A Vertical 2-D Model for Wave Propagation in Vegetated and Non-Vegetated Waters

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***Abstract**: A vertical two-dimensional numerical model has been applied in the simulation of wave propagation through vegetated and non-vegetated waters. The model is based on the finite difference code called SOLA-VOF, which solves the Navier-Stokes equations and uses the fractional volume of fluid (VOF) to track the free surface. The subgrid model is used for turbulence closure, and the effect of vegetation is simulated by adding the drag and inertia forces of vegetation into the flow momentum equations. The model has been tested by computing propagation of regular and random waves in vegetated channels, as well as solitary wave runup over a vertical wall and on a sloping beach with and without effect of vegetation. The model reasonably well reproduces the experimental observations, and demonstrates the wave energy dissipation and wave runup reduction by vegetation.*

Keywords: *Waves, wave runup, vegetation, vertical two-dimensional, VOF method, attenuation*

1. INTRODUCTION

Vegetation plays an important role in the sustainable development of aquatic environment. It not only provides food and shelter to many organisms in rivers, estuaries and coastal areas, but also is known to dissipate incoming wave energy and enhance deposition of sediment near coastal zones. Until recently, shoreline protection typically involved construction of hard structures, such as jetties and breakwaters, to dissipate and reflect wave energy. These measures alter nearshore hydrodynamic and circulation patterns and disrupt regional and local morphodynamic processes. The latest trends in coastal engineering are focusing more and more on non-intrusive forms of shoreline protection, such as vegetation. Aquatic vegetation can help to regulate water levels, improve water quality, reduce flood and storm damages, provide important fish and wildlife habitats, and support recreational activities.

In recent years, the importance of vegetation in the wave hazard reduction and coastal protection has attracted more and more attentions. Several groups of researchers had conducted experiments to study the wave attenuation by vegetation, such as Kobayashi et al. (1993), Dubi and Torum (1997), Möller et al. (1996), and Augustin et al. (2009). Li and Yan (2007) studied numerically the effects of vegetation on regular waves and currents, and Li and Zhang (2010) proposed a three-dimensional (3D) wave model for pollutant mixing in vegetation field. However, these numerical models did not consider breaking waves. In order to simulate breaking and non-breaking waves, one of the choices is to use the VOF (volume of fluid) method in vertical 2-D and 3-D models. For example, Kothe and Mjolsness (1992) proposed a two-dimensional (2D) model (called RIPPLE) of incompressible fluid flows based on the VOF method. Iwata et al. (1996) used a modified version of the SOLA-VOF model for numerical analysis of breaking and post-breaking wave deformation due to submerged impermeable structures. Lin and Liu (1998) coupled the RIPPLE model with the $k-\varepsilon$ turbulence model and applied it to calculate breaking waves on a sloping beach. Troch and Rouck (1999) discussed the implementation of an active wave generating–absorbing boundary condition for a numerical model (VOFbreak2) based on the VOF method. Hieu et al. (2004) simulated breaking waves in a surf zone using a VOF-based two-phase flow model. Lin and Xu (2006) developed a Numerical Water FLUME called NEWFLUME to simulate wave propagation and different hydraulic problems. Ketabdari et al. (2008) and Xiao and Huang (2008) described the development of a numerical model based on RANS and $k-\varepsilon$ equations to estimate the impact of wave propagation on a sloped beach.

The purpose of this study is to develop a vertical 2D flow model with the VOF free-surface treatment to simulate the propagation of breaking and non-breaking waves in vegetated and no-vegetated waters. A drag force term has been implemented into the momentum equations to represent the effect of vegetation on the flow. Several experimental cases, including solitary, regular and random waves with and without vegetation effect, have been calculated for validating this model. The results will be presented in next sections.

