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Numerical study of turbulence and wave damping induced by vegetation canopies

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ABSTRACT

Vegetation canopies control mean and turbulent flow structure as well as surface wave processes in coastal regions. A non-hydrostatic RANS model based on NHWAVE (Ma et al., 2012) is developed to study turbulent mixing, surface wave attenuation and nearshore circulation induced by vegetation. A nonlinear $k-\varepsilon$ model accounting for vegetation-induced turbulence production is implemented to study turbulent flow within the vegetation field. The model is calibrated and validated using experimental data from vegetated open channel flow, as well as nonbreaking and breaking random wave propagation in vegetation fields. It is found that the drag-related coefficients in the $k-\varepsilon$ model C_{fk} and C_f can greatly affect turbulent flow structure, but seldom change the wave attenuation rate. The bulk drag coefficient C_D is the major parameter controlling surface wave damping by vegetation canopies. Using the empirical formula of Mendez and Losada (2004), the present model provides accurate predictions of vegetation-induced wave energy dissipation. Wave propagation through a finite patch of vegetation in the surf zone is investigated as well. It is found that the presence of a finite patch of vegetation may generate strong pressure-driven nearshore currents, with an onshore mean flow in the unvegetated zone and an offshore return flow in the vegetated zone.

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1. Introduction

Aquatic vegetation such as mangrove and seagrass is of great importance for a number of biological and physical processes in the coastal system. The most significant impact of vegetation is to increase flow resistance and reduce flow speed within the vegetation (Kadlec, 1990; Nepf, 1999; Shi et al., 1995; Wu et al., 1999), thus promoting sedimentation and the retention of suspended sediments (Lopez and Garcia, 1998; Nepf and Ghisalberti, 2008; Tsujimoto, 2000). In this sense, coastal vegetation acts as a sediment binder that resists coastal erosion. Vegetation can also dissipate wave energy (Augustin et al., 2009; Dalrymple et al., 1984; Dubi and Torum, 1997; Kobayashi et al., 1993; Li and Zhang, 2010; Lovas and Torum, 2001; Mendez and Losada, 2004; Suzuki et al., 2011) and provide significant buffering of storm surge (Loder et al., 2009; Sheng et al., 2012; Wamsley et al., 2010). More importantly, wetland vegetation can increase habitat and species diversity by introducing spatial heterogeneity to the velocity field (Shields and Rigby, 2005) and improve water quality by removing nutrients and producing oxygen in stagnant regions (Schultz et al., 2002; Wilcock et al., 1999).

The complex array of leaves, stems, branches and other components of vegetation can tremendously alter the mean flow and turbulent mixing in vegetated aquatic environments (Jarvela, 2005; Kadlec, 1990; Nepf, 1999; Nepf and Vivoni, 2000; Shi et al., 1995). Vegetation induces additional drag on the flow field, reduces mean flow in vegetated regions, converts large-scale mean kinetic energy to small-scale turbulent kinetic energy within stem wakes, and breaks up large-scale eddies to increase turbulent dissipation (Nepf, 1999). The turbulent diffusivity within the vegetation canopy can be greatly reduced due to the downward shifting of turbulent length scale (Nepf, 1999). These processes have been extensively investigated through laboratory experiments (e.g., Ghisalberti and Nepf, 2002; Lowe et al., 2005a,b; Nepf, 1999; Nepf and Vivoni, 2000; Shi et al., 1995; Zong and Nepf, 2010, 2011). Numerical studies of vegetated open channel flow have also been conducted (e.g., Shimizu and Tsujimoto, 1994; Neary, 2003; Cui and Neary, 2008). In these studies, vegetation was ideally modeled as rigid vertical cylinders. Swaying motion as well as vortex-induced vibrations was neglected. The vegetation effects on mean flow and turbulence were accounted for through vegetation-induced drag forces. Both Reynolds-averaged Navier–Stokes simulation (RANS) and large-eddy simulation (LES) were able to capture the turbulent vegetated flow structures well.

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The vegetation effect on wave attenuation was observed in the field (Moller et al., 1999) and in laboratory experiments (Dubi and Torum, 1997; Lovas and Torum, 2001). Theoretical and numerical developments have also been carried out. Most of these models are based on wave energy conservation equation. For example, Kobayashi et al. (1993) derived an analytical solution for monochromatic wave attenuation by vegetation. Their analysis showed that the wave height decays exponentially in the vegetation field. Mendez and Losada (2004) developed a model for random breaking and nonbreaking wave transformation over vegetation fields. Through the calibration and verification of the model using the laboratory measurements by Dubi and Torum (1997) for nonbreaking waves and by Lovas and Torum (2001) for breaking waves, they found that the bulk drag coefficient can be parameterized as a function of the local Keulegan–Carpenter number for a specific type of plant. Suzuki et al. (2011) implemented the Mendez and Losada (2004) formulation in a full spectrum model SWAN, with an extension to include a vertical layer schematization for the vegetation. The model was shown to predict wave damping over both laboratory and field vegetation canopies reasonably well. Chen and Zhao (2012) derived two theoretical models for random wave dissipation due to vegetation, based on Hasselmann and Collins' treatment of energy dissipation and Longuet–Higgins' probability density function for joint distribution of wave height and period. Both models can reasonably predict wave height distribution over vegetation. The wave energy equation models cannot describe the instantaneous variation of the free surface. Recently, wave-resolving models have also been employed to study wave processes through vegetation patch. Augustin et al. (2009) conducted numerical studies of wave damping by emergent and near-emergent wetland vegetation using a wave-resolving nonlinear Boussinesq model COULWAVE (Lynett et al., 2002). The vegetation effect was modeled by a quadratic friction term, which was calibrated using the laboratory data. Their model could predict the instantaneous free surface damping by vegetation. However, the detailed flow structure and mixing under waves were not captured. Another type of wave-resolving model that has been recently developed in the coastal community is the nonhydrostatic wave model (Lin and Li, 2002; Ma et al., 2012; Stelling and Zijlema, 2003). The nonhydrostatic model not only predicts instantaneous free surface variation, but also captures 3D flow structures and turbulent mixing. It has also been employed to study wave–vegetation interaction by, for instance, Li and Yan (2007) and Li and Zhang (2010). In their model, turbulence was simulated by the Spalart and Allmaras (1994) turbulence model, which considers vegetation-induced turbulence production. The model was capable of predicting nonbreaking random wave damping due to vegetation. However, its capability of simulating breaking waves in the surf zone was not shown. In addition, nearshore circulation induced by the vegetation patch was not well understood.

