Ocean Engineering 75 (2014) 138–147

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

A 3-D model for irregular wave propagation over partly vegetated waters

Jie-Min Zhan [a,*], Ling-Hui Yu [a], Chi-Wai Li [b], Yok-Sheung Li [b], Quan Zhou [a], Yi Han [a]

[a] Department of Applied Mechanics and Engineering, SunYat Sen University, Guangzhou 510275, China
[b] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong, China

ARTICLE INFO

Article history:
Received 8 September 2011
Accepted 2 November 2013
Available online 5 December 2013

Keywords:
Irregular waves
Vegetated waters
VOF method
RNG k–ε turbulence model
Wave attenuation

ABSTRACT

A 3-D model for irregular wave propagation over partly vegetated waters is established using the Navier–Stokes equations with the RNG k–ε turbulence model and VOF method to capture the free surface. The model is based on FLUENT and utilizes User-Defined Functions (UDF). The applicability of the proposed model is assessed thoroughly by test cases of open channel flow through vegetation, flow in a partly vegetated open channel, uni-directional irregular wave propagation over waters with vegetation and multi-directional irregular wave refraction and diffraction over an elliptic shoal. The computed results agree well with the experimental data. Finally, the case of multi-directional irregular wave propagation over partly vegetated waters is simulated to show the effect of a vegetated zone on the wave characteristics.

© 2013 Elsevier Ltd. All rights reserved.

1. Introduction

Vegetation plays a key role in the sustainable development of aquatic environment and coastal engineering. It provides habitat and food to various species of aquatic animals. Vegetation also reduces the flow velocity, dissipates wave energy and enhances deposition of sediment, offering protection to shoreline and riverbed from flood and wave attack (Bouma et al., 2005).

In recent years, wave attenuation by vegetation has become a popular topic in coastal engineering. An analysis was carried out by Kobayashi et al. (1993), which was based on the solution of the continuity and the linearized momentum equations in two-dimensions. Laboratory experiments on waves over vegetation were carried out by Dubi (1995), Möller et al. (1996), and Augustin et al. (2009). Li and Yan (2007) studied numerically the effects of regular waves and currents on flow through vegetation. Li and Zhang (2010) proposed a three-dimensional model for pollutant mixing in a vegetation field under waves. Suzuki et al. (2008) investigated wave dissipation in a vegetated salt marsh by a numerical model incorporating the effect of vegetation. A vegetation model in terms of porosity and permeability was coupled with a VOF model and verified by comparison to a physical flume experiment. However, only uni-directional irregular wave was considered in the previous studies. In reality, waves in nature do not just propagate in one direction, but are usually multi-directional. Furthermore, the bed of a water body generally is partly, rather than fully, covered by vegetation. Therefore, the transverse momentum transfer at the interface between vegetated and non-vegetated regions becomes very significant and the resulting flow structure is three-dimensional. The Reynolds stresses, $-\rho\overline{u'v'}$ and $-\rho\overline{u'w'}$(ρ is density of fluid, u', v', w' are the fluctuating velocity components in x, y, z directions, respectively), then become one of the major factors determining the flow structure (Nezu and Onitsuka, 2001; White and Nepf, 2007). These factors are of great practical significance in the study of propagation of irregular waves over partly vegetated water bodies.

The mathematical models used to simulate water waves could be the Laplace equation based on potential flow, mild slope equation for wave refraction and diffraction, Boussinesq type equations and Navier–Stokes equations. One of the major difficulties encountered in using the Navier–Stokes equations is the description of the evolution of the free surface. Several methods have been developed and applied in wave simulations, which can also be used to tackle this problem, including the Marker And Cell (MAC) method (Huang et al., 1998), Level Set method (Iafrati et al., 2001; Yue et al., 2003) and Smoothed Particle Hydrodynamics (SPH) method (Gotoh et al., 2004; Shao, 2006). The Volume of Fluid (VOF) method was introduced by Hirt and Nichols (1981) through the SOLAVOF algorithm. Since VOF method represents the free surface in a relatively simple and accurate way, it is widely utilized to solve viscous flow problems with moving free surface including wave problems.

The relatively accurate modeling of turbulence effect is the advantage of using the Navier–Stokes equations. Lemos (1992)

* Corresponding author. Tel./fax: +8620 84111130.
E-mail address: cejmzhan@gmail.com (J.-M. Zhan).

0029-8018/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.oceaneng.2013.11.005

developed a numerical model that solved the Reynolds Averaged Navier–Stokes (RANS) equations for the mean flow using the standard k–ε model for the turbulence field. Lin and Liu (1998) carried out a detailed investigation and evaluation of breaking wave kinematics and turbulence in the surf zone based on the RANS equations coupled with an improved k–ε model using the nonlinear algebraic Reynolds stress closure assumption. Christensen and Deigaard (2001) discussed the computed results of 3D breaking waves obtained by solving the Navier–Stokes equations using the Large Eddy Simulation (LES) method. Utilizing the computer software, FLOW-3D, the k–ε model, RNG model and LES method were tested using the case of solitary wave propagation in Choi et al. (2008). Zhan et al. (2010) established a numerical wave tank using the Navier–Stokes equations and the VOF method. Three turbulence models, the standard k–ε, realizable k–ε and RNG k–ε were incorporated. An effective numerical method for wave absorption in the outflow boundary employing the porous media concept was also proposed.

In this study, the RNG k–ε turbulence closure model and the VOF method to capture the free surface are employed, which are available in the CFD code, FLUENT. Vegetation is modeled as a source term in the momentum equations. The applicability of the proposed model is assessed thoroughly by four test cases of open channel flow through vegetation, flow in a partly vegetated open channel, uni-directional irregular wave propagation over waters with vegetation and multi-directional irregular wave refraction and diffraction over an elliptic shoal. Finally, the case of multi-directional irregular wave propagation over partly vegetated waters is simulated to show the effect of a vegetated zone on the wave characteristics.

