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Spectral distribution of wave energy dissipation by salt marsh vegetation

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ABSTRACT

Spectral energy dissipation of random waves due to salt marsh vegetation (*Spartina alterniflora*) was analyzed using field data collected during a tropical storm. Wave data (significant wave heights up to 0.4 m in 0.8 m depth) were measured over a two-day period along a 28 m transect using 3 pressure transducers. The storm produced largely bimodal spectra on the wetland, consisting of low-frequency swell (7–10 s) and high-frequency (2–4.5 s) wind-sea. The energy dissipation varied across the frequency scales with the largest magnitude observed near the spectral peaks, above which the dissipation gradually decreased. The wind-sea energy dissipated largely in the leading section of the instrument array in the wetland, but the low-frequency swell propagated to the subsequent section with limited energy loss. Across a spectrum, dissipation did not linearly follow incident energy, and the degree of non-linearity varied with the dominant wave frequency. A rigid-type vegetation model was used to estimate the frequency-dependent bulk drag coefficient. For a given spectrum, this drag coefficient increased gradually up to the peak frequency and remained generally at a stable value at the higher frequencies. This spectral variation was parameterized by employing a frequency-dependent velocity attenuation parameter inside the canopy. This parameter had much less variability among incident wave conditions, compared to the variability of the bulk drag coefficient, allowing its standardization into a single, frequency-dependent curve for velocity attenuation inside a canopy. It is demonstrated that the spectral drag coefficient predicts the frequency-dependent energy dissipation with more accuracy than the integral coefficient.

1. Introduction

Wave propagation through vegetation is an important physical process along many coastal regions of the world, and along the shores of large inland lakes. Waves approaching vegetated shores lose energy due to obstructing vegetation. This reduces shore erosion and is of engineering significance for shoreline protection. The role and importance of coastal wetlands as a natural defense system against storm waves is generally acknowledged (e.g., Costanza et al., 2008; Dixon et al., 1998; Gedan et al., 2011; Lopez, 2009). Utilization of coastal wetlands to augment structural measures for mitigation of coastal flooding due to storm surge and waves is promoted in several regions of the world (e.g., Borsje et al., 2011; CPRA, 2012).

A body of literature exists quantifying reduction rates of integral wave heights due to vegetation (for summary, see Anderson et al., 2011; Jadhav and Chen, in review). Theoretical models based on energy conservation, have been proposed for application to both monochromatic waves (Dalrymple et al., 1984), and for narrow-banded random waves (Mendez and Losada, 2004). Kobayashi et al. (1993) presented an approach based on continuity and momentum equations, which assumed an exponential decay of integral wave height. Chen and Zhao (2012) proposed a vegetation-induced dissipation model based on the formulation of Hasselmann and Collins (1968) for energy dissipation of random waves by bottom friction. All these models assume rigid vegetation. A number of recent studies have underscored the importance of accounting for the stem and blade motion of flexible vegetation, and have proposed models that account for it (Bradley and Houser, 2009; Mullarney and Henderson, 2010; Riffe et al., 2011). Wave attenuation has been studied in a controlled laboratory environment (Augustin et al., 2009; Dubi and Tørum, 1996; Løvås and Tørum, 2001; Stratigaki et al., 2011), in field conditions involving salt marshes (Bradley and Houser, 2009; Cooper, 2005; Jadhav and Chen, in review; Möller, 2006; Möller and Spencer, 2002; Möller et al., 1999; Riffe et al., 2011), coastal mangrove forests (Mazda et al., 2006; Quartel et al., 2007), and vegetated lakeshores (Lövstedt and Larson, 2010). Most of these studies primarily focused on the attenuation of integral wave heights or wave energy, and estimation of integral bulk vegetation drag coefficients. As a step beyond integral dissipation characteristics, Lowe et al. (2005) developed an analytical model to predict the magnitude of the in-canopy velocity of

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waves propagating over a model canopy made up of rigid cylinders. Lowe et al. (2007) extended this model to random waves and predicted that high frequency components of wave energy would dissipate more efficiently inside the canopy. The model was verified with measurements taken from an artificial rigid cylinder canopy submerged on a barrier reef (random wave conditions) for 2 h and assuming a constant drag coefficient.

In the case of natural vegetation under random waves generated by a tropical cyclone, there are no published studies that examine in detail the frequency-based characteristics of wave energy dissipation and drag coefficient, though some studies have illustrated such characteristics with an example (Bradley and Houser, 2009; Paul and Amos, 2011). The present study investigates the spectral characteristics of wave energy dissipation due to natural vegetation, and the relationship between dissipation and the incident wave energy spectrum, using comprehensive field data. The study also identifies spectral variation of the vegetation drag coefficient. We hypothesize that the frequency-varying spectral drag coefficient will predict spectral distribution of energy dissipation more accurately than an integral drag coefficient. To test the hypothesis, a new method is developed to parameterize the spectral drag coefficient over the entire range of measured wave spectra. The spectral and integral drag coefficients are then both used to estimate energy dissipation losses, and these estimates are compared to the observed dissipation to assess the validity of the hypothesis.

