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NUMERICAL SIMULATION OF WAVES AND CALCULATION OF HYDRODYNAMIC CHARACTERISTICS OVER DIFFERENT SEAWALLS

Swetha D[1], K. Murali[2] and V. Sundar[3]

Abstract: *Seawalls are the most widely adopted coastal protection structure. Depending on site requirements and design considerations, a variety of seawalls may be adopted. The provision of serrations and dentations over a planar slope could improve the energy dissipation. The present study utilizes numerical modelling. This is achieved through characterizing friction coefficient for seawalls with serrations and dentations as roughness elements and utilising it in numerical simulation of wave run-up and reflection. It is observed that the serrations are much effective in reducing the reflection when compared to the plane and dented seawalls.*

Keywords: *Boussinesq equations; Reflection; Run-up; Plane; Serrated and Dented seawalls; Friction coefficient.*

INTRODUCTION

The main design requirement of the seawalls is the run-up on the seaward side and reflection of wave energy back into the sea. On the other hand, dissipation of the incoming wave energy at the seawall is another effective means by which the objective of coastal defence can be achieved. This is the mechanism by which conventional rubble mound seawalls are designed. Owing to aesthetical requirements, concrete seawalls may be built. However, the concrete seawalls if made with a smooth surface do not provide the advantage of energy dissipation at the shore line. Hence, the concrete seawalls are usually roughened to provide better energy dissipation. As per Shore protection Manual (1984), this is achieved by providing the steps. Recently, it has been proposed that provision of the serrations and dentations could improve the energy dissipation (Sandhya, 2003 and Sakthivel, 2006). However, the utility of controlled laboratory experiments is limited for practical usage. In order to circumvent this difficulty, the present numerical work proposes a frame work for computation of hydrodynamic characteristics of the seawalls. This is achieved through characterizing friction coefficient for seawalls with serrations and dentations as roughness elements and utilising it in numerical simulation of run-up and the reflection coefficient (K_r).

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As waves propagate from offshore into nearshore regions, the shallow depths affect the characteristics such as amplitude, celerity and direction of the wave. Usually the process of shoaling, refraction, diffraction and wave breaking shall be considered. In order to investigate the hydrodynamic interaction of regular, random and solitary waves in the nearshore and on seawall slopes numerically, Boussinesq equations are considered. The Boussinesq equations are capable of handling nonlinear effects and dispersion characteristics reasonably well. In order to include the effects of serrations and dentations in the Boussinesq model, a friction coefficient is obtained by considering free surface flow over slopes with serrations and dentations using full Navier Stokes solution. Thus, run-up characteristics and reflection coefficient are obtained and discussed over a wide range of wave and roughness characteristics. The main objective of the present numerical work is to study the interaction of different kinds of waves over different seawalls and to calculate their hydrodynamic characteristics.

Several researchers have carried out the experimental investigations and proposed different methods to understand the interaction of waves with sloping walls, with a few proposed empirical formulae in terms of surf similarity parameter for plane and rough slopes. . Bruun (1953), through experimental investigations, studied the effect of structural shape on wave run-up and reflection reported that the slope should be milder than 1:1.5 to facilitate gradual breaking and energy dissipation. Synolakis (1987) investigated the run-up due to solitary waves on plane slopes and proposed run-up law. Sandhya (2002) and Sakthivel (2006) have carried out experimental investigations to measure the wave run-up due to regular and random waves over plane, serrated and dented sloped seawalls. Madsen et al., (1991) used the efficiency of Pade approximants to derive a new set of extended lower-order Boussinesq equations. This has been extended by several other authors for nearshore dynamics. On the other hand, various empirical approaches are available to obtain the bed friction coefficient which includes Chezy, Manning and Darcy-Weisbach friction coefficients in which the calculation of the average velocity is involved (Chow, V.T. (1959)). However, a direct numerical approach for estimation of the friction coefficient for serrated and dented slopes is not available. The method of calculating the friction coefficient of the serrated and dented seawalls is explained in the following section.

