Proc. of the 6th Intl. Symposium on Reliability Engineering and Risk Management (6ISRERM)
31 May – 1 June 2018, Singapore
Editor(s) Xudong Qian, Sze Dai Pang, Ghim Ping Raymond Ong, Kok-Kwang Phoon

Long-term Evolution of Debris Flow Activities at the Epicenter of Wenchuan Earthquake

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The 2008 Wenchuan earthquake triggered numerous landslides in the stricken area. The loose landslide materials on mountain slopes and in gullies are prone to reactivation and may transform into debris flows in the rainy season. Nine years after the 2008 Wenchuan earthquake, landslide activities are still active in the study area near the epicenter of the earthquake in Sichuan, China. The debris flows blocked the Minjiang and Yuzixi river and caused severe damage to nearby villages and reconstruction sites. How did the mechanisms evolve in these repeated debris flows? We evaluated the loose deposit volumes in catchments of the triangle study area before and after each heavy storm since the earthquake, and analyzed the triggering rainfall intensities, initiation mechanisms and runout characteristics of these debris flows. The preliminary results of a case study in Gaojiagou Ravine show that the rainfall threshold for debris flows increased with time, the initiation mechanisms evolved from landslides to channel-bed failure and subsequently to channel-bank erosion. The mobility of the debris flows decreased from 2010 to 2016 as the initiation positions moved lower and the particle size of the runout materials became coarser.

Keywords: Earthquake, Debris flow, Landslide, Slope stability, Long-term evolution.

1 Background

A debris flow is a flow of mixture of sediment and water in a manner as if it was a flow of continuous fluid driven by gravity, and it attains large mobility from the enlarged void space saturated with water and slurry (Takahashi, 2014). The 2008 Wenchuan earthquake caused tremendous numbers of collapses, landslides, and barrier lakes (e.g. Cui et al., 2008). A large quantity of loose materials deposited on the steep hillslope and supply ample source materials for the initiation of debris flows. During the rainy season, some of the hillslope deposits evolved into channel deposits and the materials in the channels gradually moved forward to the gully mouth (Zhang et al., 2014; Zhang et al., 2016). The triangle area near the epicenter suffered the most severe damage (Figure 1). This area is located between the Maoxian-Wenchuan Fault and the Yingxiu-Beichuan Fault, and on the hanging wall of the latter. A higher landslide density was identified in the hanging wall after the 2008 Wenchuan earthquake (Tolga Gorum et al., 2011). Since the 2008 Wenchuan earthquake, debris flows occurred almost annually in some of these catchments, especially in 2010, 2011, 2013 and 2016.

A number of consecutive debris flows in the Wenchuan earthquake area have been reported. But most of them focused on the first to third years right after the Wenchuan earthquake. The time span of debris flows in the triangle area has been nine years since the Wenchuan earthquake,

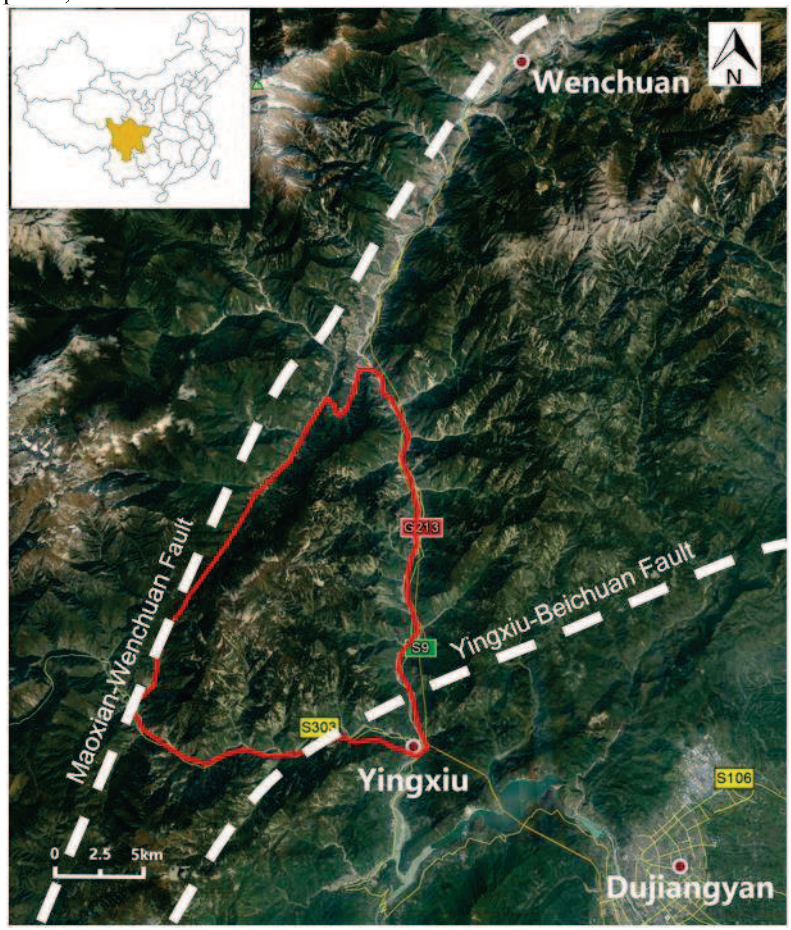

Figure 1. Location of the study area.

but debris flows are still active. To better understand the evolution process of debris flows in the seismic area and give reference to risk analysis and mitigation for engineering constructions, it is important to evaluate the long-term evolution of the rainfall threshold for debris flows in the Wenchuan earthquake area, debris flow initiation mechanisms and runout characteristics.

