PREDICTIVE FORMULAE FOR ESTIMATING OF WAVE HYDRODYNAMIC PARAMETERS IN FRONT OF SEAWALLS

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ABSTRACT

Simple predictive formulas are developed for estimating the wave hydrodynamic parameters in front of seawalls in terms of wave reflection coefficients, relative run-up, and relative run-down by using nonlinear regression analysis made by SPSS software. These formulas are calibrated based on the results of experimental modeling. The different experiments include vertical and sloped seawalls with energy dissipaters in the form of rectangular or triangular serrated blocks and slotted seawalls with or without triangular serrations. A comparative study is done between these formulas and other experimental or theoretical results obtained by different authors and it giving a reasonable agreement. The results could be used for a better hydrodynamic design of vertical structures (i.e. quay walls in harbors, vertical seawalls, caisson type breakwaters) and sloped structures (i.e. seawalls, dikes, wave absorbers in the laboratory).

Keywords: Wave Reflection, Wave Run-up, Wave Run-down, Seawalls, SPSS.

1 INTRODUCTION

Seawalls are used for the protection of sea coasts against the wave-induced erosion and dikes are used for preventing seawater overtopping into the low-lying lands during hostile environmental conditions. An optimal design of these structures require detailed information on various hydrodynamic parameters, like wave run-up, run-down, wave overtopping, and wave reflection characteristics. A detailed review of the existing literature reveals that the present study is required for understanding and gaining knowledge on the hydrodynamic effect of waves on seawalls. Some theoretical and experimental studies on different hydrodynamic aspects on vertical as well as sloped seawalls were reported in the literature. Early practical formulas for regular wave run-up on smooth and rough plane slopes and composite slopes were presented by (Hunt Jr 1959). (Chue & Shah 1981) adapted and combined a number of standard prediction formulas to produce a single equation of wider applicability for wave run-up. A formula was characterized by the surf similarity parameter (ξ) according to the wave–structure regimes for the wave run-up on smooth slopes by (Ahrens & Titus 1985). Both (van der Meer & Breteler 1990) and (Schuttrumpf et al. 1995) were proposed empirical formulas to estimate the relative wave run-down for sloping plane seawalls. A numerical studies were done by (Mallayachari & Sundar 1994) and (Isaacson et al. 2000) to obtain the wave reflection characteristics for perforated seawalls. (Neelamani & Sandhya 2005) presented predictive equations based on experimental investigations of wave reflection, run-up, run-down and wave pressures on the plan, dentated and serrated seawalls. (Reddy et al. 2007) set a numerical and experimental investigation on the performance of an offshore submerged breakwater in reducing the wave forces and wave run-up on a vertical wall. The wave reflection characteristics of a porous seawall which could be used in protecting coasts from possible sea level rising were experimentally studied using physical models by (Koraim et al. 2014). The hydrodynamic performance of vertical and sloped seawalls was investigated experimentally by (El Alfy et al. 2015) using physical model studies under regular waves of a wide range of heights, and periods. After critical reviewing, it is noticed that more formulas for estimating wave reflection, wave run-up, and wave run-down on seawalls are needed to cover the impact of different shapes of serrations as well as slots combined with serrations. So, the present study includes five different types of seawalls. The first type is impermeable plane seawall while the second type is a plane wall with rectangular dissipater blocks distributed horizontally in a regular manner on the wall surface. Also, the third type is a plane wall with triangular dissipater blocks distributed horizontally in a regular manner on the wall surface. Then the fourth type is a plane wall with regular horizontal slots, and the last type is a triangular serrated seawall with regular horizontal slots, see Fig. 1.

2 THEORETICAL APPROACH

The suitable mathematical technique which deals with the dimensions of the physical quantities involved in the phenomenon under study is the dimensional analysis. Dimensional analysis using Buckingham Pi theorem is performed to develop relationships of wave reflection (K_r), wave run-up (R_{up}), and wave run-down (R_{undown}) in terms of hydraulic and geometrical characteristics of the suggested models. It is used to obtain a functional relationship between the dependent and independent variables. It is assumed that the dependent variables, reflected wave height (H_r), the maximum wave run-up (R_{up}), and the maximum wave run-down (R_{down}) is a function of the following independent variables:

