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Journal of Hydro-environment Research 9 (2015) 145−155

Journal of Hydro-environment Research

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Research paper

A high resolution finite volume model for 1D debris flow

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Received 24 May 2013; revised 11 March 2014; accepted 11 March 2014
Available online 20 March 2014

Abstract

A high-resolution (HR) numerical model for solving 1D shallow water equations employing Voellmy flow resistance relation is developed to predict the time-dependent behavior of non-Newtonian debris flow dynamics in non-erodible channel. The governing equations are solved by the HR shock-capturing method employing the HLLC approximate Riemann solver and the TVD limiter. Based on the fractional-step approach, source terms are treated by an implicit method which makes the model well balanced even when the friction force dominates the flow. A CFL criterion accounting for the total friction velocity is employed to ensure numerically stable solutions. The comparison of numerical results with analytical solutions and experimental measurements shows that the present HR numerical modeling yields accurate solution near discontinuities beyond the first-order-accurate Godunov-type method that is widely used for modeling debris flows. The evaluation tests reveal that the present method yields numerically stable and efficient solutions of debris flows moving downslope with significant basal friction. The application to two debris flows that were experimentally generated with a fixed-volume and a continuous source reveals that the numerical model reproduces the propagation speed of debris flow on the slopes and the deposition pattern on the fan with reasonable accuracy. Overall results indicate that the present model can provide useful information on transient features of debris flow behavior through the channel with an abrupt change in bottom slope.

Keywords: Debris flow; High resolution; Riemann solver; Numerical model; Deposition

1. Introduction

Debris flow is one of the most dangerous among all fluid mixture movements. Such flow is generally considered to contain more than 50% particles larger than sand size (Varnes, 1978), and the modeling concept describes the flow with a considerable proportion of coarser particles that dominate the flow behavior (Jin and Fread, 1999). Over the recent decades, there have been lots of efforts to understand the propagation and deposition behavior of debris flows. Due to the huge difficulty of real-time field measurements, the majority of debris flow researches have focused on laboratory experiments (Major, 1997; Iverson, 2003; Kaitna et al., 2007; Iverson et al., 2010) and numerical simulations (Imran et al., 2001; Denlinger and Iverson, 2001; Naef et al., 2006; Medina et al., 2008) with the parameters that are back-calculated or calibrated to match well-documented field events. The physical modeling has provided much of what we know about the rheology of the debris flow, but the results suffer from the spatial scale effect and are approximately applicable to large-scale events.

The numerical simulation has become an ideal approach for reproducing the debris flow propagation on the slope and its runout on the fan. In numerical simulation of debris flows, practical problems are to determine representative parameters, such as bulk viscosity and yield stress, characterizing the solid-fluid mixture, and to select the appropriate flow resistance relations (Naef et al., 2006). In this study, we employ the Voellmy model as the debris flow resistance relation. Recent back analyses on debris flow events showed that the Voellmy model reveals good characteristics to model field and

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http://dx.doi.org/10.1016/j.jher.2014.03.001
1570-6443/

laboratory debris flows (Rickenmann and Koch, 1997; Ayotte and Hungr, 2000; Revellino et al., 2004; Naef et al., 2006; Medina et al., 2008; Hürlimann et al., 2003, 2008).

It is essential to employ efficient, accurate and robust numerical methods to simulate geometrically and physically complex debris flow phenomena. Jin and Fread (1999) enhanced the dynamic flood routing model to reproduce mud/debris flows based on the 1D unsteady flow equations which are solved using an implicit finite difference scheme and an explicit characteristic-based upwind scheme. Imran et al. (2001) developed a dynamic flood routing model expressed in a Lagrangian framework and solved using an explicit finite difference scheme. McDougall and Hungr (2004) employed a meshless technique based on smoothed particle hydrodynamics to solve a dam-break debris flow problem accounting for bed slope and basal friction. Unfortunately, their solutions suffered from overshooting of the asymptotic profile near the flow front and the smearing of a sharp change in the profile behind. In the last decades, Godunov-type finite volume methods have become popular in seeking numerical solutions to the debris flow equations (e.g., Brufau et al., 2000; Denlinger and Iverson, 2001; Vollmöller, 2004). Such Godunov-type method is the first-order-accurate and introduces a great deal of numerical diffusion, giving poor approximations to shock waves and other discontinuities (Toro, 2001).