This paper aims to investigate and compare the debris flow events near the epicenter in 2010, 2011, 2013 and 2016, and to analyze the evolution mechanisms from three perspectives: rainfall threshold, initiation mechanism and runout characteristics. A case study is presented to illustrate the preliminary study results.

2 Introduction to the study area

The total area of the study area is approximately 260 km^2, with an elevation difference of 3200 m from the lowest point at Yingxiu Town (873 m) to the summit (4073 m). The study area includes 13 catchments and numerous free-surface slopes, mainly consisting of rugged slopes and deep gullies. The bedrock of the study area is primarily highly weathered Quaternary Jingningian Period intrusive granite, with intensely developed joints. The cover soil is thin and mainly composed of Quaternary glacial deposits, diluvium, colluvium and alluvium. The study area is located within the Mianchi-Yingxiu zone of rainfall with an annual rainfall of 933 mm.

The maximum recorded 24-h rainfall was 270 mm. Most of the yearly rainfall occurs during the wet season from May to September (Gao et al., 2014). The groundwater is mainly shallowly restored magmatic rock fissure water, and the supply is almost equal to the discharge (Zhang et al., 2012).

3 Research methodology

A GIS analysis platform is adopted to interpret satellite images over the study area. Digital Elevation Model (DEM) with a spatial resolution of 25 m was used to generate slope angles and elevations. One SPOT image of the study area in 2008, two sets of Worldview-2 satellite images in 2010 and 2011, and two sets of SPOT images in 2013 and 2016 were collected. From these images, the catchment boundary and the branches are delineated, and the landslide scars and deposits are identified.

Field investigations were undertaken to confirm visual interpretation based on the remote sensing data. Landslide scars and debris flow deposition fans are investigated to determine the age and geometry dimensions. The average deposit thickness was measured using a laser range finder. Fine depositional material samples were collected and sieving tests were performed in the geotechnical laboratory of the Hong Kong University of Science and Technology. A large number of high-resolution pictures of coarse deposition materials were taken for grid-by-number analysis (Zhang et al., 2011) and for runout characteristics analysis.

Nineteen rain gages and one meteorological station were installed along the S303 and G213 after the heaviest rainfall storms in 2013. A rockfall monitoring system, a high resolution camera and many particles vibration sensors were installed at selected ravine mouths. From these sensing devices, accurate rainfall data and real-time debris flows information were captured, providing great assistance in debris flow hazard analysis.

4 Preliminary results

Detailed research of debris flow evolution has been conducted in Gaojiagou Ravine, one of the 13 catchments in the study area. On 14 August 2010, 3 July 2011, 13 July 2013, and 6 July 2016, four large-scale debris flows were triggered by heavy storms in Gaojiagou Ravine.

4.1 *Rainfall intensity*

Rainfall records are compared in the four debris flow events, all the four triggering rainfall intensities exceeded the empirical rainfall threshold generated from the recent local events (Zhou and Tang, 2013). The initiation rainfall intensities of the Gaojiagou debris flows show an increasing trend after the significant drop in 2008 due to the Wenchuan earthquake. The rising trend of the rainfall threshold is mainly attributed to the reduced source materials, the increased particle size and the restoration of vegetation. With the outburst of previous debris flows, the amount of the source materials retained in the ravine decreased with time, and the loose materials consolidated over time; the fine particles in the surface soil layer eroded in overland flow, and the remaining coarser particles are of higher erosion resistance (Chang et al., 2011); the vegetation on the loose soil deposits developed gradually and the roots enhanced the erosion resistance significantly, particularly the critical shear stress that is required to initiate erosion (Shen et al., 2017).

4.2 *Initiation mechanisms*

The 2008 Wenchuan earthquake produced an enormous amount of loose materials in Gaojiagou Ravine, which can reactivate and transform into debris flows. On 14 August 2010, many soil

