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Numerical study of vegetation damping effects on solitary wave run-up using the nonlinear shallow water equations

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ABSTRACT

Vegetation damping effects on propagating water waves have been investigated by many researchers. This paper investigates the effects of damping due to vegetation on solitary water wave run-up via numerical simulation. The numerical model is based on an implementation of Morison's formulation for vegetation induced inertia and drag stresses in the nonlinear shallow water equations. The numerical model is solved via a finite volume method on a Cartesian cut cell mesh. The accuracy of the numerical scheme and the effects of the vegetation terms in the present model are validated by comparison with experiment results. The model is then applied to simulate a solitary wave propagating on a plane slope with vegetation. The sensitivity of solitary wave run-up to plant height, diameter and stem density is investigated by comparison of the numerical results for different patterns of vegetation. The numerical results show that vegetation can effectively reduce solitary wave propagation velocity and that solitary wave run-up is decreased with increase of plant height in water and also diameter and stem density.

1. Introduction

Tsunamis are one of the most dreadful natural disasters that can have catastrophic effects on human life and cause immense socioeconomic damage. Tsunamis are defined as a series of extremely long waves generated in a body of water by an impulsive disturbance such as an underwater earthquake, submarine landslide, volcanic activity, or bolide impact that vertically displaces the water (Clague et al., 2003). As a tsunami propagates shoreward it undergoes changes caused by the offshore bathymetry and can increase significantly in height near the shoreline, traveling inland considerable distances with the potential to cause large property damage and loss of life. Since most of the tsunami hazard mitigation in coastal regions is related to their run-up on beaches, understanding and predicting the wave run-up process is an important aspect of the coastal wave mitigation effort. Wave run-up has been observed to vary significantly depending upon the local bathymetry and incidence of planted vegetation along the coastline. Vegetation such as mangroves and salt marshes, as well as belts of sea grass and seaweed are being increasingly recognized as important for dissipating wave energy and improving the safety of the coastal zone (Tanaka, 2009). Vegetation could reduce wave run-up significantly, reducing the adverse effects in a tsunami event. Thus, a study of wave-induced water flow through vegetation is fundamental to an understanding of how wave run-up due to a tsunami event may be reduced by planted vegetation along the coastline.

In general, the damping of water waves is caused by the energy loss through work performed on the plants. Different numerical and analytical models have been proposed to relate the interactions between waves and vegetative plants to explain the damping effects of vegetation by using the conservation of energy equation and accounting for vegetation effects in an energy dissipation term or by using the momentum approach and accounting for vegetation resistance as a drag force. Dalrymple et al. (1984) estimated wave dissipation due to vegetation using linear wave theory by integrating the force on a cylinder over its vertical extent. Kobayashi et al. (1993) presented an analytical solution showing how the monochromatic wave decays exponentially in vegetation based on the vertically two-dimensional continuity and linearized momentum equations for small-amplitude waves. Mendez and Losada (2004) developed an empirical model for estimating wave transformation in vegetation on straight and parallel contours based on the energy conservation equation for normally incident waves. Augustin et al. (2009) simulated irregular wave propagation in flexible vegetation in a shallow-water wave basin with the COULWAVE model based on the modified Boussinesq equations including the effects of vegetation. Huang et al. (2011) studied solitary wave interaction with emergent, rigid vegetation in a wave flume using the Boussinesq equations with the effects of vegetation. Mei et al. (2011) presented analytical and numerical solutions for long surface waves of small amplitude and attenuation on the macro-scale for different bathymetries and coastal forest configurations. Tang et al. (2011) developed a model based on the parabolic mild slope equation for studying linear wave transformation in vegetation. Chen and Zhao (2012) developed a model based on the SWAN model for studying random linear wave transformation in vegetation.