2. GOVERNING EQUATIONS AND BOUNDARY CONDITIONS

The governing equations used in this study are the vertical two-dimensional Reynolds-averaged continuity and Navier-Stokes (RANS) equations describing the conservation of mass and momentum. The momentum equations include additional source terms representing the spatially averaged resistance effect due to vegetation. The continuity and momentum equations in the Cartesian coordinate system are written in tensor form as

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

$$\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}=g_i-\frac{1}{\rho}\frac{\partial p}{\partial x_i}+\frac{1}{\rho}\frac{\partial \tau_{ij}}{\partial x_j}+F_i \tag{2}$$

where t is the time; x_i is the coordinate in the ith direction, with i=1, 2; u_i is the flow velocity in the ith direction; p is the pressure; g_i is the gravitational acceleration in ith direction; ρ is the density of flow; F_i is the force experienced by the flow due to vegetation per unit volume; and τ_{ij} is the stress due to viscosity and turbulence, determined by

$$\tau_{ij}=\rho\left(\nu+\nu_t\right)\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right) \tag{3}$$

where v is the kinematic viscosity, and v_t is the turbulent eddy viscosity. Using the Smagorinsky sub-grid scale (SGS) model (Breuer et al., 2003), the eddy viscosity is given by

$$\nu_t=C_s^2\Delta^2\sqrt{2S_{ij}S_{ij}} \tag{4}$$

where C_s is a coefficient between 0.1-0.15, Δ is a length scale equals to $\left(\Delta_1\Delta_2\right)^{1/2}$ with Δ_i being the grid spacing in the ith direction, and S_{ij} is the rate of strain $S_{ij}=\left(\partial u_i/\partial x_j+\partial u_j/\partial x_i\right)/2$.

Consider a group of vegetation elements shown in Figure 1. The vegetation stems are conceptualized as cylinders. The vegetation elements experience the drag force and the inertia force from the flow. The drag force is due to the viscous effect and pressure gradient, and the inertia force is due to the fluid acceleration around the stems. The resultant force on a single vegetation stem per unit depth is given by

$$f_i=\frac{1}{2}\rho C_D b_v u_i\sqrt{u_j u_j}+\rho C_M b_v t_v\frac{\partial u_i}{\partial t} \tag{5}$$

where b_v is the width of the vegetation stem, t_v is the thickness of the vegetation stem, C_D is the drag force coefficient, and C_M is the inertial force coefficient. The first term on the right-hand side of Eq. (5) denotes the drag force and the second term the inertia force. The averaged force per unit volume in the vegetation domain is $F_i=Nf_i/\rho$ (Li and Yan, 2007; Li and Zhang, 2010), in which N is the number of vegetation stems per unit bed area, in 1/m^2.

In order to capture the water surface elevation, a function F is firstly introduced by Hirt and Nichols (1981) that indicates the fraction of a mesh cell. The function of F is governed by

$$\frac{\partial F}{\partial t}+\frac{\partial\left(u_i F\right)}{\partial x_i}=0 \tag{6}$$

If F=1, the cell is full of fluid. If F=0, the cell is empty. If F is between 0 and 1, the cell must be a surface cell. Here, the donor-acceptor developed by Hirt and Nichols (1981) can be used to capture the free surface.

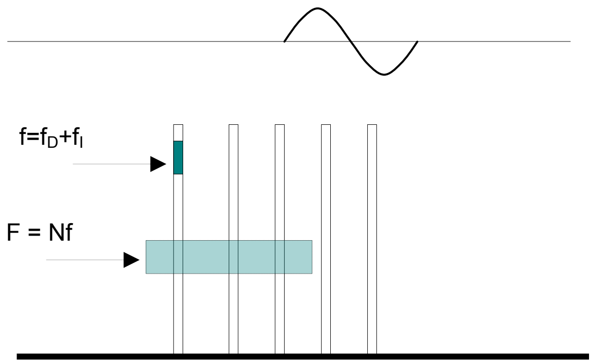

Figure 1 Spatially-Averaged Forces on Vegetation

The boundary conditions include the wave maker boundary on the inlet or seaside boundary, the Sommerfeld radiation conditions (Orlanski, 1976) on the outlet boundary, and a sponge layer in front of the open outlet boundary to absorb the wave energy (Larsen and Daney, 1983).

