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Numerical simulations of wave propagation over a vegetated platform

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ABSTRACT

Vegetated platforms have been constructed in recent years for the purpose of shore protection. This paper addresses some fundamental questions concerning the vegetated platform: (1) What is the difference in wave attenuation between a vegetated platform and a simple platform, and how much can vegetation increase the efficiency of reducing wave transmission? (2) Are there any differences between the effects of stems and roots on wave attenuation? (3) Does vegetation always reduce wave transmission? (4) Is it possible to develop an empirical formula for estimating the wave transmission of a vegetated platform? To answer the above questions, a numerical model solving the Navier–Stokes equations for wave propagation over a vegetated platform is established and validated by several existing laboratory experiments. A total of 244 numerical experiments based on this model have been carried out. The simulated results suggest that the platform plays a major role and the vegetation plays a supporting role in reducing wave transmission except for some special cases. Stems tend to have a larger influence than roots in reducing wave transmission with the same height. The roots always help reduce wave transmission, while the stems may increase wave transmission when the platform width is in the range of 37.5–62.5% of the incident wavelength. Based on our numerical experiments and existing laboratory data, the paper proposes a simple formula for predicting the wave transmission coefficient of a vegetated platform for engineering applications.

1. Introduction

Recently, the interest in wave attenuation by vegetation has increased as coastal engineers search for sustainable solutions to mitigate the impacts of climate change and natural hazards (e.g., Augustin et al., 2009; Chen and Zhao, 2012; Nepf, 2012; Wu et al., 2012; Jadhav et al., 2013; Ma et al., 2013; Maza et al., 2013; Zhan et al., 2014; Anderson and Smith, 2014; Hu et al., 2014; Liu et al., 2015; Zhu and Chen, 2015; Mattis et al., 2015; Maza et al., 2015). Depending on the location of vegetation in the water column and the vegetation height relative to the water depth, coastal vegetation is usually classified as submerged, emergent, and suspended vegetation (e.g., Plew, 2010; Huai et al., 2012). Suspended vegetation is porous media and suspends downwardly from the free surface to some distance above the bottom boundary, which is a reverse of submerged vegetation. However, the influences of submerged and suspended vegetation on the flow field are completely different. The major difference between the suspended vegetation and submerged vegetation is the influence of bottom boundary layer beneath the suspended vegetation (Plew, 2010). The influence of suspended vegetation on ecosystems is complicated. In many places of the world, exotic suspended species are a severe problem, as invasive floating vegetation may completely cover the water surface, absorb oxygen and solar radiation, and block irrigation channels and hamper navigation (Huai et al., 2012). However, some suspended vegetation is a rich source of biogas, and some can be utilized to absorb organic material and heavy metals. Species with relatively rigid stems can also be utilized to reduce wind wave energy for shore protection.

Numerous laboratory experiments on wave attenuation by different submerged and emergent vegetation models have been carried out, including rigid and flexible cylindrical dowels (e.g., Augustin et al., 2009; Anderson and Smith, 2014), artificial vegetation with rigid stems (e.g., Nepf, 1999; Wu et al., 2011) and flexible plants (e.g., Ghisalberti and Nepf, 2006; Blackmar et al., 2014), and real vegetation (e.g., Wu et al., 2011). However, there are few experiments that consider suspended vegetation with surface waves. Plew (2010) conducted laboratory experiments that explored aspects of the flow through suspended canopies constructed from rigid cylinders. The experiment provided details on the flow structure that may be vertically divided into a bottom boundary layer, a canopy shear layer, and an internal canopy layer. Later, Huai et al. (2012) presented a simple three-layer analytical model for open channel flow through suspended rigid vegetation with various heights and showed good agreement with the experimental data in Plew (2010). Wang et al. (2014) successfully used the hydrostatic finite

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volume coastal ocean model (FVCOM) to simulate the flow around suspended rigid vegetation by introducing momentum sink terms into the governing equations. So far, few researchers have used the Navier–Stokes model to simulate the flow through suspended vegetation.