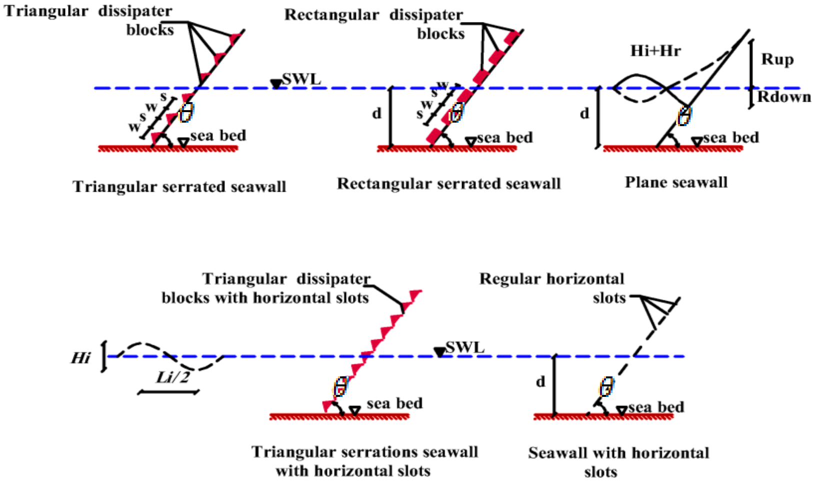

Figure 1. Definition sketches of seawalls physical models.

water density, ρ_w; gravitational acceleration, g; local incident wave length, L_i; deep zone wave length, L_o; wave period, T; local incident wave height, H_i; deep zone wave height, H_i; still water depth, d; spacing between energy dissipater blocks, s; width of dissipater blocks, w; slots ratio per 1.0 m^2 of the wall surface, G; and seawall slope angle with seabed, θ. According to dimensional analysis, the general function relationship between these variables can be written as:

$$f(H_i, L_i, T, H_o, L_o, H_r, R_{up}, R_{down}, \rho_w, d, g, \theta, w, s, G) = 0.0 \qquad (1)$$

Where f is a function, the resulting basic functional eq. (1) contains 15-dimensional variables. It means that n = 15 variables, where m = 3 basic quantities, mass (M), length (L), and time (T), then 12 dimensionless terms (12 πs) are produced. Therefore, the density of water (ρ_w), gravitational acceleration (g), and wave length (L_i) are selected as repeating variables. The π groups are formed by multiplying the product of the primary variables with unknown exponents by each of the remaining variables. In order to satisfy dimensional homogeneity, the exponents of each dimension are equated on both sides for each π equation and then solve for the exponents and the forms of the dimensionless groups. The variables could be written in non-dimensional form by the following functions:

$$f_1(\pi_1,\pi_2,\pi_3,\pi_4,\pi_5,\pi_6,\pi_7,\pi_8,\pi_9,\pi_{10},\pi_{11},\pi_{12})=0.0 \qquad (2)$$

$$f_2\left(\frac{H_i}{L_i},K_r,\xi,\frac{H_i}{gT^2},\frac{R_{up}}{H_i},\frac{R_{down}}{H_i},\frac{d}{L_i},\frac{s}{w},G,\cot\theta\right)=0.0$$

(3) $$K_r,\frac{R_{up}}{H_i},\frac{R_{down}}{H_i}=f_3\left(\frac{H_i}{L_i},\xi,\frac{H_i}{gT^2},\frac{d}{L_i},\frac{s}{w},G,\cot\theta\right)$$

(4)

So, as presented through eq. (4) the hydrodynamic performance of the five tested seawalls has been checked in response to non-dimensional seawall and wave characteristic. The definitions and ranges of these non-dimensional parameters are listed in Table 1.

Table 1. Ranges of non-dimensional seawall and wave characteristics.

