Effect of Emerged Coastal Vegetation on Wave Attenuation Using Open Source CFD Tool: REEF3D

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Abstract

Coastal vegetation is a soft solution for protecting the coast from the action of waves by attenuating the wave height and reducing the energy of the waves. Effect of wave height attenuation as a result of the presence of emerged coastal vegetation is studied numerically by resolving the Reyn-olds-averaged Navier–Stokes (RANS) equations. A three-dimensional nu-merical wave tank model is simulated using an open source computational fluid dynamics (CFD) software REEF3D, and wave attenuation due to emerged coastal vegetation is determined. An artificial, rigid, emerged vege-tation for a length of 2 m is developed in a numerical wave tank of REEF3D. The model is tested for regular waves of height 0.08, 0.12, and 0.16 m and wave periods of 1.8 and 2 s in a water depth of 0.40 and 0.45 m. The wave heights are measured at different locations along the vegetation meadow at 0.5 m intervals. The devolved numerical model is corroborated by comparing the obtained numerical results with the experimental results as reported by John et al. (Experimental investigation of wave attenuation through artificial vegetation meadow, ISH—HYDRO,[1]).The numerically obtained results are concurrent with the experimental results.

Keywords: Coastal vegetation, Numerical model, Computational Fluid Dynamics (CFD), Wave attenuation

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1 Introduction

A close relationship has been maintained by the mankind with the sea for the centu-ries, because of his activity along the coast. Urbanization and industrialization of coastal areas compelled the mankind to develop the coastal facilities to cater the de-mand. The intent of coastal engineering is to deliver a sustainable enlargement of the susceptible coastal zone facing catastrophic scenarios and also meeting the require-ments for the safeguarding of coastline. Coastlines are dynamic systems which are vulnerable to storm surges, tsunamis, cyclones, and erosion. The usage of hard solution like con-ventional breakwaters, seawalls, and groynes will dissipate and reflect wave energy and thereby protect that part of the region. When hard solutions are adopted, it will indulge erosion or accretion in the adjacent shorelines due to the alteration of natural hydrodynamics and sediment movement.

Coastal plant life can diminish the wave height and the energy of the waves. Reports on the assessment of damage due to 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 Tamil Nadu (in India) reveal that intact and healthy mangroves saved many lives by dramatically reducing the intensity of the storm surge due to the cy-clone and decelerated the gush of tsunami wave shoreward [2, 3].

The energy of the wave depends on the wave steepness, crest angle, depth, the im-pact on the structure, etc. The shape of the structure plays a major role while interact-ing with highly nonlinear waves, including reflection, overtopping, transmission, breaking, and evolution of vortices. These flow problems are resolved numerically by using different computational fluid dynamics (CFD) software. REEF3D is an open source software and free. REEF3D software has been used to solve the continuum mechanics problems in coastal engineering. For the calculation of wave propagation and wave hydrodynamics, a three-dimensional new level set with better density inter-polation is established by resolving the incompressible Navier–Stokes equations. The level set method is used for modeling the free surface [4] under the approximation of two-phase flow, allowing for the simulation of complicated phenomena such as break-ing wave forces [5], wave transformation [6], and floating bodies in waves [7].

Many experimental and numerical studies on coastal vegetation have been conducted to observe the efficacy of coastal vegetation in wave attenuation. Previous studies include studies on coastal kelp forests [8–11] and mangroves [12–15] and numerical studies [9, 16]. In India, the soft measures of coastal protection have gained im-portance after tsunami. Some of the early works include experimental investigations on the effect of vegetation on reducing the wave run-up [17] and experimental investi-gation of wave attenuation through an artificial vegetation meadow [1].

This work aims at simulation and validation of emerged artificial rigid coastal vegeta-tion using CFD software REEF3D. The numerical wave tank is used for the simula-tion, and the numerical solutions are well suited to assess the effect of emerged artifi-cial rigid vegetation on the attenuation of the waves. Thus, an initial study is present-ed on the attenuation of waves with rigid emerged vegetation, and the numerically obtained results are validated with the experimental results which are carried out in a wave flume at the Department of Applied Mechanics and Hydraulics, NITK Surathkal.

