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Shallow sediment transport flow computation using time-varying sediment adaptation length

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Abstract

Based on the common approach, the adaptation length in sediment transport is normally estimated astemporally independent. However, this approach might not be theoretically justified as the process of reaching the sediment transport equilibrium stage is affected by the flow conditions in time, especially for fast moving flows, such as scour-hole developing flows. In this study, the two-dimensional (2D) shallow water formulation together with a sediment continuity-concentration (SCC) model were applied to flow with mobile sediment boundary. A time-varying approach was proposed to determine the sediment transport adaptation length to simulate the sediment erosion-deposition rate. The proposed computational model was based on the Finite Volume (FV) method. The Monotone Upwind Scheme of Conservative Laws (MUSCL)-Hancock scheme was used with the Harten Lax van Leer-contact (HLLC) approximate Riemann solver to discretize the FV model. In the flow applications of this paper, a highly discontinuous dam-break, fast sediment transport flow was used to calibrate the proposed time-varying sediment adaptation length model. Then the calibrated model was further applied to two separate experimental sediment transport flow applications documented in the literature, i.e. a highly concentrated sediment transport flow in a wide alluvial channel and a sediment aggradation flow. Good agreement with the experimental data were obtained with the proposed model simulations. The tests prove that the proposed model, which was calibrated by the discontinuous dam-break bed scouring flow, also performed well to represent rapid bed change and steady sediment mobility conditions.

Key Words: Finite volume model, Harten Lax van Leer-contact solver, Monotonic upwind scheme, Sediment transport, Shallow water model, Time-varying sediment adaptation length

1 Introduction

Different numerical models have been proposed to simulate the sediment laden flows in various applications (e.g. Chen et al., 2007; Wu and Wang, 2007; Lin and Wang, 2006; Chen et al., 2011; Huai et al., 2011; and Lin et al., 2011). The sediment continuity (SC) model is one of the most common sediment transport models, which only considers the movement of sediment bed load capacity; hence it is also sometimes referred as the capacity model (Capart and Young, 1998). This model utilises the sediment volumetric transport rate to determine the sediment load and thus the bed elevations with regard to the temporal and spatial changes. In the more recent developments of the SC model, the non-equilibrium conditions caused by the bed load transient lag (Singh et al., 2004) and the higher order time-iteration accuracy in the alluvial flow simulation (Garcia-Martinez et al., 2006) were investigated. However, since the SC model only considers the sediment continuity equation, it could not be used to accurately represent the sediment transport flows with high suspended concentration.

Realising the shortcomings of the SC model, Armanini and Di Silvio (1988) initiated a set of sediment continuity-concentration (SCC) equations to improve the sediment transport representation by including the exchange effect of the sediment bed and suspended loads. Their model was solved in a 1D domain but it considered the non-equilibrium lag of the sediment transport. These equations were further tested by many researchers, i.e. by Valiani and Caleffi (2001) and

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Wu and Wang (2007) for the case of dam-break sediment transport flow, and good correspondence between the numerical simulation and experimental data was observed.

Throughout the studies on sediment transport flow, a lot of different formulas for the sediment adaptation length L_A were proposed, as the characteristics of the sediment transport transition from non-equilibrium to equilibrium stage are hard to be uniformly predicted for different flow events. There were significantly different values of L_A being proposed in literature (refer to studies by Wu et al., 2004; Wu, 2007). Nakagawa and Tsujimoto (1980), Phillips and Sutherland (1989) and Wu et al. (2000) used the average saltation step length of sediment in their experimental bed forms to be L_A in their numerical modelling studies. Bell and Sutherland (1983) found from their scour-hole development experiment on the bed degradation flow that L_A was time-dependent. Wu et al. (2004) also used the explicit time function on L_A to test on the degradation flow cases, although their results showed that there were no significant differences in between the time-dependent L_A with the time-independent ones.

