Experimental study of entrainment behavior of debris flow over channel inflexion points

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Abstract: On-spot observation and field reconnaissance of debris flows have revealed that inflexion points in the longitudinal profile of a movable channel may easily become unstable points that significantly affect their entrainment behavior. In this study, small-scale flume experiments were performed to investigate the entrainment characteristics of debris flows over two types of inflexion points, namely, a convex point, which has an upslope gradient that is less than the downslope gradient; and a concave point, which has an upslope gradient that is greater than the downslope gradient. It was observed that when debris flowed over a convex point, the entrainment developed gradually and progressively from the convex point in the downstream direction, and the primary control factors were the slope gradient and friction angle. Conversely, when debris flowed over a concave point, the entrainment was characterized by impacting and impinging erosion rather than traditional hydraulic erosion, and the impingement angle of the flow significantly determined the maximum erosion depth and outflow exit angle. An empirical relationship between the topography change and the control factors was obtained from the experimental data.

Keywords: Debris flow; Entrainment; Inflexion points; Erosion; Impingement angle

Introduction

Debris flows entraining massive sediments while flowing down steeply hillslopes or channels may become exceptionally mobile and destructive (Hungr 2005). The entrainment factors that may increase the magnitude of the debris flow and substantially amplify its destructive power include the mobilization of discrete landslides, coalescence of erosional rills, and exceptional concentration of the surface water (Cannon et al. 2001; Wang et al. 2003; Godt and Coe 2007; Coe et al. 2008). For example, the Tsing Shan debris flow in 1990, which is considered to be the largest debris flow event in Hong Kong, had a small initial slip of 400 m³ but enlarged to a final volume of 20,000 m³ through the entrainment of colluvium along its flow path (King 1996). A giant debris flow that developed in...
the Wenjia catchment of China on 13 August 2010 transported about 3 million m$^3$ of sediment, most of which originated from the 2008 Wenchuan earthquake-induced landslides, to the downstream river (Tang et al. 2012).

Some mechanisms of debris-flow entrainment have been proposed. Sassa (1985) suggested that loading by overriding debris flows could transiently increase the pore pressure in saturated bed sediments, and that an excess pore pressure might nearly liquefy the bed, thereby significantly reducing the bed sediment shear strength and facilitating entrainment. Takahashi (1978, 1991) proposed that saturated bed sediment failed as a whole and groundwater pressure in the sediment was in equilibrium with the sloping water table in an overriding debris flow, and there was thus no transient development of excess pore pressure. Hungr (2005) derived a modified equation from Takahashi's equation based on the observation that a steady seepage condition could hardly be achieved within the short duration of the passage of a surge peak. Iverson et al. (2011) performed debris flow flume tests and observed positive feedback and momentum growth when a debris flow entrained wet bed sediments. Iverson (2012) considered the mass and momentum exchange between a debris flow and an underlying sediment layer, and suggested that the entrainment rates satisfied a jump condition involving shear traction and velocity discontinuities at the flow bed boundary.

With regard to the calculation of the entrainment rate, Takahashi et al. (1986) suggested the concept of the equilibrium sediment concentration and used it to evaluate the erosion entrainment rate, while Egashira et al. (2001) proposed an erosion rate formula based on the assumption that the bed slope always adjusts to its equilibrium state when a debris flow occurs over an erodible bed. However, Suzuki et al. (2009) found some problems in the application of these formulas under highly unsteady conditions, and proposed a new entrainment rate equation based on the assumption that the difference between the amounts of sediment in the debris flow and the equilibrium state controls the erosion and deposition. Brufau et al. (2000) encountered a paradox in the use of Egashira's equation to calculate the entrainment rate on an adverse slope, namely, that the equation always tends to produce deposition even when erosion should occur. They thus introduced the slope of the energy line and obtained ideal results even for adverse slopes.

It is obvious from the foregoing that the entrainment process of a debris flow is closely related to the topographic conditions of the channel. Shied et al. (1996) proposed that the process of deposition within the range of the abrupt variation of the bed inclination was non-equilibrium, and that the local concentration could not be estimated by Takahashi's equilibrium equation. Hence, in the present study, we investigated the effects of the topographic inflexion points along the channel on the entrainment behavior of a debris flow. Such inflexion points are mainly formed by plentiful loose material, which might have originated from landslides and avalanches induced by intense seismic shaking and post-seismic rainfalls (Lin et al. 2006; Koi et al. 2008; Lin et al. 2008; Khattak et al. 2010). The super strong erosion by debris flows happened at these inflexion points such as Zhouqu event of August 8, 2010 and Qingping event of August 13, 2010 in the western China greatly reduced the stability of channel beds and rockfall dams, and hence increased debris-flow magnitude (Tang et al. 2011; Hu et al. 2012; Cui et al. 2013)(Figure 1).

As shown in Figure 2, the abrupt deposition of loose material in the channel changes the original bed morphology, resulting in an irregular distribution of inflexion points, where the upslope gradient is not equal to the downslope gradient. This alternation of steep and gentle slopes in the longitudinal profile of the channel may easily cause the inflexion points to become unstable points where strong erosion is initiated. As described by Tang et al. (2012), the thick accumulations of loose landslide material in the Wenjia mainstream reshaped the channel topography and made it prone to erosion and remobilization into debris flows during periods of intense and prolonged rainfall. The above-mentioned theories and equations of debris flow entrainment involve various factors that affect the entrain process, including the sediment pore pressure and water content and the changes in mass and momentum. However, the effects of external topographic conditions such as inflexion points were rarely considered in the development of the theories and equations.