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Experimental study of viscous debris flow characteristics in drainage channel with oblique symmetrical sills

Tao Wang[a], Xiaoqing Chen[a,*], Kun Li[b], Jiangang Chen[a], Yong You[a]

[a] Key Laboratory of Mountain Hazards and Earth Surface Processes, Institute of Mountain Hazards and the Environment, Chinese Academy of Sciences, Chengdu 610041, China
[b] School of Civil Engineering and Architecture, Southwest Petroleum University, Chengdu 637001, China

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ABSTRACT

In this study, experiments were performed in a 6-m-long flume to determine the characteristics of viscous debris flows in a new type of drainage channel with oblique symmetrical sills. The debris flow velocity was measured and subsequently used to characterise the viscous debris flow. The influences of the channel slope, transverse length of sills, and row spacing of sills on the debris flow velocity and the velocity reduction ratio P were investigated. The experimental results indicated that the viscous debris flow velocity increased as the channel slope increased from 0.10 to 0.15. However, the velocity decreased as the ratio of the transverse length of sills to the row spacing of sills increased from 0.13 to 0.53. Different combinations of the channel slopes, transverse lengths of sills, and row spacing of sills reduced the velocity by 14.2%–51.1% compared to the velocity in a smooth channel. The effects of the channel slopes, transverse lengths of sills, and row spacing of sills on P could be described using a power-law equation. Most of the errors in P prediction ranged from − 25.0% to 25.0%. A comparison of P in drainage channels with different deceleration measures indicated that P increased with an increase in the length of a channel with deceleration measures. These experimental results serve as a useful reference for the design of drainage channels with oblique symmetrical sills.

1. Introduction

Debris flows are mass movement phenomena commonly occurring in mountainous regions worldwide and can travel several kilometers in a series of surges (Iverson et al., 2011; Pudasaini, 2012; Mergili et al., 2017). Debris flows can lead to obvious geomorphic evolution in the region of the debris flow fan and pose a major threat to local residents and infrastructure (Hungr et al., 2001; Godt and Coe, 2007; Xu et al., 2012; Cui et al., 2013; Han et al., 2018).

Debris flow in which the stress is dominated by viscoplastic stress are termed as viscous debris flow (Takahashi, 2009). Viscous debris flow is one of the main type of debris flow worldwide (Takahashi, 2003). It is a destructive natural disaster that can cause huge loss of life and property; in particular, it can damage towns, villages, traffic routes, and hydropower projects (Cui et al., 2011). Therefore, it is imperative to accelerate the development of mitigation measures and prevent debris flow disasters. Structures used for general debris flow prevention and control engineering include check dams (Chanson, 2004; Mizuyama, 2008; Hassanli et al., 2009; Chen et al., 2015a), flexible net dams (Canelli et al., 2012; Volkwein et al., 2015), drainage systems (Takahisa, 2008; Brunkal and Santi, 2016), and debris flow storage basins (Gems et al., 2014).

Debris flow drainage channels are a major mitigation measure implemented downstream of debris flow basins (VanDine, 1996). Based on the deceleration measure employed, debris flow drainage channels can be classified into two types. The V-type drainage channel proposed by Wang (1996) is a typical drainage channel without deceleration measures (Fig. 1a). Specifically, a V-type drainage channel is characterized by a high debris flow velocity, a high discharge capacity, and low siltation (Wang, 1996). A V-type drainage channel is suitable for channels with gentle slopes ($0.01 < i \leq 0.05$, where i is the channel slope) (Chen et al., 2015b). However, the main disadvantages of drainage channels without deceleration measures are erosion caused by hyperconcentrated silt flows and debris flow abrasion destruction (Chen et al., 2014a). Fig. 1b shows a typical drainage channel with deceleration measures: the Dongchuan-type drainage channel proposed by Li (1997). A Dongchuan-type drainage channel is suitable for channels with moderate slopes ($0.05 < i \leq 0.20$) (Chen et al., 2015b). Furthermore, drainage channels with pre-fabricated reinforced concrete boxes or dissipation baffles are suggested to be applied to channels with

* Corresponding author.
E-mail address: xqchen@imde.ac.cn (X. Chen).

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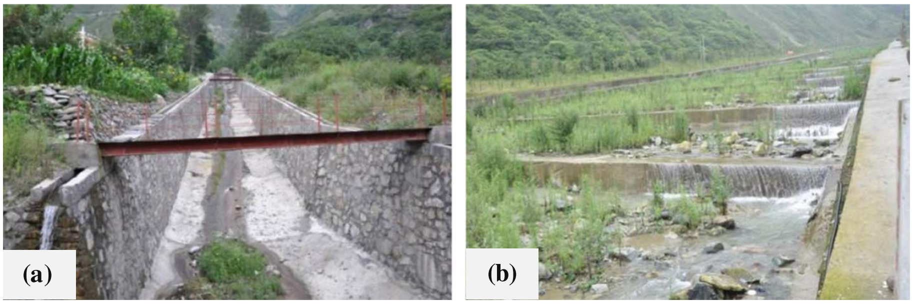

Fig. 1. Drainage channels with and without deceleration measures (a: V-type drainage channel without deceleration measures, Wuming gully1, Sichuan Province, China; b: Dongchuan type drainage channel, Hongchun gully, Sichuan Province, China).

steep slopes ($0.20 < i$) (Chen et al., 2015b; Wang et al., 2017). Wang et al. (2012a, 2012b) performed a field experiment to study the effect of a step-pool system on the energy dissipation of debris flows in Wenjia Gully (gully slope $i = 0.18$), Sichuan Province, China. The results showed that the step-pool system was suitable for dissipating the energy of small-magnitude debris flows.