Parameter	Ranges of applicability
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
Slots ratio for 1.0 m^2(G)	0.13, 0.23, and 0.33
Cot θ	0, 0.267, 0.577, and 1.0

3 FORMULAS CALIBRATION BY SPSS

Investigating the effect of ξ, d/L_i, and H_i/L_i or H_i/gT^2 on k_r, R_{up} and R_{down} is not only essential to understand the hydrodynamic characteristics of the existing seawall for coastal regions. However, also, it helps to realize the performance of the seawall under normal and extreme wave actions. Moreover, investigating the effect of s/w, G, and cot θ on k_r, R_{up} and R_{down} is required to select the appropriate structures configuration. Based on the above dimensionless parameters in eq. (4), a non-linear regression analysis is carried out on about 70% of the observed data using SPSS (Levesque 2006) to obtain predictive equations for estimating the values of K_r, R_{up}/H_i, and R_{down}/H_i as follow:

$$K_r,\frac{R_{up}}{H_i},\frac{R_{down}}{H_i}=a_1\left(\frac{d}{L_i}\right)^{b_1}\left(\frac{H_i}{L_i}\right)^{c_1}(\xi)^{d_1}(\cot\theta)^{e_1}\left(\frac{s}{w}\right)^{f_1}(G)^{g_1} \qquad (5)$$

The values of parameters, a_1, b_1, c_1, d_1, e_1, f_1, and g_1 for the plane, rectangular serrated, triangular serrated seawall, slotted seawall and slotted seawall with triangular serrations in the case of vertical and sloped wall faces are listed in Table 2. These formulas are applied to a specific applicability range of non-dimensional parameters as mentioned in Table 1.

4 FORMULAS VERIFICATION

The remaining 30% of the observed data are used to verify the predicted values of K_r, R_{up}/H_i, and R_{down}/H_i which obtained from eq. (5). The data points are reasonably distributed on either side of a 45° line which is used for observing the correlation between the predicted and observed K_r. Figures 2a, 2b, and 2c are plotted to depict the correlation between the measured and predicted values of K_r, R_{up}/H_i, and R_{down}/H_i for the plane wall, rectangular serrated wall, and slotted wall with triangular serration for the sloped case. As well figures 2d, 2e, and 2f demonstrate the residuals and the corresponding mean square errors for the predicted values of K_r, R_{up}/H_i, and R_{down}/H_i based on eq.(5).

Table 2. Estimated parameters of eq. (5) for predicting wave reflection, wave run-up, and wave run-down for different seawall types.

Wall type	**a_1**	**b_1**	**c_1**	**d_1**	**e_1**	**f_1**	**g_1**
Reflection coefficient (K_r) for vertical seawall (cot θ = 0.0)							
Plane, R^2= 0.91	0.92	0.05	-0.04	0.0	0.0	0.0	0.0
Rectangular Serrated R^2= 0.55	0.4	0.33	-.039	0.0	0.0	-0.03	0.0
Triangular serrated R^2= 0.5	0.48	0.17	-0.25	0.0	0.0	0.03	0.0
Slotted, R^2=0.99	0.4	0.017	-0.02	0.0	0.0	0.0	-0.3
Slotted + triangular serrations, R^2=0.99	0.4	-0.05	0.006	0.0	0.0	0.0	-0.29
Reflection coefficient (K_r) for 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	0.0
Rectangular Serrated R^2= 0.78	0.25	0.06	-0.82	-1.0	-1.3	-0.06	0.0
Triangular serrated R^2= 0.74	0.31	-0.07	-0.61	-0.8	-1.1	0.04	0.0
Slotted, R^2=0.9	0.29	-0.34	0.9	1.4	1.2	0.0	-0.4
Slotted + triangular serrations, R^2=0.9	0.25	-0.34	0.94	1.48	1.25	0.0	-0.4
Relative run-up (R_{up}/H_i) for sloped seawalls (cot θ from 0.267 to 1.0)							
Plane, R^2= 0.99	0.48	-0.49	-2.09	-3.64	-3.55	0.0	0.0
Rectangular Serrated R^2= 0.72	0.81	-0.48	-1.21	-2.41	-2.3	-0.09	0.0
Triangular serrated R^2= 0.87	0.62	-0.51	-1.59	-2.95	-2.84	-0.05	0.0
Slotted, R^2=0.99	0.3	-0.55	-1.9	-3.5	-3.4	0.0	-0.2
Slotted + triangular serrations, R^2=0.98	0.28	-0.56	-1.94	-3.5	-3.4	0.0	-0.2
Relative run-down (R_{down}/H_i) for sloped seawalls (cot θ from 0.267 to 1.0)							
Plane, R^2= 0.94	0.72	-0.49	0.48	0.83	0.78	0.0	0.0
Rectangular Serrated R^2= 0.74	0.67	-0.77	0.57	0.59	0.46	-0.19	0.0
Triangular serrated R^2= 0.8	0.63	-0.77	0.46	0.46	0.37	-0.06	0.0
Slotted, R^2=0.96	0.36	-0.5	0.4	0.7	0.62	0.0	-0.3
Slotted + triangular serrations, R^2=0.95	0.4	-0.5	0.45	0.76	0.7	0.0	-0.2