The following section describes the spectral energy dissipation model proposed by Chen and Zhao (2012) which is used to estimate drag coefficients and introduces the velocity attenuation factor. Sections 3 and 4 describe the field program and the wave conditions. Section 5 contains data analysis, where spectral characteristics of the observed energy dissipation are examined. In Section 6, spectral variation of estimated drag coefficient is demonstrated, and the spectral behavior of the mean velocity attenuation parameter is quantified. The mean velocity attenuation parameter and average drag coefficients are then applied to predict energy dissipation and compared with the existing prediction methods in Section 7. Finally the results are discussed, followed by a summary and conclusions.

2. Spectral energy dissipation model

Assuming the linear wave theory holds, the evolution of normally-incident random waves propagating through vegetation can be expressed with the following wave energy balance equation,

$$\frac{\Delta\left(E_j C_{g,j}\right)}{\Delta x} = -S_{ds,j} \tag{1}$$

where subscript j represents the jth frequency component of a wave spectrum, E is the spectral wave energy density, $C_g = nc$ is the group velocity, $c = \sqrt{(g/k)\tanh(kh)}$ is the phase speed, k is the wave number, h is the still water depth, g is the acceleration due to gravity and coefficient n is given by $n = (1/2)[1 + (2kh / \sinh 2kh)]$. The cross-shore coordinate is given by x pointing landward and S_{ds} is the energy dissipation due to vegetation per unit horizontal area. All other source terms are considered negligible compared to the vegetation induced losses.

The spectral wave energy dissipation due to vegetation is obtained by using a reorganized form of the model proposed by Chen and Zhao (2012). Their model treats vegetation as rigid, cylindrical elements that impart drag forces on the flow. Further, only the drag forces due to pressure differences are considered, as they are much larger than those arising from friction in the hydraulic regimes encountered in the field conditions.

In this model, the spectral energy dissipation due to vegetation is expressed by,

$$S_{ds,j} = \frac{1}{2}\frac{C_{D,j} b_v N_v}{g}\left(\frac{\sigma_j}{\sinh k_j h}\right)^2 \left(\sum_{-h}^{-h+sh} U_{z,rms}(z)\cosh^2\left[k_j(h+z)\Delta z\right]\right)E_j \tag{2}$$

where $C_{D,j}$ is a bulk drag coefficient, b_v is the stem diameter, N_v is the vegetation population density, σ_j is the wave angular frequency, s is the ratio of vegetation height, h_v, to the still water depth, h, and U_{rms} is the root-mean-squared (RMS) velocity given by,

$$U_{z,rms} = \sqrt{2\sum_{j=1}^{j=N_f}\frac{\sigma_j^2\cosh^2 k_j(h+z)}{\sinh^2 k_j h}E_j\Delta\sigma} \tag{3}$$

where N_f is the total number of frequency components of a spectrum.

Eq. (2) is based on the quadratic representation of the shear stress induced by the vegetation. We parameterize the shear stress due to vegetation drag at elevation z (positive upwards with origin at the still water level) due to jth component of the spectrum as,

$$\tau_{z,j} = -\frac{1}{2}\rho b_v N_v C_d \alpha_j u_{z,j}\left|\alpha_j u_{z,j}\right|\Delta z \tag{4}$$

where ρ is the density of water and $\alpha_j u_{z,j}$ is the vegetation-affected velocity at elevation z, and C_d is the drag coefficient corresponding to this velocity. The velocity attenuation parameter, α, is defined as the ratio of the vegetation-affected velocity, u'_z, to the velocity in the absence of vegetation, u_z, at elevation z inside the canopy:

$$\alpha_{z,j} = \frac{u'_{z,j}}{u_{z,j}}. \tag{5}$$

This parameter is similar to Lowe et al. (2005) but not exactly the same.

Similar to the definition of α (Eq. (5)), the ratio of the vegetation-affected RMS velocity at an elevation z, $U'_{z,rms}$, to the RMS velocity in the absence of vegetation, $U_{z,rms}$, at elevation z inside the canopy is defined as,

$$\alpha_{z,r} = \frac{u'_{z,rms}}{u_{z,rms}}. \tag{6}$$

Using these definitions, Chen and Zhao (2012) formulation is reorganized and the spectral distribution of energy dissipation is expressed as,

$$S_{ds,j} = \frac{1}{2}\frac{\overline{C}_D b_v N_v}{g}\frac{\alpha_{z,j}^2}{\alpha_{z,r}^2}\left(\frac{\sigma_j}{\sinh k_j h}\right)^2\left(\sum_{-h}^{-h+sh} U_{z,rms}\cosh^2\left[k_j(h+z)\right]\Delta z\right)E_j \tag{7}$$

where $\overline{C}_D$ is the spectrally-averaged, or integral, drag coefficient. To facilitate solution of Eq. (7), α is assumed to be independent of depth, and a normalized form of α is introduced as,

$$\alpha_{n,j} = \frac{\alpha_j}{\alpha_r}. \tag{8}$$

Note that while α_j is always less than 1, $\alpha_{n,j}$ can be greater than 1. Using $\alpha_{n,j}$, Eq. (7) can then be re-written as,

$$S_{ds,j} = \frac{1}{2}\frac{\overline{C}_D b_v N_v}{g}\alpha_{n,j}^2\left(\frac{\sigma_j}{\sinh k_j h}\right)^2\left(\sum_{-h}^{-h+sh} U_{z,rms}\cosh^2\left[k_j(h+z)\right]\Delta z\right)E_j. \tag{9}$$