2 Numerical Model of Emerged Vegetation

2.1 Governing equations

REEF3D is an open source computational fluid software package and can be used to solve complex problems in coastal engineering, hydrodynamics, offshore and envi-ronmental engineering, as well as marine CFD.

In the present numerical model, the incompressible Navier–Stokes equations are solved with RANS turbulence closure. Cartesian mesh is used to achieve wave propa-gation with higher stability and accuracy. Fifth-order WENO scheme is used for the convection terms of the momentum equations. Third-order TVD Runge–Kutta scheme is used for performing time stepping. Staggered grid with projection method is used to solve the pressure which ensures tight pressure–velocity coupling. Ghost cell-immersed boundary method is used to consider boundaries with irregularity. The numerical model is completely parallelized on the basis of domain decomposition strategy and MPI (message passing interface).

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + g_i \tag{2}$$

Where ρ is the density, u is the time averaged velocity, p is the pressure, ν_t is the eddy viscosity, ν is the kinematic viscosity and g is the acceleration due to gravity. Projection method is used to determine the pressure and BiCGStab is adopted to resolve the subsequent Poisson equation. k-ω model is adopted for modeling of turbulence.

2.2 Free surface

The free surface of the waves is modelled by adopting the level set method. The signed distance function is the shortest distance from the interface is determined by level set function. The interface of the two fluids can be differentiated by using the sign of the function and it is described in the equation below.

$$\phi(\vec{x}, t) \begin{cases} > 0 & if\ \vec{x}\ is\ in\ phase\ 1 \\ = 0 & if\ \vec{x}\ is\ at\ the\ interface \\ < 0 & if\ \vec{x}\ is\ in\ phase\ 2 \end{cases} \tag{3}$$

Under the effect of external velocity u_j the level set function is moved with the convection equation as mentioned below.

$$\frac{\partial \phi}{\partial t} + u_j \frac{\partial \phi}{\partial x_j} = 0 \tag{4}$$

The convection term in Eq. (4) is resolved by adopting the Hamilton–Jacobi version of the WENO scheme [18], and third-order TVD Runge–Kutta scheme is adopted for the time stepping [19]. When the interface between two fluid changes, the level set function modifies its signed distance property. To maintain mass conservation and ensure signed distance property, the level set function is reinitialized after every time step. In the current study, a PDE-based reinitialization equation is solved [20].

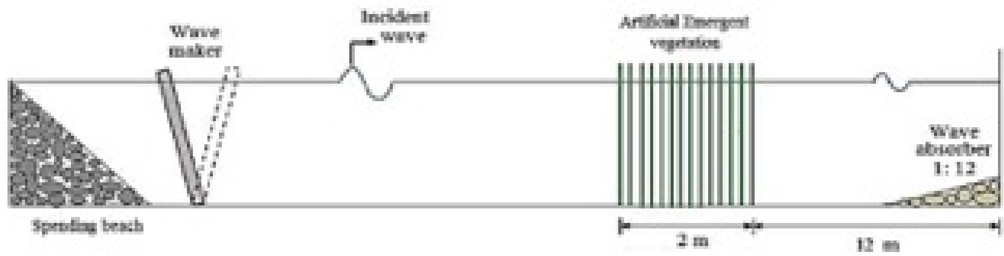

Figure 1: Experimental setup of emerged vegetation in wave flume [1]

Figure 2: Experimental model arrangement to investigate wave attenuation over emergent vegetation [1].

2.3 Assumptions

In experimental investigation, the emerged plant model is made up of nylon rods and it is observed that the nylon rods show negligible sway movement in the wave prop-agating direction for the action of waves generated. Therefore, in the present numerical study, in REEF3D, the flexibility of the vegetation is neglected and vegetation is assumed and modeled as rigid solid cylindrical structure. The placement of cylinders is in line with experimental setup.

2.4 Numerical model validation

The numerical validation is based on the physical experiments carried out in the wave flume by John [1]. Figure 1 shows a schematic diagram of the experimental setup. The physical model of emerged artificial rigid vegetation meadow shown in Fig. 2 is of 2 m width, placed on the horizontal part of the flume bed and tested for wave heights 0.08, 0.12, and 0.16 m and different wave periods of 1.8 and 2 s in distinct water depths of 0.40 and 0.45 m. The vegetation characteristics and experimental conditions are described in Table 1.