As depicted through fig.2, the values of correlation factor for K_r are $2x10^{-7}$, 0.0005, 0.019 for plane, rectangular serrated, and slotted with triangular serrations respectively, while for wave run-up the values of correlation are 0.0004, $1x10^{-5}$, 0.0004, and also for wave run-down these values are 0.0015, 0.0054, and 0.0003. It is noticed that the agreement between observed and predicted values is slightly converged. Also, the values of residuals are found rather small with negligible correlation coefficient and symmetrically distributed around the line of zero error.

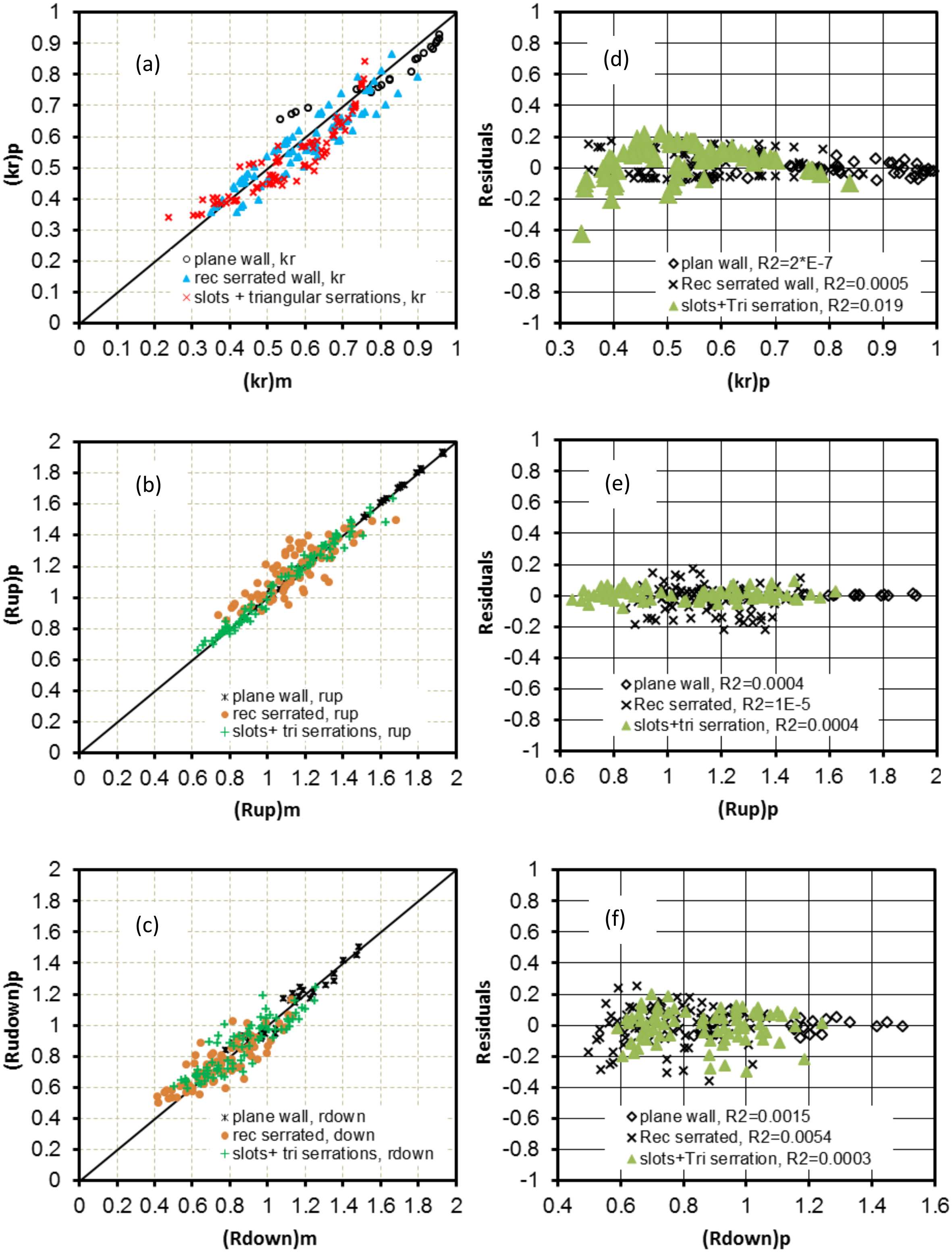

Figure 2. Residuals and comparison between the measured and predicted wave reflection coefficient, wave run-up, and wave run-down for the sloped plane, rectangular serrated, and slotted with triangular serrations walls by using nonlinear regression.

