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Impact of the 2008 Wenchuan earthquake in China on subsequent long-term debris flow activities in the epicentral area

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ABSTRACT

The 2008 Wenchuan earthquake triggered the largest number of landslides among the recent strong earthquake events around the world. The loose landslide materials were retained on steep terrains and deep gullies. In the period from 2008 to 2015, numerous debris flows occurred during rainstorms along the Provincial Road 303 (PR303) near the epicentre of the earthquake, causing serious damage to the reconstructed highway. Approximately 5.24×10^6 m^3 of debris-flow sediment was deposited shortly after the earthquake. This paper evaluates the evolution of the debris flows that occurred after the Wenchuan earthquake, which helps understand long-term landscape evolution and cascading effects in regions impacted by mega earthquakes. With the aid of a GIS platform combined with field investigations, we continuously tracked movements of the loose deposit materials in all the debris flow gullies along an 18 km reach of PR303 and the characteristics of the regional debris flows during several storms in the past seven years. This paper presents five important aspects of the evolution of debris flows: (1) supply of debris flow materials; (2) triggering rainfall; (3) initiation mechanisms and types of debris flows; (4) runout characteristics; and (5) elevated riverbed due to the deposited materials from the debris flows. The hillslope soil deposits gradually evolved into channel deposits and the solid materials in the channels moved towards the ravine mouth. Accordingly, channelized debris flows became dominant gradually. Due to the decreasing source material volume and changes in debris flow characteristics, the triggering rainfall tends to increase from 30 mm h^{-1} in 2008 to 64 mm h^{-1} in 2013, and the runout distance tends to decrease over time. The runout materials blocked the river and elevated the riverbed by at least 30 m in parts of the study area. The changes in the post-seismic debris flow activity can be categorized into three stages, i.e., active, unstable, and recession.

1. Introduction

Debris flows are among the most frequent mass movement processes in mountainous areas after a strong earthquake (Keefer, 1984; Jakob and Hungr, 2005; Lin et al., 2006). The 12 May 2008 Wenchuan earthquake in China triggered about 56,000 landslides (Parker et al., 2011; Gorum et al., 2011). Numerous loose deposits were retained on steep hillslopes exceeding 40° in many places or in channels. These deposits are in a quasi-stable state in the dry season but can provide source materials for debris flows in the wet season (Zhang et al., 2012). Province Road 303 (PR303) is the only path from the epicentre of the Wenchuan earthquake, Yingxiu, to the Research and Conservation Centre for Giant Panda at Wolong (Fig. 1). During the past seven years (2008–2015), numerous debris flows occurred along PR303 (Fig. 1), particularly during the storms on 14 August 2010, 4 July 2011, and 10 July 2013. The mixture of debris and water transports rapidly from low-order tributaries and eventually joins with a trunk drainage where an alluvial fan builds. Such mass transport processes are considered as the main cause of hillslope evolution (e.g., Larsen et al., 2010; Griffiths et al., 2015). Several questions arose regarding the characteristics of the regional debris flows in the Wenchuan earthquake area. How did the source materials evolve during these storm events? How did the triggering rainfall for debris flows change over time? How could the initiation mechanisms of debris flow change? How did the runout and deposition characteristics evolve? How long will it take for the debris flow activity to be stable after the Wenchuan earthquake? Answers to these questions are very important both for understanding the evolving characteristics of debris flows after a strong earthquake and for developing long-term strategies for debris flow risk mitigation. Most previous studies focused on the coseismic landslide activities. There have been limited records on the evolution of debris flows over a long period after a strong earthquake (Nakamura et al., 2000; Chiou et al., 2007; Lin et al., 2008). During rainy seasons, mass movements in gullies are enhanced and contribute a large quantity of source materials for debris flows via hillslope failures. A sequence of five debris flows captured by a monitoring system in the

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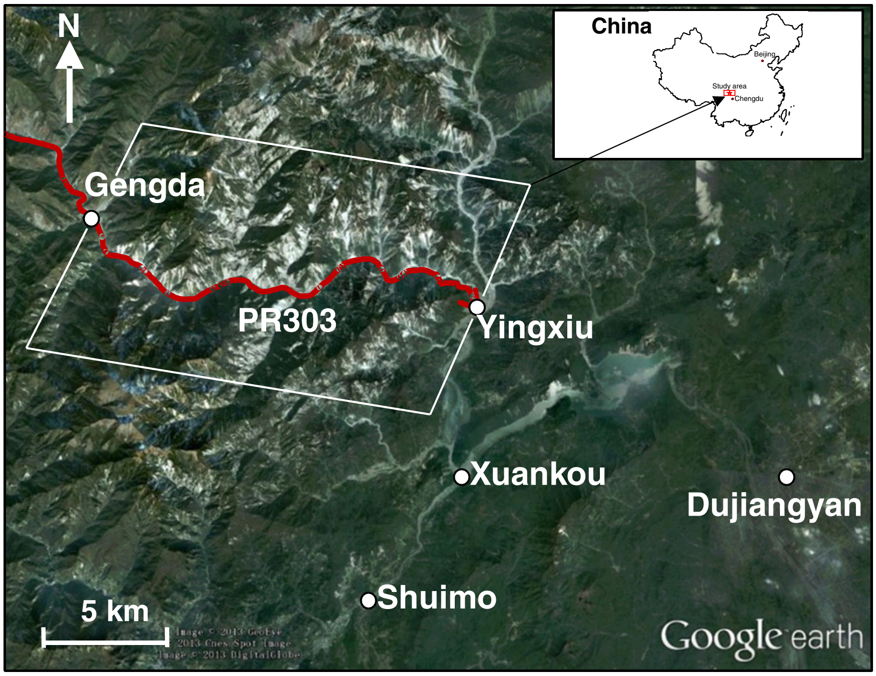

Fig. 1. Location of the study area. The image is from Google Earth.