Previous studies have shown that most of the longitudinal gradients of debris flow fans associated with the Wenchuan earthquake-affected areas have slopes ranging from 0.07 to 0.16 (Qu et al., 2015). According to the slopes of the debris flow fans, the Dongchuan-type drainage channel is commonly used. However, this channel has some disadvantages. (1) Large particles easily settle in the channel because of the reduction in the debris flow velocity and cause blocking and deposition (Chen et al., 2010). (2) Debris flow deposition occurs at the outlet of the drainage channel (Chen et al., 2014a). (3) Ground sills block the hydraulic connection between upstream and downstream areas and hinder the improvement of the aquatic environment in channel beds (Chen et al., 2014b). Therefore, a new type of drainage channel with oblique symmetrical sills was proposed by Chen et al. (2010). The new drainage channel could improve the hydraulic connectivity and ecological function of channel (Chen et al., 2014b).

To demonstrate the effectiveness of this new drainage channel in controlling viscous debris flows in channels, a series of flume tests were performed at the Dongchuan Debris Flow Observation and Research Station. In this study, the effects of the channel slope, row spacing of sills, and length of transverse sills were considered. Based on existing research methods and the results obtained from the flume tests, the characteristics of the drainage channels with oblique symmetrical sills were analysed, including the flow patterns, debris flow velocities, velocity reduction ratio, and mechanism of energy dissipation under different conditions.

2. Experimental facility and procedures

A schematic diagram of the flume model used in this study is shown in Fig. 2. The experimental apparatus included four components: a 1.20 m^3 hopper on the upstream side, a 6-m-long drainage channel with a rectangular cross section of 0.40 × 0.40 m (width × height), oblique symmetrical sills, and a 1.15 m^3 tailing pool downstream of the channel. The bottom slab was a steel plate, whereas the two sidewalls of the flume were made of transparent organic glass.

The channel slope i, transverse lengths of sills B, and row spacing between two near rows of sills R_s were the three primary parameters considered in this experiment. The slopes of the debris flow fans in the Wenchuan earthquake region ranged from 0.07 to 0.16 (Qu et al., 2015). Consequently, the channel slope i of the flume was set as 0.10, 0.12, and 0.15. As shown in Fig. 2, there were two symmetrical sills in a same row, and the transverse lengths of sills B were maintained to be less than half of the width of the channel (channel width = 0.40 m). Therefore, B was set as 0.08, 0.12, and 0.16 m. In this experiment, the row spacing between two near rows of sills R_s was set as 0.30, 0.40, and 0.60 m because previous studies suggested that R_s was 0.33 to 1.50 times the width of the channel (Li, 1997; Chen et al., 2014b). θ is the angle between a sill and a sidewall (Fig. 2). The viscous debris flow velocities were affected slightly when θ ranged from 45° to 80° (Zhang, 2014). Therefore, θ was set as 60°. The oblique symmetrical sills arranged in the drainage channel were made of steel tubes with a rectangular cross section of 0.04 × 0.04 m (width × height) and were fastened to the bed of the channel using screws. The specific experimental parameters are listed in Table 1.

Preliminary experiments suggested the distance from the channel inlet to the first row of sills (L_1) should be 1.60 m. This portion of the channel ensured that the debris flow was driven by gravity instead of the pressure caused by the fluid in the hopper. The lengths of the upstream and downstream sections of the channel with sills are L_2 and L_3. To ensure that the debris flow velocities were affected by the same length of the channel with sills, ($L_2 + L_3$) should be kept as a constant. Moreover, ($L_2 + L_3$) depends on the row spacing R_s (0.30, 0.40, and 0.60 m). Consequently, ($L_2 + L_3$) can be set as 1.20, 2.40, or 3.60 m. Generally, many rows of sills are arranged in drainage channels (Li, 1997; Chen et al., 2014b). Therefore, ($L_2 + L_3$) was set as 3.60 m. Li (1997) suggested that the downstream section of the channel with sills be chosen as the observation section for obtaining the debris flow velocity in flume experiments. To keep the length of L_3 as a constant, L_3 was set as 1.20 m in this experiment. The distance from the end row of sills to the channel outlet (L_4) was set as 0.80 m.

The soil materials used in this experiment were collected from Jiangjia Gully, Dongchuan County, Yunnan Province, China. The test materials were filtered using a 20 × 20 mm steel mesh to remove solid particles with diameters larger than 20 mm (Fig. 3). According to the grain-size distribution parameters of the debris flow deposits in Jiangjia Gully, the total weight of the grains with diameters smaller than 20 mm occupied 85% of the total weight of all the grains (Li et al., 2015). Thus, the soil materials can be used to represent real debris flow materials.

The debris flow density was set as 2000 kg/m^3 in this experiment because the densities of most of the viscous debris flows occurring in Jiangjia Gully ranged from 1700 to 2300 kg/m^3 (Takahashi, 2003). A mixture of the soil sample and water was prepared according to the required density of debris flow (2000 kg/m^3) before performing an experiment. The experiment was started after this mixture had soaked. Debris flow samples were obtained using a sampling instrument during the experiment, and the soil material volumetric concentration obtained using the drying method was approximately 62.5%. In this study, the volume of debris flow was kept constant at 0.80 m^3.

Rheological parameters are key parameters for debris flows. They can affect the deformation, flow, and depositional behaviour of debris flows (Domnik et al., 2013; Boetticher et al., 2016). In this study, the debris flow was considered to be a Bingham fluid. Yang et al. (2013) analysed the rheological parameters of debris flow in Jiangjia Gully and found that the viscosity and yield strength of debris flow with a density of 2000 kg/m^3 were 0.99 Pa·s and 280 Pa, respectively.

During the experiment, two digital videos recorded the process of debris flow. These videos were also used to determine debris flow velocity. The average velocity of debris flow at the L_3 section was calculated as