THEORETICAL BACKGROUND

General

The standard Boussinesq equations for variable water depth were first derived by Peregrine (1967), using the depth-averaged velocity as a dependent variable. The assumption of weak frequency dispersion effects makes the standard Boussinesq equations invalid for the intermediate and deep waters. In the derivation of Madsen et al. (1991), additional terms are provided in the momentum equation for considering the physical effects of frictional damping and wave breaking. Although, the methods of derivation adopted by various authors are different, the resulting dispersion relationship of the extended Boussinesq equations is similar. The relationship may be written in the form:

$$\omega^2 = ghk^2 \frac{1-\left(\alpha+\frac{1}{3}\right)(kh)^2}{1-\alpha(kh)^2} \tag{1}$$

Despite their improved dispersion relationship, the extended Boussinesq equations are still restricted to situations with weakly nonlinear interactions.

Model Equations

The continuity equation with Boussinesq approximation is as follows:

$$\eta_t + \nabla.\left\{(d+\eta)\left[u_\alpha + \left(z_\alpha + \frac{1}{2}(d-\eta)\right)\nabla\left(\nabla.(du_\alpha)\right) + \left(\frac{1}{2}z_\alpha{}^2 - \frac{1}{6}\left(d^2 - d\eta + \eta^2\right)\right)\nabla\left(\nabla.u_\alpha\right)\right]\right\} = 0 \tag{2}$$

The momentum equation is:

$$\begin{aligned} &u_{\alpha t} + (u_\alpha.\nabla)u_\alpha + g\nabla\eta + z_\alpha\left\{\frac{1}{2}z_\alpha\nabla\left(\nabla.u_{\alpha t}\right) + \nabla\left(\nabla.(du_{\alpha t})\right)\right\} \\ &+\nabla\left\{\frac{1}{2}\left(z_\alpha{}^2 - \eta^2\right)(u_\alpha.\nabla)(\nabla.u_\alpha) + \frac{1}{2}\left[\nabla.(du_\alpha) + \eta\nabla.u_\alpha\right]^2\right\} \\ &+\nabla\left\{(z_\alpha - \eta)(u_\alpha.\nabla)\left(\nabla.(du_\alpha)\right) - \eta\left[\frac{1}{2}\eta\nabla.u_{\alpha t} + \nabla.(du_{\alpha t})\right]\right\} = 0 \end{aligned} \tag{3}$$

Where, η is surface elevation, d is still water depth, u_α is horizontal velocity vector at the water depth $z = z_\alpha = -0.531d$, $\nabla = \left(\partial/\partial x, \partial/\partial y\right)$ is the horizontal gradient operator, g is gravitational acceleration and subscript t is partial derivative with respect to time.

Boundary conditions

Solutions of the Boussinesq equation for wave propagation over a finite domain requires appropriate boundary conditions to be specified in the numerical model. Two kinds of boundary conditions are primarily used. These are total reflecting vertical wall and absorbing boundary condition. In some cases, partial reflection boundary condition can also be adopted.

NUMERICAL PROCEDURE FOR SERRATIONS AND DENTATIONS

Inclusion of serrations and dentations is not possible in the Boussinesq model as it provides only a depth-averaged representation of the flow. Furthermore, the effects such as flow separation and eddy dissipation cannot be accurately modelled in the depth-averaged models. On the other hand, use of a 3D flow model for the computation of wave run-up and reflection coefficient is highly resource sensitive. However, since the serrations and dentations are basically roughness elements provided over the slope, their effects can be included in the Boussinesq model as bed friction coefficient (f_b). As per the literature, no direct approach is available for the calculation of the hydrodynamic characteristics over the serrated and dented slopes. In the present numerical study, a new approach of estimating f_b is attempted using general purpose RANS model. In the RANS approach, the actual 3D geometric details of the serrations/dentations are modelled and the energy loss due to the presence of serrations and dentations is obtained. This approach will provide the flow behaviour and energy loss of the incoming flow as a function of Froude number (Fr) and Reynolds number (Re). A 3D model domain as schematized in Fig.1 with the longitudinal sectional view is considered for computing energy loss due to the presence of serrations and dentations. The figures also show a schematic representation of the flow during run-up of a wave on the slope.