The dimensions of emerged vegetation and wave parameters are similar to the physical

Plant	Characteristics of modelled vegetation		Wave height h (m)	Wave period T (s)	water depth d(m)	Relative vegetation height (hs/d)
Emerged rigid vegetation	length of rod	0.50 m	0.08	8	0.40	1.25
	Diameter of rod	0.16 m	0.12	2.0	0.45	1.11
	Density (plants /m^2)	108	0.16	2.0	0.45	1.11

Table 1: Vegetation physical characteristics and experimental conditions [1]

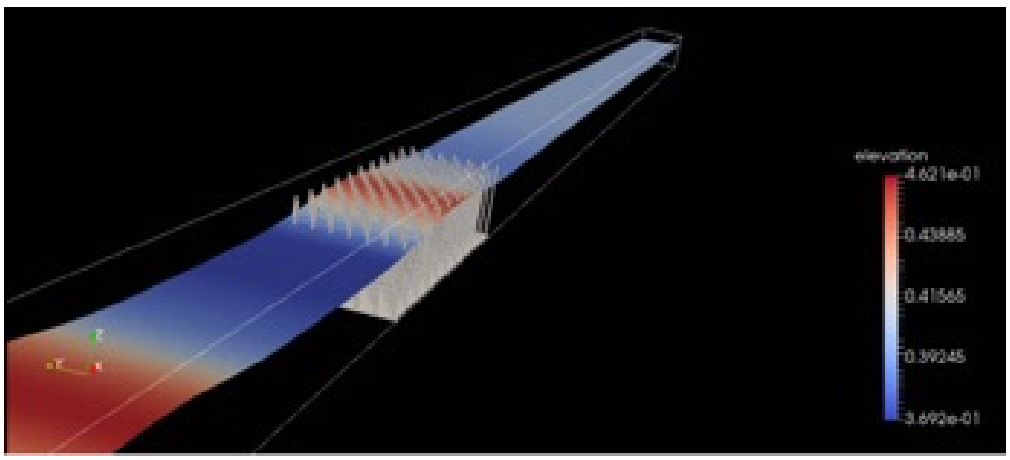

Figure 3: Three dimensional numerical wave tank with emerged vegetation

experiment. The simulated time is 20 s. Waves are generated in the interme-diate water depth using linear wave theory. The 3D numerical wave tank used in this study is illustrated in Figs. 3 and 4, respectively. The numerical tank is 20.0 m long, 0.71 m wide, and 0.7 m high. Waves of height 0.08, 0.12, and 0.16 m are generated at different water depths of 0.40 and 0.45 m with time periods of 1.8 and 2 s, respec-tively. A grid size of 0.0125 m is used for the modeling of the numerical wave tank. Water surface elevation along the vegetation meadow is measured by using the numerical probes.

