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Numerical simulation of flow and bed morphology in the case of dam break floods with vegetation effect*

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Abstract: The purpose of this study is to establish a depth-averaged 2-D hydrodynamic and sediment transport model for the dam-break flows with vegetation effect. The generalized shallow water equations are solved using an explicit finite volume method with unstructured quadtree rectangular grid, and in the hydrodynamic model, a Harten-Lax-Van Leer (HLL) approximate Riemann solver is used to calculate the intercell flux for capturing the dry-to-wet moving boundary. The sediment transport and bed variation equations in a coupled fashion are calculated by including the bed variation and the variable flow density in the flow continuity and momentum equations. The drag force of vegetation is modeled as the sink terms in the momentum equations. The developed model is tested against lab experiments of the dam-break flows over a fix bed and a movable bed in vegetated and non-vegetated channels. The results are compared with experimental data, and good agreement is obtained. It is shown that the reduced velocity under vegetated conditions leads to a decrease of the peak discharge and a rise of the water level of rivers and also an enhancement of the sediment deposition.

Key words: finite volume method, Harten-Lax-Van Leer (HLL) approximate Riemann solver, sediment transport, vegetation effect

Introduction

Vegetations, such as grasses, shrubs and mangroves, frequently grow in watercourses, floodplains and places near coastal waters. Vegetations can help to regulate the water levels, increase the bank stability, restore or improve the cleanliness of the water, provide important fish and wildlife habitats, and support recreational activities. On the other hand, the vegetations on the floodplain can maximize the flood risk by minimizing conveyance and increase obstruction to the movement of water in the channel[1]. Due to the favorable impacts on the environment, riparian/littoral vegetation zones or wetlands have been constructed for the purpose of river restoration and ecosystem management. Flooding waves frequently occur in areas near rivers, reservoirs and lakes and generate serious damages owing to heavy rain or dam break. Recent years, the effective and efficient numerical models were developed for understanding the flooding wave propagation in urban areas, complex open channels and overland flow systems. In order to solve the 2-D shallow water equations, a recent trend is to use the finite volume method (FVM) due to the simplicity of implementation, combined with the good flexibility for space discretization[2-4]. Because the dam-break flows are usually in mixed flow regimes and with discontinuities, the often used numerical schemes are the shock-capture schemes, such as total variation diminishing (TVD) schemes, Godunov type schemes[3-5]. During such a flooding hazard involving rapid transients, the interaction between the flow and the bed can

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be significant. It is often necessary to account for the process of morphological changes when simulating such severe dam break flows. In early numerical models for simulating dam break flows over mobile beds, uncoupled solutions were often adopted, without accounting for the effects of the sediment transport and the bed deformation on the movement of the flow. One of the problems in movable-bed modeling is that under the dam-break flow conditions the sediment concentration is so high and the bed varies so rapidly that their effects on the flow cannot be ignored. To predict correctly the consequences of a dam failure in a complex topography, the interaction between the flow and the bed morphology must be considered in modeling, several models for simulating dam break flows over mobile beds based on the coupled solutions were developed[6-9]. The flows through rigid and flexible vegetations are primarily studied in vegetated open channels, for the turbulence structure and the related transport processes in vegetated environments[10,11].

How to estimate and mitigate the risk of the inundation in a vegetated area is a crucial question. Although increasing efforts have been devoted to investigate the characteristics of the vegetation-flow, our understanding of the underlying flood wave-vegetation-sediment interactions is still very limited. In the present study, a depth-averaged 2-D hydrodynamic and sediment transport model is developed to simulate the flooding waves without and with vegetation based on the finite volume method. The quadtree mesh with the local refinement technique is used for improving the simulation accuracy. The proposed model is used to calculate the dam-break flows over a mobile bed with and without vegetation, and then it is verified against measured data.

1. Numerical model

1.1 *2-D hydrodynamic, sediment transport equations*

The numerical model consists of the 2-D shallow water equations describing the mass, the momentum and the sediment transport. The generalized 2-D shallow water equations are as follow

$$\boldsymbol{U}_t + \boldsymbol{F}_x + \boldsymbol{F}_y = \boldsymbol{S} \tag{1}$$

where $\boldsymbol{U}_t$, $\boldsymbol{F}_x$, $\boldsymbol{F}_y$ and $\boldsymbol{S}$ in Eq.(1) are the vectors of the conserved variables, the fluxes and the source terms, respectively, defined as follows:

$$\boldsymbol{U} = \begin{bmatrix} h \\ hu \\ hv \\ hC_t \end{bmatrix}, \quad \boldsymbol{F}_x = \begin{bmatrix} hu \\ huu \\ huv \\ huC_t \end{bmatrix}, \quad \boldsymbol{F}_y = \begin{bmatrix} hv \\ huv \\ hvv \\ hvC_t \end{bmatrix},$$

$$\boldsymbol{S} = \begin{bmatrix} \dfrac{\rho_b}{\rho}\dfrac{E-D}{1-p'} \\ -gh\dfrac{\partial z}{\partial x} - n^2 u\sqrt{u^2+v^2}\,h^{-1/3} - \dfrac{gh^2}{2\rho}\dfrac{\partial \rho}{\partial x} - f_x \\ -gh\dfrac{\partial z}{\partial y} - n^2 v\sqrt{u^2+v^2}\,h^{-1/3} - \dfrac{gh^2}{2\rho}\dfrac{\partial \rho}{\partial y} - f_y \\ E-D \end{bmatrix} \tag{2}$$

where t is the time, h is the flow depth, z is the water level, u and v are x and y components of the depth-averaged velocity, respectively. n is the Manning roughness coefficient, g is the gravitational acceleration, ρ is the density of the water and sediment mixture in the water column, determined by $\rho = \rho_w(1-C_t) + \rho_s C_t$, C_t is the volumetric concentration of the total-load sediment, dimensionless, ρ_b is the density of the water and sediment mixture in the bed surface layer, determined by $\rho_b = \rho_s(1-p') + \rho_w p'$, p' is the porosity of the bed material, ρ_w and ρ_s are the water and sediment densities, respectively. E and D are the sediment entrainment and deposition fluxes, respectively.

The sediment entrainment and deposition are estimated as[12]

$$E = \alpha \omega_s c_b \tag{3}$$

$$D = \alpha \omega_s c \tag{4}$$

where α is an empirical coefficient, ω_s is the settling velocity of the sediment particle, ν is the kinematic viscosity, d is the sediment diameter, and c_b is the depth-averaged sediment transport capacity.

The bed deformation can be determined by

$$(1-p')\frac{\partial z_b}{\partial t} = D - E \tag{5}$$

where z_b is the bed surface elevation above a reference datum.

1.2 *Resistance due to vegetation*

The effect of the vegetation on the flow can be simulated by an internal source of the resistant force per unit fluid mass added into the momentum equations, the drag force exerted on the vegetation per unit volume can be expressed as[11]

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