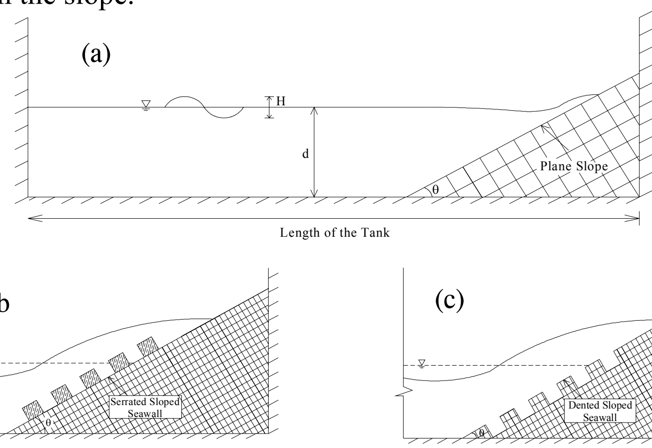

Fig.1 Typical sketches showing runup on different types of slopes (a) Plane (b) Serrated (c) Dented

The energy loss over the slope can be represented with the velocities V_1 and V_2, and flow depths y_1 and y_2. Considering that the leading parameter for determining the flow behaviour over the slope is the Froude number (*Fr*), the serrations and dentations were considered over a flat bed in a staggered (zig-zag) manner. The staggered arrangement has been chosen as per the experimental studies of Sakthivel (2006). The plan and the sectional view of the staggered serrations over the slope in case of 3D are shown in Fig.2.

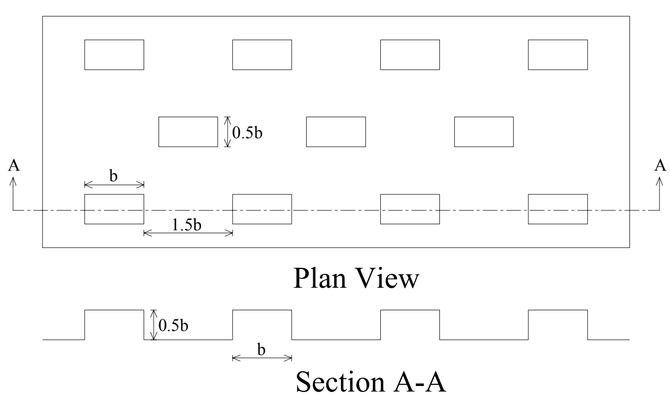

Fig.2 General layout of the Serrated slope considered by Sakthivel (2006)

This approach is expected to provide the energy loss without the effect of the slope. The size of the serrations and dentations chosen in the present 3D study is 100mm x 50mm x 50mm @

100mm c/c. The dimension of the serration/ dentations are height (a), length(b) and the spacing (c) During the parametric study various combinations of aspect ratios (a/b) and the relative spacing ratios (c/b) were considered in 2D. A schematic sketch of the model of 2D serrated slope considered for numerical modeling is shown in Fig. 3. The major parameters considered in the studies are also incorporated in the figure. With the above computational setup, the velocities V_1 and V_2, and flow depths y_1 and y_2, are taken at locations where the flow is steady and uniform. Using the momentum equation, the frictional resistance R_f is calculated. The simulation is carried out for the Froude number (Fr) varying from 0.2 to 1.0. Finally, a parametric study for serrations has been carried out in 2D considering their practical limitations.