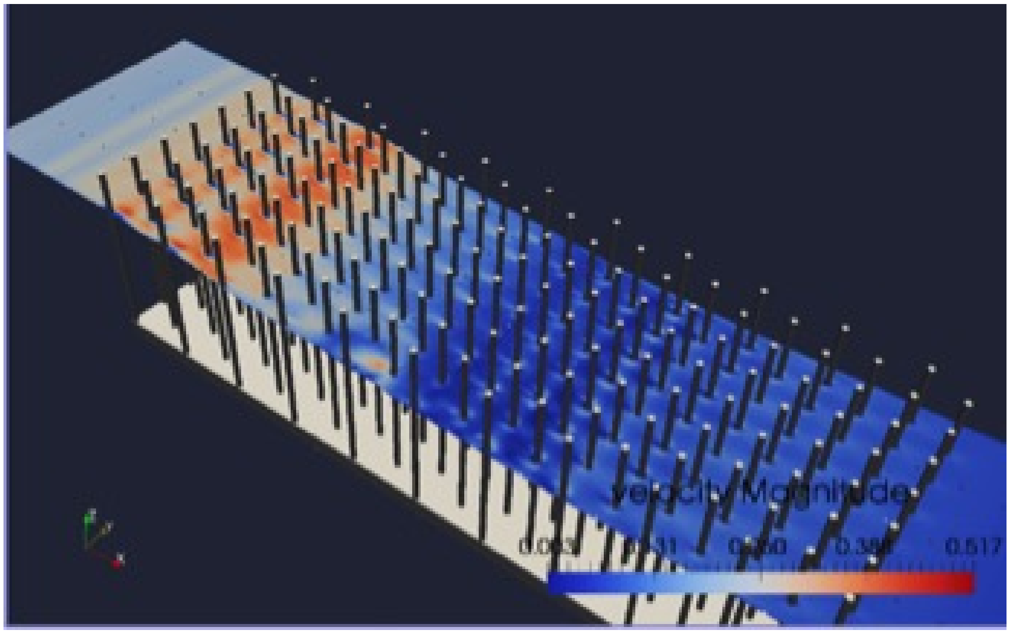

Figure 4: Interaction of waves with emerged vegetation in numerical wave tank

3 Results and Analysis

3.1 Grid convergence study

The performance of the numerical wave tank is carried out in a two-dimensional rec-tangular wave tank of length 12 m. Regular waves of wave height 0.08 m are generat-ed based on the linear wave theory in a water depth of 0.4 m. The elevation of the water depth is measured using the numerical wave probe in the working zone. Mesh sizes of 0.05, 0.025, 0.0125, and 0.00625 m are used for studying grid convergence, and the results obtained for different mesh sizes are compared as illustrated in Fig. 5.

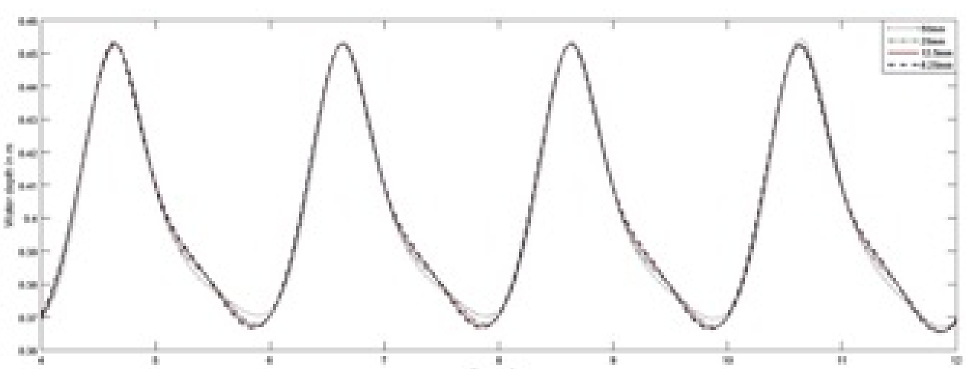

Figure 5: Results of grid convergence study for mesh sizes of 0.05 m, 0.025 m, 0.0125 m and 0.00625 m

It is evident from Fig. 5 that for the mesh size of 0.05 m, the crests and troughs of the waves are damped out and the results are improved for mesh size of 0.025 m. There is no much variation in the wave profile for 0.0125 and 0.00625 m as both converge to a single solution and give the same results. From the grid convergence study, it can be concluded that 0.0125 m is the optimum grid size, and hence, the same grid size is used to study the effect of emerged coastal vegetation on attenuation of the waves.

