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Effects of wave steepness and relative water depth on wave attenuation by emergent vegetation

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A B S T R A C T

A physical model experiment was conducted to investigate the effects of wave nonlinearity on the attenuation of irregular waves propagating through a stand of uniform, emergent vegetation in constant water depth. The experimental conditions spanned relative water depths from near shallow to near deep water waves ($0.45 < kh < 1.49$) and wave steepness from linear to nonlinear conditions ($0.03 < ak < 0.18$). The wave height to water depth ratios were in the range $0.12 < H_S/h < 0.34$, and the Ursell parameter was in the range $2 < Ur < 68$. Frictional losses from the sidewall and bottom were measured and removed from the wave attenuation in the vegetated cases to isolate the influence of the vegetation. The normalized wave height attenuation for each case was fit to the decay equation of Dalrymple et al. (1984) to determine the damping factor α, which was then used to calculate the bulk drag coefficient C_D. This paper shows that the damping factor is dependent on the wave steepness ak across the range of relative water depths from shallow to deep water and that the damping factor can increase by a factor of two when the wave steepness ak approximately doubles. In turn, this causes the drag coefficient C_D to decrease on average by 23%. The drag coefficient can be modeled using the Keulegan–Carpenter number using the horizontal orbital wave velocity estimated from linear wave theory as the characteristic velocity scale. Alternatively, the Ursell parameter can be used to parameterize C_D to account for the effect of wave nonlinearity, particularly in shallow water, for vegetation of single stem diameter.

1. Introduction

The need to explore sustainable approaches to maintain coastal ecological systems has been widely recognized for decades (Ward et al., 1984; Fonseca and Cahalan, 1992; Nepf, 1999; Mendez and Losada, 2004). These systems face a number of challenges due to global climate change and patterns in coastal population growth. Submerged aquatic vegetation and emergent vegetation in estuaries and shorelines can provide ecosystem services, including wave-energy reduction and erosion control (Kastler and Wiberg, 1996; Bartholdy et al., 2004; Möller, 2006). Numerous studies of wave attenuation by vegetation have examined a variety of numerical and analytical methods to describe the wave energy dissipation. A common approach is to consider the vegetation as an array of rigid cylinders and estimate the dissipation due to the resulting force (Dalrymple et al., 1984; Kobayashi et al., 1993; Asano et al., 1992; Dubi and Tørum, 1995; Vo-Luong and Massel, 2008). Dalrymple et al. (1984) used the conservation of energy by integrating the force on a rigid vertical cylinder for monochromatic waves within the vegetated zone. Kobayashi et al. (1993) estimated the energy dissipation due to rigid vegetation induced forces using the conservation of momentum for regular waves whose wave height decays exponentially. The analytical solution was compared with artificial kelp experiment conducted by Asano et al. (1988) and predicted wave attenuation reasonably well.

Most of the early wave attenuation models for vegetation were simplified using four main assumptions: (1) rigid plants, (2) regular waves, (3) uniform emergent vegetation, and (4) linear wave theory. Since the development of these early models, there have been several investigations that consider the flexibility of vegetation. Asano et al. (1992) extended the solution of Kobayashi et al. (1993) to include the interaction between the water wave and vegetation motion. The interactive solutions were connected by a linearized damping coefficient determined by an iterative approach. Dubi and Tørum (1995) extended the analytical solution of Asano et al. (1992) to allow the linear relationship of the damping force with velocity to be calculated effectively without iteration. Mendez et al. (1999)

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extended the analytical solution for regular waves to irregular waves considering vegetation motion compared with the experimental data given by Asano et al. (1992) and Dubi and Tørum (1995). Mullarney and Henderson (2010) derived an analytical model to predict the transfer function between the water wave and stem motion after tuning with a single calibration parameter. Based on the analytical model, they predicted that the frequency-dependent wave dissipation was about 30% of the rate of wave dissipation for rigid vegetation. Riffe et al. (2011) used the theoretical model derived from Mullarney and Henderson (2010) to compare with their field experiment. They measured the wave height attenuation over a salt marsh vegetated area and employed the theory of Mullarney and Henderson (2010) for rigid and flexible vegetation motion. Both models resulted in a good fit to the measured attenuation after fitting the drag coefficients, although the fitted drag coefficient in the rigid vegetation model was below the expected range. The model provided a reasonable prediction of drag coefficients by natural vegetation motion. Augustin et al. (2009) conducted a laboratory experiment to measure wave height decay through both rigid and flexible synthetic dowels for emergent and nearly emergent cases. Although there was a fairly wide scatter in the drag coefficients, they parameterized their observed drag coefficients using both the Reynolds number and Keulegan–Carpenter number. Later, they compared their results to a time-dependent wave propagation model based on the modified Boussinesq equations (Lynett et al., 2002) with adjustable bottom friction factor to account for the energy loss due to the vegetation. The bottom friction factor was determined by matching the model results to the experimental data, and they showed that the friction factor could be parameterized by the Ursell parameter for the range of $10 < \mathrm{Ur} < 45$. However, they found that rigid and flexible vegetation gave similar friction factors under the same conditions in the range $3000 < \mathrm{Re} < 9000$. On the other hand Riffe et al. (2011) showed that drag coefficients calibrated with the rigid-vegetation model were below the expected range and that wave dissipation for flexible vegetation was 50% of the dissipation for rigid vegetation. This may draw into question how important the plant motion may be in determining the wave attenuation rates.

