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Numerical study of periodic long wave run-up on a rigid vegetation sloping beach

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ABSTRACT

Coastal vegetation can reduce long wave run-up on beaches and inland propagation distances and thus mitigate these hazards. This paper investigates periodic long wave run-up on coastal rigid vegetation sloping beaches via a numerical study. Rigid vegetation is approximated as rigid sticks, and the numerical model is based on an implementation of Morison's formulation [21] for rigid structures 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 model is validated by comparison with experimental results. The model is then applied to simulate various hypothetical cases of long periodic wave run-up on a sloping vegetated beach with different plant diameters and densities, and incident long waves with different periods. The sensitivity of long wave run-up to plant diameter, stem density and wave period is investigated by comparison of the numerical results for different vegetation characteristics and different wave periods. The numerical results show that rigid vegetation can effectively reduce long wave run-up and that wave run-up is decreased with increase of plant diameter and stem density. Moreover, the attenuation of long periodic wave run-up due to vegetation is sensitive to the variation of the incident wave period, and the attenuation of wave run-up is not increased or decreased monotonically with incident wave period.

1. Introduction

As a long wave propagates shoreward it undergoes changes caused by the offshore bathymetry and can increase significantly in height near the shoreline, run-up on the beach and travel inland considerable distances with the potential to cause large property damage including damage to infrastructure and facilities, devastation of coastal ecosystems and settlements, and massive loss of human life. Long wave run-up has been observed to vary significantly depending upon the local bathymetry and vegetation characteristics 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 safety in the coastal zone [25]. Coastal vegetation may not only provide a shield to coastal structures including breakwaters and seawalls but may also reduce wave inundation and run-up. Understanding and predicting a long wave run-up and inland propagation process is an important aspect of the coastal wave mitigation effort. Thus, a study of long wave water propagation through vegetation on a beach is fundamental to an understanding of how long wave run-up may be reduced by planted vegetation along a coastline.

There has been a lot of work done to study the mitigating effects of vegetation on coastal wave run-up using numerical simulations, and different numerical and analytical models have been proposed to relate the interactions between coastal waves and plants to explain the damping effects of vegetation [14,7,29,30,1,8,20,28,23,4,9,33,26,17,18,11,34,27,12,15,36,32,6,16]. The often-used numerical models for water wave propagation on vegetation include phase averaged wave models that account for the effects of vegetation in an energy dissipation term and phase-resolved models that account for vegetation resistance as drag and inertial forces. Compared to phase averaged wave models [11,16,23,27,4,6], phase-resolved models, such as Boussinesq, shallow water or RANS, use the momentum equations and are capable of directly simulating dynamic wave shape deformations [14,7,29,30,1,8,20,9,33,26,17,18,34,5,12,15,36,32]. [14] presented an analytical solution showing how a monochromatic wave decays exponentially in vegetation based on the vertically two-dimensional continuity and linearized momentum equations for small amplitude waves. [7] proposed a model consisting of a numerical simulation based on the one-dimensional shallow water equations in which the resistance of vegetation was evaluated by drag

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forces on trees and drag coefficients of pines estimated on the basis of field observations and laboratory experiments. [30] improved the expression of drag force so that the vertical stand characteristics of trees were considered more realistically, and proposed depth-averaged equivalent drag coefficients for various tropical trees on the basis of field investigations in Sri Lanka, Thailand, and Indonesia. [1] simulated irregular wave propagation in flexible vegetation in a shallow-water wave basin with the COULWAVE Boussinesq equations including the effects of vegetation. [8] studied solitary wave interaction with emergent rigid vegetation in a wave flume using the Boussinesq equations with the effects of vegetation. [20] 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. [9] studied the effects of tree density distribution on tsunami mitigation using the Boussinesq equations including drag and inertia forces caused by vegetation. [33] developed a shallow water model that simulated long waves in a vegetation zone under breaking and non-breaking conditions and the numerical results showed that vegetation along a coastal shoreline has a positive benefit in reducing wave run-up on sloping beaches. [26] developed a model for investigating the effects of damping due to vegetation on solitary wave run-up that was based on the nonlinear shallow water equations and the numerical results showed that vegetation can effectively reduce solitary wave propagation velocity and solitary wave run-up is decreased with increases of plant height in water and also diameter and stem density. [17] developed a RANS model to investigate wave propagation through a finite patch of vegetation in the surf zone and the numerical results showed that the presence of a finite patch of vegetation may generate strong near-shore currents with an onshore mean flow in the unvegetated zone and an offshore return flow in the vegetated zone. [18] presented a RANS model for wave and submerged vegetation which couples the flow motion with plant deformation, and velocities inside and outside a flexible vegetation meadow were validated. [34] presented a vertical 2-D RANS model for wave propagation through vegetated and non-vegetated waters in which the k-ε model was used for turbulence closure. [15] developed a mathematical model for small-amplitude periodic waves propagating through an aquatic forest within a finite extent. [36] presented a coupled wave-vegetation model based on the non-hydrostatic WAVE model (NHWAVE) excluding turbulence and diffusion for simulating the interaction between waves and submerged flexible plants. [22] studied the efficiency of mangrove width to attenuate wave energy using the extended XBeach model in which wave attenuation by vegetation was implemented, and their results show that long waves need more distance for attenuation. [19] studied the influence of solitary wave steepness, vegetation density and vegetation arrangement on tsunami wave attenuation using a three dimensional numerical approach based on IHFOAM. [31] studied the effect of wave-vegetation interaction on wave setup using the extended XBeach model in which wave attenuation by vegetation was implemented, and their results show that the effect of wave-vegetation interaction on wave setup may be relevant for a range of typical coastal geomorphological configurations. These researches have explained the damping effects of vegetation on waves using numerical simulations, and improved our insight into the mitigating effects of coastal vegetation on water wave propagation. However, compared to the progress made on modeling wave propagation on a vegetated plane, wave run-up on a planted sloping beach has been less well studied. Notably, long periodic wave run-up on a planted sloping beach, and the effects of vegetation characteristics such as vegetation density, diameter on a long periodic wave run-up mitigation effects have been less studied. Moreover, the relationship between the wave period and vegetation mitigation effects on long wave run-up has rarely been studied.