3.2 Attenuation of waves due to emerged vegetation

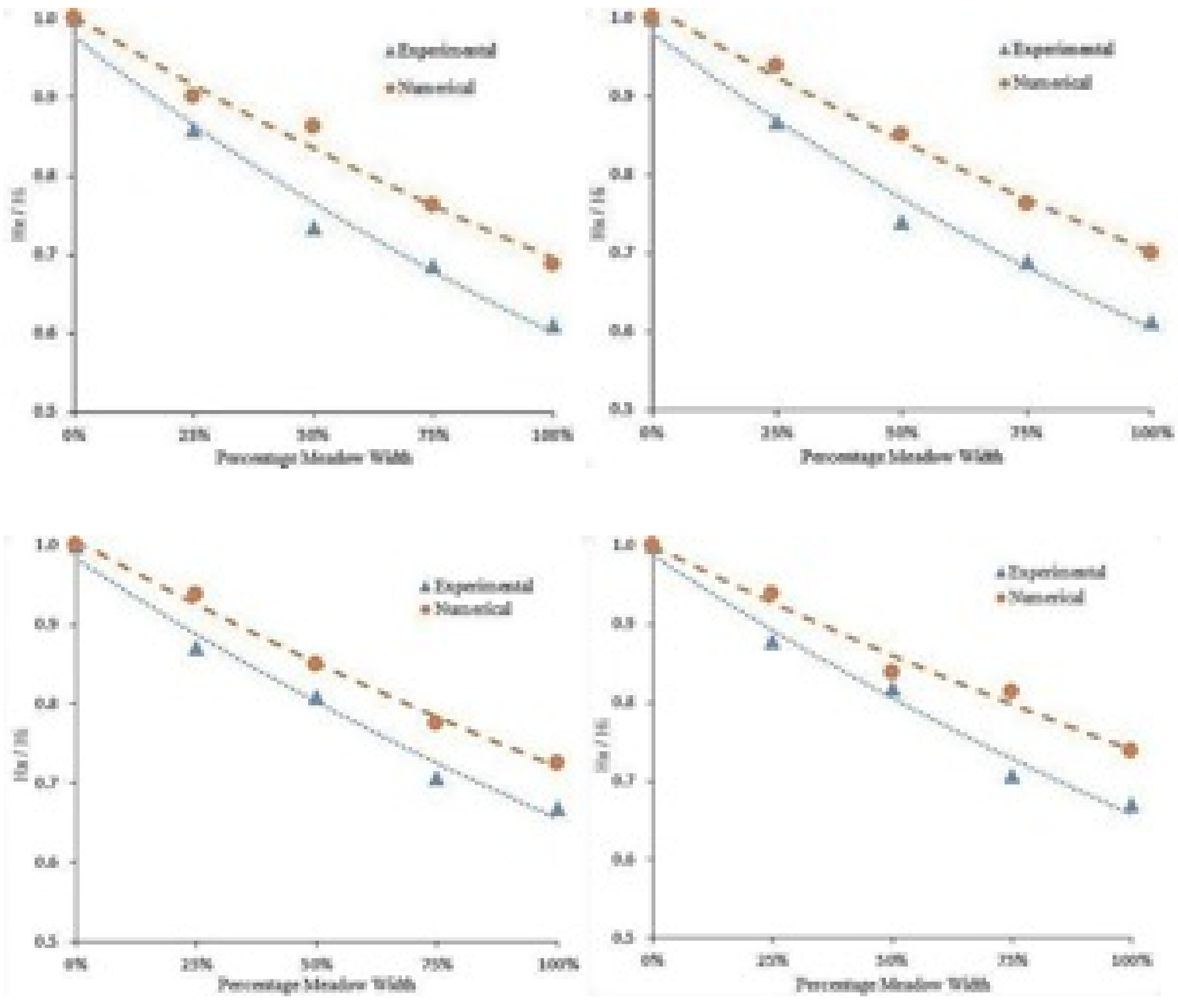

Figure 6: Relative wave height (Hs/Hi) measured along the emerged vegetation meadow for a) h = 0.08 m, T = 1.8 s, hs/d= 1.25, b) h = 0.08 m, T = 2 s, hs/d = 1.25, c) h = 0.08 m, T = 1.8 s, hs/d = 1.11 and d) h = 0.08 m, T = 2 s, hs/d= 1.11.