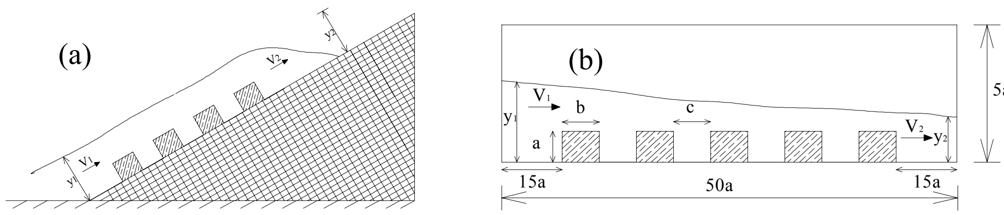

Fig.3 Schematic representation of hydraulic gradient over (a) Sloping and (b) Horizontal serrated slopes

Estimation of friction coefficient (f_b)

The change in momentum per unit time in the body of water in a flowing channel must be equal to the resultant of all the external forces that are acting on the body. Utilizing this principle, to a channel of rough slope as shown in Fig.4, the expression for the momentum change per unit time enclosed between sections 1 and 2 may be written as

$$P_1 - P_2 + W\sin\theta - R_f = \rho q\left(V_2 - V_1\right). \qquad (3)$$

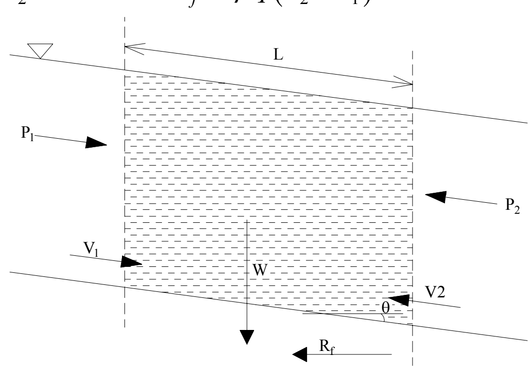

Fig 4. Schematic representation of momentum

In the above, P_1 and P_2 are the resultants of pressure acting on the two sections; W is the weight of water enclosed between the sections; and R_f is the total external force due to frictional resistance acting along the bed. Utilizing the above relationship, the frictional resistance R_f between the two sections can be estimated if other parameters can be measured from the RANS model. This resistance obtained is correlated with the bed friction coefficient (f_b) through the relationship given below.

$$R_f = \frac{f_b}{H} u_{avg} \left| u_{avg} \right| \tag{4}$$

In equation.4, u_{avg} is the average velocity and H is the average head. Utilizing this bottom friction coefficient in the Boussinesq model, the hydrodynamic characteristics such as run-up and the reflection coefficient for the serrated and dented slopes are calculated. In the present case, a community Boussinesq code known as FUNWAVE has been used after suitable adaptation.

Parametric study

Even though the above procedure is most complete with all the 3D effects, it is resource intensive to carry out a parametric study. Hence, the parametric study for the bed friction coefficient of the serrated slope is carried out in 2D. The ranges of the parameters a/b and c/b were 0.11 to 1.0 and 0.25 to 1.66 respectively. The studies were carried out as a function of Froude number (Fr), varying from 0.2 to 1.

The computed friction coefficient (f_b) as a function of Froude number Fr is shown in Fig.5 using the above mentioned 2D and 3D approaches for a/b=0.5 and c/b=0.5. The agreement between the two approaches is found to be good. It is inferred from the results that the height wise separation of flow from the serrations, included in the 3D approach, is responsible for about 5% of the frictional losses. The friction on the wall and stream wise separation effects account for about 95% of the energy losses. Hence, the parametric study that has been carried out using 2D approximation appears to have merit and the results replicates the behaviour of 3D serrations. Over the range of Fr considered, the friction coefficient varies between 0.023 to 0.016. An average value of f_b can be 0.0195.