2. Numerical model

In this section the governing equations and boundary conditions used to establish the 3-D numerical model for irregular wave propagation over vegetated water are presented. This model was based on the commercial code FLUENT, with the finite volume approach to solve the governing differential equations. User-Defined Functions written in C programming language, which can enhance the capability of FLUENT, were used to implement the multi-directional irregular wave boundary condition, porous wave absorber and the resistance force induced by vegetation.

2.1. Governing equations

The RANS equations and RNG $k-\varepsilon$ turbulence model are used to simulate the flow of an incompressible, viscous fluid. Additional source terms for the drag force and turbulent kinetic energy due to vegetation are included in the equations. VOF method is adopted to capture the fluctuating water surface.

2.1.1. Continuity and momentum equation

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i)=0 \quad i=1,2,3 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u_i)+\frac{\partial}{\partial x_j}(\rho u_i u_j)=-\frac{\partial p}{\partial x_i}+\rho g_i+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\rho\overline{u_i^{'}u_j^{'}}\right]-F_i \tag{2}$$

$$-\rho\overline{u_i^{'}u_j^{'}}=\mu_t\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}\rho k\delta_{ij} \tag{3}$$

where u_i and $u_i^{'}$ are the mean and fluctuating velocity components, ρ is density of fluid, p is the static pressure, g_i is the ith component of the gravitational acceleration, μ and μ_t are the molecular and turbulent viscosities respectively, δ_{ij} is Kronecker delta, $-\rho\overline{u'_i u'_j}$ is Reynolds stress, which represents the effects of the turbulent flow on the mean flow field. $k=(1/2)\overline{u_i^{'}u_i^{'}}$ is the turbulent kinetic energy and F_i is the resistance force induced by vegetation. Considering a single stem, the force f_i per unit depth is given by Morison et al. (1950):

$$f_i=f_{Di}+f_{Ii}=\frac{1}{2}\rho C_D b_v u_i\sqrt{u_j u_j}+\rho C_M b_v t_v\frac{\partial u_i}{\partial t} \tag{4}$$

where f_{Di} is the drag force, f_{Ii} the inertia force, b_v the width of stem, t_v the thickness of stem, C_D the drag coefficient and C_M the inertia coefficient. In the present study, either the flow without wave, or plants assuming no thickness (as artificial kelp) in the wave cases, the last term is ignored. The average force per unit volume within the vegetation zone is given by Li and Zhang (2010)

$$F_i=Nf_i=\frac{1}{2}N\rho C_D b_v u_i\sqrt{u_j u_j}+N\rho C_M b_v t_v\frac{\partial u_i}{\partial t} \quad i=1,2,3 \tag{5}$$

where N is number of stems per unit area, unit in $1/m^2$.

2.1.2. Turbulence model

To appropriately model the Reynolds stress, the RNG $k-\varepsilon$ model which is based on renormalization-group methods is employed. The turbulence kinetic energy k and its rate of dissipation ε are obtained from the following transport equations:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_j}(u_j\rho k)=\frac{\partial}{\partial x_j}\left(\alpha_k\mu_{eff}\frac{\partial k}{\partial x_j}\right)+G_k+G_b-\rho\varepsilon-Y_M+C_{fk}F_i u_i \tag{6}$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_j}(u_j\rho\varepsilon)=\frac{\partial}{\partial x_j}\left(\alpha_\varepsilon\mu_{eff}\frac{\partial\varepsilon}{\partial x_j}\right)+C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{1\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}-R_\varepsilon+C_{1\varepsilon}\frac{\varepsilon}{k}C_{fk}F_i u_i \tag{7}$$

$$\mu_t=\rho C_\mu\frac{k^2}{\varepsilon},\ G_k=\mu_t\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j} \tag{8}$$

where G_k represents the generation of turbulent kinetic energy due to the mean velocity gradients, G_b is the generation of turbulent kinetic energy due to buoyancy. Since the present simulations do not involve temperature gradients, therefore this term is omitted in the simulations. Y_M is the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate. As the flow is assumed incompressible, this term is again omitted in the present model. α_k and α_ε are the inverse effective Prandtl numbers, $C_{1\varepsilon}=1.42$ and $C_{2\varepsilon}=1.68$ are the empirical constants and μ_{eff} is the effective viscosity. The main difference between the RNG and standard $k-\varepsilon$ model is the additional term R_ε in the ε equation, which makes the performance of the RNG model superior for certain classes of flows. The detailed description of this model can be found in Yakhot and Orszag (1986).

$C_{fk}F_i u_i$ and $C_{1\varepsilon}(\varepsilon/k)C_{fk}F_i u_i$ are source terms in the k and ε equations, respectively due to vegetation resistance, which are given by Lopez and Garcia (1997). In this study C_{fk}=0.05 as used by Neary (2003).

2.1.3. Volume of fluid method

The free surface is captured by the VOF method. The volume fraction function F_q is defined as the ratio of the volume occupied by the qth phase in a cell to the total volume of the cell. In the present study, there are only two phases, air and water. If $0<F_q<1$, the cell contains the interface between air and water. F_q is determined by:

$$\frac{\partial F_q}{\partial t}+\frac{\partial}{\partial x_i}(F_q u_i)=0 \quad q=1,2 \tag{9a}$$

$$F_1+F_2=1 \tag{9b}$$

Download English Version:

https://daneshyari.com/en/article/1725875

Download Persian Version:

https://daneshyari.com/article/1725875

Daneshyari.com