Free-surface breakwaters have generated a great deal of interest in the coastal and ocean engineering community for a long time. Compared with rubble-mound breakwaters, free-surface breakwaters have several advantages: (1) low construction cost; (2) applicability for poor soil foundation and complex bathymetry; (3) less interference to the ecosystem; and (4) easy relocation and recyclability (e.g., McCartney, 1985; Dong et al., 2008). Floating plate is a classical type of free-surface breakwater, which has proved useful in reducing wave transmission (e.g., Patarapanich and Cheong, 1989; Neelamani and Reddy, 1992; Neelamani and Gayathri, 2006; Dong et al., 2008; Zidan et al., 2012; Koraim, 2013; Acanal et al., 2013). To have sufficient wave height reduction by a floating plate-type breakwater, the structure is usually designed to be a long thin plate or a large box.

Recently, a new type of breakwater has attracted researchers' attention, which is composed of three parts: platform, vegetation stems, and vegetation roots. It has been built in the Mississippi River Delta, USA (Fig. 1). This vegetated platform is a sustainable green infrastructure product designed for shore protection and marsh restoration in estuaries. It also provides wild life with spawning habitat and is attractive to human for recreation. The vegetated platform is similar to a suspended wetland. It operates in the upper part of the water column where most of the wave energy is concentrated, which thus reduces the wave transmission and protects the shoreline just as a surface breakwater does. Although vegetated platforms have been put into engineering practice, few studies on this type of breakwater exist to the best knowledge of the authors. This paper is aimed at filling the knowledge gap by investigating the efficiency of vegetated platform in wave energy reduction, and addressing the following questions: (1) Are there any differences between a vegetated platform and a simple platform in terms of wave attenuation? How efficient is suspended vegetation in wave attenuation? (2) Do the stems and roots of suspended vegetation have the same effects on wave transmission? (3) Does the vegetation always reduce the transmitted wave height? (4) As empirical formulas have already been used to estimate the wave transmission in the condition of a simple, non-vegetated platform, would it be possible to extend them to vegetated platforms?

Vegetated platforms can protect a shoreline from erosion by reducing the wave impact. Yet investigation on this critical role of vegetation on the platform is scarce at present, and a means for reliably determining wave height reduction by a vegetated platform in engineering practice is not yet available. The objective of this paper is to employ the re-normalization group (RNG) k–ε turbulence model and the volume of fluid (VOF) method based on the Navier–Stokes solver in the computational fluid dynamics (CFD) code, FLUENT, to simulate wave propagation over a vegetated platform. This paper is organized as follows. Section 2 presents a description of the methodology used in this paper focusing on the momentum sink term. Section 3 assesses the applicability of the proposed model thoroughly by comparing the numerical results with laboratory data. In Section 4, we simulate a total of 244 cases of diverse vegetated platforms with various parameters using the validated CFD model. In Section 5, we propose an empirical formula for determining the wave transmission coefficient for a given vegetated platform. Finally, Section 6 summarizes the findings with several conclusions.

2. Numerical model

In this section, the governing equations and numerical wave tank used to establish the vertically two-dimensional (2-D) numerical model for wave propagation over vegetated platforms are presented. This model is based on the CFD code FLUENT, which uses the finite volume method to solve the Navier–Stokes equations. To enhance the capability of FLUENT, user-defined functions written in C programming language have been employed to build the numerical wave tank and consider the resistance force induced by vegetation. In the wave tank, the reflected waves from the working zone can be eliminated by the relaxation method to make sure the wave generation is stable. Further information about the relaxation method can be found in Engsig-Karup (2006) and Afshar (2010). The model has been validated by Zhan et al. (2014) for free-surface flows through submerged and emergent vegetation. Therefore, this paper is focused on its applicability to flows through suspended vegetation. For details about the VOF method and other parameter settings, the reader is referred to Zhan et al. (2014).

The paper uses the Reynolds-averaged Navier–Stokes (RANS) equations and RNG k–ε turbulence model to simulate the flow of an incompressible viscous fluid. Additional source terms for the drag force caused by suspended vegetation are added into the momentum equations and turbulence models. The VOF method is utilized to capture the fluctuating water surface.

2.1. Continuity and momentum equations

For completeness, the governing equations, including the drag forces induced by vegetation, are briefly described as follows:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i)=0m, i=1,2 \qquad (1)$$

Fig. 1. Vegetated platforms in Mississippi River Delta (photo credit: Martin Ecosystems).