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Numerical Modelling and Corroboration of Wave Interaction with Coastal Vegetation using Open Source CFD Tool: REEF3D

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ABSTRACT

Coastal vegetation has gained ace importance in coastal protection because of the ill effects of the hard structures with the purpose of protecting the important ecosystem shore line in domains like economy, construction, installation and mechanism of protection. Though coastal vegetation is environmental friendly and cost effective yet its behavior with wave is very complex and not completely understood.

The main goal of the present study is to develop a three-dimensional numerical wave flume to assess the effect of coastal rigid submerged vegetation on wave attenuation using the open source computational Fluid Dynamics (CFD) software REEF3D. The numerical model is developed for artificial rigid submerged vegetation in a numerical wave tank. The model is tested for wave heights 0.08 m and 0.16 m and wave periods 1.8 sec and 2 sec in water depth of 0.40 m, measurements of wave heights at different locations along the vegetation meadow is recorded. The performance of the numerical model is validated with the experimental results.

KEYWORDS

coastal protection, Coastal vegetation, Numerical model, Computational Fluid Dynamics (CFD), Wave attenuation.

1. INTRODUCTION

Coastal systems are widely used and threatened natural systems (Halpern.et al. 2008; Lotze et al., 2006). The consequence is an overall decline which is affecting a number of critical benefits (Barbier et al., 2011). Coastlines are dynamic systems which are vulnerable to strong winds, storm surges, tsunamis, cyclones and erosion. Conventional structures such as breakwaters, seawalls and jetties are used to dissipate and reflect wave energy thereby alters the near-shore hydrodynamics and regional sediment transport characteristics resulting in foment of worse scenario in its surroundings. The installation cost of hard structures for coastal protection is very high; strong negative public reaction to rock emplacements along the coast often aggravates the problem (Bray et al., 1995).

Reports on the assessment of damage due the 1999 Odisha cyclone along the coast of the Indian state of Odisha and the 2004 Indian Ocean tsunami on some of the coastal districts of Tamilnadu (in India) reveals that intact and healthy mangroves saved many lives by dramatically reducing the intensity of the storm surge due to the cyclone and decelerated the gush of tsunami wave shoreward (Das and Vincent, 2009; NIO, 2005).

The energy of the wave depends on the wave steepness, crest angle, depth and the impact on to the structure etc. The shape of the structure is important for highly non-linear wave structure interaction, including breaking, run-up, overtopping, transmission, reflection, evolution of vortices etc. These flow problems are numerically solved by different Computational Fluid Dynamics (CFD) software's.

REEF3D is a free, open source code for continuum mechanics problems, has been applied to a selection of common problems in coastal and offshore engineering. The capability of REEF3D in coastal engineering confirmed in the paper by Arun Kamath et al. (2012).

Many studies on both experimental and numerical have been conducted to find out the effect of coastal vegetation on wave energy dissipation by attenuation of waves. Previous studies include studies on coastal kelp forests (Jackson, 1984; Dalrymple et al., 1984; Dubi and Torum, 1994; Lovas and Torum, 2001; Rosman et al., 2013, Mendez and Losada, 2004; Sánchez-González et al., 2011; Koftis et al., 2012; Zeller, 2014), mangroves (Struve et al., 2003;Vo-Luong and Massel, 2008; Bao, 2011; Husrin, 2012; Strusinska-Correia, 2013), Numerical studies (Coops et al., 1996; Bouma et al., 2005; Eldina et al., 2008; Arun Kamath et al., 2012). In India, the soft measures of coastal protection have gained importance after tsunami. Some of the early works include experimental investigations on the effect of vegetation in reducing the wave run up (Sundar et al., 2011), Experimental investigation of wave attenuation through artificial vegetation meadow (Beena et al., 2016).

This work aims simulation and validation of submerged artificial rigid coastal vegetation using CFD software REEF3D. Numerical wave tank is used for the simulation and the numerical solutions are well suited to assess effect of submerged artificial rigid vegetation on attenuation of waves. Thus an initial study is presented on the attenuation of waves with rigid submerged vegetation and the numerical results are validated with the experimental results which are carried out in wave flume at Department of Applied Mechanics and Hydraulics, NITK Surathkal, India carried out by Beena M John (2016).

