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Evolution of debris flow activities in Gaojiagou Ravine during 2008–2016 after the Wenchuan earthquake

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ABSTRACT

The 2008 Wenchuan earthquake in Sichuan, China triggered numerous landslides in the stricken area. The loose landslide materials retained on mountain slopes and in gullies are prone to reactivation and may transform into debris flows in the rainy season. Nine years after the Wenchuan earthquake, debris flows are still active in Gaojiagou Ravine 16.5 km north of the epicentre. 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. The four debris flows blocked the Minjiang River twice and caused severe damage to nearby villages and reconstruction sites. Several questions arise from these repeated debris flows. Did the level of triggering rainfall change in the four debris flow events? How did the initiation mechanism evolve over time? What are the differences in the runout characteristics in the four events? How did the check dams constructed in 2012 function in the subsequent debris flows? In this paper, we evaluated the loose deposit volumes in Gaojiagou Ravine before and after each of the four debris flows and the runout volumes, and analysed the triggering rainfall intensities, initiation mechanisms and runout characteristics of the four debris flows. The rainfall threshold for the debris flows in Gaojiagou Ravine increased over time, and 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.

1. Introduction

A debris flow is a very rapid to extremely rapid surging flow of saturated debris in a steep channel (Hungr et al., 2014). Mass wasting due to earthquakes plays an essential role in triggering debris flows and other geohazards (e.g., Lin et al., 2004; Dadson et al., 2004; Chen et al., 2011; Chen et al., 2012; Chen et al., 2014; Zhang et al., 2014a; Shen et al., 2016; Robinson et al., 2016). 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. 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., 2014c; Zhang et al., 2016). These deposits supply ample source materials for the initiation of debris flows.

The Gaojiagou Ravine is located on the right side of the Minjiang River, the National Road G213 and the Province Road S9 (Fig. 1). G213 and S9 are vital highways connecting Wenchuan County and Yingxiu Town, the epicentre of the 2008 Wenchuan earthquake. The distance from the ravine to the epicentre is 16.5 km. Since the 2008 earthquake, four large-scale debris flows occurred in Gaojiagou Ravine, respectively in 2010, 2011, 2013 and 2016. The debris flows in 2010 and 2011 poured into the Minjiang River, changed the flow path of the river and flooded the vicinity area. Particularly in 2011, the Mingjiang River was completely blocked and over 400 m of bridge foundations of G213 was ruined. In 2012, two large check dams and several small dams were constructed to prevent debris flows from running into the Minjiang River. However, the reservoirs of the two dams were almost filled by the 2013 and 2016 debris flows. Several researchers studied the debris flow in 2011 as it caused intensive destructions. Gao et al. (2014) analysed the initiation mechanism and "block-burst" movement characteristics of the 2011 debris flow. Chang et al. (2016) evaluated the possibility of river blocking by debris flows based on the movement characteristics of the 2011 Gaojiagou debris flow. However, the long-term evolution of debris flow activities in the research area has not been examined. The four large debris flow events together make Gaojiagou Ravine an ideal research area to study debris-flow evolution mechanisms.

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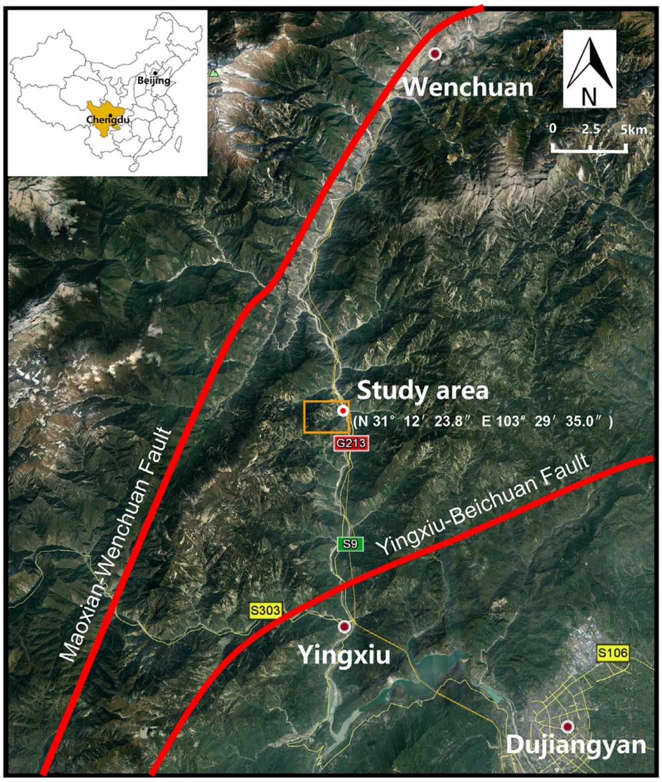

Fig. 1. Location of the study area.

