Geomorphology 241 (2015) 72–82

Contents lists available at ScienceDirect

Geomorphology

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

Exploring the velocity distribution of debris flows: An iteration algorithm based approach for complex cross-sections

Zheng Han [a,b,*], Guangqi Chen [a], Yange Li [b,c], Wei Wang [a], Hong Zhang [a]

[a] Department of Civil and Structural Engineering, Kyushu University, West 2-1110, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan
[b] School of Civil Engineering, Central South University, Changsha 410075, China
[c] State Key Laboratory of Geohazard Prevention and Geoenvironment Protection, Chengdu University of Technology, Chengdu 610000, China

ARTICLE INFO

Article history:
Received 12 October 2014
Received in revised form 17 March 2015
Accepted 31 March 2015
Available online 18 April 2015

Keywords:
Debris flow
Velocity distribution
Integral solution
Iteration algorithm

ABSTRACT

The estimation of debris-flow velocity in a cross-section is of primary importance due to its correlation to impact force, run up and superelevation. However, previous methods sometimes neglect the observed asymmetric velocity distribution, and consequently underestimate the debris-flow velocity. This paper presents a new approach for exploring the debris-flow velocity distribution in a cross-section. The presented approach uses an iteration algorithm based on the Riemann integral method to search an approximate solution to the unknown flow surface. The established laws for vertical velocity profile are compared and subsequently integrated to analyze the velocity distribution in the cross-section. The major benefit of the presented approach is that natural channels typically with irregular beds and superelevations can be taken into account, and the resulting approximation by the approach well replicates the direct integral solution. The approach is programmed in MATLAB environment, and the code is open to the public. A well-documented debris-flow event in Sichuan Province, China, is used to demonstrate the presented approach. Results show that the solutions of the flow surface and the mean velocity well reproduce the investigated results. Discussion regarding the model sensitivity and the source of errors concludes the paper.

1. Introduction

A debris flow is a rapid, gravity-driven mass movement that involves water-charged, predominantly coarse-grained inorganic and organic materials moving down a steep and confined channel (VanDine, 1985; Iverson, 1997). It is widely accepted that debris flow plays an important role in landscape evolution (Glade, 2005; Stock and Dietrich, 2006; Brayshaw and Hassan, 2009; Berger et al., 2011; Iverson et al., 2011; Wrachien and Mambretti, 2011; Tang et al., 2012; Han et al., in press). Debris flows travel at high velocity down the channel and start to deposit over a fan where the slope angle decreases distinctly (Whipple and Dunne, 1992). Accompanying with the high traveling velocity, immense destructive impact of debris flows (e.g., impact force, run-up, and superelevation of the flow) often endangers human lives and infrastructure facilities, and causes severe fatalities every year (Dowling and Santi, 2014). In this sense, debris-flow velocity is an essential factor in the design of hazard mitigation works (Rickenmann, 1999; Han et al., 2014).

Direct in-situ measurement of debris-flow velocity is a big challenge, because debris flows often begin without warning and last short time periods. However, the existing measurement and observation data still provide an insight into debris-flow velocity. Iverson and Vallance (2001), Tecca et al. (2003), Kang et al. (2004) and Johnson et al. (2012) reported an asymmetrical distribution of surface velocity, i.e., that velocity is greater along the thalweg than that of both sides. Johnson et al. (2012) also demonstrated that debris-flow velocity is much higher at the top surface than that of the bottom. Laboratory flume experiments (Egashira et al., 1989; Hotta et al., 1998; Hotta and Ohta, 2000; Drago, 2002; Medina and Bateman, 2010) have highlighted this vertical distribution, and different profile laws were proposed to match the measurements. Studies on this issue come to a common consensus that the asymmetrical velocity distribution can be partly explained by the basal shear strength and topographic relief of the cross-section. However, the asymmetrical velocity distribution currently lacks fundamental physical understanding, and theoretically quantifying the velocity distribution is still a major task.