3. NUMERICAL SOLUTION METHOD

The governing equations are discretized using the finite difference method on the staggered grid system. The momentum equations are discretized using an explicit scheme, with a hybrid upwind/central difference scheme for the convection terms and the second-order difference scheme for the diffusion terms. The coupling of velocity and pressure is achieved through an iteration procedure which makes sure the velocity field satisfies the continuity equation. Details of the numerical algorithm can be found in Nichols et al. (1980).

4. MODEL TEST

4.1. Regular wave propagation in vegetated channel

The developed model has been tested against the experimental data of Asano et al. (1993) in the case of regular wave propagation in a vegetated channel. The experiments were conducted in a wave flume of 27 m in length, 0.5 m in width, and 0.7 m in height. Vegetation was simulated by flexible polypropylene strips with a specific gravity of 0.9, length 0.25 m, width 0.052 m, and thickness 0.3 mm. The vegetation zone was 8 m long, and the number density of strips was 1110 or 1490 m^{-2}. The water depth ranged from 0.45 to 0.52 m, wave frequencies from 0.5 to 1.4 *Hz*, and wave height from 0.086 and 0.113 m. The numerical model has been set up to replicate the experimental conditions. The computational domain is 14 m long. The grid spacing is 0.05 and 0.02 m in *x* and *y* directions, respectively, and the time step is 0.005 s. The waves are finite amplitude waves specified by the second-order Stokes theory. Because of flexible model vegetation, the drag coefficient is set as 0.09 and 0.19 for the two cases in Figure 2. The comparison of calculated and measured wave heights over the vegetation zone is shown in Figure 2. The calculated wave height is determined as the difference between the maximum and minimum water levels at each point. It can be seen that the computed results agree well with the measured data. The model provides a reasonable estimate for the amount of wave height attenuation by vegetation.

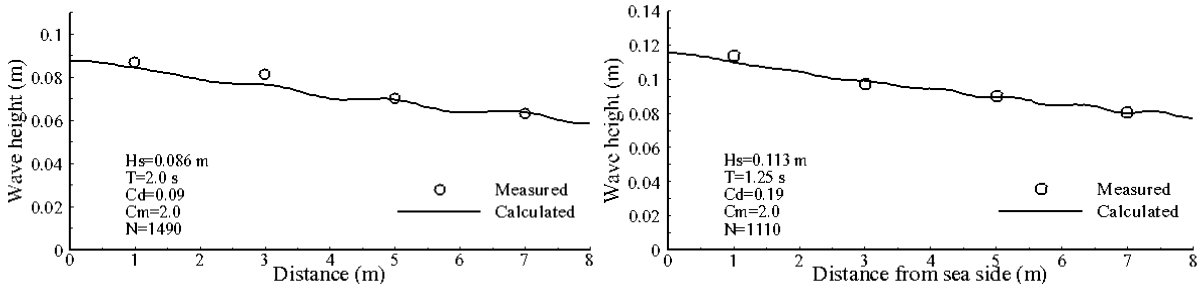

Figure 2   Calculated and Measured Heights of Regular Waves in a Vegetated Channel

4.2. Random wave propagation in vegetated channel

The numerical solution for random waves has been compared to the experimental results for an artificial kelp field given by Dubi and Torum (1997). The artificial kelp models were L. hyperborea with a plant area per unit height of b_v=0.025 m and a height of 0.2 m. The vegetation field, located at the center of the flume, had a total length of 9.3 m. The number of uniformly distributed plants per unit horizontal area was N=1200 units/m^2. Two experimental runs (IR5WD63 and IR7WD68) have been used for validating the present model. The water depth was 0.6 m for both runs, and the other parameters are described in Figure 3. The input irregular waves have the Joint North Sea Wave Project (JONSWAP) spectrum with a shape parameter of 3.3. Figure 3 compares the computed results and measured data for root-mean-square wave height along the channel. Actually the drag coefficients depend on the flow conditions and plant type, especially flexible vegetation, and here they are set as constant representing average values (Mendez and Losada, 2004). The agreement is pretty good and shows that the model can correctly predict the root-mean-square height of random waves with vegetation effect.

