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Numerical investigation of wave-induced flow in mound–channel wetland systems

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ABSTRACT

Coastal wetlands are an important ecosystem in nearshore regions, but they are also significant in affecting the flow patterns within these areas. Wave-induced flow in wetlands has complex circulation characteristics because of the interaction between waves and plants, especially in discontinuous vegetation. Here, a numerical investigation is performed to analyze the wave-averaged flow in vegetated mound–channel systems. Different water levels, vegetated conditions, and mound configurations are studied with the COULWAVE (Cornell University Long and Intermediate Wave) Boussinesq model.

Model simulations show rip currents in the mound–channel systems, whose strength varies with different mound separation distances. The relative influence of vegetation depends on both mound configuration and water level. Approximately a 15% change in significant wave height results as waves propagate over the vegetated mounds, while up to a 75% decrease in the mean shoreward flow speed through vegetation is observed. In addition, vegetation influences the spatial distribution of mean water level within the wetlands. Dimensional analysis shows that rip current strength and primary circulation size depend on mound spacing, water depth, wave height, and vegetation cover.

1. Introduction

As a transition region between ocean and land, wetlands are significant ecosystems that maintain water quality, provide natural habitat for a variety of species, and slow down erosion (Shutes, 2001; Gaciaa and Duarteb, 2001; Thullen et al., 2002). Besides its ecological function in coastal regions, wetland vegetation also influences wave dynamics. During the past two decades, studies have elucidated the potential of coastal wetlands to mitigate flow impact in extreme events and protect onshore infrastructure (e.g., Kobayashi et al., 1993; Shafer et al., 2003; Loder et al., 2009; Wamsley et al., 2010). With the projected increase in extreme weather events from global climate change and the rising population at the coast, using vegetation as a natural coastal buffer from wave impact remains an attractive research topic, especially in developing countries with wide coastlines.

In previous research, two common methods for studying waves in wetlands are scaled laboratory experiments with artificial or live vegetation (e.g., Bouma et al., 2005; Augustin et al., 2009; Bouma et al., 2010; Vandenbruwaene et al., 2011; Anderson and Smith, 2014) and numerical simulations (e.g., Huang et al., 2011; Suzuki et al., 2012). Though these studies are efficient in learning the wave height transformation through vegetation coverage and calibrating the drag effect by vegetation, their bathymetric layouts have been relatively simple. Bathymetry in these studies is either constant depth or a plane slope, while in reality wetlands typically consist of vegetated mounds separated by channels.

In addition, no studies have focused on the quantification of vegetation's effect on the wave-induced flow circulation within wetlands. Rip currents are seaward jet flows from the surf zone with relatively higher velocity. They are commonly observed in nearshore regions with varying bathymetry, especially bar–channel systems. The variability in bathymetry induces alongshore variation of wave breaking around the bar–channel system, causing relatively more intense breaking across the bars. The process of wave pump model for rip current (e.g., Nielsen et al., 2001, 2008) by wave breaking raises water to higher level above the bars, compared with water level in the channels. This mechanism results in variations in significant wave height and mean water level distributions, which provides the primary driving force for alongshore flows feeding rip channels (MacMahan et al., 2006; Dalrymple et al., 2011). Rip currents are important processes to transport coastal pollutants, nutrients and sediments seawards, which may also cause erosion to shorelines. Since both natural and constructed wetlands typically consist of mound–channel systems, it is necessary to study the characteristics of rip current potential within these areas. Though similar

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to typical rip current phenomenon in bar–channel bathymetry, the circulation characteristics within discontinuous wetlands tend to be more complex.

Because of the transient nature of rip currents, field studies with stationary instrument deployments suffer from the difficulty in measuring changing bathymetry and flow patterns simultaneously (e.g., Haller et al., 1997; MacMahan et al., 2006). Basin-scale laboratory experiments could provide controlled conditions with better repeatability, but the tradeoff between measurement resolution and instrument interaction may affect the accuracy of the results. In these aspects, numerical simulation has its edge over field and laboratory studies.

Using a basin-scale laboratory experiment and the COULWAVE Boussinesq model with emergent and near-emergent vegetation setups, Augustin et al. (2009) observed that wave height through a continuous rectangular vegetation region decreased more significantly than in the adjacent non-vegetated area. The generated alongshore wave height gradient then attempted to reach equilibrium with energy focusing towards the low wave height area, resulting in locally higher wave height behind the vegetation patch. Bradley and Houser (2009) observed an increase in wave height through a distance of the submerged seagrass in their field experiment. A similar wave height increase could be predicted by the model of Méndez et al. (1999), which incorporated the effect of wave reflection. Bradley and Houser (2009) hypothesized that wave height increase was attributed to the seagrass blades' obstruction acting like a bathymetric step that decreased wavelength and increased wave height through shoaling. Overall, these various phenomena in previous research imply that wave height evolution within vegetation is case-dependent and difficult to predict. This complexity may be further amplified in complex vegetated mound–channel bathymetry. Moreover, the efficiency of vegetation in wave dissipation is dependent on various parameters, such as stem stiffness, density and incident flow conditions (e.g., Bouma et al., 2005; Ondiviela et al., 2014; Paul et al., 2011; Vandenbruwaene et al., 2015), and significant protection against flow impact is not always guaranteed. For instance, according to a literature review by Ondiviela et al. (2014), seagrass does not protect the shoreline in all cases, and the optimal setups are with shallow depth and low-energy wave conditions. Vandenbruwaene et al. (2011) also reports potential flow acceleration within discontinuous vegetation patches.