2. NUMERICAL MODEL

2.1 REEF3D

The software which used for this work is released version 17.03 of open source software REEF3D running on Mac OS X EI Capitan operating system. REEF3D has an extensive range of features to solve hydraulic, coastal and marine engineering flow problems. In the current numerical model level set method is used for locating the phase interface, and it represented implicitly by zero level set of smooth signed distance function. In contrast to the VOF method the level set function varies across the interface. It is an Eulerian approach means that the shape and location of interface independent of the underlying grid structure and uniform Cartesian grid systems are used. The WENO (Weighted Essentially Non Oscillatory) scheme also used because it handle large gradients right up to the shock very accurately by taking local smoothness into account.(Arun Kamath et al.,2012).

2.2 Governing equations

REEF3D solves the incompressible Reynolds-averaged Navier–Stokes (RANS) equations together with the continuity equation to solve the fluid flow problem.

$$\frac{\partial U_i}{\partial x_i} = 0 \quad \text{- (1)}$$

$$\frac{\partial U_i}{\partial} + U_j \frac{\partial U_i}{\partial X_j} = -\frac{1}{\rho}\frac{\partial}{\partial X_i} + \frac{\partial}{\partial X_j}\left[(v + v_t)\left(\frac{\partial U_i}{\partial X_j} + \frac{\partial U_j}{\partial X_i}\right)\right] + g \quad \text{- (2)}$$

Where u is the time averaged velocity, ρ is the density of the fluid, p is the pressure, ν is the kinematic viscosity, ν_t is the eddy viscosity and g is the acceleration due to gravity. By using the projection method the pressure is determined (Chorin, 1968) and by using Bi CG Stabsolver the resulting Poisson equation is solved with a preconditioned (van der Vorst, 1992). K–ω model is used for turbulence modelling using the two equation proposed by Wilcox (1994).The strain in the flow due to the waves leads to unphysical overproduction of turbulence in the wave tank. To avoid this, eddy viscosity limiters are used as shown by Durbin (2009). Also, the strain due to the large difference in density at the interface between air and water causes an overproduction of turbulence at the interface. This is avoided by free surface turbulence damping around the interface as shown by Naot and Rodi (1982). The damping is carried out only around the interface using the Dirac delta function. REEF3D is fully parallelized using the domain decomposition strategy and MPI (Message Passing Interface).

2.3 Free Surface

The free surface is determined with the level set method. The zero level set of a signed distance function $\phi(x,t)$is used to represent the interface between water and air (Osher and Sethian,1988). Moving away from the interface, the level set function gives the shortest distance from the interface. The sign of the function distinguishes between the two fluids across the interface as shown in the below equation**:**

$$\Phi\,(\vec{x},\,t)\begin{cases} > 0\; i\; \vec{x}\; is\; in\; pha\quad 1 \\ = 0\; i\; \vec{x}\; is\; in\; in\qquad ha \\ < 0\; i\; \vec{x}\; is\; in\; pha\quad 2 \end{cases} \qquad \text{- (3)}$$

The level set function is moved under the influence of an external velocity field u_j with the convection equation:

$$\frac{\partial \phi}{\partial} + U_i \frac{\partial \phi}{\partial x_j} = 0 \qquad \text{- (4)}$$

The level set function loses its signed distance property on convection and is reinitialized after every iteration using a partial differential equation based re-initialization procedure by Peng et al.(1999) to regain its signed distance property.

3. NUMERICAL MODEL VALIDATION

The numerical validation is based on the physical experiments carried out in the wave flume by Beena M John (2016), Department of Applied Mechanics and Hydraulics, NITK Surathkal. Figure 1 shows a schematic diagram of the present experimental setup. The physical model of submerged artificial rigid vegetation meadow of 2 m width, placed on the horizontal part of the flume bed and tested for wave heights 0.08 m and 0.16 m and wave periods 1.8 sec and 2 sec in water depths of 0.40 m. The attenuated wave heights at different locations along the vegetation is recorded using numerical wave probes along the meadow. The vegetation rods are 0.008 m in diameter and 0.21 m long and the density of the vegetation is 394 plants/m^2. Figure 1 shows the simulation of numerical wave tank with submerged rigid vegetation.

The dimension of submerged vegetation and wave parameters are similar to the physical experiment. The simulated time is 30s. The generated waves are 5th – order Stokes waves and weighted Essentially Non-Oscillatory (WENO) scheme is used for the velocity discretization.

