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Numerical model for coastal wave propagation through mild slope zone in the presence of rigid vegetation

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ABSTRACT

The study of wave propagation on coastal vegetation field is fundamental to assessing the effectiveness and limitations of vegetation in coastal protection. This paper presents a refraction–diffraction wave model for the investigation of wave propagation through a coastal mild slope zone in the presence of rigid vegetation via numerical simulation. The model is based on the implementation of a module for vegetation-induced wave energy dissipation in the parabolic mild slope equation. The model is capable of simulating both wave refraction and diffraction and economical in computation and may bridge the gap between the wave energy spectrum and the phase-resolved models for wave propagation through coastal vegetation fields. The model is validated through by comparison with experimental results. The model is subsequently applied to a simulation of a wave propagating on a plane in the presence of different patterns of rigid vegetation. The sensitivity of the wave height to the plant height, the diameter and the stem density is investigated by comparison of the numerical results for wave height attenuation that results from different patterns of rigid vegetation. The numerical results show that wave height attenuation due to rigid vegetation has a higher variability for the different rigid plant conditions and that the attenuation of the wave height due to the rigid vegetation increases alongside the plant height under water as well as the diameter and plant stem density. The results further indicate that for wave propagates through coastal rigid vegetation zones with a high plant height under water, large diameter and high stem density, the wave height along the propagating direction is decreased nonlinearly with the increase of the wave propagating distance, and nonlinearity is more obvious for the plant with a higher height under water as well as a larger diameter and higher stem density.

1. Introduction

The present study of wave propagation on coastal vegetation is essential for understanding the effectiveness and limitations of vegetation that is used for the purpose of protection along the coastline. Many believe that coastal vegetation can regulate water levels, reduce flood and storm damage, improve water quality, provide a natural habitat for coastal wildlife and support recreational activities. Additionally, theories posit that coastal vegetation significantly dissipates incoming wave energy and increases the land's capacity to resist landward propagating flood waves, like a storm surge or other adverse weather events (Anderson and Smith, 2014; Nandasena et al., 2012; Ondiviela et al., 2014; Stijn et al., 2012; Theoharris et al., 2013). Concern about rising sea levels and the durability of coastal revetment and shore line defense engineering has encouraged researched in the mechanisms that dissipate water wave energy in coastal vegetation.

Generally, wave attenuation due to vegetation is caused by energy that is lost through the plants. The degree of wave attenuation depends on both the vegetation's characteristics (plant height, diameter, density, stiffness and the bending of shoots) and the wave parameters (wave height, period and direction), and the quantification of dissipated wave energy on vegetation is difficult to express in a universal form. The results of various studies on wave attenuation due to vegetation contain are largely variable, which confirms the complexity of such system. Numerical modeling studies have recently enlarged our insights about coastal vegetation's mitigating effect on water wave propagation. Different numerical models have been proposed that explain the damping effects of vegetation on waves. The often-used numerical models for water wave propagation on vegetation include the phase-averaged wave energy models, which use wave energy spectrum equations, including SWAN, that account for the effect of vegetation in an energy dissipation term and there are also phase-resolved models that use momentum approach equations, such as Boussinesq or shallow water, that account for vegetation resistance as drag and inertial forces. Chen and Zhao (2012) developed an equation based on the SWAN model for the study of random linear wave transformations on the vegetation zone. Suzuki et al. (2012) simulated the wave dissipation on a vegetation field by implementing the Mendez and Losada formulation (2004) in a full spectrum model SWAN equation. This

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included an extension of vertical layer schematization to assess the sensitivity of the model to the shape of the frequency spectrum, directional spreading and layer schematization. Augustin et al. (2009) simulated irregular wave propagation on flexible vegetation in a shallow water wave basin with the COULWAVE model based on the modified Boussinesq equations, including the effects of vegetation. Huang et al. (2011) studied the solitary wave interaction with emergent, rigid vegetation in a wave flume using the modified Boussinesq equations, including the effects of vegetation. Kobayashi et al. (1993) presented an analytical solution that showed how the monochromatic wave decays exponentially in vegetation, which was based on the shallow water equations for small-amplitude waves. Mei et al. (2011) presented analytical solutions for studying the effects of emergent coastal forests on the propagation of long surface waves of small amplitude based on the shallow water equations. Wu and Marsooli (2012) developed a shallow water model for simulating long waves on vegetation zone under breaking and non-breaking conditions, and the numerical results showed that vegetation along the coastal shoreline has a positive benefit in reducing wave run-up on sloping beaches, whereas vegetation in open channels causes conflicting impacts: reducing inundation in the downstream areas, but increasing flood risk in a certain distance upstream. Tang et al. (2013) developed a model for investigating the effects of damping due to vegetation on solitary water wave run-up, that was based on the nonlinear shallow water equations and its numerical results showed that vegetation can effectively reduce the velocity of solitary wave propagation and that solitary wave run-up is decreased with increases of plant height in water and also diameter and stem density. Ma et al. (2013) developed a non-hydrostatic RANS model to investigate wave propagation through a finite patch of vegetation in the surf zone and its numerical results showed that the presence of a finite patch of vegetation may generate strong pressure-driven nearshore currents, with an onshore mean flow in the unvegetated zone and an offshore return flow in the vegetated zone. Normally, the wave energy spectral models describe variations in wave energy, which are mainly used for the analysis of the wave's refraction, especially in the field far from the wave diffraction. Furthermore, because these models employ relatively coarse computational grids, they are quite efficient in storage and computation and usually used to simulate wave refraction on quite large scales in offshore and coastal zones. The phase-resolved models directly simulate the dynamic wave shape deformations, which are mainly consumed in storage and computation as the grids, are related to the wavelength and period. Because phase-resolved models are fine, they are usually used to simulate wave transformation in coastal zones on scales much smaller than the wave energy spectral models. In the coastal zone, the waves are always in shallow water and undergo an obvious combined transformation of refraction and diffraction due to the coastal topography. The mild slope equation is an effective wave model for describing the variations of the wave amplitude of a wavelength. Compared to the wave energy spectral models, the mild slope equation is capable of simulating both wave refraction and diffraction and is more economical for storage and computation compared to the phase-resolved models. Therefore, it is usually used to simulate wave transformation on relative large scales in coastal zones. However, compared to progress on modeling wave propagation on vegetation, there has been less research on modeling this process through the mild slope equation.