This paper focuses on a more complicated bathymetric layout with a mound–channel system, whose prototype is Dalehite Cove in Galveston Bay, Texas, US. First, we introduce the laboratory experimental design used for model validation and the numerical model background. Then, model calibration and validation are conducted with experimental data. Third, numerical results of significant wave height, rip current, water level distribution, and swirling strength of the mean flow are analyzed. Finally, two dimensionless relations for these flow phenomena are developed, followed by conclusions.

2. Methodology

2.1. Wetland layout

Truong (2011) and Truong et al. (2014) conducted experiments in a 36.6 × 22.9 × .15 m wave basin in the Haynes Coastal Engineering Laboratory at Texas A&M University, US (Fig. 1). Three concrete conical-frustum mounds with 5.38 m bottom diameter, 2.02 m top diameter and 0.08 m height were constructed in a row 20.55 m from the wavemaker, representing the mounds in Dalehite Cove. The scale factor between the physical model and the prototype was 1:6.5, using Froude scaling based on surveys by HDR Engineering, Inc. in August 2009. The vegetation was represented by 0.016-m diameter and 0.077-m height rigid wooden dowels affixed to the tops of the mounds and two wave conditions. The total stem number was 154, resulting in a stem density with 48 stems/m^2 (Fig. 1 in Truong et al. (2014)). Three distances between mounds' centers ($S = 5.48$ m, 7.02 m and 8.66 m), two water levels (0.50 m and 0.36 m), and two wave conditions (wave height 0.17 m and 0.06 m) were tested in the experiments. An instrument array with 19 capacitance wave gauges and 5 Acoustic Doppler Velocimeters were mounted on a moving bridge to map water surface elevation and induced current along cross-shore regions. Both non-vegetated and vegetated mounds were tested for each setup to study the influence of vegetation. More details about the experimental design are described in Truong (2011) and Truong et al. (2014).

A reference wave gauge was fixed in the offshore region to estimate the repeatability of the incident wave condition. Most experimental trials had approximately 5% variability in the wave gauge measurements. The accuracy of the Nortek Vectrino ADVs used in the experiment was 0.5% of the measured value plus 1 mm/s uncertainty. For the measured current range in the experiments, the total theoretical uncertainty of ADV measurement was within 1%. More details about the experimental data analyses are described in Truong, (2011) and Truong et al. (2014).

2.2. Numerical model theory

In research of wave propagation in shallow and intermediate depth conditions, the Boussinesq-type equations are widely applied in both one- and two-dimensional horizontal applications. In previous studies, Boussinesq modeling was also successfully applied in research of rip current in bar–channel system and jet-like current by bathymetry variability (e.g., Chen et al., 1999, 2000). The numerical model used here, COULWAVE, is originally based on the Boussinesq-type equations in Liu (1994), with several additional terms to consider the effect of bottom friction and wave breaking. This depth-integrated model is applicable to simulation of fully nonlinear and weakly dispersive waves over variable bathymetry (Lynett and Liu, 2002; Lynett et al., 2008). Defining the dimensionless variables as,

$$(x,y)=\frac{(x',y')}{\lambda},\quad z=\frac{z'}{h_o},\quad t=\frac{\sqrt{gh_o}t'}{\lambda},$$
$$h=\frac{h'}{h_o},\quad \zeta=\frac{\zeta'}{a_o},\quad p=\frac{p'}{\rho g a_o},$$
$$(u,v)=\frac{(u',v')}{\varepsilon\sqrt{gh_o}},\quad w=\frac{w'}{\varepsilon/\mu\sqrt{gh_o}},$$

the dimensionless governing equations (continuity and momentum equations) are (Lynett and Liu, 2002):

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

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

where h is the local water depth, ζ is the free surface elevation, $\mathbf{u}_\alpha=(u_\alpha, v_\alpha)$ is the reference horizontal velocity vector at z_a from still water level (Nwogu, 1993; Liu, 1994), R_f is the bottom friction effect, R_b is the wave breaking effect, ε is the ratio between wave amplitude and depth ($\frac{a_o}{h_o}$) for nonlinearity, μ is the ratio between depth and wavelength ($\frac{h_o}{\lambda}$) for frequency dispersion and **H.O.T.** is the higher order nonlinear and dispersive terms in the order of $O(\mu^2)$ (e.g., Lynett et al., 2002; Lynett and Liu, 2002; Lynett et al., 2008; Løvholt et al., 2013).

The influence of vegetation is accounted for within the bottom friction term, $R_f=f\frac{\mathbf{u}_b|\mathbf{u}_b|}{h+\zeta}$, where f is the non-dimensional friction coefficient and $\mathbf{u}_b$ is the horizontal velocity vector at the bed. Such approximation for vegetation is reasonable for bulk roughness, given the difficulty and high computational cost in modeling individual plants in large domains. The higher quadratic bottom friction used to represent vegetation provides more resistance against incident flows, which could slow down wave celerity. In general, f is in the range of 10^{-3} to 10^{-2} for a normal seabed (Lynett et al., 2008). Here, the background