In this paper, a new model is developed to study turbulence, wave damping as well as nearshore circulation induced by vegetation canopy. The model is based on the non-hydrostatic WAVE model (NHWAVE), which was recently developed by Ma et al. (2012). A two-equation $k-\varepsilon$ turbulence model accounting for vegetation-induced turbulence production is implemented to simulate turbulent flow within the vegetation. The model is tested against vegetated open channel flow, nonbreaking random wave dissipation over vegetation fields and vegetation-induced breaking random wave damping on a sloping beach. Then the model is employed to study nearshore currents induced by a finite patch of vegetation in the surf zone.

This paper is organized as follows. The governing equations are presented in Section 2. The nonlinear $k-\varepsilon$ model with vegetation effects are introduced in Section 3. The numerical method and boundary conditions are given in Section 4. Model calibrations and verifications as well as the model's capability to simulate breaking and nonbreaking random wave attenuation in vegetation fields are given in Sections 5 to 7. Wave propagation through a finite patch of vegetation and resulting nearshore circulation are studied in Section 8. The conclusions are finally given in Section 9.

2. Governing equations

Within the canopy, the flow moves around each stem, such that the velocity field is spatially heterogeneous at the stem scale (Nepf and Ghisalberti, 2008). A double-averaging scheme (Raupach and Shaw, 1982) is required to account for this heterogeneity. All the flow variables represented by ϕ are decomposed into time means $\overline{\phi}$ and fluctuations ϕ' as well as into their volume average $\langle\overline{\phi}\rangle$ and a departure therefrom $\overline{\phi}''$ (Raupach and Shaw, 1982). Applying this averaging scheme, the continuity and momentum equations are written as (Ayotte et al., 1999)

$$\frac{\partial\langle\overline{u}_i\rangle}{\partial x_i^*}=0 \tag{1}$$

$$\frac{\partial\langle\overline{u}_i\rangle}{\partial t^*}+\left\langle\overline{u}_j\right\rangle\frac{\partial\langle\overline{u}_i\rangle}{\partial x_j^*}=-\frac{1}{\rho}\frac{\partial\langle\overline{p}\rangle}{\partial x_i^*}+g_i+\frac{\partial\tau_{ij}}{\partial x_j^*}+f_{Fi}+f_{Vi} \tag{2}$$

where

$$\tau_{ij}=-\left\langle\overline{u'_i u'_j}\right\rangle-\left\langle\overline{u}''_i\overline{u}''_j\right\rangle+\nu\frac{\partial\langle\overline{u}\rangle}{\partial x_j^*} \tag{3}$$

$$f_{Fi}=\frac{1}{V}\iint_{S_i}\overline{p}n_i dS \tag{4}$$

$$f_{Vi}=-\frac{\nu}{V}\frac{\iint_{S_i}\partial\overline{u}_i}{\partial n}dS \tag{5}$$

and where x_i^* is the Cartesian coordinate, $\langle\overline{u}_i\rangle$ is the double-averaged velocity component (written as $u_i=(u,v,w)$ hereafter for simplicity), ρ is water density, $\langle\overline{p}\rangle$ is double-averaged pressure, $g_i=-g\delta_{i3}$ is the gravitational body force. The kinematic momentum flux τ_{ij} includes the conventional turbulent and viscous stresses and a dispersive flux term $\left\langle\overline{u}''_i\overline{u}''_j\right\rangle$, which is negligible for uniform canopies (Ayotte et al., 1999). The viscous f_{Vi} and form drag f_{Fi} arise from the spatial perturbation of velocity and pressure, which are typically modeled together as

$$f_{di}=f_{Fi}+f_{Vi}=\frac{1}{2}C_D\lambda u_i|\mathbf{u}| \tag{6}$$

where u is the velocity vector. C_D is the drag coefficient. $\lambda=b_vN$ is the vegetation density, which is measured as frontal area per unit volume, thus having dimensions of length^{-1}. b_v is the stem size, N is the number of stems per unit area. For oscillatory flow, inertia force is not negligible and is given by

$$f_{vmi}=C_M\frac{\pi b_v^2}{4}N\frac{\partial u_i}{\partial t} \tag{7}$$

where C_M is the virtual mass coefficient.

In order to accurately represent bottom and surface geometry, a terrain-following σ-coordinate is adopted.

$$t=t^*\quad x=x^*\quad y=y^*\quad \sigma=\frac{z^*+h}{D} \tag{8}$$

where $D(x,y,t)=h(x,y)+\eta(x,y,t)$, h is water depth, η is surface elevation. Then the governing equations (Augustin et al., 2009) and (Ayotte et al., 1999) are transformed to become

$$\frac{\partial D}{\partial t}+\frac{\partial Du}{\partial x}+\frac{\partial Dv}{\partial y}+\frac{\partial\omega}{\partial\sigma}=0 \tag{9}$$