The wave heights measured at different locations in the numerically simulated model along the 2-m meadow of emerged vegetation model are compared with the experimental results. It is observed that attenuation of wave height along the meadow is following exponential decay. For the wave height of 0.08 m, different relative veg-etation heights (hs/d =1.25, 1.11), and different time periods (T =1.8, 2 s), the wave heights measured along the vegetation meadow of length 2 m at 0.5-m intervals are illustrated in Fig. 6. The attenuation of wave height observed at the exit of the emerged vegetation meadow for hs/d =1.25 and T =1.8 and 2 s is 39.00 and 31.80% in the case of exper-imental study and 32.80 and 30.00% in the present numerical study, respectively. Further, the attenuation of wave height observed at the exit of the emerged vegetation meadow for hs/d =1.11 and T =1.8 and 2 s is 33.10 and 32.90% in the case of exper-imental study and 27.50 and 26.20% in the present numerical study, respectively.

For the wave height of 0.12 m, different relative vegetation heights (hs/d =1.25, 1.11), and different time periods (T =1.8, 2 s), the wave heights measured along the vegetation meadow of length 2 m at 0.5-m intervals are illustrated in Fig. 7.

The attenuation of wave height observed at the exit of the emerged vegetation meadow for hs/d =1.25 and T =1.8 and 2 s is 37.20 and 36.80% in the case of exper-imental study and 28.30 and 30.00% in the present numerical study, respectively. Further, the attenuation of wave height observed at the exit of the emerged vegetation meadow for hs/d =1.11 and T =1.8 and 2 s is 32.00 and 32.30% in the case of exper-imental study and 24.80 and 25.00% in the present numerical study, respectively.

3.3 Influence of relative vegetation height on attenuation of wave

The relative vegetation height indicates the depth of submergence of the vegetation with respect to the depth of water. An increase in relative plant height (hs/d) results in higher attenuation of incident wave height as evident from experimental and numeri-cal results illustrated in Fig. 9a, b for hs/d =1.25 and hs/d =1.11, respectively.