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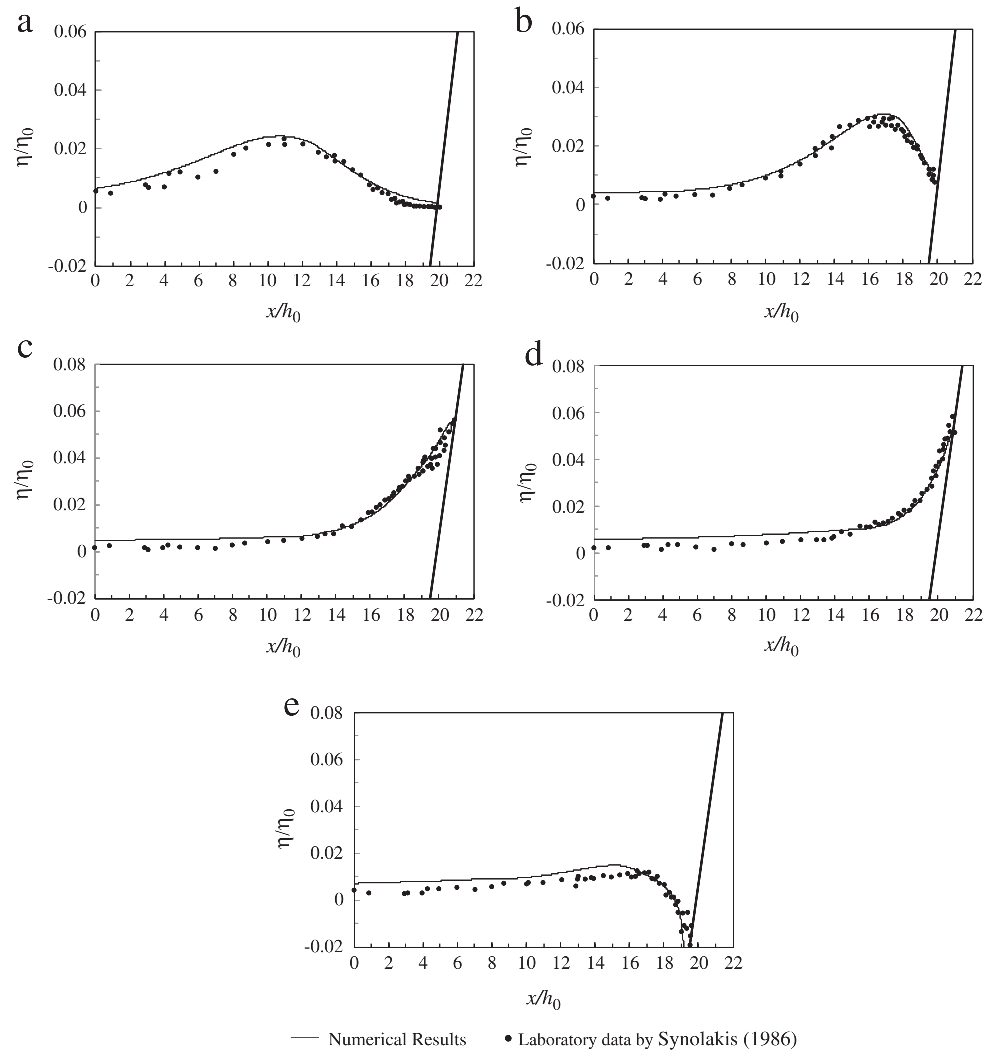

Fig. 1. Run-up of a non-breaking solitary wave with $H/h_0 = 0.0185$ on 1:19.85 slope beach at different non-dimensional times $t(g/h_0)^{0.5}$: (a) 30; (b) 40; (c) 50; (d) 60; and (e) 70.

The wave propagating and run-up processes in a shallow water zone can be modeled by the nonlinear shallow water equations. The present paper numerically investigates the effects of damping due to vegetation on solitary water wave run-up. The proposed model is developed by an implementation of Morison's formulation for vegetation induced inertia and drag stresses in the nonlinear shallow water equations. The model is solved using a finite volume formulation in conjunction with Cartesian cut cell meshes. The model is firstly tested for solitary wave run-up on a non-vegetated sloping beach to examine the accuracy of the present numerical scheme. The model is then tested for regular wave propagation through vegetation to examine the effects of the vegetation induced terms in the present model. Finally, the model is applied to investigate solitary wave propagation and run-up on a plane slope with vegetation. The sensitivity of the solitary wave run-up to plant height and diameter, as well as plant stem density is investigated by comparison of the numerical results with different patterns of vegetation.

2. Governing equations

The nonlinear shallow water equations have been used extensively for simulations of shallow water flows involving wave run-up and overtopping (Apotsos et al., 2012; Briganti and Dodd, 2009; Carrier et al., 2003; Zijlema and Stelling, 2008; Dutykh et al., 2011). As the water wave approaches the shoreline, the wavelength becomes shorter and the amplitude becomes larger. Therefore, the effects of wave nonlinearity become increasingly dominant and frequency dispersion become negligible. Thus, the nonlinear shallow water equations may be used for modeling the behavior of water waves in these zones. It should be noted that actual wave breaking cannot be modeled correctly but can be approximated by very steep waves which can be resolved by the numerical solver described in Section 3. When the resistance offered by vegetation is considered, the shallow water equations take the following conservative form:

$$h_t + \nabla\cdot(h\mathbf{V}) = 0 \tag{1}$$

$$(h\mathbf{V})_t + h\mathbf{V}\cdot\nabla\mathbf{V} = \mathbf{S}_\mathrm{b} + \mathbf{S}_\mathrm{f} + \mathbf{S}_\mathrm{veg} \tag{2}$$

In the above equations, h is the water depth, $\mathbf{V} = (u,v)^T$ the depth-averaged velocity, $\mathbf{S}_\mathrm{b}$ accounts for bathymetry bed slope, $\mathbf{S}_\mathrm{f}$ for bottom induced friction term and $\mathbf{S}_\mathrm{veg}$ for vegetation induced drag term per unit area, and defined as:

$$\mathbf{S}_\mathrm{b} = \left(-gh\frac{\partial\eta}{\partial x}, -gh\frac{\partial\eta}{\partial y}\right)^T \tag{3}$$

$$\mathbf{S}_\mathrm{f} = \left(-\frac{1}{\rho}\tau_x^\mathrm{f}, -\frac{1}{\rho}\tau_y^\mathrm{f}\right)^T \tag{4}$$