In this study, a summary of the research studies on the sediment adaptation length was given, and a time-varying sediment adaptation length approach to model L_A was proposed and tested with various experimental data from the literature. The combination of 2D shallow water and SCC models was used to simulate the sediment bed and suspended loads movement in a 2D depth averaged flow. The proposed model with the time-varying sediment adaptation length concept was firstly calibrated by a highly discontinuous dam-break fast sediment transport flow, and then the calibrated model was used to simulate the applications of a highly concentrated sediment transport flow in a wide alluvial channel and a sediment aggradation flow. For all tests, the experimental measurements from literature were used for validation. The model proved that the employed time-varying sediment adaptation length not only improved the numerical simulation of fast scour-hole development flow, such as the discontinuous dam-break sediment transport flow, but it can also universally improve the simulation of the rapid bed change and the steady sediment mobility conditions in flow.

2 Governing equations

2.1 Shallow water model

The proposed model described in this paper was built using the sediment continuity-concentration model combined with the 2D shallow water flow equations. Equations (1) – (3) show the two-dimensional fully conservative shallow water equations, combined with the terms from the SCC model as suggested by Cao et al. (2004).

$$\frac{\partial \phi}{\partial t}+\frac{\partial \phi u}{\partial x}+\frac{\partial \phi v}{\partial y}=\frac{g}{1-\lambda}\left(e_s-d_s\right) \tag{1}$$

$$\frac{\partial \phi u}{\partial t}+\frac{\partial\left(\phi u^2+\phi^2/2\right)}{\partial x}+\frac{\partial \phi uv}{\partial y}=g\phi\left(S_{ox}-S_{fx}\right)-\frac{\phi^2\left(\rho_s-\rho_w\right)}{2\rho}\frac{\partial C}{\partial x}+\frac{ug\left(\rho_o-\rho\right)\left(d_s-e_s\right)}{\rho\left(1-\lambda\right)} \tag{2}$$

$$\frac{\partial \phi v}{\partial t}+\frac{\partial \phi uv}{\partial x}+\frac{\partial\left(\phi v^2+\phi^2/2\right)}{\partial y}=g\phi\left(S_{oy}-S_{fy}\right)-\frac{\phi^2\left(\rho_s-\rho_w\right)}{2\rho}\frac{\partial C}{\partial y}+\frac{vg\left(\rho_o-\rho\right)\left(d_s-e_s\right)}{\rho\left(1-\lambda\right)} \tag{3}$$

The variable ϕ refers to the geopotential, and is given by $\phi = g\cdot h$, where h is the water depth and g is the gravitational acceleration. u, v are the depth averaged flow velocities in the streamwise and lateral directions respectively. ρ_s, ρ_w are the density of sediment and water respectively, and $\rho=\rho_w\left(1-C\right)+\rho_s C$ and $\rho_o=\lambda\rho_w+\left(1-\lambda\right)\rho_s$. C is the flux-averaged volumetric sediment concentration of the total sediment load, and λ is the sediment bed porosity. x, y and t denote the spatial-longitudinal, spatial-transverse and time domains, respectively.

In the applications with a movable bed, a source term on the right hand side of Eq. (1) is implemented to capture the influence of erosion rate e_s and deposition rate d_s to the flow continuity. In Eqs. (2) – (3), the second and third terms on the right hand side represent the spatial variations of sediment concentration and momentum transfer due to the process of sediment exchange between the water flow and erodible bed. Ferreirra and Leal (1998), Yang and Greimann (1999), Brufau et al. (2000) and more recently Xia et al. (2010) had suggested that the effects of those two terms in Eqs. (2) – (3) are insignificant in most sediment flow applications. For more source terms modelling information on the momentum equation, one could also refer to Pu et al. (2012).

In Eqs. (2) – (3), S_{ox} and S_{oy} are the bed slopes in the streamwise and lateral directions, respectively, and the friction slopes of the channel S_f are given by

$$S_{fx}=\frac{n^2u\sqrt{u^2+v^2}}{h^{4/3}}\text{, and} \tag{4}$$

$$S_{fy}=\frac{n^2v\sqrt{u^2+v^2}}{h^{4/3}} \tag{5}$$