(a): wave reflection coefficient, (b): wave run-up, (c): wave run-down, (d): residuals of wave reflection coefficient, (e): residuals of wave run-up, (f): residuals of wave run-down.

5 FORMULAS VALIDATION

The empirical equations are validated by comparison with previous predictions and experiments for the limiting cases of the seawall. Figure 3 describes a comparison between the results of present work (i.e. vertical plane impermeable seawall, vertical rectangular serrated seawall, s/w=2.0, and vertical triangular serrated seawall, s/w=2.0) and the results of other authors and formulas for predicting the wave reflection coefficient for vertical impermeable seawalls. The different formulas which used for predicting the values of K_r at wave periods (i.e. d/L_i = 0.183 to 0.574), wave steepness (i.e. H_i/L_i = 0.0297 to 0.1593) are described as follow:

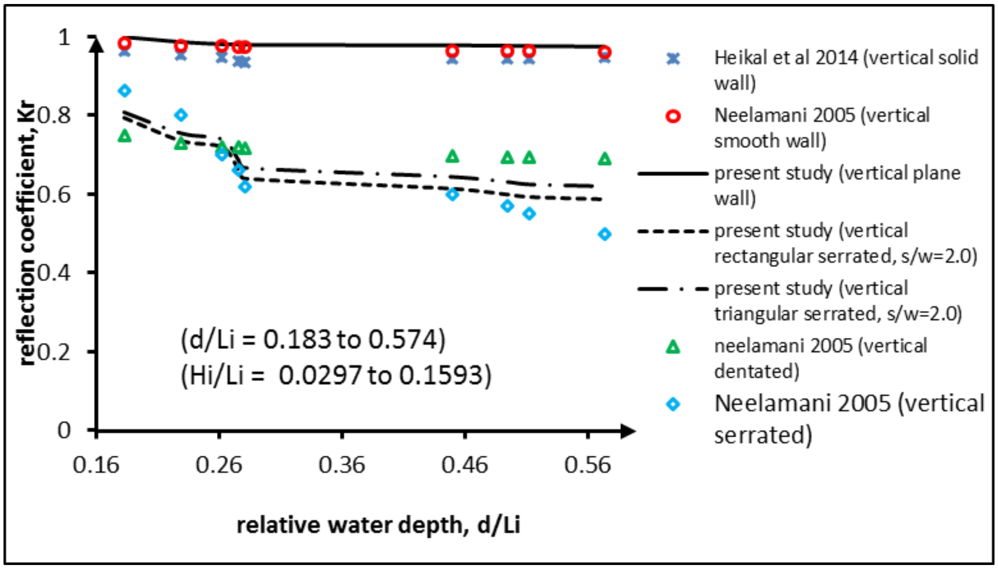

Figure 3. Comparison between the present study (vertical plane smooth wall and serrated wall) with previous works for wave reflection coefficient versus relative water depth.

Vertical plane seawall (present study):

$$kr = 0.919\left(\frac{d}{L_i}\right)^{0.054}\left(\frac{H_i}{L_i}\right)^{-0.049} \tag{6}$$

Vertical rectangular serrated seawall (present study):

$$kr = 0.401\left(\frac{d}{L_i}\right)^{0.334}\left(\frac{H_i}{L_i}\right)^{-0.389}\left(\frac{s}{w}\right)^{-0.027} \tag{7}$$

Vertical triangular serrated seawall (present study):

$$kr = 0.485\left(\frac{d}{L_i}\right)^{0.172}\left(\frac{H_i}{L_i}\right)^{-0.249}\left(\frac{s}{w}\right)^{0.032} \tag{8}$$

After (Heikal et al. 2014):

$$kr = 0.83\left(\frac{d}{L_i}\right)^{0.16}\left(\frac{H_i}{L_i}\right)^{-0.12} \tag{9}$$