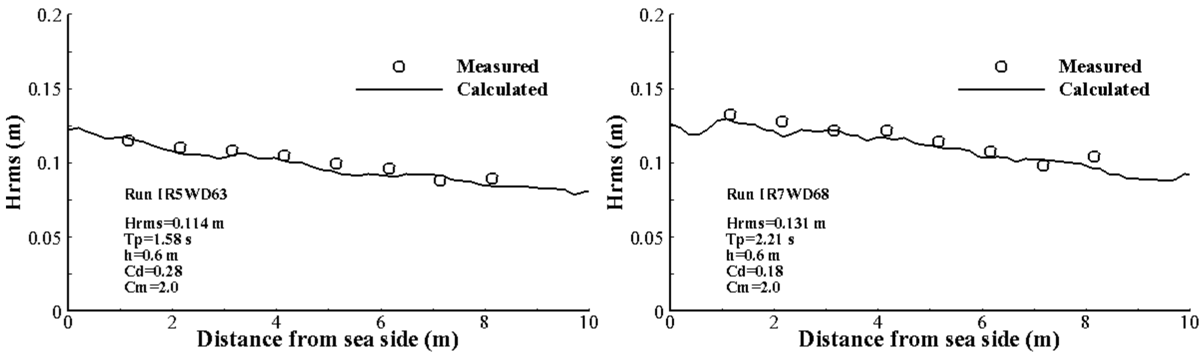

Figure 3 Calculated and Measured Root-Mean-Square Heights of Random Waves in a Vegetated Channel

4.3. Solitary wave runup over vertical wall

The developed model has been used to simulate the solitary wave propagation through vegetated and non-vegetated channels and runup over a vertical wall at the downstream end. The experiments reported by Camfield and Street (1968) investigated this without vegetation effect in the channel. The still water depth was 0.35 m, and the wave height changed in different experimental runs. The developed model is tested using the experimental cases without vegetation and then applied to predict the wave runup with vegetation in the channel. The computation domain is 8 m long, the grid spacing is 0.04 and 0.01 m in *x* and *y* directions, respectively, and the time step is 0.002 s. The vegetation elements used are rigid and have a diameter of 0.01 m and a height of 0.3 m. The vegetation zone is located between 5 m to 7 m. The vegetation density is 1000 units/m^2. The drag and inertia coefficients of vegetation are set as 1.0 and 2.0, respectively.

Figure 4 shows the computed flow pattern and water surface elevation at different elapsed times in the case of wave height 0.14 m and without vegetation in the channel. The solitary wave travels from the left side, touches the vertical wall at 4.4 s, and runs up against the vertical wall; it reaches the maximum runup at 4.77 s, and then falls down from the wall and reflects back to the channel. The solitary wave runup evolution on the vertical wall is reasonably calculated by the developed model. Figure 5 shows that the calculated wave runup results agree well with experiment data in cases without vegetation effect. Here, R is the runup of a solitary wave on a vertical wall, d is the still water depth, and H is the solitary wave height. Figure 5 also shows the relation of R/d and H/d in cases with vegetation in the channel. One can see that the presence of vegetation causes energy dissipation and decreases the wave runup height on the vertical wall.

