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Modeling wave attenuation induced by the vertical density variations of vegetation

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ABSTRACT

A phase-averaged model, SWAN, and a phase-resolving RANS-type numerical model, NHWAVE, were compared to previously reported physical model data to evaluate the effectiveness of these models in simulating the attenuation of irregular waves propagating over emergent vegetation with variations in stem heights. The physical model was conducted with two treatments of vegetation, one with a uniform stem height and the other with different heights approximating a linear distribution in stem density over the vertical. The number of stems in the second treatment was doubled so that the total projected area over the vertical was the same between the two tests. The drag coefficients C_D used by SWAN-SL (single-layer in SWAN), SWAN-ML (multi-layer in SWAN) and NHWAVE to model the presence of the vegetation were calibrated separately against the physical model data after removing the effects of bottom and sidewall friction. Although it was expected that every model would have to be recalibrated for a given wave condition and water depth due to the dependence of C_D on the Keulegan–Carpenter number, this paper showed that it was also necessary to recalibrate C_D in SWAN-SL for a given wave condition and water depth when the two different vegetation treatments were applied. Conversely, it was shown that the C_D values in NHWAVE and SWAN-ML changed very little between the two treatments, highlighting the utility of a layered SWAN and RANS model for estimating wave attenuation when the aboveground biomass is no longer uniform over the vertical. The vertical structure of vegetation-induced turbulent kinetic energy, eddy viscosity and dissipation rate were investigated numerically using NHWAVE.

1. Introduction

Quantification of how coastal wetland vegetation protects the coastline has been of substantial interest in reducing the impacts of costal hazards and protecting human development in coastal zones (Fonseca and Cahalan, 1992; Mendez and Losada, 2004; Nepf, 2004; Ward et al., 1984; Pinsky et al., 2013; Guannel et al., 2015). Salt marshes can provide shoreline protection from wave reduction and promote the retention of suspended sediments (Lopez and Garcia, 1998; Nepf and Ghisalberti, 2008; Tsujimoto, 2000; Moller, 2006). Most studies for the bulk drag coefficient have been proposed using a variety of analytical and numerical models in the literature (Dalrymple et al., 1984; Kobayashi et al., 1993; Mendez et al., 1999; Maza et al., 2013). To investigate these assumptions, Wu and Cox (2015a, 2015b) conducted laboratory investigations and found that the assumption of uniform vegetation had the largest influence on wave attenuation (140% to 170% change in the drag coefficient, Wu and Cox, 2015b), followed by the assumption of linear wave theory (23% average change in drag coefficient, Wu and Cox, 2015a), and the assumption of rigid stems (0% to 7%, Augustin et al., 2009; Ozeren et al., 2013). This work continues the investigation of Wu and Cox (2015b) by looking at the numerical modeling of wave attenuation through vegetation when there is a vertical variation in the aboveground biomass (i.e. when the stem height is no longer uniform). For brevity, we refer the reader to those papers for a more detailed literature review and provide only an overview.

The wave height decay rate, which was approximated by Dalrymple et al. (1984) as

$$\frac{H_s(x)}{H_{s,1}} = \frac{1}{1+\alpha x} \tag{1}$$

where H_s (x) is the significant wave height at a horizontal distance x from the leading edge of the vegetation at G1, $H_{s,1}$ is the significant wave height at G1, and α is a damping factor. In this paper, the vegetation transmission coefficient, $K_v(x)$, refers to the attenuation of the significant wave height purely due to the presence of vegetation, is defined as

$$K_v = \frac{H_s(x)}{H_{s,1}} \tag{2}$$

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where the subscript v represents vegetation. Under the assumption of uniform stem height, *s*, composed of rigid cylinders with diameter, *D*, under the action of regular waves, and neglecting inertial effects, Dalrymple et al. (1984) used linear wave theory with the energy dissipation by the vegetation modeled with a bulk drag coefficient, C_D, to relate the attenuation α to the wave properties and number of vegetation stems per unit horizontal area, *N*. Later, Mendez and Losada (2004) rederived this formula to account for irregular wave transformation over a vertically uniform vegetation canopy at a flat bottom and derived the damping factor as

$$\alpha = \frac{1}{3\sqrt{\pi}} C_D D N H_{\mathrm{rms}} k \frac{\sinh^3 ks + 3\sinh ks}{\sinh kh(\sinh 2kh + 2kh)} \tag{3}$$

where H_{rms} is the root-mean-square wave height using the Rayleigh distribution (e.g., Goda, 2010). The variable *k* is the wave number based on the peak wave period, and *h* is the still water depth. This formulation can represent the physical processes within hydrodynamics and vegetation characteristics. The phase-averaged spectral model SWAN (Booij et al., 1999) that has been modified to account for vegetation effects is called SWAN-VEG (Suzuki et al., 2012). Suzuki et al. (2012) implemented SWAN with only calibrated bulk drag coefficients since physical processes within the vegetation considered the diameter, density, and height of vegetation extended by Mendez and Losada (2004).