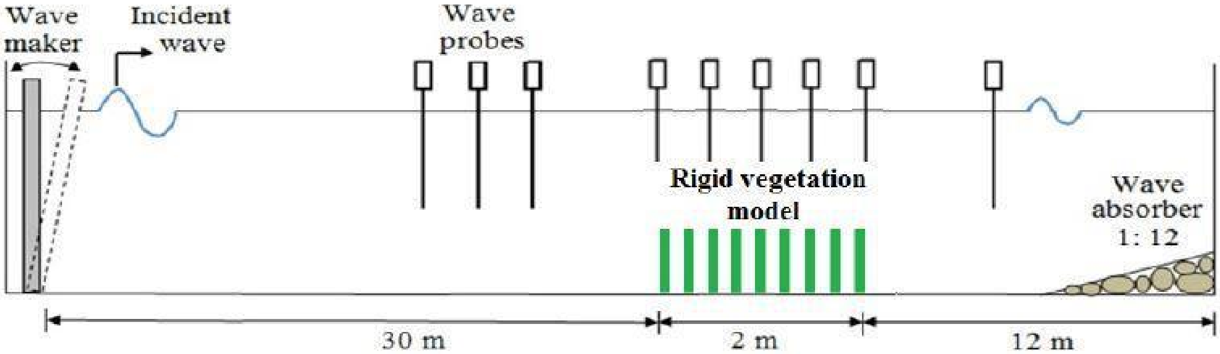

FIGURE 1. Schematic diagram of experimental set up (Source: Beena M John, 2016)

A 3D numerical wave tank of 20.0m long, 0.71m wide and 1.0m high is used for the wave generation and the wave heights are 0.08 and 0.16m generated at water depth of 0.40m The waves simulate for time periods of 1.8 sec and 2 sec. 0.008m size grids are used for the domain. The wave simulated for 30s.

Numerical beach and wave generation zones are shown in Figure 1. Water surface elevation measured by numerical probes and those probe readings are in the form of surface elevations in m. These surface elevations convert into wave heights by Mat lab programming. The probe locations are described in the Figure 1. The simulation view is shown in figure 2, 3.

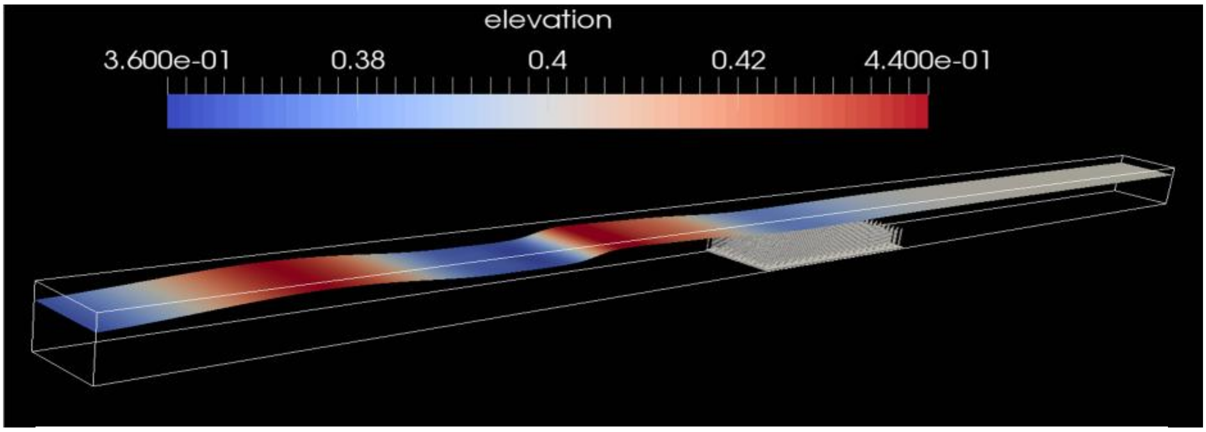

FIGURE 2. Simulation view from the generation zone with colour scale representation of the wave elevation