The present paper numerically investigates the effects of damping due to rigid vegetation on long periodic wave run-up. Rigid vegetation is approximated as rigid sticks and the numerical model is based on an implementation of Morison's formulation [21] for rigid structures, 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 bare sloping beach and long periodic wave run-up on a partially-vegetated sloping beach to examine the accuracy of the present model. Then, the model is applied to simulate various hypothetical cases of long period wave run-up on a sloping vegetated beach with different plant diameters and densities, and incident waves with different periods. The sensitivity of wave run-up to plant diameter and density, as well as incident wave period, is investigated by comparison of the numerical results for different vegetation characteristics and different wave periods.

2. Numerical methods

2.1. Governing equations

Wave propagation and run-up processes in a shallow water zone can be modeled by the nonlinear shallow water equations as wave nonlinear effects are more prominent than dispersion effects in these zones. As a wave approaches the shore line, the wave length becomes shorter and amplitude becomes larger. Therefore, the effects of wave non-linearity become increasingly dominant and frequency dispersion becomes negligible. Thus, the nonlinear shallow water equations may be used for modelling the behavior of waves in these zones. Vegetation attenuation effects on waves can be approximated by including plant induced inertia and drag stresses in the nonlinear shallow water equations in which rigid vegetation is approximated by rigid sticks and the Morison's formulation [21] for rigid structures induced inertia and drag stresses is implemented. When the attenuation offered by vegetation is considered, the shallow water equations take the following conservative form:

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

$$(h\mathbf{V})_t + h\mathbf{V}\cdot\nabla\mathbf{V} = \mathrm{S_b} + \mathrm{S_f} + \mathrm{S_{veg}} \tag{2}$$

In the above equations, h is water depth, $\mathbf{V} = (u, v)^T$ depth-averaged velocity, $(\ ,\ )^T$ means the transpose matrix, $\mathbf{S}_\mathrm{b}$ 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:

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

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

$$\mathrm{S_{veg}} = \left(-\frac{1}{\rho}\tau_x^\mathrm{veg}, -\frac{1}{\rho}\tau_y^\mathrm{veg}\right)^T \tag{5}$$

where η is water surface level from a horizontal datum, g the acceleration due to gravity, ρ water density, τ_x^f and τ_y^f are friction forces in x and y directions respectively, defined here as:

$$\tau_x^\mathrm{f} = \frac{1}{2}\rho c_\mathrm{f} u|\mathbf{V}| \tag{6}$$

$$\tau_y^\mathrm{f} = \frac{1}{2}\rho c_\mathrm{f} v|\mathbf{V}| \tag{7}$$

c_f bed friction coefficient, τ_x^veg and τ_y^veg are drag and inertia forces on plants in x and y directions respectively. The general rigid plants are usually approximated as rigid sticks with bending effects ignored, and τ_x^veg and τ_y^veg can be defined based on the Morison's equations [21] for rigid structures as:

$$\tau_x^\mathrm{veg} = \frac{1}{2}\rho c_\mathrm{d} b_\mathrm{veg} h_\mathrm{veg} N_\mathrm{veg} u|\mathbf{V}| + c_\mathrm{int}(hu)_t \tag{8}$$

$$\tau_y^\mathrm{veg} = \frac{1}{2}\rho c_\mathrm{d} b_\mathrm{veg} h_\mathrm{veg} N_\mathrm{veg} v|\mathbf{V}| + c_\mathrm{int}(hv)_t \tag{9}$$

where b_veg is stem width normal to wave propagating direction, h_veg stem height under water, N_veg number of stems per unit area, c_d and c_int are drag and inertia force coefficients, defined based on the ones