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An experimental study of dilute debris flow characteristics in a drainage channel with an energy dissipation structure

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ABSTRACT

An experimental study was performed to determine the characteristics of a dilute debris flow in a drainage channel with an energy dissipation structure and a channel slope i of 15%. Flow pattern, debris flow depth, and velocity downstream of the energy dissipation structure were investigated along with the energy dissipation characteristics. Dilute debris flow velocity and depth were measured, analyzed, and subsequently used to characterize the dilute debris flow. The flow pattern in the drainage channel indicated that the dilute debris flow was highly turbulent and that flow depth initially increased. However, this increase was followed by a noticeable decrease after passing through the energy dissipation structure. The experimental results also indicated that the debris flow velocity gradually decreased as the length of the energy dissipation structure increased, whereas flow depth gradually increased with increasing length of the energy dissipation structure. Velocity characteristics and depths of the dilute debris flow downstream of the energy dissipation structure were also affected to some extent by variations in the width of the energy dissipation structure. The energy dissipation ratio gradually increased with increasing length and width of the energy dissipation structure for $i = 15\%$, and the maximum energy dissipation ratio was approximately 58.69%. These experimental results provide a theoretical foundation for optimal design of drainage channels with energy dissipation structures.

1. Introduction

Debris flows are a common type of mass movement in mountainous areas and can travel several kilometers in a series of surges (Iverson, 1997). Debris flows are generally accepted as one of the primary geomorphic processes in steep mountainous areas (Pierson, 1980; Takahashi, 1991; Hungr et al., 2001; VanDine and Bovis, 2002; Godt and Coe, 2007; Cui et al., 2013). In particular, after the devastating 5.12 magnitude earthquake in Wenchuan, China, a large amount of loose material with a total volume of approximately 2.6×10^9 m^3 was deposited in gullies (Parker et al., 2011), which could be easily eroded to form debris flows (Shieh et al., 2009). In addition, four types of disaster chains that were caused by the earthquake were identified based on field investigations and field experiments reported by Xu et al., (2012). The initial active period for debris flow disasters can persist for 5–10 years following an earthquake (Cui et al., 2011; Tang et al., 2009; Wu et al., 2011). A considerable number of debris flows were triggered after the Wenchuan earthquake including debris flows in the Zoumaling Gully (Tang et al., 2012; Zhang et al., 2014), the Wenjia Gully (Yu et al., 2013; Cui et al., 2014; Huang and Li, 2014), the Xiaojia Gully (Liu et al., 2014), and Zhouqu (Tang et al., 2011; Hu et al., 2012). The same problem also occurred in the Chi-Chi earthquake area (Taiwan), where numerous landslides and collapses were triggered, and many debris flows occurred in the 10 years after the earthquake (Chen et al., 2006; Chiou et al., 2007; Liu et al., 2008; Wu et al., 2011). Triggering thresholds for debris flows, such as antecedent cumulative rainfall and one-hour rainfall intensity, decreased significantly after the Wenchuan and Chi-Chi earthquakes because of the amount of loose sediments that had been deposited in the gullies (Chen et al., 2006; Liu et al., 2008; Tang et al., 2009), and the scale of natural debris flows was significantly amplified by a series of cascading landslide dam failures (Cui et al., 2013; Zhou et al., 2013).

Therefore, it is critical to prevent disasters and mitigate losses for local residents. Debris flow mitigation measures can be classified as structural or nonstructural. Structural measures include check dams (Armanini and Larcher, 2001; Chanson, 2004; Hassanli et al., 2009), drainage systems (Takahisa, 2008; You et al., 2011), flexible barriers (Canelli et al., 2012), and debris flow basins (Ikeya, 1989; Liu et al., 2013), whereas nonstructural measures include warning and evacuation systems, appropriate land use, and retrofitting of buildings (Navratil et al., 2013; Okano et al., 2012). After the Wenchuan earthquake, a large number of debris flows occurred in gullies that had never experienced a debris flow disaster before the earthquake (the number of new debris flow gullies increased more than 1000-fold). Moreover, the new debris

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flow gullies are characterized by large longitudinal slopes, abundant material with drainage areas of less than five km^2, and a high occurrence frequency, whereas the characteristics of debris flow density and discharge appear to be variable (Cui et al., 2010). Debris flow prevention measures have been constructed in the new debris flow gullies, as these gullies are considered a serious threat to the safety of local residents, traffic routes, and hydropower projects. In particular, to ensure the safety of highways during the rainy season, debris flow drainage channels were constructed to allow for highway crossings of the debris flows.