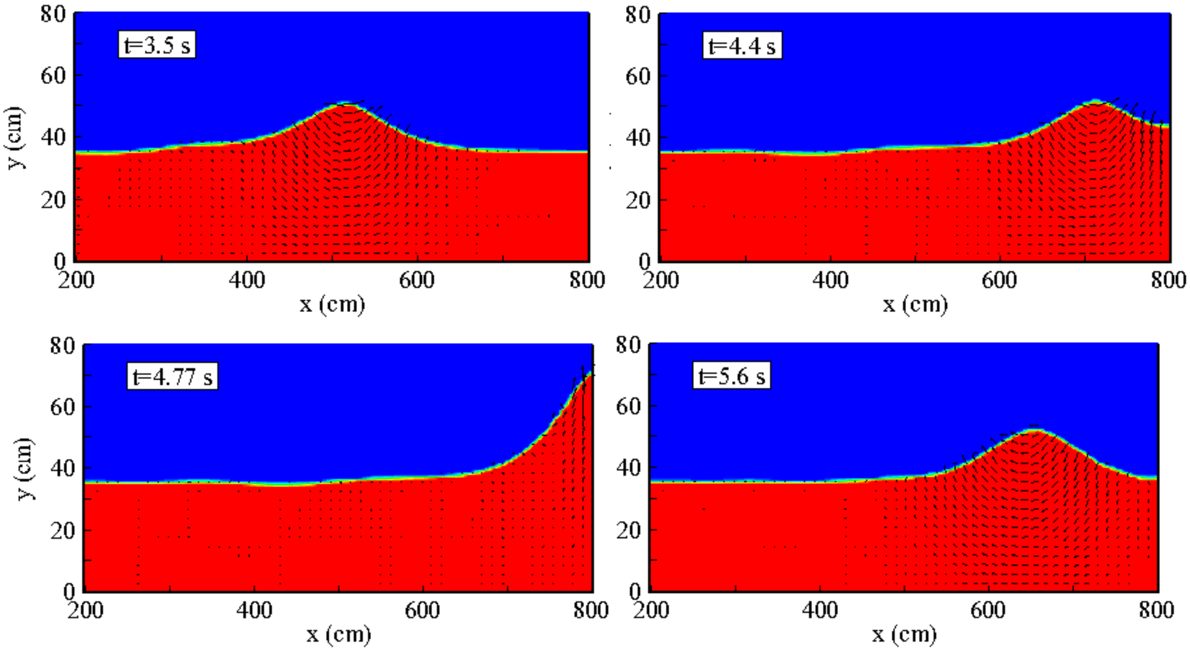

Figure 4 Calculated Flow Pattern in the Case of Solitary Wave Runup over a Vertical Wall (Red color indicates zone of *F*=1, fully occupied by water, and blue color for *F*=0, fully empty)

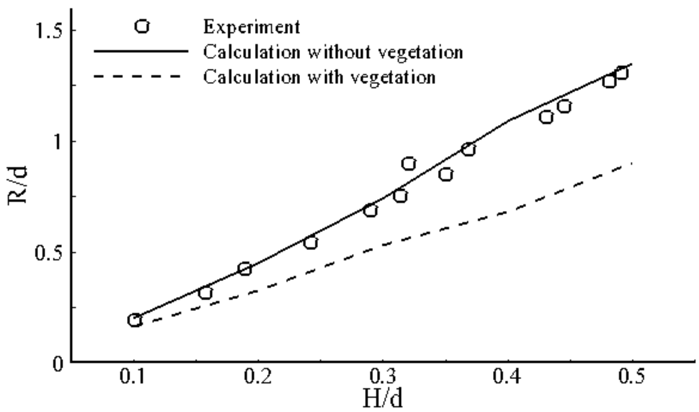

Figure 5 Calculated and Measured Solitary Wave Runup over a Vertical Wall

4.4. Solitary wave runup on vegetated and non-vegetated sloping beaches

The model has been tested by simulating the solitary water runup over vegetated and non-vegetated beaches. Firstly, the experimental data of breaking solitary wave runup of Synolakis (1987) was used to validate the model's ability to capture wave profile in the case of wave breaking. The beach had a slope of 1:20. In the case selected, the still water depth is 0.21 m, and the ratio of wave height to still wave depth, H/d, is 0.28. The computational domain is 14 m long and 0.5 m high. The slope starts at 4 m from the sea boundary. A uniform grid is used, with grid spacing of 0.025 and 0.005 m in *x* and *y* directions, respectively. The time step is 0.004 s. The calculated and measured water surface elevations at different elapsed times are shown in Figure 6, in which the water surface elevation and the *x*-coordinate are normalized by the still water depth and the time is normalized as $t^* = t\sqrt{g/H}$. The wave shape becomes asymmetrical due to the effect of the sloping beach. Its front face becomes steeper and steeper, and ultimately breaks. The wave height reaches a maximum value at the breaking point and decreases after the wave breaks. The breaking wave continues to run up the slope until it reaches the maximum runup height. This demonstrates that the developed model can handle the breaking wave reasonably well.

