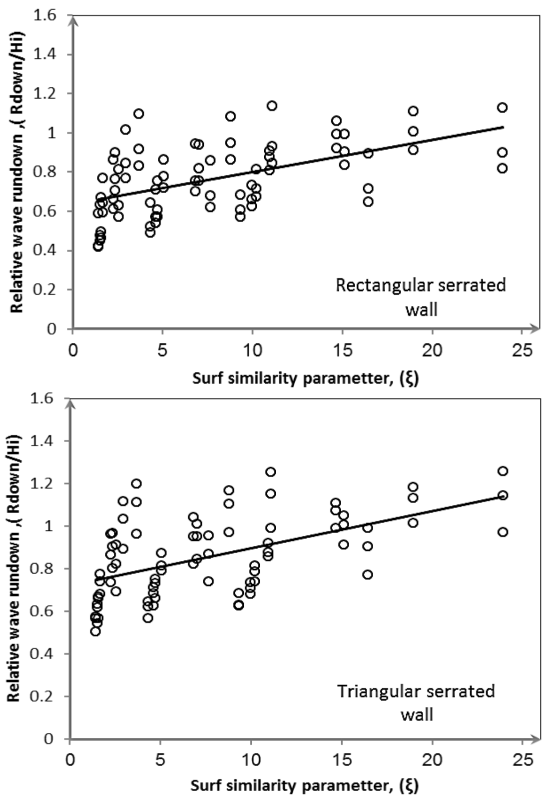

Fig. 10.b. Effect of surf similarity parameter (ξ) on (R_{down}/H_i) for rectangular and triangular serrated seawall.

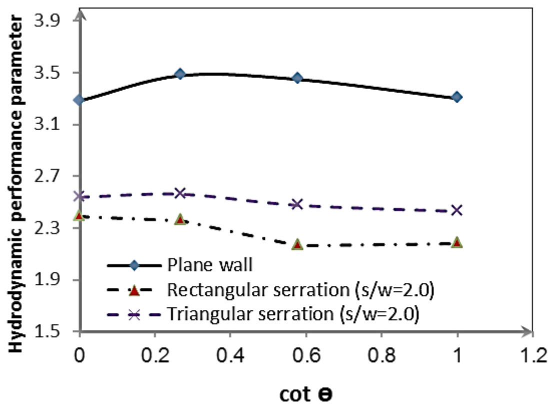

Fig. 11. Effect of seawall slope (cotθ) on performance parameter for plane wall, rectangular, and triangular serrated seawall with (s/w=2.0) at (d/L_i=0.183 to 0.574). (d/L_i=0.183 to 0.574).

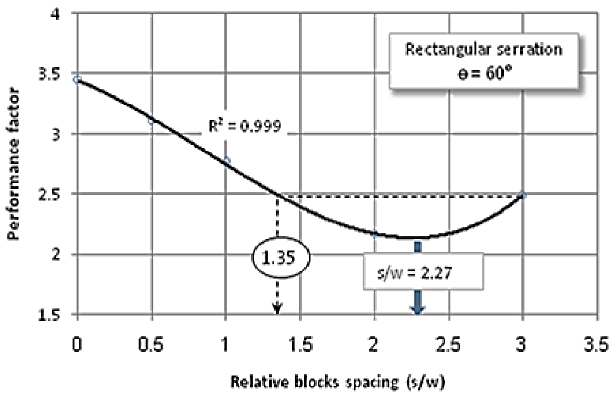

Fig. 12.a. Effect of relative spacing between blocks (s/w) on (performance parameter) for rectangular serrated seawall with ($\theta=60^o$) at (d/L_i=0.183 to 0.574).

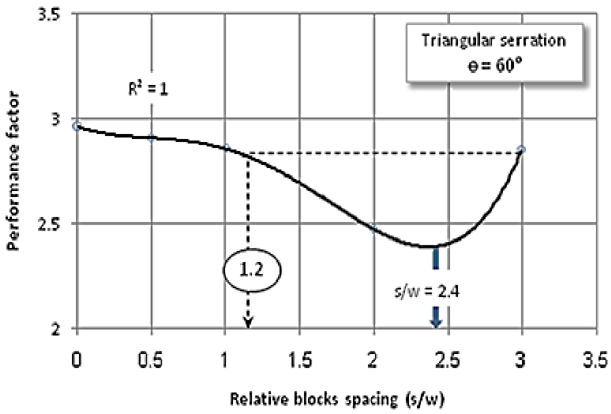

Fig. 12.b. Effect of relative spacing between blocks (s/w) on (performance parameter) for triangular serrated seawall with ($\theta=60^o$) at (d/L_i=0.183 to 0.574).