Ichinosawa catchment, Japan, in 2003 illustrated the seasonality of sediment transport (Imaizumi et al., 2006). Changes in volumes of channel deposits estimated from photographs showed that the maximum deposition (14,000 m^3) occurred in spring and the minimum deposition (390 m^3) occurred near the end of autumn. In the Illgraben catchment in Switzerland, according to Berger et al. (2011), on average approximately 100,000 m^3 of debris flow materials per year were transported from 2000 to 2009 based on observations. The Chenyulan River watershed in central Taiwan was used to evaluate the impact of the 1999 Chi-Chi earthquake on the occurrence of debris flows, and to explore the initiation conditions of debris flows (Lin et al., 2003; Chang et al., 2011a). Significant differences before and after the earthquake were noticed in (1) the rainfall intensity and amount of precipitation required for triggering debris flows; (2) the covering area of a drainage basin in which debris flows occurred; and (3) the frequency of large-scale debris flows (Lin et al., 2003). The source materials in a catchment during three torrential rainfall events after the Chi-Chi earthquake (i.e., Toraji event on 31 July 2001, Haitang event on 20 July 2005, and the 9 June 2006 event) decreased with the occurrence of repeated debris flows, which were recorded as 402,585 m^3, 269,500 m^3 and 256,000 m^3, respectively (Chang et al. 2011a). Relationships among earthquake disturbance, tropical rainstorms and debris movements in Taiwan were also reported by Chen and Hawkins (2009). They reviewed mass movement ratios of new and reactivated landslides before and after the Chi-Chi earthquake. Subsequent to the 1999 earthquake, the heavy rainfall associated with typhoons resulted in the development of numerous landslides as well as the reactivation of some pre-existing movements. However, many of the landslides formed at the time of the Chi-Chi earthquake did not appear to have been reactivated. During Typhoon Toraji in 2001, 13% of the mass movements delivered debris to the channel network, significantly less than 24% at the time of Typhoon Herb (before 1999). This might be due to inter-block locking of the loosened material and the removal of surface debris, facilitating the free egress of water (Chen and Hawkins, 2009). Hence most earthquake-induced landslides remained confined to hillslopes (Dadson et al., 2004). After the Wenchuan earthquake, numerous debris flows occurred in the earthquake stricken area and many of these events have been reported. For example, Tang et al. (2015) investigated the catastrophic impact of a debris flow in the Hongchun catchment near the earthquake epicentre. The study revealed that earthquake shaking severely disturbed the surface strata and that the hillslopes were then conditioned to enhance the likelihood of future landsliding and debris flows under heavy rainfall conditions. Xu et al. (2012) investigated the source material evolution in 11 debris flows in the vicinity of Qingping Town in the Wenchuan earthquake area that occurred during 12-14 August 2010. In these debris flow events, approximately 20% of the landslide deposits evolved into debris flows. Yet the changing characteristics of regional debris flows in the past seven years after the strong earthquake are still poorly documented.

In order to check the impact of the 2008 Wenchuan earthquake on the subsequence debris flow activities, we consistently examined the post-seismic debris flow activities along PR303 in the epicentral area of the Wenchuan earthquake via extensive field investigations, remote sensing and laboratory testing during the past seven years (Zhang et al., 2013, 2014a, 2014b; Zhang and Zhang, 2015). The characteristics of earthquake-induced landslides in 2008 and the rain-induced landslides in 2010 have been reported earlier. This paper aims to evaluate the evolution of debris flows that occurred after the Wenchuan earthquake in the epicentral area. The detailed objectives are to: (1) analyse the movement of source materials of the debris flows; (2) discuss the triggering rainfall, initiation mechanisms and types of these debris flows; (3) evaluate the evolution of runout characteristics and the elevated riverbed due the deposited materials; and (4) propose a preliminary conceptual model on the evolution of debris flow activity, which provides a critical reference on the impacts of a strong earthquake and the subsequent rainstorms on the post-seismic debris flow activities. In this paper, the term 'landslide' refers to a slope failure, i.e., masses of rock, earth or debris moving down a slope, and the term 'debris flow' refers to a fluidized debris mass movement, which is generally induced by shallow failures or erosion and entrainment of hillslope or channel materials by surface runoff after intense rainfall.

2. Geological setting

PR303 is primarily along the Yuzixi River that is bounded by terrains with elevations from 880 m at Yingxiu Town (the epicentre) to 5040 m at the highest mountain peak (Fig. 1). The terrain in this area is rugged and very steep as revealed in a slope gradient analysis in a GIS platform