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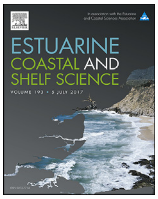

Evolution of wave spectra in mound-channel wetland systems

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ABSTRACT

Wetlands characterized by vegetation growing in patches, separated by non-vegetated open spaces (channels), widely exist in coastal regions. Since wave energy is an important factor that influences shoreline and wetland stability and causes damage, understanding wave-spectrum evolution in such patchy vegetation is essential to minimizing erosion and coastal hazards. Here, we conducted a numerical investigation on the evolution of irregular waves across various frequency components in mound-channel wetland systems. Simulations with a Boussinesq model showed the impact of patchy vegetation on wave energy was both frequency- and space-dependent. Energy amplification was induced by mound channel wetland systems in specific harmonics and locations. Compared with uniform bathymetry, patchy vegetation on the tops of mounds also influences wave shoaling and nonlinear interaction, intensifying wave energy transfer toward the higher harmonics. This phenomenon became more pronounced for the longer-period incident waves. With increasing incident wave period, mound-channel wetland systems had different impacts on the dominant-frequency and high-harmonic energy; attenuation of the dominant-frequency energy decreased with longer incident periods, while the trend in the high-harmonic energy reversed. This study provides insight regarding wave attenuation by wetlands when there is spatial variability in the wetland configuration. The reduced dominant wave energy by both attenuation and energy transfer may influence sediment transport in mound-channel wetland systems, which is related to long-term stability of shorelines and coastal wetlands.

1. Introduction

The present study investigates how mound-channel wetland systems influence wave energy in the nearshore and estuarine areas. There is evidence that coastal wetlands have various ecological benefits for coastal communities, such as providing habitats for flora and fauna, maintaining water quality and enhancing environmental resilience (e.g., Cimon-Morin et al., 2015; Cunniff, 2015; Karjalainen et al., 2016; Silliman et al., 2012). In addition, wetlands can directly mitigate the physical stress of shoreline erosion and wave activity (e.g., Arkema et al., 2013; Costanza et al., 2008; Gacia and Duarte, 2001; Neubauer et al., 2002). According to Cunniff (2015), such a “natural defense” is also more cost-effective than typical hard structures, such as breakwaters and levees.

The subject of wave dissipation by vegetation has attracted numerous studies since the 1980s. Dalrymple et al. (1984) and Kobayashi et al. (1993) derived analytical solutions for the energy decay and wave speed reduction induced by vegetation for monochromatic waves, while Méndez et al. (1999) and Méndez and Losada (2004) extended the models to irregular wave application. In the following years, field studies, laboratory experiments and numerical modeling demonstrated the capacity of vegetation for attenuating wave energy (e.g., Augustin et al., 2009; Loder et al., 2009; Morgan et al., 2009; Wamsley et al., 2010). Recently, the role of vegetation on irregular wave attenuation was found to be frequency-dependent. Bradley and Houser (2009) and Anderson and Smith (2014) observed more energy dissipation in the high-frequency components (compared to low frequencies) by both natural and artificial vegetation. In a field study by Jadhav et al. (2013), the drag coefficient of vegetation depended on wave frequency, and they proposed a frequency-dependent curve for velocity attenuation to better parameterize the drag coefficient across the frequency domain. Wu and Cox (2015) concluded that wave steepness and water depth affected wave energy dissipated by vegetation. Some studies also recognized that wave dissipation was related to vegetation properties like stiffness and density (e.g., Bouma et al., 2005; Paul and Amos, 2011), while Augustin et al.

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(2009) and Ozeren et al. (2013) observed little difference between wave attenuation by rigid and flexible plants. External factors like current and incident wave energy might undermine vegetation's capacity to dissipate waves (e.g., Ondiviela et al., 2014; Paul et al., 2011). However, our understanding of coastal wetlands in mitigating natural hazards is not yet as well-established as it is for hard structures (Cunniff, 2015). For instance, studies on wave dynamics in patchy wetlands are still limited.

In field settings, patchiness is a common property of coastal wetlands (e.g., Rietkerk et al., 2004; Rietkerk and van de Koppel, 2008). The uncertainty of growth and seasonal variability may result in non-vegetated channels in-between vegetation patches. Silliman et al. (2015) and van Wesenbeeck et al. (2008) reported a higher plant growth rate when vegetation was grouped into patches to maximize the positive species interaction. Under appropriate hydrodynamic and abiotic conditions, Bouma et al. (2009) and Balke et al. (2012) observed enhanced sediment accretion induced by the attenuated hydrodynamic energy inside vegetation patches, which induced additional marsh growth. Yet, the dynamics of wave-spectrum evolution in patchy vegetation, which is relevant to the stability of wetlands and wave energy dissipation, is not well understood.