In addition to extending models to account for the flexibility of the vegetation, there have been several studies to extend earlier work from regular to irregular waves. Mendez et al. (1999) and Mendez and Losada (2004) presented an empirical model for wave transformation of regular waves or random waves, including wave damping and wave breaking over vegetation fields at variable depths. H_{rms}, the root-mean-square wave height was used to estimate the damping factor α. Because wave attenuation varies with density, height, stiffness of the plant and wave conditions, the variability of wave height attenuation through vegetation is difficult to quantify universally. Lowe et al. (2007) showed that wave attenuation would dissipate more efficiently within submerged rigid canopies due to the enhanced in-canopy flow increased by higher frequency wave motions. Bradley and Houser (2009) and Paul and Amos (2011) showed that higher frequencies had higher attenuation in the case of natural vegetation under random waves. Jadhav et al. (2013) applied a spectral energy dissipation model to rigid vegetation in order to study spectral drag coefficient dependence on the frequency domain instead of the integral drag coefficient. They found that the spectral drag coefficient was frequency dependent and varied over a range of KC numbers. However, they did not explain the physical mechanism for these observations.

There has been some research to investigate the third assumption regarding the uniform density of the plants with respect to water depth (i.e. uniform array of cylinders vs. a natural stand of vegetation). Neumeier (2005) characterized the vertical biomass distribution and the lateral obstruction ratio using optical methods and has shown that there is significant vertical variation in plant structure. Suzuki et al. (2012) described an implementation of wave attenuation by vegetation in the SWAN model considering a two-layer vegetation which requires calibration with laboratory or field observations. The model has been shown to calculate the wave dissipation over vegetation fields under waves including a vertical layer schematization for vegetation. Blackmar et al. (2014) used a small scale physical model study to show that the attenuation coefficients estimated for two different vegetation stands can be combined linearly when a heterogeneous stand of the two vegetation types are considered. They also showed that a time-resolving wave propagation model can also be used to predict the attenuation through a heterogeneous stand using a linear combination of the attenuation coefficients for each stand calculated separately. Overall, there has been little work on the effects of the vertical variation of the vegetation density (or lateral obstruction) compared to vegetation fluctuation and irregular waves.

Similarly, there has been little work to consider the fourth assumption of wave linearity. In a nearshore wave study in the absence of vegetation, Guza and Thornton (1980) considered Ursell numbers to show that nonlinearity may cause significant energy transfer cross spectral frequencies and that nonlinearity amplified the harmonics in higher frequencies especially in shallow water conditions. More recently, Kaihatu et al. (2007) used a nonlinear wave model to study the effects of nonlinear waves damped over viscous mud. Since vegetation is another form of wave damping, we might expect that nonlinear wave–wave interaction processes may play an important role in wave energy dissipation caused by vegetation.

This literature review indicates that significant progress has been made in wave height attenuation by vegetation. However, there still exists wide scatter in the drag coefficients and some uncertainty in the relative importance of wave flexibility, lateral obstruction, and wave nonlinearity. No study has, thus far, systematically investigated the importance of wave nonlinearity on the attenuation by vegetation; and this is the central aim of this paper. Using the same idealization of Mendez and Losada (2004) and earlier authors, we consider only a uniform stand of rigid vegetation with uniform cross-section over the vertical to isolate the effect of wave nonlinearity. We conduct physical model tests with control of the incident significant wave height $H_{s,1}$, spectral peak period T_p, and water depth h to explore a range of relative water depths from near shallow to near deep water wave conditions and wave steepness from nearly linear to highly nonlinear conditions. The measured wave heights throughout the vegetation are reduced to determine a damping factor α and bulk drag coefficient C_D following Mendez and Losada (2004). Then, the subsequent section describes the effect of incident wave nonlinearity on the attenuation by vegetation by observing the evolution of wave spectra. Finally, a discussion and conclusions are given.

2. Experimental design

Following Dalrymple et al. (1984), wave height decay can be modeled as,

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

where $H(x)$ is the wave height at a distance x through the plant bed, $H_{s,1}$ is the total significant wave height at the leading edge of the vegetation using $H_s = 4.004\sqrt{m_0}$ where m_0 is variance of the free surface time series, and α is a damping factor. For this paper, the attenuation of the significant wave height due to the presence of vegetation relative to the incident wave height is referred to as the