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The role of bank erosion on the initiation and motion of gully debris flows

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ABSTRACT

The erosion of sediment through the exchange of momentum and energy transfer within the debris flow affects the unstable motion of the debris flow. Many models have been established to study the impact of erosion on debris flow motion, but most of the models were based on bed erosion. This paper analyzed the process of unstable motion of debris flows through an experimental flume to contrast bank erosion-dominated conditions and bed erosion-only conditions. The experiments showed that bank erosion enhanced the formation and propagation of debris flows. The volume of sediments eroded by water and the debris flow mass for the bank erosion-dominated conditions was much greater than that for the bed erosion-only conditions. The height and velocity of the debris flows fluctuated, and the total basal normal stress and pore pressure increased unsteadily along the path under both conditions. However, bank erosion increased the velocity of the debris flow and made the motion fluctuation more obvious. Physical equations were established and the analyses suggested that bank erosion-dominated debris flows had increased resistance and gradient enhancement than that of bed erosion-only debris flows.

1. Introduction

Debris flows are a widely distributed and frequently occurring hazard in mountainous regions. Many different types of mass movements are regarded as debris flows (Iverson, 1997): debris torrents, debris floods, mudflows, mudslides, and hyperconcentrated flows. However, it is more important to classify debris flows according to their dynamic characteristics. The forces that support the largest particles during the motion of these kinds of flows mainly result from two actions (Armanini et al., 2009): the dispersive pressure resulting from collisions among the particles (Bagnold, 1954) and the plastic strength of the interstitial fluid when this is composed of a clay or mud slurry (Coussot and Ancey, 1999). Turbulence of the interstitial fluid is generally too weak to support the largest particles (Takahashi, 1978). For each specific type of flow, different rheological schemes using one of the two cited mechanisms are generally applied (Armanini et al., 2005). Based on the composition of the solid materials and fluid, debris flows are also classified as one-phase debris flows and two-phase debris flows (Wang et al., 2014). A one-phase debris flow is non-Newtonian, has a large yield stress, and exhibits laminar flow and intermittent features in many cases. In two-phase debris flows, the solid phase consists of gravel and boulders and the liquid phase consists of water with clay and silt in suspension (Wang et al., 1999). It has been observed that the relative motion between the solid phase and the liquid phase is obvious, with the liquid phase transporting the solid phase from the debris flow body to the debris flow head, passing the energy to the flow head (Wang et al., 2014). In this study, debris flows are defined as flows composed of mixtures of water and non-cohesive and relatively large particles, which corresponds to stony debris flows or two-phase debris flows. For this kind of debris flow, the friction force is of fundamental importance, because the resistance of the debris flow is mainly induced by collision of the coarser fraction. Visco-plastic debris flows or mudflows, in which the stoppage is the result of reduction of stresses below a threshold value, are not discussed in this paper (Coussot, 1997; Fraccarollo and Papa, 2000).

After the 2008 Wenchuan Earthquake in China, many mass movements occurred on the banks of mountainous gullies in Sichuan province in southwestern China. The loose, coarse particle materials from these mass movements were easily moved by floods and formed stone debris flows. The loose materials on the banks played a significant role in the formation and motion of the debris flows where (1) floods from heavy rainfalls eroded the loose materials on the banks and washed them directly into the debris flows and (2) floods eroded the gully bed and washed away the materials at the bottom of the riverbanks, causing the banks to steepen, become unstable, and eventually, for the unstable materials to fall into the river and become part of the debris flow.