A number of consecutive debris flows in the Wenchuan earthquake area have been reported. Chen et al. (2014) studied two repetitive debris flows in Xiaojiagou Ravine and two debris flows in Pubugou Ravine from 2008 to 2011, focusing on flow properties, physical interactions and runout distances. Zhang et al. (2014b) analysed the solid material movements, initiation mechanisms and depositional morphology of three debris flows in Pubugou Ravine from 2008 to 2011. These studies covered debris flow activities in the first three years after the earthquake. Chen et al. (2011) pointed out that the impact of the Wenchuan earthquake on debris flow activities would be significant in the first 5–6 years and much less afterwards. The timespan of Gaojiagou debris flows has been nine years since the earthquake 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, runout characteristics and deposition properties.

This paper aims to investigate and compare the four debris flow events in Gaojiagou Ravine near the epicentre in 2010, 2011, 2013 and 2016, and to analyse the evolution mechanisms from four perspectives: rainfall threshold, initiation mechanism, runout characteristics and depositional property changes.

2. Study area

2.1. Morphology

The total area of the Gaojiagou ravine is approximately 3.72 km^2, with an elevation difference of 1809 m from the ravine mouth (1051 m) to the apex (2860 m). The geographical coordinates of the ravine mouth are N 31°12′23.8″ and E 103°29′35.0″ (Fig. 1). The ravine consists mainly of rugged slopes with an average longitudinal gradient of 551‰ along the longest flow channel (Fig. 2). There are five deep gully branches in the ravine: Primary Gully, Nantianmen Gully, Longwo

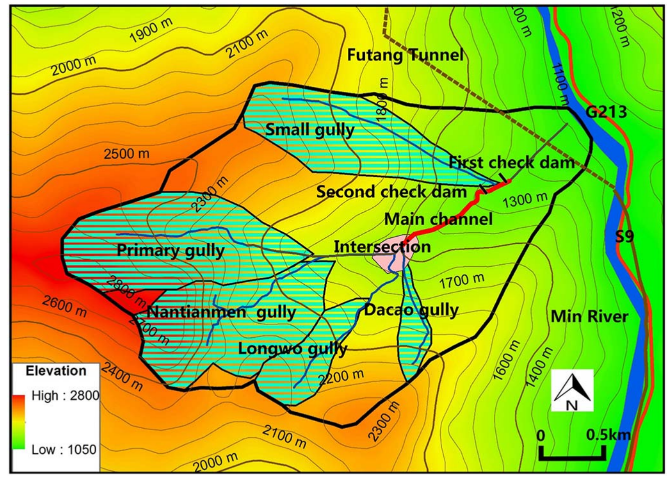

Fig. 2. Elevations and branches of Gaojiagou Ravine.

Gully, Dacao Gully and Small Gully. As shown in Fig. 2, the Primary Gully, Nantianmen Gully and Longwo Gully joint at an intersection point from which the main flow channel starts.

2.2. Geological conditions

The bedrock of the study area is primarily highly weathered Quaternary Jingningian Period intrusive granite, with intensely developed joints (Fig. 3). The cover soil is thin and mainly composed of Quaternary glacial deposits, diluvium, colluvium and alluvium. According to Zhang et al. (2014c), slopes consisting of hard rocks such as granite and diorite are relatively high and steep; hence extensive collapses occurred during the Wenchuan earthquake and a tremendous amount of loose materials was retained on the steep hillslope and in the gullies. The calculated area of the landslide scars and soil deposits is as high as 53% of the total ravine area before the 2010 debris flow (Fig. 4b).

2.3. Hydrological conditions

The ravine 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 primary river system is the Minjiang River, an important tributary of the Yangtze

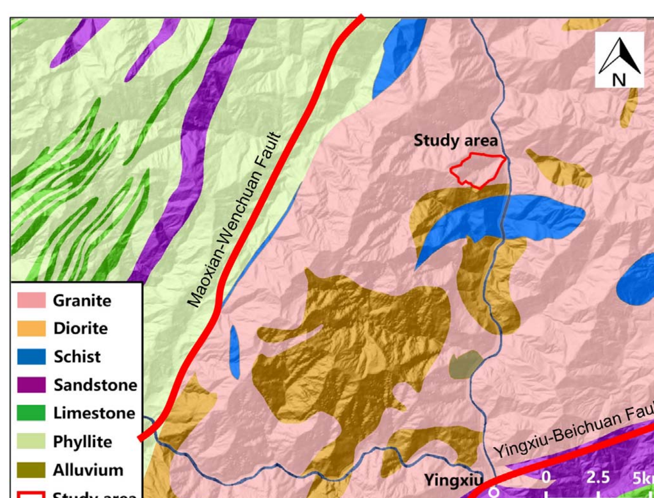

Fig. 3. Geological settings of the study area.