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Numerical modeling of vegetation-induced dissipation using an extended mild-slope equation

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ABSTRACT

This paper presents an incorporation of vegetation-induced wave dissipation in a planar numerical wave propagation model based on the extended mild-slope equation (EMSE). The implementation was incorporated in a purely mathematical method in the light of current theoretical studies. To examine the performance of the phase-resolving model, a comprehensive comparison with phase-averaged SWAN is made to test and validate the implementation. Moreover, new in-situ measurements in a mangrove forest are presented aiming to test the wave energy damping by vegetation using the observed wave spectra. From our validation results it can be concluded that wave dissipation due to vegetation is equally well reproduced in this model. It is found that the wave parameters (wave height and period) and vegetation parameters (plant width, height and density) are all influencing factors. An interesting finding is that relatively high-frequency waves are more dissipated than low frequency waves, especially for larger wave heights. In this study, we found that diffraction is of great significance in wave propagation over inhomogeneously distributed vegetation. Theoretically, the phase resolving EMSE represents the physical process of diffraction better than the phase-averaged model SWAN.

1. Introduction

Aquatic intertidal and supratidal vegetation, such as mangroves, reeds and salt marshes are recognized to be increasingly important in coastal wave attenuation and erosion prevention, due to increased attention to climate change which may result in more frequent, intense ocean storms (Grinsted et al., 2013; Möller et al., 2014). Actually, some natural vegetated coasts have shown to be effective in mitigating ocean born disasters. For instance, mangroves along the coast of west-eastern India have significantly alleviated the disastrous effects of tsunamis (Kathiresan and Rajendran, 2005). Previous research (Jadhav and Chen, 2013; Möller, 2006; Riffe et al., 2011) has proven that vegetation fields are not only valuable landscapes and a part of ecosystems but also act as safeguards against storm surges.

The interaction between water motion and vegetation is a complicated process as represented by strong nonlinear, small scale dynamic features. Previous studies successfully developed basic key features of wave–vegetation interaction (Dalrymple et al., 1984; Dubi and Torum, 1994; Kobayashi et al., 1993; Massel et al., 1999). Common practice during this initial research phase has been to simplify plants as strips with a certain density, semi-empirically estimating the wave dissipation based on the Morison equation. Recently, various experiments have been carried out, demonstrating the attenuation effect of wave by vegetation and determining the drag coefficient from the theoretical equations (Koftis et al., 2013; Sanchez-Gonzalez et al., 2011; Stratigaki et al., 2011a, 2011b; Hu et al., 2014). When it comes to the numerical modeling, Li and Yan (2007) developed a complex three-dimensional numerical model to simulate wave-flow-vegetation interaction, carrying out physical experiments as validation. This model could well represent the velocity variation inside and outside the vegetation canopy. However, wave-breaking was not taken into account even though it is an essential process in the nearshore and intertidal vegetated regions. Additionally, the intensive computational expense in 3-D models based on the Navier–Stokes equation limits the applicable capability of models on relatively large scales. Maza et al. (2013) also studied the hydrodynamic natures of swaying and no swaying submerged vegetation. However, the intense computational cost limits it only for 1-D and experimental cases at present. To resolve this issue, Vo-Luong and Massel (2008) proposed a 1-D model with an original mild-slope equation for wave propagation in mangrove

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forests by linearizing the attenuation factor in terms of wave-trunk interactions (using $F \propto fu$ instead of $F \propto u^2$), in which f is an averaged value. A drawback is that the linearization could limit its application, especially for larger waves. Tang et al. (2015) included the vegetation effect into the parabolic mild slope equation, discussing the influence of different wave conditions and vegetation parameters. Nevertheless, it is a spectral model, very different from EMSE (time-dependent model). Apart from this, the major advantages of using the mild-slope equation based model are not well presented in Tang et al. (2015). Among recent studies, the most applicable one that can be used in practical cases involving large domains is the vegetation version of the SWAN model (Suzuki et al., 2012) using Mendez and Losada's (2004) attenuation expression for irregular waves. The SWAN model has been shown to be capable of simulating wave propagation in shallow water vegetation. Theoretically, a phase-resolving model like EMSE represents physical processes such as diffraction better than the phase-averaged model SWAN.

Compared to 3D models based on the Navier–Stokes equations, the EMSE model has an enormous computational advantage for large-scale applications, and the utilized numerical method alternating direction implicit (referred as ADI) method is unconditionally stable. Compared to the SWAN model, diffraction and wave breaking can theoretically be represented better in the extended mild-slope based model, since it is a phase resolving and time-domain model. Hence, the EMSE model could perform better when the spatial vegetation distribution is non-uniform. This is discussed in detail in Section 5. Compared to the model of Vo-Luong and Massel (2008), the EMSE model avoids the aforementioned linearization in vegetation forcing, exploring the non-linear dissipation nature of wave energy in a time-dependent extended mild slope equation. The implementation of the attenuation factor γ_v, obtained through a theoretical derivation, is one of the focuses in this paper. It provides a computationally efficient solution to predict the decay of wave energy.