Drainage channels are important prevention measures that can be constructed in any area where debris flows form and accumulate. These channels are widely used in debris flow prevention engineering because of their simple structure that is easy to construct and can be made of local materials. The Dongchuan-type drainage channel design and a V-shaped drainage channel design have been used extensively in debris flow prevention and mitigation projects (Fig. 1). Extensive studies have been conducted using both drainage channel designs (Wang, 1996; Li, 1997; Zhang and Lu, 2002; You and Liu, 2008; Chen et al., 2009; Huang et al., 2009; You et al., 2011). A V-type drainage channel is characterized by increased debris flow velocity, improved discharge capacity, and reduced siltation. This type of drainage channel may be suitable for use in debris flow gullies with a broad debris basin or where the main river has sufficient transport capacity. A Dongchuan-type drainage channel can reduce flow velocities and alleviate gully erosion and can be applied to debris flow gullies that are located upstream of towns, highways, and other critical infrastructure types. The problem of erosion during debris flow discharge affects both types of drainage channels, and from the perspective of anti-abrasion properties, a Dongchuan-type drainage channel is superior to a V-type drainage channel. The minimum longitudinal gradient of a Dongchuan-type drainage channel is 5% and 3.5% when discharging viscous and dilute debris flows, respectively. The minimum longitudinal gradient of a V-type drainage channel is >1% and >0.3% when discharging viscous and dilute debris flows, respectively. A V-type drainage channel is more suitable for solving the problem of sedimentation in gullies with gentle slopes by avoiding cumulative deposition in the drainage channel, which can affect performance. Reasonable longitudinal gradients for a Dongchuan-type drainage channel and V-type drainage channel typically range from 5% to 20% (Li, 1997), but numerous new debris flow gullies with steep slopes appeared in the earthquake area ($15\% < i < 50\%$; i = channel slope) after the Wenchuan Earthquake. If Dongchuan-type debris flow drainage channels and V-shaped drainage channels are selected to discharge debris flows in gullies with small watersheds and large longitudinal slopes, the drainage channels can easily be damaged by scouring and abrasion. Thus, a new type of drainage channel with an energy dissipation structure is proposed based on previous engineering experience and practical requirements of damage mitigation. During 2012 and 2013, this new type of drainage channel was used to effectively discharge a debris flow into a debris flow basin, protect a nearby highway, and minimize losses of property and life (Chen et al., 2014a; Chen et al., 2014b).

To demonstrate the effectiveness of this new type of drainage channel in preventing debris flows in gullies, an experimental study was performed at the Dongchuan Debris Flow Observation and Research Station (DDFORS). Based on existing research methods and results obtained by studying the drainage channel, the characteristics of drainage channels with energy dissipation structures were analyzed, including flow patterns, debris flow depths, velocities at the rear of the energy dissipation structure, and energy dissipation characteristics. These experimental results may provide a theoretical foundation for an optimized design for drainage channels with energy dissipation structures that are used to control debris flows.

2. Experimental configuration

Experiments were conducted at DDFORS, Chinese Academy of Sciences. A drainage channel with an energy dissipation structure is a new type of debris flow channel consisting of several energy dissipation structures that are installed at appropriate locations between two sidewalls. The experimental model consisted of four components: a hopper, a drainage channel, an energy dissipation structure, and a tailing pool. The experiments were conducted in an L = 8-m-long open water channel with a rectangular cross section of 0.6×0.5 m (width × height). All sidewalls in the test section were made of reinforced glass, and the bottom slab was a steel plate. Fig. 2 is a schematic of the experimental configuration, where L is the length of the channel, B is the channel width, L_1 is the length of the inlet section, L_2 is the length of the energy dissipation structure section, L_3 is the length of the outlet section, b is the width of the energy dissipation structure, and w is the length of the energy dissipation structure, which was 0.3 m. In a narrow and steep gully, the slope of the drainage channel is steeper. For example, the watershed area of the Xiaogangjian gully is approximately 1.36 km^2, and the average channel slope of the gully bed is approximately 41.2%, with a volume of source material distributed in the upstream region of the watershed area of approximately 334.3×10^4 m^3. To protect the safety of a highway and local residents, a drainage channel with an energy dissipation structure was proposed and built crossing the highway and discharging debris flows into a debris flow basin (Chen et al., 2014a). The channel was built from a series of prefabricated reinforced concrete boxes with open top surfaces, and the remaining five sides enclosed with stones (with diameters ranging from 0.03 m to 0.05 m). Stones were filled to 2/3 of the height of the concrete boxes. This type of concrete box was used to construct the sidewalls of a drainage channel by Chen et al., (2014b). However, in this study, prefabricated reinforced concrete boxes were installed in the channel slab as an energy dissipation structure. In the experiments, the energy dissipation structure in the drainage channel was made of 0.005-m-thick steel plates, which effectively resisted debris flow

(a) Dongchuan-type drainage channel

(b) V-type drainage channel

Fig. 1. Drainage channels used for debris flow mitigation engineering.