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A depth-averaged two dimensional shallow water model to simulate flow-rigid vegetation interactions

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Abstract

This paper presents a well-balanced depth-averaged 2D shallow water model for simulating flow-rigid vegetation interactions. The rigid vegetation is modeled as vertical cylinders. A formula of drag force induced by the rigid vegetation is included in the momentum equations as a sink term. Since the bed friction and drag force terms have similar expressions, they are incorporated to be discretized using a splitting implicit scheme which can avoid an exaggerated force when the water depth becomes weak. Limiting value of the incorporated resistance term is derived to ensure stability. The proposed scheme is solved in a finite volume Godunov-type framework based on rectangular mesh with the HLLC approximate Riemann solver to discretize the convection part of equations, while a finite difference method is used to discretize the remaining terms. The MUSCL method is employed to achieve second-order accuracy in space and the second-order accuracy in time is obtained by applying the Runge-Kutta method. The model is tested against measured laboratory experimental data of the interaction of solitary waves with emergent, rigid vegetation. The computed results show good agreement with the experimental data.

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Keywords: 2D shallow water model; rigid vegetation; drag force; splitting implicit scheme; Godunov-type framework; HLLC approximate Riemann solver;

1. Introduction

Aquatic vegetation growing in open channels, floodplains and coast is of great importance for biological and physical processes in river and coastal systems. The significant impact of aquatic vegetation is to increase bed

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roughness, reduce flow velocity and capacity within the vegetation [1-3]. Thus, vegetation plays an important role in regulating water level, making the shoreline stable and mitigating the fluvial flood risk. In recent years, a considerable number of research efforts have been devoted to study the flow-vegetation interactions including laboratory experiments, field measurements, analytical solutions and numerical models.

Klopstra *et al*. [4] proposed a new analytical model for hydraulic roughness with submerged vegetation by dividing the water body for open channel flow into vegetation layer and surface free water layer. Turbulent shear stress was described by the eddy viscosity model of Boussinesp in the vegetation layer, and a logarithmic velocity profile was presented in surface free water layer. Huthoff *et al*. [5] developed an analytical solution of the depth-averaged flow velocity in presence of the submerged rigid cylindrical vegetation based on the two-layer method: vegetation layer and surface free water layer. A three- layer model for the vertical velocity profile with submerged rigid vegetation in open channel flow was proposed by Huai *et al*. [6], where the flow body was distributed into an upper non-vegetated layer, an outer layer and a bottom layer within vegetation. Liu *et al*. [7] proposed an analytical solution for vertical velocity profiles in flows with submerged shrub-like vegetation adopting the momentum theorem and the mixing-length turbulence model. A large number of numerical models have been developed to model flow-vegetation interactions. The commonly used numerical approaches include Boussinesp wave equations [8-10], Navier-Stokes equations and 2D shallow water equations [13-15]. In these models, the rigid vegetation is modelled as vertical cylinders, and the drag force caused by that similar to that for flow around cylinders is included in the momentum equations as a sink term. The drag force is usually discretized using the fully explicit scheme which makes the numerical model less stable, especially with the very shallow water and wet/dry fronts. Wu *et al*. [15] proposed a semi-implicit scheme discretizing the bed friction and drag force terms.

In this paper, a well-balanced depth-averaged 2D shallow water model, which are based on the conservation laws of mass and momentum, is presented to simulate the flow-rigid vegetation interactions over complex domains involving wetting and drying. The bed friction and drag force terms are incorporated to be discretized using a splitting implicit scheme. The HLLC approximate Riemann solver is adopted to evaluate the convection flux terms. This model has second order accuracy both in space and time by applying the MUSCL and Runge-Kutta methods.

2. The mathematical formulation

Liang and Borthwick [16] derived a set of pre-balanced shallow water equations which can automatically preserve the steady state of motionless water surface for wet-bed applications. Considering the effects of vegetation, the model can be expressed as

$$\frac{\partial \mathbf{q}}{\partial t} + \frac{\partial \mathbf{f}}{\partial x} + \frac{\partial \mathbf{g}}{\partial y} = \mathbf{S} \tag{1}$$

where

$$\mathbf{q} = \begin{bmatrix} \eta \\ q_x \\ q_y \end{bmatrix}, \quad \mathbf{f} = \begin{bmatrix} q_x \\ q_x^{\,2}/h + \frac{1}{2}g(\eta^2 - 2\eta z_b) \\ q_y \end{bmatrix}, \quad \mathbf{g} = \begin{bmatrix} q_y \\ q_x \\ q_y^{\,2}/h + \frac{1}{2}g(\eta^2 - 2\eta z_b) \end{bmatrix},$$
$$\mathbf{s} = \begin{bmatrix} 0 \\ -\frac{\tau_{bx}}{\rho} - g\eta\frac{\partial z_b}{\partial x} - \frac{1}{\rho}F_x - S_x^{tur} \\ -\frac{\tau_{by}}{\rho} - g\eta\frac{\partial z_b}{\partial y} - \frac{1}{\rho}F_y - S_y^{tur} \end{bmatrix} \tag{2}$$

in which η =the water level; q_x, q_y =the unit width depth integrated discharges in the *x*, *y* directions respectively;