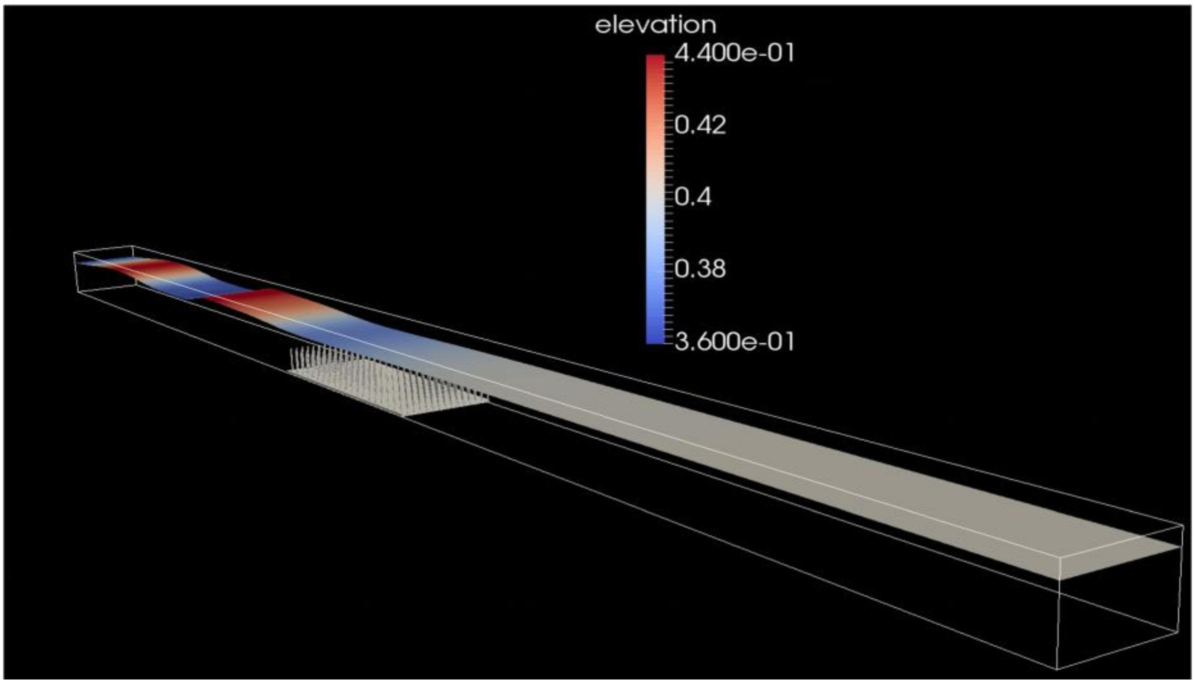

FIGURE 3. Simulation view from the absorption with colour scale representation of the wave elevation

The grid size, dx = 0.008m is used. The numerical results are in the form of surface elevation which is converted to wave height using mat lab and validate the numerical results with the experimental results.

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Plant type	Characteristics of vegetation model		Wave height (m)	Wave period, T (s)	Water depth, d (m)	Relative vegetation height (hs/d)
Submerged rigid vegetation	Length of rod	0.21 m	0.08 0.16	1.8 2	0.40	0.525
	Diameter of rod	0.008 m				
	Density (plants/m2)	394				

Table 1. Vegetation characteristics and experimental conditions

4. RESULTS AND ANALYSIS

The wave heights measured at different locations in the numerically simulated model along the 2m meadow of submerged vegetation model is compared with the experimental results. It is observed that attenuation of wave height along the meadow is following exponential decay.

For hs/d = 0.525 and T=1.8 sec, the wave height measured at the end of the meadow is 50.6% of an incident wave height for 0.08 m wave height and 61.9% of an incident wave height for 0.16 m.

