Geomorphology 194 (2013) 84–93

Contents lists available at SciVerse ScienceDirect

Geomorphology

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

Longitudinal spreading of granular flow in trapezoidal channels

C.W.W. Ng, C.E. Choi *, R.P.H. Law

Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong

ARTICLE INFO

Article history:
Received 29 November 2012
Received in revised form 12 April 2013
Accepted 14 April 2013
Available online 20 April 2013

Keywords:
Discrete element method
Flume modeling
Trapezoidal channel
Longitudinal spreading
Mobility analysis

ABSTRACT

Debris flows have a long runout distance and can result in devastating consequences. The mobility of debris flows are influenced by their rheological behavior and the topography of their flow path. Trapezoidal cross-sectional channels can more accurately model channelized topography and yield more accurate mobility analyses. However, the flow mechanisms influencing mobility in trapezoidal channels are not well understood. A 5-m-long uniform trapezoidal flume with adjustable sidewall angles is used to investigate the mobility of dry granular surge flows. Experimental tests are conducted for sidewall angles of 30°, 45°, and 90°. Numerical back-analysis using the discrete element method (DEM) is subsequently conducted to interpret the flume experiments. Furthermore, a new dimensionless group, π_1, is presented to characterize the flow mechanism of longitudinal spreading. Experimental and numerical results both reveal that increasing sidewall angles reduce flow mobility. Steep sidewalls increase flow depths, which promotes longitudinal spreading. Longitudinal spreading is responsible for attenuating the flow mass and reducing mobility. The dimensionless group, π_1, shows to be an appropriate indicator for characterizing the longitudinal spreading mechanism of a flow mass. The consideration of longitudinal spreading and channel sidewall angle is demonstrated to be necessary for a comprehensive mobility assessment.

1. Introduction

Debris flows occur in mountainous regions without warning and can result in devastating consequences to downstream facilities. Active and passive countermeasures (Mizuyama, 2008) can be used to mitigate this hazardous phenomenon. Active measures include debris-resisting structures such as check dams (Remaitre et al., 2008), rigid and flexible barriers (Wendeler et al., 2008; Canelli et al., 2012), or an array of baffles (Ng et al., 2013). However, active measures alone can be inadequate, and passive measures may be used in parallel with active measures. Passive measures include conducting detailed risk assessments (Xu et al., 2012), monitoring systems (Bacchini and Zannoni, 2003), and relocation of settlements. Detailed risk assessment requires a thorough understanding of debris flow mechanisms in order to properly predict the travel distance of landslide debris (Tie, 2012). However, debris flow dynamics are complex, and mobility analysis can be influenced by the rheological behavior of the material and the topography of the debris flow track (Ancey, 2007).

The channel geometry and degree of lateral confinement are important variables that can significantly alter the mobility of landslide debris (Law, 2008; Zhou and Ng, 2010). Kwan and Sun (2006) demonstrated that mobility analysis can be improved for channelized landslide debris by more accurately modeling the topography. More specifically, trapezoidal cross-sectional channels (Speerli et al., 2010) are adopted in their mobility analysis compared to the conventional use of rectangular cross-sectional channels for investigating mobility of landslide debris (Iverson, 1997; Major, 1997; Denlinger and Iverson, 2001; Law et al., 2007; Pudasaini et al., 2007). The use of trapezoidal channels yields more accurate predictions in mobility analysis. However, the influence of the degree of sidewall inclination on debris flow mechanisms is not well understood.

The influence of trapezoidal geometry on flow behavior is readily available in hydraulic engineering; however, studies for debris flow are limited. For uniform and steady flows, the best hydraulic section is the cross section that yields the greatest discharge with the smallest wetted perimeter. The best hydraulic section for a given geometry can be determined using the Manning equation. For a trapezoidal channel, the best hydraulic section has 60° sidewalls (Jain, 2001; Abdulrahman, 2007). The applicability of the concept of the best hydraulic section to highly complex and transient debris flow is questionable; however, it may serve as a simple preliminary basis for comparison.

This study examines the influence of trapezoidal sidewall angle on debris flow mechanisms and mobility with a series of flume experiments. Numerical back-analysis of the flume experiments is conducted using the DEM to better understand the flow mechanisms. Furthermore, dimensional analysis is conducted to investigate the dominant flow mechanism influencing mobility by varying sidewall angles within a trapezoidal flume.

* Corresponding author. Tel.: +852 6388 0285.
E-mail address: cechoi@ust.hk (C.E. Choi).

0169-555X/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.geomorph.2013.04.016

2. Dimensional analysis for longitudinal spreading

A new dimensionless group developed in this study interprets the longitudinal spreading of granular surge flow along a uniform channelized flow path. The dimensionless group adopts surge dynamics (Savage and Hutter, 1989; Hungr, 1995; Iverson, 1997; Jakob and Hungr, 2005) to describe the longitudinal spreading motion. The dimensionless group compares the downslope driving pressure with the lateral earth pressure that promotes spreading during the transportation process.

The dimensionless group is derived from the following depth-averaged momentum equation (Savage and Hutter, 1989) and is presented as follows:

$$\frac{d\langle u\rangle}{dt} = \left(\tan\theta - \mu_b - k\frac{\partial h}{\partial x}\right) g\cos\theta \tag{1}$$

where $\langle u\rangle$ is the depth-averaged flow velocity parallel to the channel bed, θ is the channel inclination, μ_b is the basal friction coefficient characterizing the interaction between the flowing debris and the stationary channel bed, k is the lateral earth pressure coefficient, h is the flow depth, x is the longitudinal dimension of the flow, and g is the gravitational acceleration.