After (Neelamani & Sandhya 2005):

$$kr = 0.66 + \left[\frac{0.22}{d/L_i} \right] \quad \text{(for serrated wall)} \tag{10}$$

$$kr = \frac{d}{L_i}\left[1.5\left(\frac{d}{L_i}\right) - 0.03 \right] \quad \text{(for dentated wall)} \tag{11}$$

The figure shows that for vertical smooth impermeable seawalls obtained by present study, (Heikal et al. 2014), and (Neelamani & Sandhya 2005), the values of K_r does not affect by the wave period in terms of d/L_i. The agreement between the three studies is acceptable in predicting K_r for vertical plane seawalls. Also,, the figure shows that the values of K_r decrease as d/L_i increase for serrated seawalls presented in the present study (i.e. vertical rectangular serrated seawall, s/w=2.0, and vertical triangular serrated seawall, s/w=2.0) and serrated and dentated seawalls presented by (Neelamani & Sandhya 2005).

Figure 4 exhibits a comparison between the results of present work (i.e. vertical plane seawall, vertical slotted seawall, G=0.33; and vertical slotted triangular serrated seawall, G=0.33) and the results of other authors and formulas for predicting the relative wave run-up for vertical solid and porous seawalls. The figure shows that the values of R_{up}/H_i decrease as d/L_i increase for all studies. Acceptable agreement between present study and (Heikal et al. 2014) in predicting R_{up}/H_i for solid vertical walls at long and transition wave periods. The exact comparison cannot be achieved because of using different experimental criteria in the laboratory by different investigators.

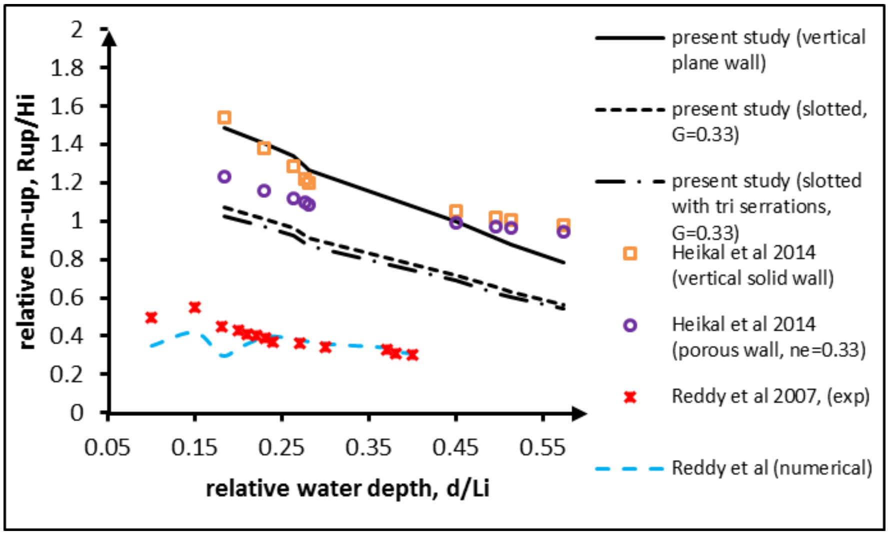

Figure 4. Comparison between the present study (vertical plane, vertical slotted wall, and slotted triangular serrated wall) with previous works for wave relative run-up versus relative water depth.

The different formulas which used for predicting the values of R_{up}/H_i at wave periods (i.e. d/L_i = 0.183 to 0.574), wave steepness (i.e. H_i/L_i = 0.0297 to 0.1593) are described as follow:

For present study:

Vertical plane seawall:

$$\frac{R_{up}}{H_i} = -1.7\left(\frac{d}{L_i}\right) + 1.8 \tag{12}$$

Vertical slotted seawall:

$$\frac{R_{up}}{H_i} = -1.2\left(\frac{d}{L_i}\right) + 1.3 \quad \text{[slots ratios, G=0.33]} \tag{13}$$

Vertical slotted triangular serrated seawall:

$$\frac{R_{up}}{H_i} = -1.22\left(\frac{d}{L_i}\right) + 1.23 \quad \text{[slots ratios, G=0.33]} \tag{14}$$

After (Heikal et al. 2014):