Numerical simulation methods are an available way to estimate debris-flow velocity over complex topography. Several models have been developed and applied for this purpose (e.g., Brufau et al., 2000; Imran et al., 2001; de Joode and van Steijn, 2003; Hungr et al., 2005; Mangeney et al., 2007; Bouchut et al., 2008; Medina et al., 2008; Wang et al., 2008; Beguería et al., 2009; Crosta et al., 2009a,b; Lin et al., 2009; Pirulli and Pastor, 2012; Liu et al., 2013; Han et al., 2015). However, these numerical simulations often have limitations relating to the multi-phase physics of the flows and the rheological parameters which are

* Corresponding author. Tel.: +81 80 6459 7998; fax: +81 92 802 3386.
E-mail address: hankzzz@163.com (Z. Han).

http://dx.doi.org/10.1016/j.geomorph.2015.03.043
0169-555X/

difficult to measure (Rickenmann et al., 2006; Berti and Simoni, 2014). These methods mostly use shallow water assumption to reduce the Navier–Stokes equations to a much simpler two-dimensional description with a height-field representation, so that the velocity is inherently homogeneous through the flow depth. The effect of DEM resolution on the simulated results is significant. Resolution of commonly used DEMs for simulation varies from 3 to 10 m, and a debris-flow channel is sometimes a few to tens of meters wide (May and Gresswell, 2004). These narrow widths mean that only a few cells within a DEM may cover a channel cross-section, and detailed information about its relief would be unavailable. Although DEMs measured by LiDAR are in higher resolutions (<3 m) and beneficial to get better results, higher resolutions significantly decrease the computation efficiency (Sodnik et al., 2012). This trade-off implies that numerical methods are limited to analyze the velocity distribution at a cross-section.

At the current stage, debris-flow velocity can be conventionally back-calculated from previous superelevation events (Hungr et al., 1984; Iverson et al., 1994; Suwa and Yamakoshi, 2000; McClung, 2001; Prochaska et al., 2008; Scheidl et al., 2015). The so-called vortex equation may presently be the most accurate way to estimate velocity. However, this method works only at the channel bend because superelevation should be known beforehand, and the estimated velocity is uniform across the channel. Another way is the usage of empirical equations. In consideration of the complexity of debris flows in both space and time, the simplified Manning–Strickler equation is commonly used to approximate the velocities of debris flows, which can be unsteady and non-uniform along steep channels (Rickenmann, 1999; Chen et al., 2007). However, the flow depth is difficult to predict. The resulting velocity is also uniform across the channel, and could not represent the measured asymmetric velocity distribution.

Han et al. (2012, 2014) proposed a new approach for analyzing the velocity distribution, in which cross-sections were classified as three categories (V-shaped, trapezoidal, and rectangular) and direct solutions of double integration for flow depth and velocity distribution were given. To reduce the complexity of double integration, complex cross-sections were generalized into simple polygons. In this procedure, some terrain relief of the bed surface, as well as superelevations at the bend, cannot be taken into account. Therefore, the preliminary approach is still limited especially for natural channels with irregular beds.

In this paper, we address the problems in the previous methods and develop a new approach to estimate debris-flow velocity distribution in a channel cross-section with irregular shape. The approach firstly replicates the bed surface by an irregular line defined by a series of vertices. The bed is partitioned into infinitesimal segments using linear interpolation. Given a pre-defined peak discharge of the event, an iteration algorithm based on the Riemann integral method is then proposed to search an approximated flow surface. Subsequently, horizontal and vertical velocity profile laws are integrated to determine velocity distribution in the cross-section. A well-documented debris-flow case with six individual cross-sections is used to demonstrate the capability and performance of the approach.

2. Methodology

2.1. Theoretical solution for an unknown flow surface

The first and essential step to analyze the velocity distribution is the determination of flow depth. For back-calculation of a previous event, flow depth at a site can be directly estimated from the residual mud line on the sidewall. However, the residual mud line was often washed by rainfall and may be not so clear to estimate the flow depth.