In Eq. (1), the term, $d\langle u\rangle/dt$ characterizes the material acceleration of any specified location of the granular mass. The terms on the right represent the contribution of body and surface components that accelerate or decelerate the granular mass. The first term ($\tan\theta$) on the right represents the body translational motion downslope, the second term (μ_b) on the right represents the basal surface frictional resistance, and the last term ($k\,\partial h/\partial x$) on the right characterizes the lateral earth pressure within the granular mass. In particular, the third term, quantifies the rate of deformation of the granular mass caused by the lateral earth pressure within the granular mass.

The constitutive property of the Savage and Hutter (1989) variation of the shallow water equations is complicated by a nonlinear earth pressure coefficient that premultiplies the pressure in the downslope momentum balance (Gray et al., 1999). The idea behind the k term stems from the classical problem of soil mechanics in retaining walls. Savage and Hutter (1989) used the Mohr–Coulomb and basal sliding law to show that the earth pressure is a piecewise constant function of the downslope velocity divergence (Gray et al., 1999). The earth pressure coefficient k is considered constant for simplicity.

The use of the $k\,\partial h/\partial x$ term from Eq. (1) is shown in Fig. 1; the difference between the depths of the two blocks is given as $\partial h/\partial x$. Arbitrary heights are chosen to dictate a typical side profile of a debris torrent where $h_1 < h_2$ and $h_2 < h_3$. A typical flow profile of a granular mass surging downslope at an inclination θ is shown. The head of the granular mass typically moves faster than the tail of the granular mass; this is because of the contribution of downslope pressure in the front of the mass and upslope pressure in the tail of the granular mass. Within the tail of the granular mass, the $k\,\partial h/\partial x$ term is positive (internal pressure pointing upslope) and the $k\,\partial h/\partial x$ term is negative within the head of the granular mass (internal pressure driving the material downslope). If a slice of granular material is taken from the head of the granular mass, with reference to the aforementioned sign convention, a negative $k\,\partial h/\partial x$ value is attained that provides a positive contribution to the acceleration in Eq. (1). If a slice is taken from the tail of the granular mass, then the $k\,\partial h/\partial x$ value is positive, which is against the downslope motion.

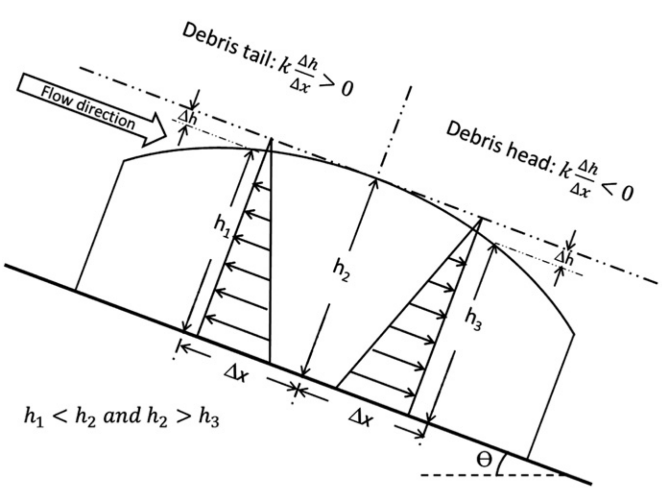

Fig. 1. Schematic of earth pressure term.

With reference to Eq. (1), the following relationship is deduced about the head and tail of the granular mass:

$$\text{Head}: \; k\frac{\partial h}{\partial x} < 0 \rightarrow \frac{d\langle u\rangle}{dt} \; \text{increases} \rightarrow \text{accelerates downslope faster}$$

$$\text{Tail}: \; k\frac{\partial h}{\partial x} > 0 \rightarrow \frac{d\langle u\rangle}{dt} \; \text{decreases} \rightarrow \text{accelerates downslope slower.}$$

This apparent difference in momentum transfer within the granular mass produces a relatively faster downslope movement at the frontal position but a slower downslope movement at the tail position. The rate of acceleration of the head and tail is representative of the longitudinal translation process or extension of the granular mass in the longitudinal direction. In other words, the internal earth pressure at the tail of the granular mass pushes the granular mass in an upslope direction, meanwhile the internal earth pressure at the head of the granular mass pushes the granular mass in a downslope direction. Therefore, the $k\,\partial h/\partial x$ term is conveniently used to represent longitudinal translational motion or component that describes the distribution of granular material away from the centroid of the granular mass. The last term ($\tan\theta\, g\cos\theta$) in Eq. (1) characterizes the downslope translational motion of the granular mass.

The value of k is assumed constant for simplicity. The translational motion term from Eq. (1), $g\tan\theta\cos\theta$, is used to represent and derive a characteristic time for the downslope translational motion. The earth coefficient term ($k\,\partial h/\partial x$) of Eq. (1), representing the internal earth pressure of the flow is used to derive a characteristic time for the spreading motion of the mass.

The characteristic time for downslope translational motion is given as follows:

$$T_d = \sqrt{\frac{2L}{g\tan\theta\;\cos\theta}} \tag{2}$$

where L is the tangential length of the flow channel. The characteristic time for the longitudinal spreading motion is given as follows:

$$T_p = \sqrt{\frac{2L}{gk\left|\frac{\partial h}{\partial x}\right|\cos\theta}}. \tag{3}$$

The ratio of the two characteristic times, termed π_1 for this study, is given as follows

$$\pi_1 = \frac{T_p}{T_d} = \frac{\text{Characteristics time for longitudinal spreading motion}}{\text{Characteristics time for downslope translational motion}} = k\sqrt{\left|\tan\theta/\frac{\partial h}{\partial x}\right|}. \tag{4}$$

The dimensionless group highlights the importance of $\partial h/\partial x$ on the longitudinal spreading motion of granular surge flow. A large π_1