Vertical solid wall:

$$\frac{R_{up}}{H_i} = 0.52\left(\frac{d}{L_i}\right)^{0.19}\left(\frac{H_i}{L_i}\right)^{-0.4} \tag{15}$$

Vertical porous wall:

$$\frac{R_{up}}{H_i} = 0.46\left(\frac{d}{L_i}\right)^{-0.07}\left(\frac{H_i}{L_i}\right)^{-0.11}\left(\frac{b}{d}\right)^{-0.08}\left(n_e\right)^{-0.43} \quad \text{[wall porosity, } n_e\text{=0.33]} \tag{16}$$

The values of R_{up}/H_i which obtained by (Reddy et al. 2007) were figured based on numerical and experimental studies at wave periods (i.e. d/L_i = 0.1 to 0.4), and both results give the same trend as the present study, where R_{up}/H_i decreases as d/L_i increases.

Figure 5 presents a comparison between the present study for the plane sloped seawall and other previous theories and formulas for predicting R_{up}/H_i for smooth sloped seawalls. The figure shows a good agreement between the present study and results obtained by (Chue & Shah 1981).

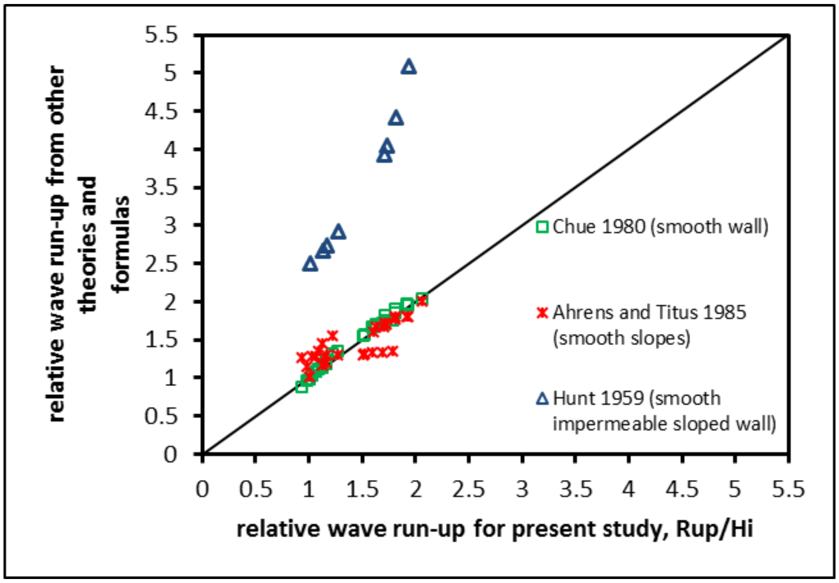

Figure 5. Comparison between the present study (sloped plane wall) with other theories and formulas for wave relative run-up

Also, the figure shows a slightly acceptable agreement with results obtained by (Ahrens & Titus 1985) and the present study while no agreement between results obtained by (Hunt Jr 1959) and the other studies. The different formulas which used for predicting the values of R_{up}/H_i under wide ranges of slope angles (i.e. $0.267 \le \cot\theta \le 1.0$) are described as follow:

For present study $2.5 \le \xi \le 24.0$:

$$\frac{R_{up}}{H_i} = 0.487\left(\frac{d}{L_i}\right)^{-0.499}\left(\frac{H_i}{L_i}\right)^{-2.09}\left(\xi\right)^{-3.644}\left(\cot\theta\right)^{-3.552} \tag{17}$$

After (Chue & Shah 1981) $2.5 \le \xi \le 24.0$:

$$\frac{R_{up}}{H_i}=1.8\left(1-3.11\left(\frac{H_i}{L_i}\right)\right)\xi\left(1-e^{-\sqrt{\pi/2\theta}/\xi}\right) \tag{18}$$

After (Ahrens & Titus 1985) $\xi \geq 3.5$

$$\frac{R_{up}}{H_i}=1.18\left(\frac{\pi}{2\theta}\right)^{0.375}e^{\left(3.187\left(\frac{\eta_c}{H_i}-0.5\right)^2\right)} \tag{19}$$

After (Hunt Jr 1959) $0.5 \leq \xi \leq 4.0$

$$\frac{R_{up}}{H_i}=\xi \tag{20}$$

Figure 6 shows a comparison between the present study for the sloped plane seawall and other previous theories and formulas for predicting R_{down}/H_i for smooth sloped seawalls at a wide range of slope angles (i.e. $0.267 \leq \cot\theta \leq 1.0$). The figure shows that the values of R_{down}/H_i increase as Iribarin number (ξ) increases for all formulas.