Our intension of introducing the vegetation dissipation term into the 2-D time-dependent model (EMSE) is to undertake the non-linear dissipation nature, and to show the advantage of EMSE model in dealing with vegetation. The inspiration to extend the original mild slope equation with dissipation due to vegetation is based on the work by Li (1994). By means of mathematical derivations in the wave energy conservation equation and the governing mild slope equation, a vegetation induced dissipation term γ_v is introduced into the governing equation similar to the energy attenuation by wave breaking or energy growth by wind presented in Stratigaki et al. (2011a, 2011b).

To check and validate our implementation, a comprehensive comparison is made between the EMSE and the SWAN model and validation tests are carried out. Part I of the validation compares the dissipation capability of EMSE with SWAN and theoretical model (Mendez and Losada). Validation II tests the damping effect of EMSE model due to term γ_v in a constant water depth with experimental data from Sanchez-Gonzalez et al. (2011). Validation III uses measured mangrove field data from Vo-Luong and Massel (2008), unraveling the significant roles that wave breaking and shoaling effect play in shallow water. Validation IV applies a new data set acquired in the intertidal mangrove forests of the South China Sea to validate the spectral dissipation in EMSE with observed wave spectra.

To explore whether for instance the better inclusion of diffraction offers advantages over the SWAN model, a theoretical model comparison case was performed in a large coastal domain where vegetation is utilized as coastal protection in a configuration of field patches like detached breakwaters. This case shows that the vegetation fields operate like breakwaters for which diffraction is an essential physical process, resulting in differences between the two models. Whether this would lead to a preference for the EMSE model over the SWAN model remains as yet a theoretical issue, but the fact that these two models perform efficiently in larger domains is an important contribution to the literature.

2. Numerical methods

2.1. Extended mild slope model equation

This section elaborates the mathematical process of incorporating the vegetation dissipation into the mild slope equation associated with the energy conservation equation, in the form of wave energy attenuation. This concept can likewise be found in other studies such as Beels et al. (2010), which discuss the effect of wave energy converters to the wave field in the time-dependent mild-slope equation.

2.1.1. Governing equation

Berkhoff (1972) first proposed the 2-D mild-slope equation in the planar domain. To consider the vegetation dissipation here, the formula of the governing equation is written as follows:

$$\nabla(CC_g \bullet \nabla\Phi) + (n\omega^2 + i\omega\gamma_v - G)\Phi = 0 \tag{1}$$

where Φ is the velocity potential function, c is the phase velocity, c_g is the group velocity, $n = c_g/c$, ω is the angular frequency, γ_v is the dissipation factor due to vegetation and G is the higher order term of bottom slope which is defined as:

$$G = g_1(kh)\nabla^2 h + g_2(kh)(\nabla h)^2 \tag{2}$$

Both g_1 and g_2 have complicated expressions according to Chamberlain and Porter (1995).

2.1.2. Derivation of γ_v

To solve Eq. (1), it is first necessary to obtain the expression of γ_v. This section is the mathematical deduction to obtain the formula of damping factor γ_v in the governing equation. The wave velocity potential becomes as follows:

$$\Phi = -\frac{igA}{\omega} e^{i\psi} \tag{3}$$

where A is the amplitude of wave and ψ is the phase function. Accordingly it is obvious that

$$\vec{K} = \nabla\psi = (\vec{k}_x, \vec{k}_y) \tag{4}$$

in which $\vec{k}_x$, $\vec{k}_y$ denote the wave number in the x direction and y direction (x direction is the major wave direction) respectively. Substitute Eq. (3) into Eq. (1) and reject the high order term G to facilitate writing. Eq. (1) is explicitly transformed to

$$CC_g\left[\nabla^2 A - A\vec{K}^2 + \frac{\nabla A \bullet \nabla CC_g}{CC_g} + k^2 A\right] + i\left[A\left(\frac{\vec{K} \bullet \nabla CC_g}{CC_g} + \nabla \bullet \vec{K} + \frac{k^2\gamma_v}{n\omega}\right) + 2\nabla A \bullet \vec{K}\right] = 0 \tag{5}$$

In Eq. (5), the real and imaginary parts must not be separated: they are both equal to zero; hence deriving the so-called eikonal equation and wave-action equation as follows:

$$\vec{K}^2 = k^2 + \frac{\nabla^2 A}{A} + \frac{\nabla A \bullet \nabla CC_g}{A \bullet CC_g} \tag{6}$$

and

$$2\nabla A \bullet \vec{K} + A\left(\frac{\vec{K} \bullet \nabla CC_g}{CC_g} + \nabla \bullet \vec{K} + \frac{k^2\gamma_v}{n\omega}\right) = 0 \tag{7}$$