Based on the parametric study, the variation of f_b over the range of Fr is shown in Fig.6 for a/b=0.11 and for the range of c/b= 0.33, 0.44 and 0.55. It is found that as the separation increases results in a decrease in the f_b. Further, fig.7 shows the comparison of the friction coefficient (f_b) with Froude number (Fr) for relative spacing of $(c/b = 0.33)$ in terms of the aspect ratio. The results reveal that for a relative height of 0.22 the f_b has its lowest values. In order to further understand the behaviour of f_b, a non-dimensionalised roughness height parameter $(v^* k_s/\nu)$ is considered and the friction coefficient brought out in terms of the relative spacing (c/b). It is clear that as the roughness height increases, f_b decreases and after the certain value of the roughness height parameter, f_b is having the constant value.

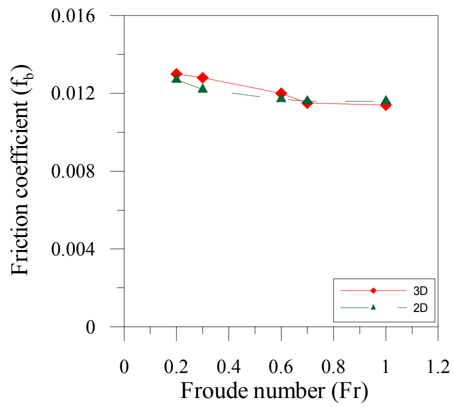

Fig.5 Comparison of estimated bed friction coefficient (f_b) between 3D and 2D using RANS solver (a/b=c/ b=0.5)

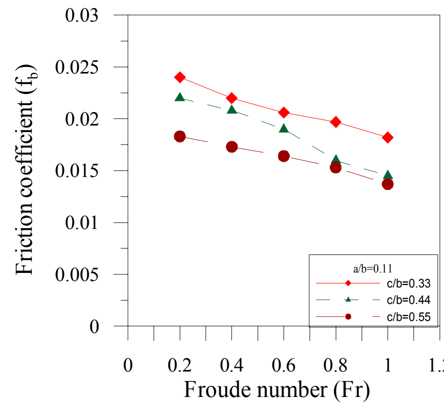

Fig.6 Variation of friction coefficient (f_b) as a function of relative spacing (Aspect ratio, a/b=0.11).

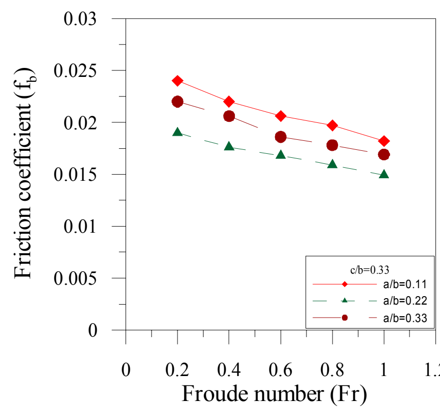

Fig.7 Variation of friction coefficient (f_b) as a function of aspect ratio (Relative spacing, c/b=0.33).

MODELLING OF WAVE TRANSFORMATION AND RUN-UP

This section details the numerical solution techniques adopted to solve the Boussinesq equations using FUNWAVE. In the present study, a composite 4th-order Adams-Bashforth-Moulton scheme (utilizing a 3rd-order Adams-Bashforth predictor step and a 4th-order Adams- Moulton corrector step) is used to step the model forward in time. The terms involving first-order spatial derivatives are differenced to the fourth order accuracy utilizing a five-point formula. All the errors involved in solving the underlying nonlinear shallow water equations are thus reduced to the 4th order in both grid spacing and the time step size. The grid convergence study is carried out and presented in the thesis. The computational domain involves the suitable discritization of grid size along the horizontal direction $\Delta x = 0.01$ m and the typical time step of $\Delta t = 0.1$ s. Spatial and temporal differencing of the higher-order dispersion terms is done to second-order accuracy.