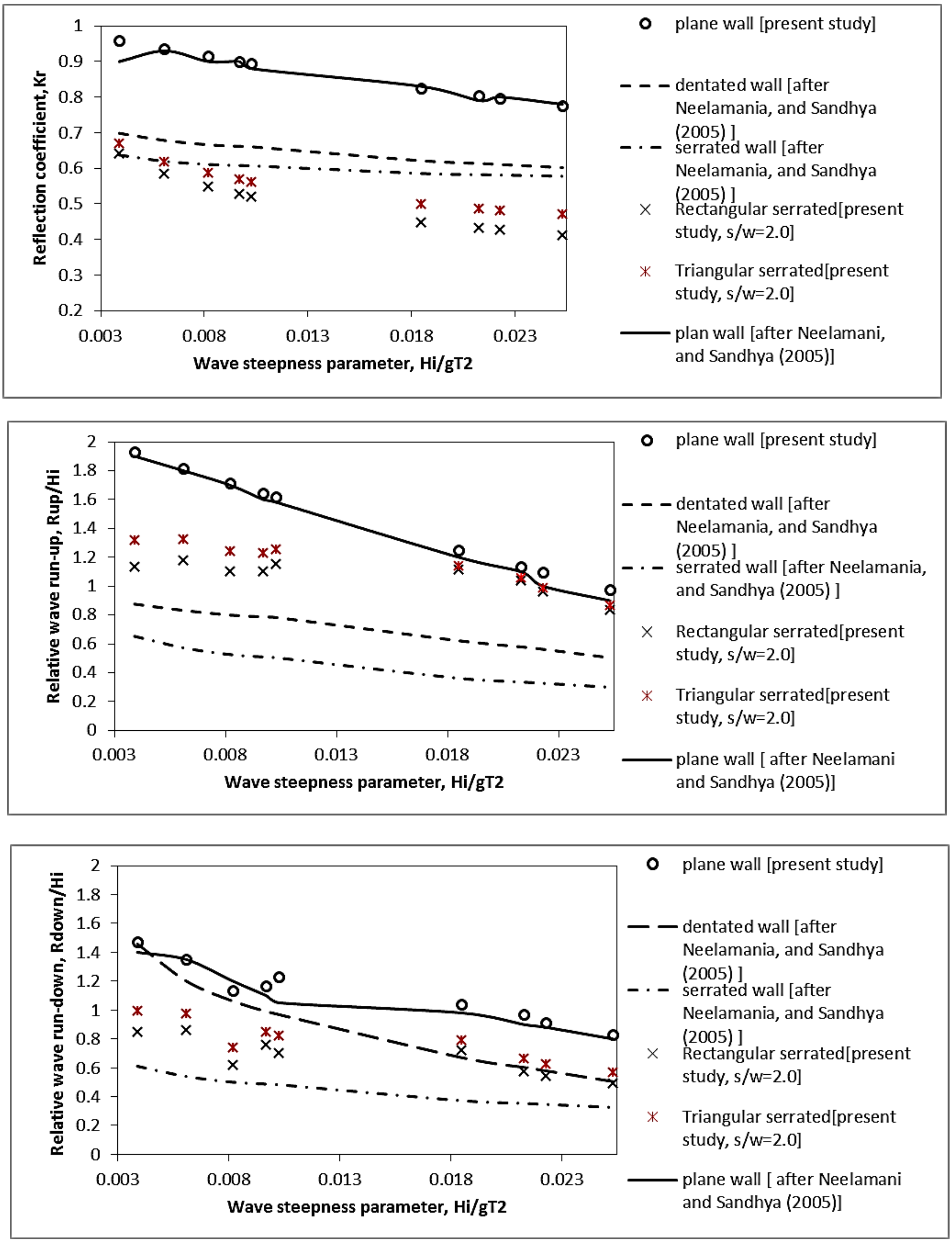

Fig. 13. Comparison between present study (rectangular and triangular serrated walls at s/w= 2.0), and models presented by Neelamani, and Sandhya (2005) for (K_r), (R_{up}/H_i), (R_{down}/H_i) versus wave steepness parameter (H_i/gT^2), at (θ=60^o and d/L_i=0.183 to 0.574).