Many efforts have been made in developing the numerical method that is able to satisfy the practical requirements of numerical modeling: at least second order accuracy on smooth parts of the solution; sharp resolution of discontinuities without significant smearing; absence of spurious oscillations in the vicinity of discontinuities; and fast convergence to the true solution as the grid is refined. One of the most promising and practically affordable approaches satisfying these requirements is the high resolution (HR) shock-capturing method. It is well known that the higher order numerical schemes encounter a fundamental difficulty associated with spurious oscillations near discontinuities, while monotone schemes without such numerical oscillations are at most first order accurate. The HR methods are based on the combination of Godunov-type methods, which takes the advantage of the conservation form of the system of equations, and numerical approaches aimed at obtaining at least second-order-accuracy in smooth part of the solution without nonphysical oscillations in the vicinity of discontinuities (Toro, 2001).

In this work a 1D numerical model is developed using a HR shock-capturing method based on the Godunov-type scheme incorporated with the modified Harten, Lax and Van Leer (HLLC) approximate Riemann solver and the total-variation-diminishing (TVD) limiter to reproduce high resolution monotone solutions. There are two challenges to improve the quality of numerical modeling of debris flows, like shallow water flows, especially when the friction source term dominates the behavior of flows moving down the slope of the dry bed. One is the accurate numerical treatment of friction source terms to prevent the solution accuracy from deteriorating. The other is the numerical technique to ensure stable solution where the friction force dominates the flow, especially at relatively low velocity. To meet these challenges and to speed-up the computation, the present numerical model is incorporated with a novel implicit treatment method for friction source term and a new CFL condition taking the friction velocity into account in its stability criterion.

In the following section, we first present the governing equations based on the shallow water equations with a flow resistance relation to determine the basal friction slope. Subsequently, the details of the present numerical method are introduced. Next, the numerical model is applied to a dam break problem and compared its solution with analytical solutions accounting for a Coulomb-type behavior with constant friction angle on constant slope bottom. It is followed by presenting the application of the numerical model to the debris flow of a fixed volume experimentally investigated by Iverson et al. (2010) in a large-scale USGS flume and a continuously feeding debris flow investigated by Paik and Kim (2012) in a laboratory flume. Finally, conclusions are drawn.

2. The numerical model

2.1. Governing equations

The shallow water equations can be applied to non-Newtonian debris flows with an appropriate flow resistance term. The hyperbolic conservation law of the continuity and momentum equations can be written as follows (Gallouët et al., 2003; Audusse et al., 2004):

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F}(\mathbf{U})}{\partial x} = \mathbf{H}(\mathbf{U}) \tag{1}$$

where

$$\mathbf{U} = \begin{pmatrix} h \\ \mathrm{hu} \end{pmatrix},\ \mathbf{F}(\mathbf{U}) = \begin{pmatrix} \mathrm{hu} \\ \mathrm{huu} + \frac{1}{2}\mathrm{gh}^2 \end{pmatrix},\ \mathbf{H}(\mathbf{U}) = \begin{pmatrix} q_i \\ \mathrm{gh}\left(S_0 - S_f\right) \end{pmatrix}$$

In above equation, t is the time; $h(x,t)$ is the flow depth; $u(x,t)$ is the depth-averaged flow velocity in the x direction; g is the gravity acceleration; q_i is the lateral inflow; S_0 is the bed slope given by the bed inclination θ.

$$S_0 = -\frac{\partial z_0}{\partial x} \tag{2}$$

where $z_0(x,t)$ is the bed level respect to the horizontal reference, as shown in Fig. 1 showing a schematic diagram of the debris flow on the slope and variables employed in this study.

In this study, the Voellmy flow resistance relation is implemented for the flow resistance term S_f of debris flows in the model. The Voellmy relation has been successfully used for back-calculating velocity and runout distance flow debris flow, and proven to be suitable for describing debris flow in