This paper presents a wave-action model that is based on the parabolic mild slope equation for the investigation of the damping effects due to rigid vegetation on a coastal wave propagation. The proposed model is developed through the implementation of a module for vegetation-induced energy dissipation in the parabolic mild slope equation. The module was developed by Dalrymple et al. (1984) and includes rigid vegetation as cylindrical obstacles, which were modified by Mendez and Losada (2004) to enable the estimation of random wave dissipation in vegetation. The present model considers the combined refraction diffraction induced by the coastal bathymetry in the presence of rigid vegetation and its computation is economical. As the often used wave energy spectrum models are mainly used to model wave refraction and phase-resolved models are mainly consumed in computation, the present model may bridge the gap between the wave energy spectrum models and the phase-resolved models for wave propagation through coastal vegetation fields. Before the model is applied, it is first tested to model wave propagation on planes in the presence of vegetation to examine the extent to which it can be applied to quantify wave energy dissipation due to vegetation. Next, the model is applied to investigate wave propagation on planes in the presence of different patterns of rigid vegetation. The sensitivity of coastal wave height to plant height under water, diameter and stem density is investigated in comparison to the numerical results of wave height attenuation due to different patterns of vegetation.

2. Governing equations

The classical mild slope equation developed by Berkhoff (1972) has now been extensively employed in the study of the reflection, refraction and diffraction of water waves in mild slope coastal fields. If a wave propagates in a principal direction, only the forward propagation of the wave is considered and the parabolic mild slope equation can be used to simulate wave refraction and diffraction on a relatively large field in an economical and efficient manner. Because the wave in a coastal vegetation field is usually in shallow water and always undergoes a breaking process, the two basic energy dissipation mechanisms dominate the wave height: dissipation due to vegetation and dissipation due to wave breaking. The dissipation effects can be accounted in the energy dissipation terms of the mild slope equation. When the wave energy damping effects offered by vegetation and breaking are considered, the wave-action model based on the existing minimax approach parabolic mild slope equation (Kirby and Dalrymple, 1994) for random water wave transformation takes the following form:

$$\begin{aligned}&\sum_{n=1}^{N} C_{gn}\frac{\partial A_n}{\partial x}+\sum_{n=1}^{N}\left(\mathrm{i}\left(\overline{k}_n-a_0k_n\right)C_{gn}+\frac{\mathrm{i}}{2}k_n^3C_nD|A_n|^2+\frac{1}{2}\frac{D_{\mathrm{b}}+D_{\mathrm{veg}}}{E}+\frac{1}{2}\frac{\partial C_{gn}}{\partial x}\right)A_n\\&-\sum_{n=1}^{N}\frac{b_1}{\omega_nk_n}\frac{\partial^2}{\partial x\partial y}\left(C_nC_{gn}\frac{\partial A_n}{\partial y}\right)\\&+\sum_{n=1}^{N}\left(\frac{\mathrm{i}}{\omega_n}\left(a_1-b_1\frac{\overline{k_n}}{k_n}\right)+\frac{b_1}{\omega}\left(\frac{(k_n)_x}{k_n{}^2}+\frac{\left(C_{gn}\right)_x}{2k_nC_{gn}}\right)\right)\frac{\partial}{\partial y}\left(C_nC_{gn}\frac{\partial A_n}{\partial y}\right)=0\end{aligned}\tag{1}$$

where N is the number of individual regular wavetrains with random phases that decompose according to the special wave spectra for the initialization, $A_n(x, y)$ is the complex amplitude of the nth wave component in the spectrum, i is the imaginary unit, ω_n is the wave angular frequency for a wave component n and $k_n(x,y)$ is the wave number for the wave component n, which is governed by the nonlinear dispersion relation (Kirby and Dalrymple, 1984):

$$\omega_n^2=gk_n\left(1+f_1(k_nh)\varepsilon^2D\right)\tanh(k_nh+f_2(k_nh)\varepsilon)$$

where $f_1(k_nh)=\tanh^5(k_nh), f_2(k_nh)=(k_nh/\sinh(k_nh))^4$, $\varepsilon=k|A_n|$, $D=(\cosh(4k_nh)+8-2\tanh^2(k_nh))/8\sinh^4(k_nh)$ and h is the still-water depth. This dispersion relation can be used for a wide range of water depths and wave conditions. $\overline{k}_n(x)$ is the average of $k_n(x,y)$ for the wave component n over the y-direction (it is assumed that the wave propagates principally in the x-direction); $C_n=\omega_n/k_n$ the wave velocity for wave component n; $C_{gn}=\partial\omega_n/\partial k_n$ the wave group velocity for the wave component n; a_0, a_1 and b_1 are the coefficients of the rational approximation that is determined by the varying aperture width θ_a. The corresponding coefficient values for $\theta_a=70°$ are: $a_0=0.994733030$, $a_1=-0.890064831$ and $b_1=-0.451640568$ (Kirby