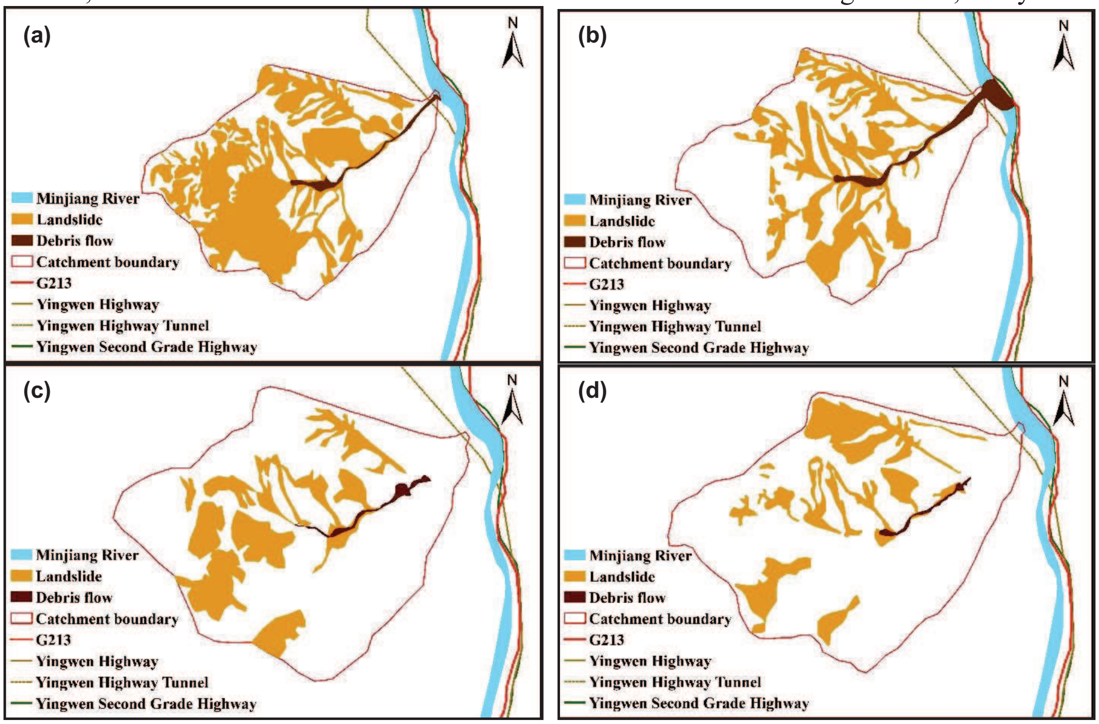

Figure 2. Distributions of hillslope loose deposits and debris flows in Gaojiagou Ravine: (a) 2010; (b) 2011; (c) 2013; (d) 2016.

deposits lost stability and slid into channels, forming debris flows (Chen and Zhang, 2014). Landslides were the dominant initiation mechanism in the early evolution course from 2008 to 2010. Failure of landslide dams was identified in the 2011 debris flow, which created a catastrophic debris flow surge. Channel-bed erosion was the dominant initiation mechanism for the debris flows in 2011 and 2013. Channel bank erosion was also observed in Gaojiagou Ravine in 2016 debris flow.

The intrinsic reasons for the changes in initiation mechanisms lie in the reduced source materials and the long-term effects of the earthquake (Figure 2). Right after the earthquake, the adequate loose and relatively fine soil deposits could reactivate easily amidst heavy rainfall; hence landslides were the dominant initiation mechanism of debris flows. As a large part of the loose materials slipped into the channels, the channel-bed erosion, instead of the landslides, became the major initiation mechanism. In the future, the source materials will continue to decrease while the vegetation will further restore on the hillslope. As a result, the channel bed erosion will decline but the erosion of bare cracked channel banks will become the major source of new debris flows.

4.3 *Runout characteristics*

From 2010 to 2016, both the travel distance and the runout distance exhibited a decreasing trend. This shortening trend is attributed to several factors. (1) The supply of the source materials reduced dramatically, hence the volume and mobility of debris flows tend to decrease with time. (2) As the initiation points of the debris flows moved to lower elevations, the potential energy of the debris decreased accordingly. (3) As the soil grains become coarser, the flow mixture has a higher content of coarse particles and lower mobility (Table. 1).

Table 1. Statistics of coarse content (gravel and cobbles) and fine content (fines and sand) of the depositional materials in four debris flow events.

Soil type	Sample 1 (2010)	Sample 2 (2011)	Sample 3 (2013)	Sample 4 (2016)
Gravel and cobble (≥2 mm)	76%	86%	92%	91%
Fines and sand (0.09-2 mm)	21%	13%	7%	9%

5 Conclusions

Four heavy storms happened in 2010, 2011, 2013 and 2016 near the epicenter after the 2008 Wenchuan earthquake, which triggered large-scale debris flows. Four debris flow events in Gaojiagou Ravine are investigated to study the long-term evolution mechanisms of debris flows in seismic areas. The following conclusions can be drawn:

- The initiation mechanisms evolved from landslides to channel-bed failure and subsequently to channel-bank erosion. The initiation positions of the four debris flows moved to lower elevations in accordance with the three initiation mechanisms.
- The runout characteristics changed greatly over time, showing a trend of decreasing travel distance and runout distance. The lowered initiation positions and the reduced fine particle content contributed to the shortened travel distance.
- The rainfall intensity values in all the four debris flow events in 2010, 2011, 2013 and 2016 exceeded the rainfall threshold of the post-seismic debris flows. The triggering rainfall shows an increasing trend.

Acknowledgments

The authors acknowledge the support from the Research Grants Council of the Hong Kong SAR (No. C6012-15G and No. 16206217) and the technical assistance from Dr Shuai Zhang on the geological settings.

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