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Evolution of debris flow properties and physical interactions in debris-flow mixtures in the Wenchuan earthquake zone

H.X. Chen, L.M. Zhang *, S. Zhang

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

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ABSTRACT

The 2008 Wenchuan earthquake triggered an exceptional number of landslides. The large amount of loose landslide materials on the steep terrains can easily turn into debris flows by heavy rainfall. During the wet seasons from 2008 to 2011, five destructive debris flows occurred repeatedly in Yingxiu, the study area near the epicenter. This paper presents the evolution of debris flow properties and physical interactions in the debris flow mixtures in the past few years. Seven dimensionless numbers are used to describe the physical interactions. The evolution of the physical interactions over time was influenced by changes in debris-flow compositions, which in turn affected the runout characteristics of the debris flows significantly. Grain contact friction was the most important physical interaction for the five debris flows in the study area. With gradual loss of fine particles over time, the viscosity of the debris-flow mixtures became lower and lower, leading to a change from the dominance of viscous shear over solid–fluid interactions and inertial grain collision to the dominance of solid–fluid interactions and inertial grain collision over viscous shear. With inertial grain collision being more and more important, the flow resistance of the debris flows increased. The mobility of the future debris flows may become smaller and smaller.

1. Introduction

A high magnitude earthquake can trigger a large number of landslides, leaving a large amount of loose materials on steep terrains. Such materials can easily lose stability and provide source materials for debris flows once triggered by heavy rainfall (L.L. Zhang et al., 2011). Hence, debris flows are often very active in earthquake stricken areas (e.g. Lin et al., 2003; Liu et al., 2008; C.W. Chang et al., 2011; Lin et al., 2011), especially in mountainous areas. Such effect can last up to 20 years (Chen et al., 2011).

The impact of earthquakes on the occurrence of debris flows has been widely researched (e.g. Lin et al., 2003; Dadson et al., 2004; Koi et al., 2008; Liu et al., 2008; Chang et al., 2009; Chen et al., 2011; H.X. Chen et al., 2012; J.C. Chen et al., 2012; Tang et al., 2012; Xu et al., 2012). Due to earthquake-induced landslides and other reasons, the activity of debris flows may change significantly after a strong earthquake compared with that before the earthquake (Dadson et al., 2004; Koi et al., 2008; J.C. Chen et al., 2012). The magnitude and frequency of debris flows can increase sharply while the critical rainfall to trigger the debris flows can decrease obviously (e.g. Lin et al., 2003; Chang et al., 2009; Chen et al., 2011; Tang et al., 2012). A stronger ground motion would lead to a larger change in debris flow density (Liu et al., 2008). The size of the contributing drainage basin in which debris flows occur can become much smaller than that before the earthquake (Lin et al., 2003; Liu et al., 2008).

The characteristics of debris flows evolve with time after a major earthquake, which is influenced by changes in supply of source materials and the mass movements of such materials. With the mass movement caused by debris flows, the amount of loose materials in debris flow gullies decreases gradually. The magnitude, frequency and density of debris flows will decrease correspondingly, while the critical rainfall to trigger debris flows may recover to a certain level. For example, Shieh et al. (2006) found that the triggering rainfall of debris flows in central Taiwan immediately after the 1999 Chi-Chi earthquake was only 1/4 of the original value, and it recovered to 1/2 of the original value in 2004, five years after the earthquake. The materials brought out by debris flows generally flow into the river system, which may elevate the river bed significantly (H.X. Chen et al., 2012). Then the mass transport along the river can affect the downstream area for a very long time (Dadson et al., 2004; Koi et al., 2008).

Although the general evolution of the activity of post-earthquake debris flows has been well researched, the understanding about the evolution of the debris flow properties and runout characteristics over time is still rather limited. The reported cases of repeated debris flows in earthquake zones are also limited. How does the composition of the debris flow material evolve with time? How do the runout characteristics of the debris flow mixture change over time? What are the key factors that govern the runout characteristics? How does one quantitatively evaluate the evolution of the key factors with time? After the Wenchuan earthquake, five debris flows occurred in Xiaojiagou Ravine and Pubugou

* Corresponding author.
E-mail addresses: chenhx@ust.hk (H.X. Chen), cezhangl@ust.hk (L.M. Zhang), zhangshuaiqj@ust.hk (S. Zhang).

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Ravine near the epicenter, Yingxiu, repeatedly from 2008 to 2011. The five repeated debris flows provide us solid evidence for answering these questions.

The behavior of debris flows varies with the composition of the flowing material (Sosio and Crosta, 2009). For muddy debris flows, experimental tests show that the flow behavior is governed by the amount and properties of the interstitial fluid (O'Brien and Julien, 1988; Major and Pierson, 1992; Coussot and Piau, 1995; Sosio and Crosta, 2009), and can be described by the Bingham model or the Herschel–Bulkley model (Laigle and Coussot, 1997; Remaitre et al., 2005; Sanchez et al., 2013). For granular debris flows, direct contact produced by the noncohesive particles, solid–fluid interactions, and grain contact friction may be dominant over viscoplastic behavior provided by the cohesive fraction (Iverson, 1997). The effects of direct grain contacts cannot be neglected in studying the rheological behavior of this type of debris flow (Sosio et al., 2007). According to Iverson (1997) and Coussot and Ancey (1999), different flow regimes can be distinguished by the use of several dimensionless numbers.