RESULTS AND DISCUSSIONS

The present study involves the computation of run-up and the reflection characteristics and the model subjected to the regular, random and solitary waves of different characteristics. A constant water depth (d) of 0.5m at the toe of the sloping wall and length of the tank of 25m are adopted for the entire numerical study. A rigid type piston type wave maker is placed at the left end from which the wave starts propagating towards the beach which is an inclined bed for which the bed friction coefficient was defined corresponding to plane, serrations and dentations. The details of the various variables and the non-dimensionalised parameters used in the present study are listed in Table 1. The validation is carried out by comparing the present numerical results with the published experimental results of Sakthivel (2006).

Table 1. Range of parameters considered in the present study

Sl No.	Parameters	Measured range
1.	Wave height (H) in m	0.07-0.18
2.	Wave period (T) in sec	1.00-4.00
3.	Relative wave height (H/d)	0.07-0.18
4.	Relative water depth (d/L)	0.06-0.64
5.	Slope of beach, θ	$30^\circ, 45^\circ, 60^\circ$ and 90°
6.	Surf similarity parameter (ξ)	1.00 - 60.00

The hydrodynamic performance of the three types of slopes due to regular, random and solitary wave actions are studied with varying wave height (in terms of the incident wave steepness, H_i/L), wave period (in terms of the relative water depths, d/L), seawall slope (in terms of $\cot\theta$) and surf similarity parameter (ξ). The reflection coefficient (K_r) and run-up (R_u/H_i) are investigated. Fig.8 shows the comparison of the computed wave run-up with that of the results reported in SPM (1984) in terms of the surf similarity parameter (ξ). From this, it is clear that the deviation observed between the two is of the order of 10%. Fig.9 shows that the reflection coefficient (K_r) is in good agreement with that of the proposed formulae of Ahrens (1981) in terms of the surf similarity parameter (ξ).

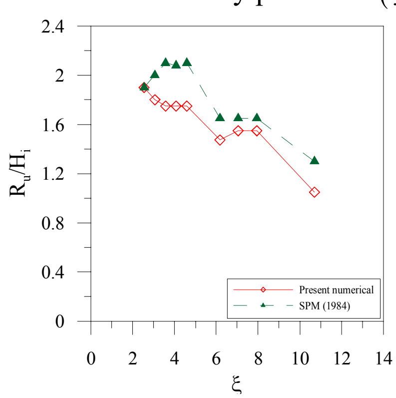

Fig.8 Comparison of computed run-up with that of SPM (1984) in terms

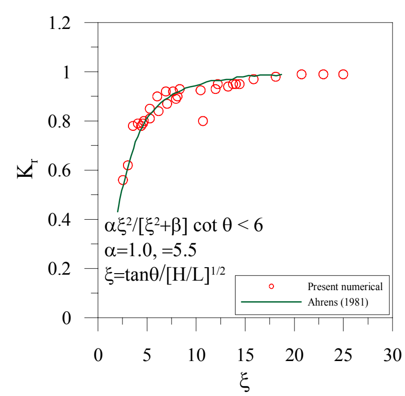

Fig.9 Validation of K_r obtained using the Boussinesq model with Ahrens (1981)

Figs. 10(a) and (b) shows the validation of the present numerical results of the wave run-up and the reflection coefficient with that of the experimental results of Sakthivel (2006) over the serrated and dented seawalls for a bed slope of 30°. When compared with experimental results, a deviation of about 13% is observed for the serrated seawall and 11% for the dented seawall in wave run-up. In the case of reflection coefficient, the said deviations for the serrated and dented seawalls are observed to be 6% and 4% respectively.