Another commonly used method is the usage of a pre-defined peak discharge of the event (Rickenmann, 1999). Generally, peak discharge of the event is a function of velocity and integral area. Under complex

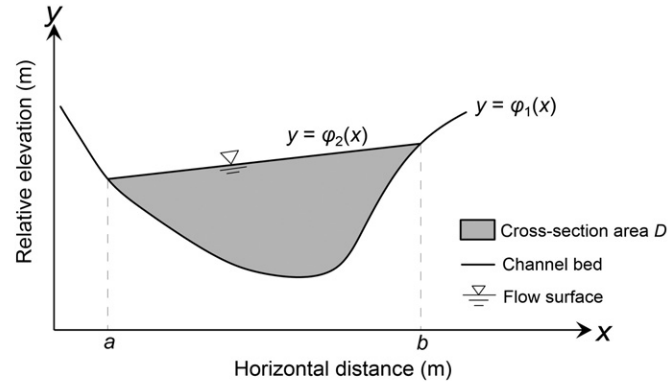

Fig. 1. Schematic illustration for the theoretical solution to an unknown flow surface at a complex cross-section. φ_1 is a function of the channel bed, and φ_2 is a function of the flow surface.

topography (Fig. 1 for example), the peak discharge of the event, Q_{event} satisfies the following condition:

$$Q_{event} = \iint_D v(x,y)\mathrm{d}\delta, \quad D \in [a \le x \le b, \varphi_1(x) \le y \le \varphi_2(x)] \tag{1}$$

where D is the integral area; φ_1 is a function of channel bed (the lower limit of integral); φ_2 is a function of flow surface (the upper limit of integral); (x, y) is the location of the cross-section; $\mathrm{d}\delta$ is an infinitesimal area in the area D; a and b are the horizontal locations of the flow surface boundary; and v is debris-flow velocity, which can be roughly estimated by the Manning–Strickler equation (Rickenmann, 1999; Chen et al., 2007):

$$v(x) = \frac{1}{n_c} h^{\frac{2}{3}}(x) I^{\frac{1}{2}} \tag{2}$$

where n_c is the roughness of bed surface; I is the slope gradient of the channel; and $h(x)$ is the flow depth, and equates to $\varphi_2(x) - \varphi_1(x)$. Theoretically, if Q_{event} is known by direct in-situ measurement, or empirically predicted by the potential mass volume (Hungr et al., 1984; Rickenmann, 1999) and rainfall strength (Wrachien and Mambretti, 2011; Chen and Chuang, 2014), then flow depth function φ_2 with a certain superelevation angle can be back-calculated. However, it is a considerable challenge to use this equation directly because bed surface function φ_1 is too complicated to describe. Therefore, we made some assumptions and simplification in the previous method, e.g., the flow surface is horizontal ($\varphi_2(x) = H$, where H is the preliminary flow surface) and the bed surface is simplified as a perfect triangular cross-section (Han et al., 2014). In this way, the integral solution of the flow surface is given as

$$H = \left[\frac{11 n_c Q_{event}}{3I^{1/2}\left(\frac{1}{\tan\theta_1} + \frac{1}{\tan\theta_2}\right)} \right]^{\frac{3}{11}} \tag{3}$$

where θ_1 and θ_2 are the slope angles of the simplified sidewalls, respectively.

The simplicity of the cross-section geometry significantly reduces the complexity of direct usage of Eq. (1), but it is still questionable whether these assumptions are appropriate for natural channels with irregular beds. Moreover, consideration of complex bed surface is also instrumental to improve the accuracy of velocity distributions.

2.2. Iteration algorithm to determine a flow surface

Because a complex bed surface and an incline flow surface at the bend, direct calculation of the flow depth may be complex. We subsequently propose a new iteration algorithm in this section to