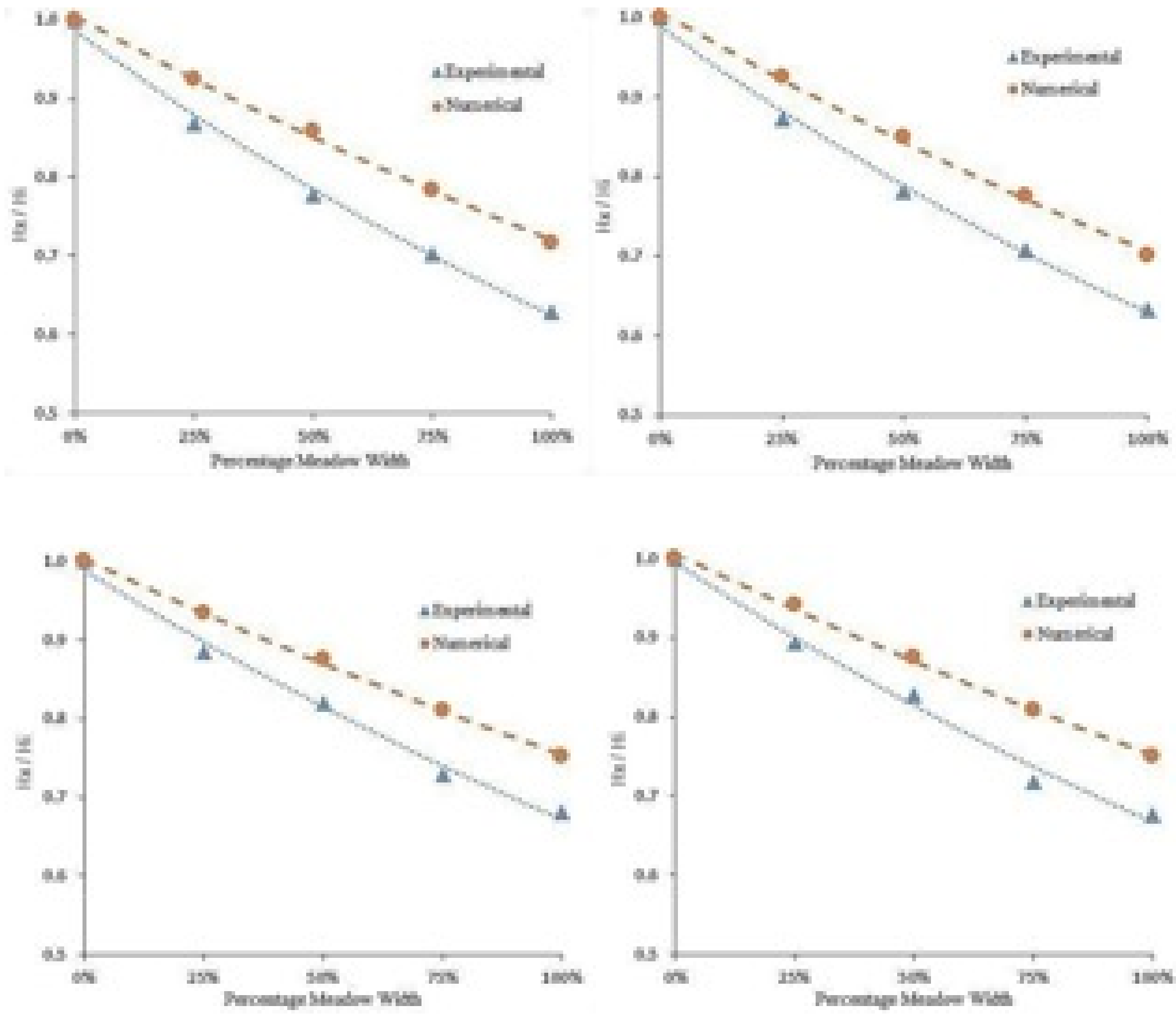

Figure 7: Relative wave height (Hs/Hi) measured along the emerged vegetation meadow for a) h = 0.08 m, T = 1.8 s, hs/d= 1.25, b) h = 0.08 m, T = 2 s, hs/d = 1.25, c) h = 0.08 m, T = 1.8 s, hs/d = 1.11 and d) h = 0.08 m, T = 2 s, hs/d= 1.11.