Augustin et al. (2009) used a wave-resolving nonlinear Boussinesq model COULWAVE (Lynett et al., 2002) to simulate the wave attenuation by emergent and near-emergent vegetation using a quadratic friction term. However, the friction factor approach cannot represent the diameter, height and density of vegetation and fails to capture the vertical flow structure under waves. Li and Zhang (2010) developed a non-hydrostatic wave-resolving model with the Spalart and Allmaras (1994) turbulence closure considering turbulence production induced by submerged vegetation. They not only predicted instantaneous non-breaking free surface elevations but also 3D flow structures and turbulence. However, its capacity of simulating heterogeneous vegetation was not shown. Blackmar et al. (2014) showed that they can combine linearly the attenuation coefficients estimated from two different vegetation stands to represent a heterogeneous stand of the two vegetation types. They also showed that a phase-resolving Boussinesq model (FUNWAVE) predicted wave attenuation through a heterogeneous stand using a linear combination of the attenuation coefficients for each stand reasonably. Marsooli and Wu (2014) used a 3D RANS model including vegetation-induced forces with Volume-of-Fluid (VOF) to capture the free surface and a mixing length for turbulence closure model. They modeled the wave attenuation and vertical profiles of velocity through submerged vegetation. However, the detailed vertical structure of turbulent kinetic energy under waves induced by vertical density variations of vegetation was not captured. No study has systematically considered the effects of vertical variations of vegetation density on wave attenuation as well as vertical structure of turbulent kinetic energy in a field setting under comparable hydrodynamic conditions.

Theoretical and numerical developments have been carried out to study wave attenuation due to rigid vegetation. However, the drag coefficients still exhibit a wide range of values under various vegetation characteristics and hydrodynamic conditions (Pinsky et al., 2013). Suzuki et al. (2012) used SWAN-VEG to model wave dissipation due to various vegetation densities and diameters of mangrove vegetation fields (Vo-Luong and Massel, 2008) by adjusting the vegetation factor. The vegetation factor is a function of diameter, density and bulk drag coefficient of vegetation in the layered model, but calibrating the bulk drag coefficient for each layer is hard to obtain accurately. Moreover, the bulk drag coefficient also depends on wave conditions and vegetation characteristics. We anticipate that it will be necessary to adjust C_D for a particular wave condition and water depth because of KC (or *Ur*) dependence (Wu and Cox, 2015a). The purpose of this study is to assess the applicability of SWAN-VEG and NHWAVE to variable vegetation density of the vertical and whether C_D must be adjusted when vegetation density over the vertical is changed and the wave conditions are held constant.

The physical model (Wu and Cox, 2015b) using two treatments of vegetation and the same total projected area between the two tests are discussed first. Then, we review two numerical models: the phase-averaged spectral model SWAN (Booij et al., 1999) that has been modified to account for vegetation effects and is called SWAN-VEG (Suzuki et al., 2012); and a three-dimensional non-hydrostatic wave-resolving RANS-type model NHWAVE (Ma et al., 2012) implemented using a nonlinear k–ε model (Lin and Liu, 1998a, 1998b; Ma et al., 2013). Both SWAN and NHWAVE are calibrated using the experimental data. Then, the subsequent section describes the effects of vertical variations of vegetation density on bulk drag coefficient and turbulent kinetic energy. The conclusions are finally given.

2. Physical model tests

Following the methodology of Neumeier (2005), Lemein et al. (2015) quantified the vertical biomass distribution for the emergent estuarine species, threesquare bulrush (*Schoenoplectus pungens*) and applied image analysis techniques to differentiate the vegetation from the red board background by taking a lateral picture. The lateral obstruction of the canopy shows a nearly linear distribution with higher density near the ground and much lower density near the top. Other species of salt marshes have different vertical density variations of vegetation as shown in Neumeier (2005) and bring into question the role lateral obstruction by the vegetation plays in wave attenuation, especially considering the relative water depth as the orbital wave velocity is strong near the free surface in deep water and nearly uniform in shallow water.

As noted earlier, Wu and Cox (2015b) conducted a physical model study with two vegetation treatments to show that a linear variation in stem density can change the C_D by 140% to 170% over the range $0.52 < kh < 1.0$ when Eq. (3) is used. Since these data are used to evaluate the numerical models, we provide an overview of the experimental setup here for completeness. Two stands of rigid vegetation were compared in this study; Type A was a uniform stem of emergent vegetation with a height of 14 cm and width of 5 mm (Fig. 1a, c). Type B was designed based on the observation of Lemein et al. (2015) that the vertical variation of vegetation density of *S. pungens* follows a linear distribution with stem heights of 2, 4, 6, 8, 10 and 12 cm, all with the same 5 mm width (Fig. 1b, d). These values were chosen to achieve constant total lateral obstruction areas between Type A (uniform) and Type B (vertically-varying vegetation density). For example, six stems of Type A would have a total obstructed area of 42 cm^2 and twelve stems of Type B (assuming two of each height) would have the same obstructed area. A total of 150 and 300 plastic strips were placed in a staggered manner for Type A and Type B with the mean spacing ΔS_a between strips of $\Delta S_{a,A} = 3.78$ (cm) and $\Delta S_{a,B} = 2.58$ (cm) as shown in Fig. 1a and b to give stem densities of $N_A = 1618$ (stems/m^2) and $N_B = 3236$ (stems/m^2), respectively. If the mean spacing between two stems is ΔS_a, $N_A/N_B = (\Delta S_{a,B})^2/(\Delta S_{a,A})^2$ where *N* is the number of vegetation stands per unit horizontal area (stems/m^2). With the ratio of vegetation density $N_A/N_B = 1/2$, the ratio of the mean spacing is estimated as $\Delta S_{a,A}/\Delta S_{a,B} = \sqrt{2}$, which is close to the measured mean spacing between strips. For this experiment, we used 5-mm-wide by 1-mm-thick rigid plastic strips similar to the materials used by Wu and Cox (2015a).

The water depth was held constant with $h = 12$ cm for all cases. At a geometric scale of 1:4, this corresponds to a prototype water depth of 48 cm, which is typical for salt marsh canopies such as *S. pungens.* The significant wave heights measured at the leading edge of the vegetation field ranged from $1.49 < H_s < 3.42$ cm (6–14 cm prototype) and were increased to be as large as possible without wave breaking to assure that the dominant dissipation mechanism for wave attenuation was due to vegetation only. Assuming Froude similitude at 1:4 geometric scale, the prototype