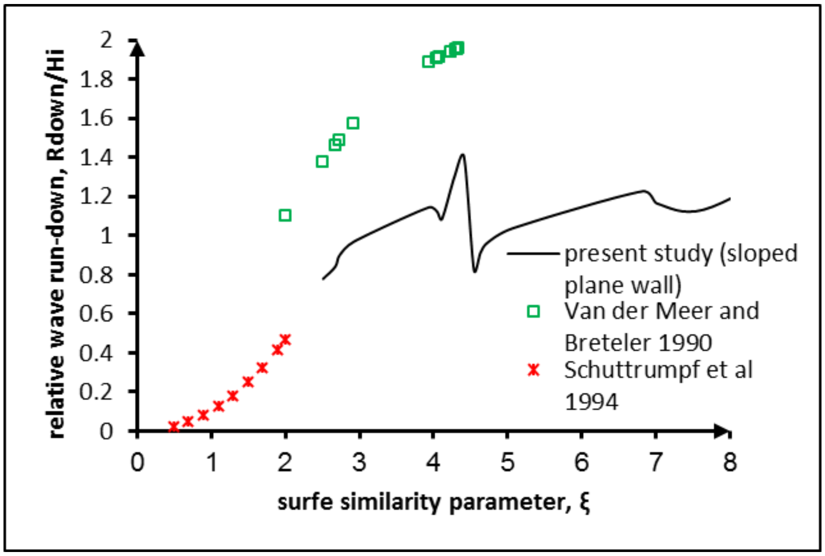

Figure 6. Comparison between the present study (sloped plane wall) with other theories and formulas for wave relative run-down.

The different formulas which used for predicting the values of R_{down}/H_i are described as follow:

For present study $2.5 \leq \xi \leq 24.0$:

$$\frac{R_{down}}{H_i}=0.723\left(\frac{d}{L_i}\right)^{-0.495}\left(\frac{H_i}{L_i}\right)^{0.485}(\xi)^{0.827}(\cot\theta)^{0.783} \tag{21}$$

After (van der Meer & Breteler 1990) $2 \prec \xi \prec 4.3$:

$$\frac{R_{down}}{H_i}=0.1\xi^2-\xi+0.5 \tag{22}$$

After (Schuttrumpf et al. 1995) $0.5 \prec \xi \prec 2.0$:

$$\frac{R_{down}}{H_i}=-0.1\xi^{2.21}$$

(23)

6 CONCLUSIONS

The hydrodynamic performance of vertical and sloped plane, rectangular serrated, triangular serrated, slotted, slotted with triangular serrations 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. Based on both the dimensional analysis and measurements, predictive formulas are proposed to predict the reflection coefficient due to regular waves for the five tested models by using SPSS software. These formulae are compared with experimental and theoretical results obtained by different authors and giving a reasonable agreement.

It is recommended to make use the obtained formulae on various coastal aspects, such as the design of energy dissipating type vertical quay wall in ports and harbors, sloped seawalls for shore protection from erosion, stability of revetments on the navigation canals sides, waves absorber which used in laboratory flumes or sloped caisson as breakwaters.

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SYMBOLS AND ABBREVIATIONS

d : Still water depth;
G : Slots ratio per 1.0 m^2;
H_i : Incident wave height;
H_o : Deep zone wave height;
H_r : Reflected wave height;
K_r, $(K_r)_m$, $(K_r)_p$: Reflection coefficient, measured, and predicted;
L_i : Incident wavelength;
L_o : Deep zone wavelength;
n_e : Porosity of porous seawall;
R^2 : Correlation factor;
R_{down}, $(R_{down})_m$, $(R_{down})_p$: Wave run-down, measured, and predicted;
R_{up}, $(R_{up})_m$, $(R_{up})_p$: Wave run-up, measured, and predicted;
s :Net spacing between dissipater blocks;
T : Wave period;
w :Width of dissipater blocks in the direction of wall slope;
θ :Slope angle between seawall and seabed;
ξ :Surf similarity parameter (Iribarren number);
SPSS :Statistical Package for Social Science; and
SWL : Still Water Level.

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