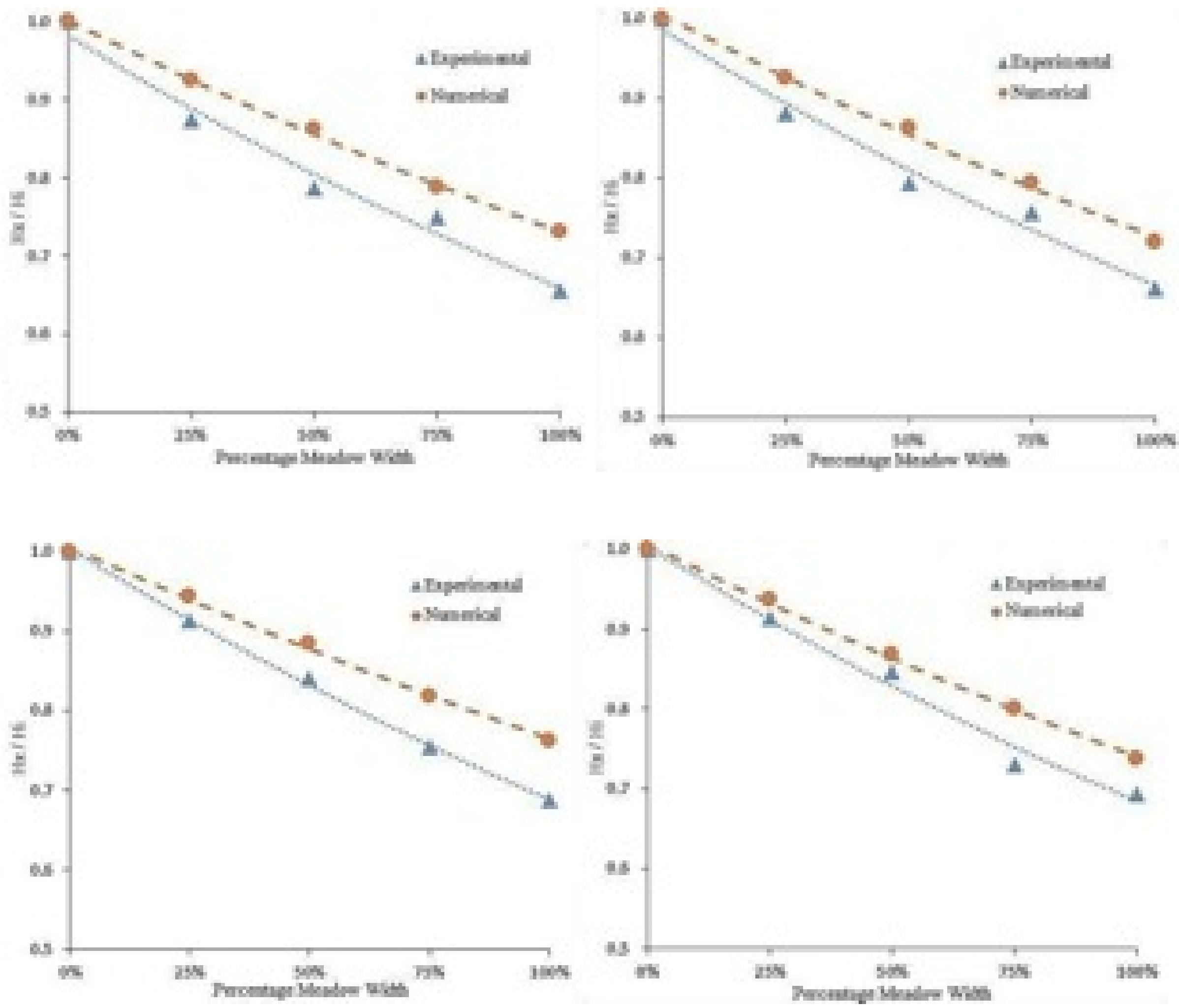

Figure 8: Relative wave height (Hs/Hi) measured along the emerged vegetation meadow for a) h = 0.08 m, T = 1.8 s, hs/d= 1.25, b) h = 0.08 m, T = 2 s, hs/d = 1.25, c) h = 0.08 m, T = 1.8 s, hs/d = 1.11 and d) h = 0.08 m, T = 2 s, hs/d= 1.11.

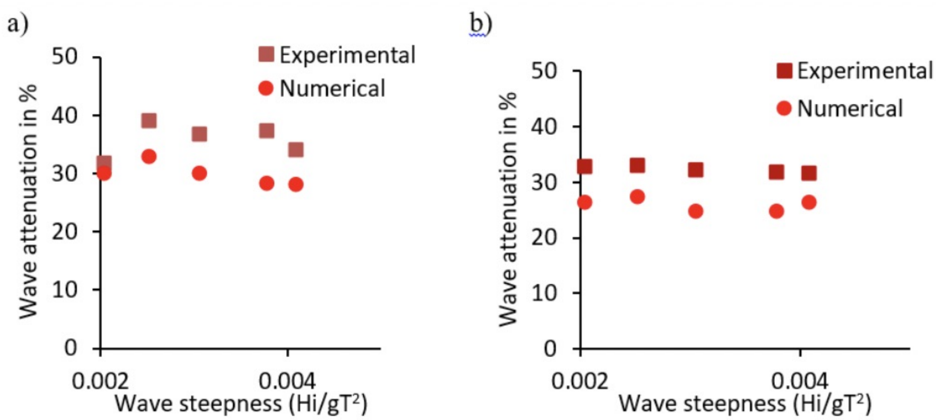

Figure 9: Influence of relative vegetation height (hs/d) on wave attenuation for emerged vegetation for (a) $hs/d = 1.25$ and (b) $hs/d = 1.11$

4 Conclusions

The open source CFD tool REF3D is used for the simulation of emerged vegetation placed in a three-dimensional numerical wave tank. The influence of water depth, incident wave height, and wave period on wave attenuation is investigated numerical-ly. Numerical results are in good agreement with the experimental results, and the wave attenuation due to emerged vegetation is following the same trend as experi-mental for the variation of wave height, wave period, and water depth.

The orbital velocity of the propagating waves is captivated by emerged vegetation resulting in developing turbulence which in turn results in loss of wave energy and wave height. The waves are attenuated in exponential trend as it propagates along the vegetation meadow. The increase in relative vegetation height (hs/d) results in higher attenuation of the waves. The numerical results obtained for emerged vegetation, at-tained an average of 85

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