Nonlinear wave interaction is a significant factor in wave-spectrum evolution, especially for shallow-water gravity waves over complex bathymetry. Whalin (1971) observed wave energy transfer toward high frequencies in a series of regular-wave experiments, which was induced by nonlinear wave interaction and uneven bathymetry. Freilich and Guza (1984) derived a one-dimensional Boussinesq model to predict the nonlinear spectral evolution of irregular waves, and observed secondary peaks at higher harmonics of the peak frequency resulting from nonlinear interaction. Liu et al. (1985) extended the work to two horizontal dimensions, which was applicable to more complicated cases. Following studies further demonstrated the relationship between wave-spectrum evolution and nearshore processes, such as wave shoaling, refraction and diffraction (e.g., Eldeberky, 2012; Hamm et al., 1993; Janssen et al., 2008; Norheim et al., 1998). With a mound in the bathymetry, Yeh et al. (1994) observed energy convergence behind a cone-shaped island. In wetlands with complex bathymetry, the presence of patchy vegetation will provide additional attenuation of wave energy. Thus, the evolution of wave spectra becomes more complicated.

This paper is focused on wave evolution in patchy wetlands characterized by vegetated mounds and unvegetated cross-shore channels (mound-channel wetland systems) using numerical simulations with a fully nonlinear and weakly dispersive Boussinesq model. The mound-channel wetland systems are idealized from a prototype engineered wetland in Dalehite Cove, Galveston Bay, TX. In the following, we introduce the applied methodology and present the simulation results. Further insight into the role of mound-channel wetland systems on wave evolution is provided in the discussion, followed by final conclusions.

2. Methodology

2.1. Boussinesq model

The numerical model used in this study is COULWAVE (e.g. Kim and Lynett, 2011; Lynett et al., 2002), which is based on the depth-integrated Boussinesq-type equations, with sub-models to include the effects of bottom friction, wave breaking and turbulent mixing. This model is fully nonlinear and weakly dispersive, and has been successfully applied in one- and two-dimensional simulations of wave propagation over uneven bathymetry (e.g., Løvholt et al., 2015; Lynett et al., 2010, 2002; Yang et al., 2015). The dimensional governing (continuity and momentum) equations are

$$\frac{\partial \zeta}{\partial t} + \nabla \cdot [(\zeta + h)\mathbf{u}_\alpha] + \mathbf{H.O.T.} = O\left(\mu^4\right), \tag{1}$$

$$\frac{\partial \mathbf{u}_\alpha}{\partial t} + \mathbf{u}_\alpha \cdot \nabla \mathbf{u}_\alpha + g\nabla\zeta + R_f - R_b - R_{ev} + \mathbf{H.O.T.} = O\left(\mu^4\right), \tag{2}$$

where ζ = free surface elevation, h = local water depth, $\mathbf{u}_\alpha$ = horizontal velocity vector at z_α from still water level and g = gravity. The effects of bottom friction and wave breaking are included in R_f and R_b, and R_{ev} accounts for the vertical and horizontal eddy viscosity of turbulent mixing. $\mathbf{H.O.T}$ represents the higher-order nonlinear and dispersive terms on the order of $O(\mu^2)$, where μ is the ratio of water depth and wavelength $\left(\frac{h}{\lambda}\right)$. Additional details regarding these terms are described in literature (e.g., Kim and Lynett, 2011; Liu, 1994; Løvholt et al., 2013; Lynett et al., 2002).

To simulate the effect of vegetation in numerical models, various approximations have been applied in previous studies. A straightforward approach is to represent vegetation as increased bottom friction (e.g., Augustin et al., 2009; Blackmar et al., 2013; Loder et al., 2009). This approach works satisfactorily in predicting large-scale flow characteristics, while small-scale patterns adjacent to individual plant stems are not as well resolved. Another approach to approximate vegetation is by including drag force terms, such as in Nepf (2004) and Huang et al. (2011), to explicitly account for the effect of stem density and better capture smaller-scale features. Applying a three-dimensional model, Maza et al. (2015) concluded that simulating the actual geometry of plants provided better prediction of wave forces, compared to the drag force approximation. Recently, Ozeren et al. (2013) and Wu et al. (2016) further demonstrated that vertical variation of vegetation also influenced wave attenuation. In our study, we focus on the wave-spectrum evolution affected by the drag effect of patchy vegetation, where we are interested in the aggregated impact of the vegetation patch on the large-scale flow. Thus, we approximate the vegetation patches as increased bottom friction (R_f in Eq. (2)) in the simulations.

2.2. Study domain

This study expands on the regular-wave experimental findings in Truong et al. (2014) and the numerical simulation findings on wave-induced circulation in Yang et al. (2015). We select the engineered site of Dalehite Cove in Galveston Bay, TX as our prototype, which is composed of constructed vegetated mounds separated by unvegetated channels; vegetation (i.e., higher bottom friction) is specified only at the top of each mound. In nature, similar patchy wetlands also commonly exist (e.g., Rietkerk et al., 2004; Rietkerk and van de Koppel, 2008). The mound spacings (S), water depths (h_o), incident wave heights (H_i) and peak periods of incident waves (T_p) are selected based on the predominant site conditions with Froude scaling (Truong et al., 2014). In the field, the average dimensions of mounds are 35 m for the bottom diameter, 13 m for the top diameter, and 0.5 m in height. The selected geometric scale factor is 1:6.5, while the corresponding time scale factor is 1:2.55. The investigations of Yang et al. (2015) and Truong et al. (2014) were limited to the research of regular waves and three mounds alongshore for all laboratory scenarios. Here, we (a) use TMA wave spectra to simulate more realistic wave conditions (Hughes, 1984), and (b) assume periodic distribution of mounds in the alongshore direction (Fig. 1). To maximize computational resources, the simulations were executed at the same 1:6.5 length

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