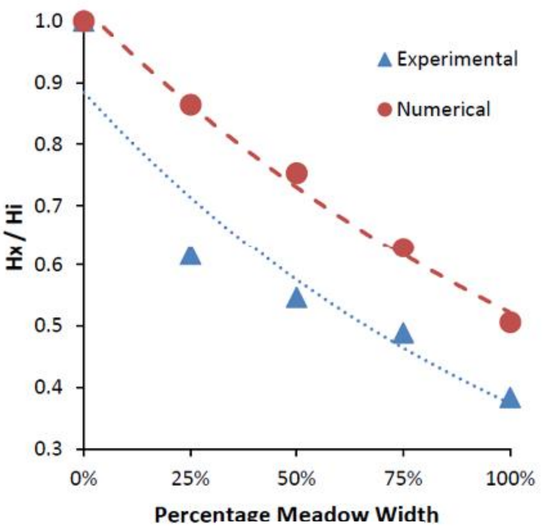

Figure: 4.a

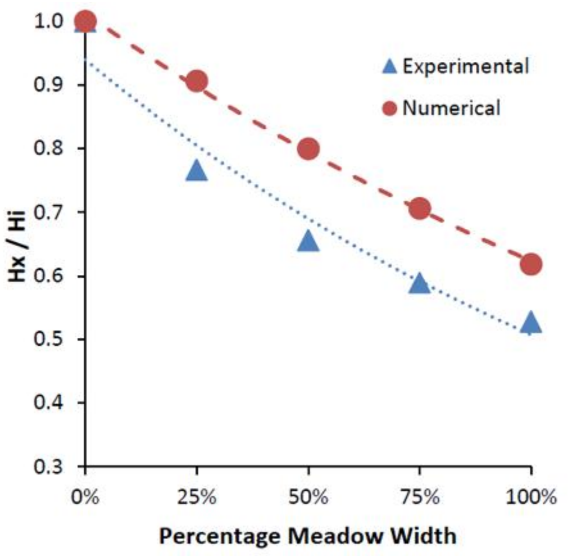

Figure: 4.b

Figure 4.a shows the relative wave height (Hx/Hi) measured along the submerged vegetation meadow for h = 0.08m, T = 1.8 s, hs/d = 0.525.

Figure 4.b shows the relative wave height (Hx/Hi) measured along the submerged vegetation meadow for h = 0.16m, T = 1.8 s, hs/d = 0.525.

For hs/d = 0.525 and T=2 sec, the wave height measured at the end of the meadow is 51.20% of an incident wave height for 0.08 m wave height and 62.50% of an incident wave height for 0.16 m.

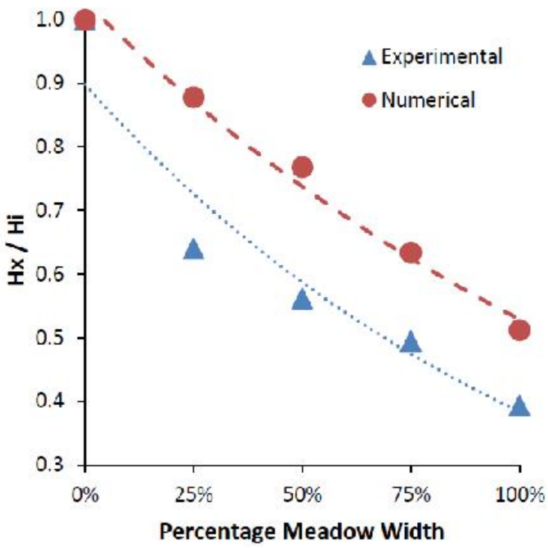

Figure: 5.a

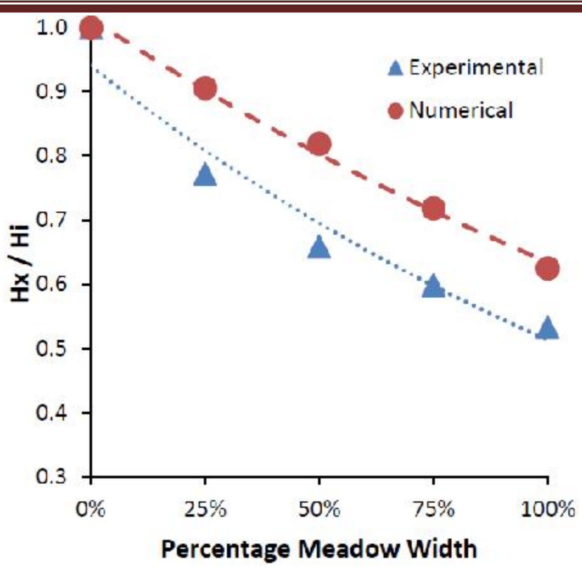

Figure: 5.b

Figure 5.a shows the relative wave height (Hx/Hi) measured along the submerged vegetation meadow for h = 0.08m, T = 2 s, hs/d = 0.525.

Figure 5.b shows the relative wave height (Hx/Hi) measured along the submerged vegetation meadow for h = 0.16m, T = 2 s, hs/d = 0.525.

5. CONCLUSIONS

The open source CFD tool REF3D is used for simulation and assessment of wave attenuation over submerged rigid coastal vegetation. The numerical results show good agreement with the experimental data. The influence of incident wave height and wave period on wave attenuation is investigated numerically. While using the higher order discretization scheme some improvement can be seen. This suggests that while, for the general case, a linear discretization scheme is sufficient, higher-order discretization schemes may be necessary for simulations involving very non-linear waves or more violent interactions. REF3D has the potential to be a usable tool for the detailed investigation of wave attenuation due to coastal rigid vegetation and wave interaction with structures, and the numerical results showing good agreement with experimental data.

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