The transport process of a debris flow may be quantified by examining the physical interactions within the debris-flow mixture, and such physical interactions are expected to change over time. The primary objective of this study is to study the evolution of the debris flow properties and physical interactions in the debris flow mixtures in the Wenchuan earthquake zone by studying the five repeated debris flows in Xiaojiagou Ravine and Pubugou Ravine. The impact of such evolution on the debris flow runout characteristics will also be investigated. The study will help to attain a better understanding of the long-term evolution of debris flows in the Wenchuan earthquake zone, which is important for debris flow risk assessment and mitigation.

2. Study area

The study area, including Xiaojiagou Ravine, Pubugou Ravine, is only 5 km from the epicenter, Yingxiu, of the 2008 Wenchuan earthquake (Figure 1). It has an elevation range between 1000 m and 3540 m above the sea level and a local relief of 2540 m. The catchment area, drainage basin length (i.e. the straight line distance between the fan apex and the farthest point on the drainage basin perimeter), and local relief of Xiaojiagou Ravine are 7.84 km^2, 3600 m, and 2100 m, respectively (H.X. Chen et al., 2012). The three parameters for Pubugou Ravine are 3.06 km^2, 2450 m, and 2100 m, respectively (Zhang et al., 2014a). There are one main drainage channel and four branches in Xiaojiagou Ravine (Figure 2); the mean slope of the main channel is 27.3°. Pubugou Ravine consists of two sub-basins as shown in Fig. 2. The mean slopes of the two gullies are both larger than 34°. The 12 May 2008 Wenchuan earthquake triggered numerous landslides, producing a large amount of loose materials in the study area (Zhang et al., 2012, 2014b). The removable material volume was estimated to be 7.44 × 10^6 m^3 in Xiaojiagou Ravine (H.X. Chen et al., 2012; Chen et al., 2013) and 5.6 × 10^6 m^3 in Pubugou Ravine. The outcropping lithologies in the study area are mainly Proterozoic magmatic rocks, namely, diorite, biotitic granite, and granodiorite (Figure 2). The maximum and mean annual precipitations in the study area are 1225 mm and 828 mm, respectively. Approximately 68% of the total precipitation falls between June and September. Yuzixi River flows from west to east, with a channel width of 20–40 m (Figure 2). The river is supplied mainly through rainfall and secondly through groundwater and alpine snow melting. According to the records in Yuzixi Hydrological Station, the maximum discharge was 1230 m^3/s and the minimum one was 4.7 m^3/s.

3. Debris flow events in Xiaojiagou Ravine

3.1. Debris flow on 14 August 2010

From 12 to 14 August 2010, a storm swept Yingxiu and its vicinity. The rainfall amounts in Yingxiu Town, Xuankou Town and Shuimo Town from 8:00 on 13 August to 8:00 on 14 August were all larger than 153 mm. These three places are about 5, 10, and 15 km from the study area, respectively (Figure 1). The debris flow at Xiaojiagou Ravine was witnessed to occur at the ravine mouth at about 5:00 on 14 August, and lasted about 30 min. The main source materials were from the colluvium in the channels deposited during the 2008 Wenchuan earthquake. The source area and deposition zone of the debris flow are shown in Fig. 3. A large amount of debris material ran out of the ravine mouth (Figure 4a). The runout material was obstructed by the right bank of Yuzixi River, causing flow along the river channel. The runout distance of a channelized debris flow can be defined as the horizontal path length from the apex of the debris fan to the lowest point of the debris fan (Rickenmann, 2005). The runout distance of the event was 593 m. The area, length, height, and average thickness of the debris fan were 54916 m^2, 545 m, 66 m, and 15 m, respectively. The average slope of the debris fan was about 7°. The total volume of the channelized debris flow was 1.01 × 10^6 m^3. A sand mine and a construction

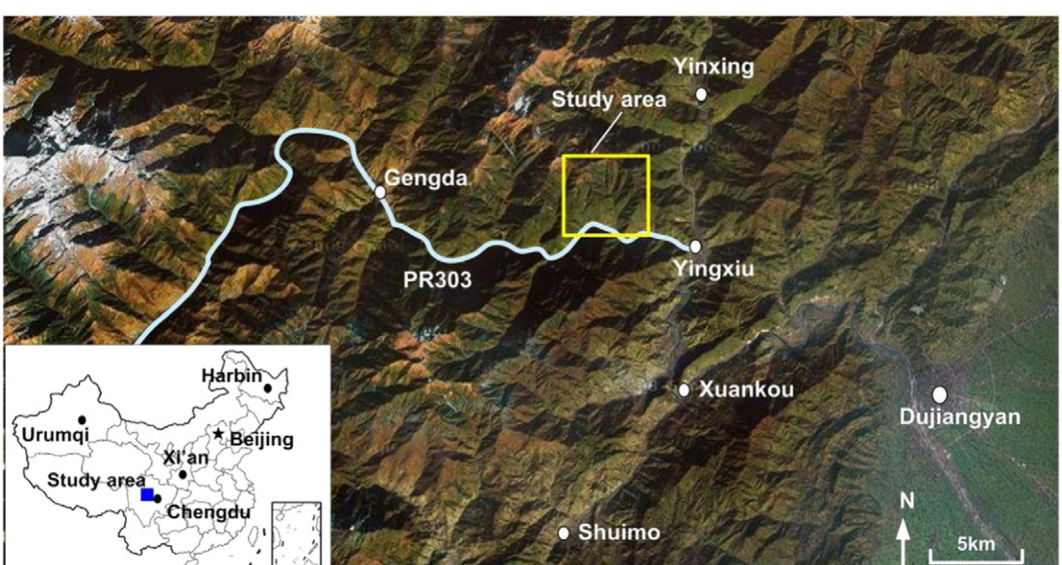

Fig. 1. Location of the study area.