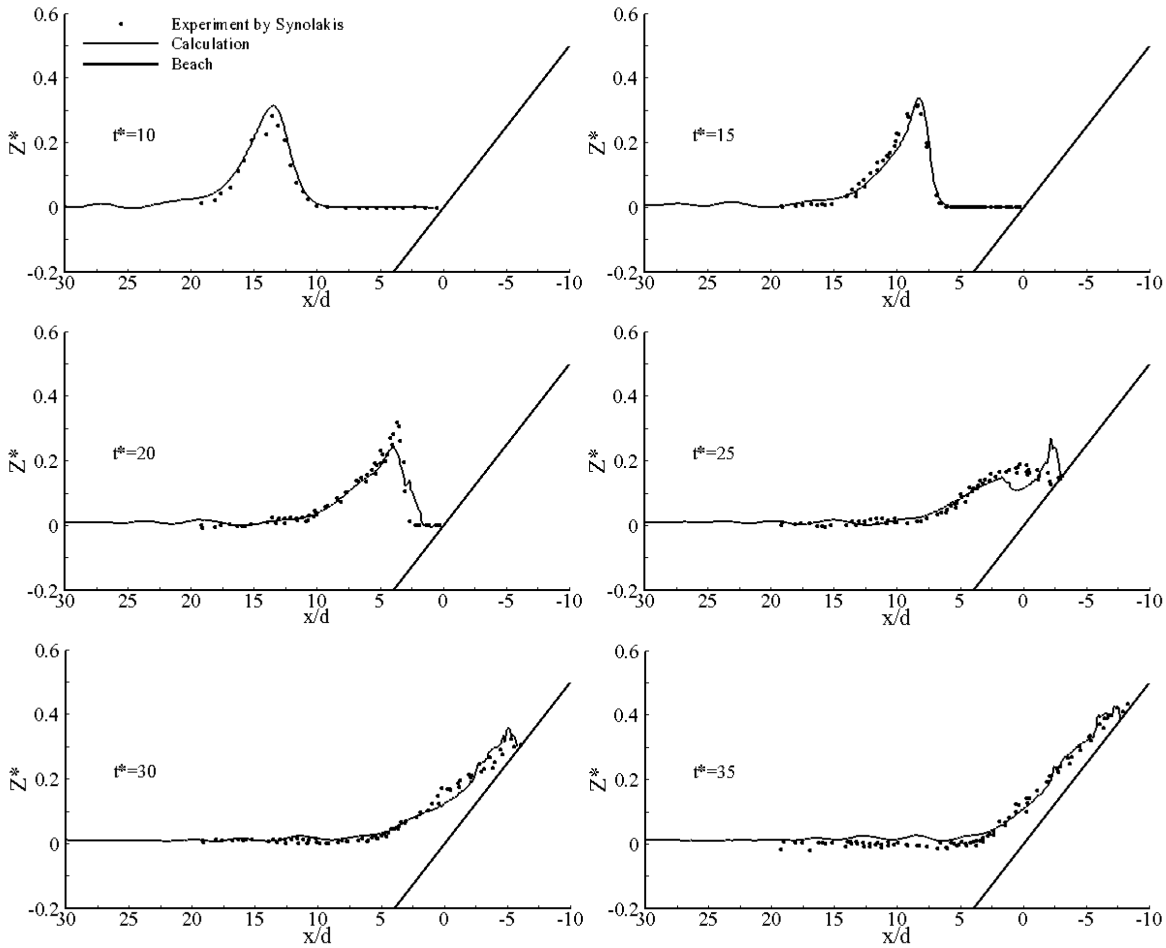

Figure 6 Measured and Calculated Breaking Solitary Wave Runup over a Sloping Beach