It is critical to understand the role of bank erosion and bed erosion on the formation and motion of debris flows. Bank erosion and bed erosion determine the threshold of rainfall that could trigger a debris flow and the magnitude of the debris flow. In a steep gully, sediment

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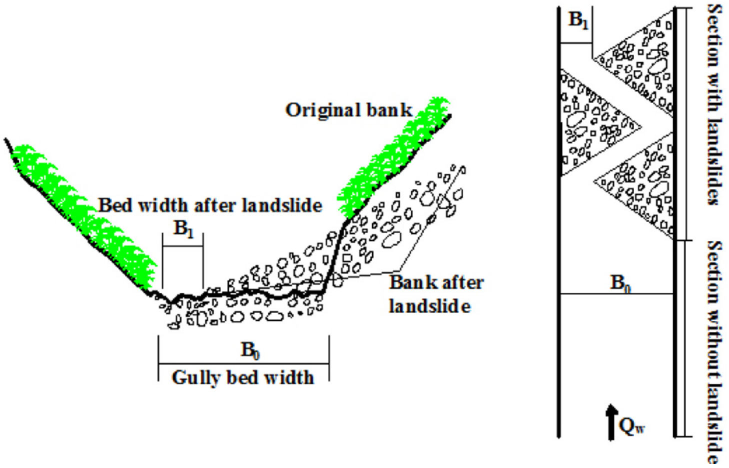
a Sections with landslide occurring on the bank slopes of the debris flow gully , Yellow River basin.

b Sections without landslides occurring on the bank slopes of the same debris flow gully, Yellow River basin.



c Sketch map of sections of a debris flow gully with and without landslides.

Fig. 1. Different sections of debris flow gully with and without landslides.

accumulates gradually due to the supply from rock-falls and landslips. Because the gully concentrates the water flow, the gully bed will likely be washed out by a large magnitude water flow following an intense rainfall event. Less frequently, the rapid melting of snow cover caused by the effects of an abrupt atmospheric temperature rise can supply an unusually large amount of water. The surface water flow at the source of a gully may only be a thread-like stream on the gully bottom. If such a stream satisfies the conditions for debris flow initiation, the flow will erode not only the channel bed but also the banks of the incised channel. In such cases, the bank erosion was probably promoted by the shear stress of the interstitial fluid. The shear stress that initiated the movement of the sediment on the bank was considered to be a half of the shear stress initiating the movement of the same amount of sediment on the bed (Takahashi et al., 1993). Some research has discussed the bank erosion process associated with debris flows. These studies suggest that on one hand, bank erosion increases the mass and density of the debris flow, while on the other hand bank erosion increases the friction resistance of the debris flow (Benda, 1990; Berti et al., 1999; Remaître, 2006; Godt and Coe, 2007; Breien et al., 2008). The density and the frictional resistance of the debris flow continue to change (Reid et al., 1997; McDougall and Hungr, 2005; Takahashi, 2009), which increases or decreases the velocity of the debris flow (Mangeney et al., 2010).

The initiation and motion of debris flows that are generated mainly through bank erosion, rather than by bed erosion, are not well understood. Field data on debris flows are of utmost importance for improving knowledge of complicated erosion processes associated with debris flows. For example, for the same debris flow gully (coordinates of the gully toe: E100°1′18″, N35°31′8″) in Tibet (Fig. 1), some sections of the bank slope were affected by many landslides, while in some sections no landslides occurred. As shown in Fig. 1a, the landslides occurring on the bank slopes occupied the most of the gully and narrowed its width from B_0 to B_1 (Fig. 1c). The water discharge rate was assumed the same in the different sections of the same gully. The same water discharge may lead to different scales of debris flows when water flows through the different sections of the gully that either contain or do not contain landslides.

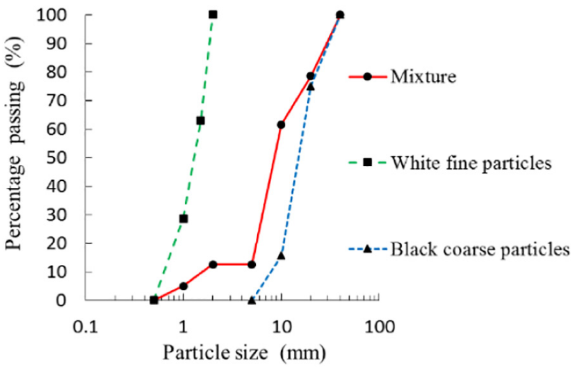


Fig. 2. Sediment size distributions used in the experiments.