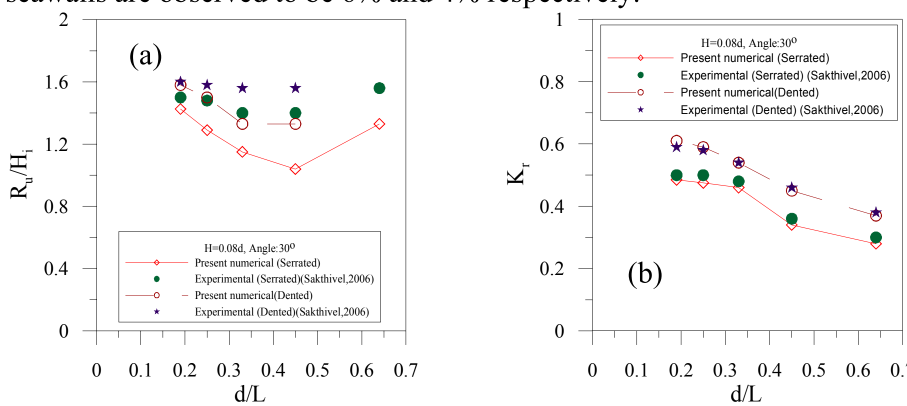

Fig.10 Comparison of the present numerical results with published experimental results of Sakthivel (2006) (a) Run-up (b) Reflection coefficient for a bed slope of 30° over the serrated and dented seawalls

Fig.11 shows the comparison of the run-up over the three seawalls for $\theta = 30^\circ$, $H_i/d = 0.12$. Plane seawall experiences highest run-up followed by dented and serrated seawalls. Fig.12 shows the comparison of the reflection coefficient over the vertical walls. Serrated seawall is found to be more effective in reducing the wave reflection compared to the plane and dented seawalls. Using FUNWAVE, the generation and propagation of solitary waves is also carried out.

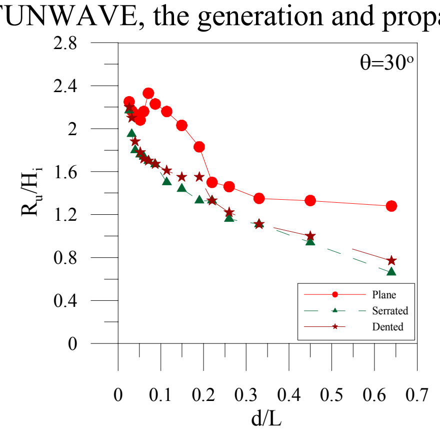

Fig.11 Intercomparison of run-up (R_u/H_i) on plane, serrated and dented seawalls $(\theta = 30^\circ, H_i/d = 0.12)$

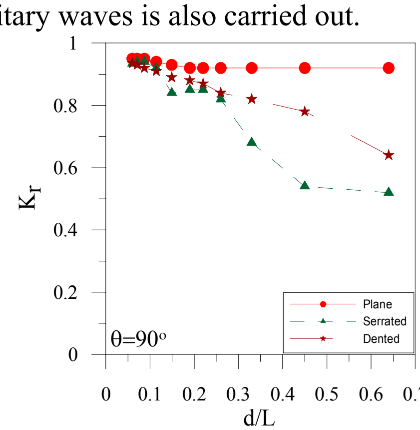

Fig.12 Intercomparison of reflection coefficient (K_r) on plane, serrated and dented seawalls $(\theta = 90^\circ, H_i/d = 0.12)$.

CONCLUSIONS

The wave reflection and the run-up on plane, serrated and the dented seawalls are assessed based on the numerical investigations by adopting a novel approach for the calculation of the friction coefficient for the serrated and dented seawalls. The numerical investigations on plane, dented and serrated seawalls are carried out for wide range of wave heights, wave periods and seawall slopes in a constant water depth of 0.5m Full Navier-Stokes solution of serrations and dentations for Fr from 0.2 to 1.0 has been successfully carried out based on the above investigations. A friction coefficient value of 0.012 and 0.0097 are adopted for serrated and dented slopes respectively. The reflection coefficient and the run-up is maximum for the plane seawall followed by the dented and serrated seawalls. The serrations are much effective in reducing the reflections as well as the run-up. The friction coefficient obtained from CFD for serrations and dentations is incorporated into FUNWAVE successfully and this approach has been successfully verified by comparing the results from FUNWAVE with that of experiments. It is clear that the numerical results are in good agreement with that of the published experimental results of Sakthivel (2006).

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