To investigate the effect of vegetation on wave runup, the vegetation zone was set up over the same beach, starting at 6.2 m from the sea boundary with a length of 2.0 m. The vegetation elements are rigid, with a height of 0.2 m, a vegetation diameter of 0.01m, and a uniform vegetation density of 1000 units/m^2. The drag and inertia coefficients are set as 1.0 and 2.0, respectively. Figure 7 compares the calculated water surface profiles along the beach with and without vegetation for the same solitary wave. One can see that vegetation delays the wave propagation and reduce the wave runup.

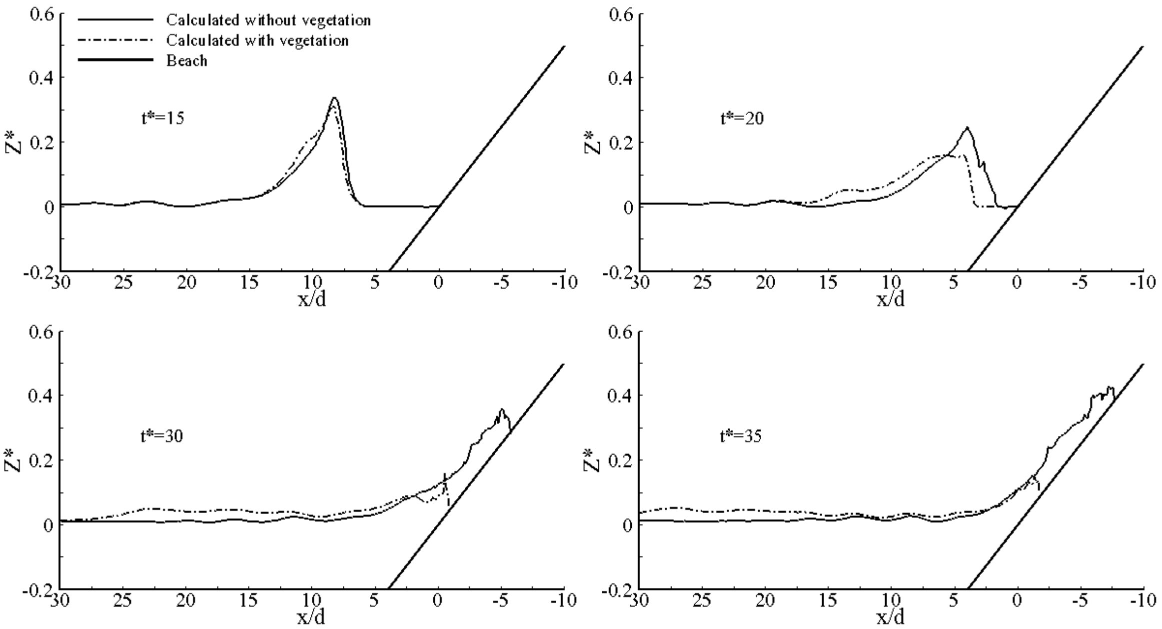

Figure 7 Computed Breaking Solitary Wave Runup over a Sloping Beach with and without Vegetation

5. CONCLUSIONS

A vertical 2-D numerical model based on the RANS equations has been developed to analyze the effect of vegetation on wave propagation. It is based on the early SOLA-VOF model, in which the VOF method is applied to track the free surface, the finite difference method on a staggered grid is adopted to solve the governing equations, and a specially designed algorithm is used to handle the coupling of velocity and pressure. A sub-grid turbulence model is added to close the RANS equations, and the drag and inertia forces are added in the momentum equations to represent the effect of vegetation. This model has been tested in several cases, including solitary, regular and random waves in surface waters with and without vegetation. The calculated results have demonstrated the reduction of wave height and wave runup due to resistance effect of both rigid and flexible vegetation. Therefore, it is a good choice to plant vegetation and restore wetland marshes for preventing surge and flood damages at coastal areas.

6. ACKNOWLEDGEMENTS

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