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Scale amplification of natural debris flows caused by cascading landslide dam failures ☆

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ABSTRACT

Debris flows are typically caused by natural terrain landslides triggered by intense rainfalls. If an incoming mountain torrent collapses a series of landslide dams, large debris flows can form in a very short period. Moreover, the torrent can amplify the scale of the debris flow in the flow direction. The catastrophic debris flows that occurred in Zhouqu, China, on 8 August 2010 were caused by intense rainfall and the upstream cascading failure of landslide dams along the gullies. In the wake of the incident, a field study was conducted to better understand the process of cascading landslide dam failures and the formation of debris flows. This paper looks at the geomorphic properties of the debris-flow gullies, estimates the peak flow discharges at different locations using three different methods, and analyzes the key modes (i.e., different landslide dam types and their combinations) of cascading landslide dam failures and their effect on the scale amplification of debris flows. The results show that five key modes in Luojiayu gully and two modes in Sanyanyu gully accounted for the scale amplification of downstream debris flows in the Zhouqu event. This study illustrates how the hazardous process of natural debris flows can begin several kilometers upstream as a complex cascade of geomorphic events (failure of landslide dams and erosion of the sloping bed) can scale to become catastrophic discharges. Neglecting recognition of these hazardous geomorphic and hydrodynamic processes may result in a high cost.

1. Introduction

Debris flows occur when masses of poorly sorted sediment, agitated and saturated with water, surge down a slope in response to gravitational attraction (Iverson, 1997). Debris flows differ from rock avalanches and sediment-laden water floods in that both solid and fluid forces influence its motion and govern the rheological properties of the debris flow (Iverson, 1997). Indeed, most debris flows mobilize from static sediment that is laden with water and poised on a slope. Usually, a landslide that becomes agitated and disaggregated as it tumbles down a steep slope can transform into a debris flow if it contains or acquires sufficient water for saturation. Some of the largest and most devastating debris flows have originated in this manner (e.g., Plafker and Ericksen, 1978; Scott et al., 1995). When mass movement occurs, the sediment–water mixture transforms into a flowing, liquid-like state, which eventually transforms back into nearly rigid deposits (Iverson, 1997).

In mountainous areas, excessive rainfall or snowmelt usually causes strong flash floods upstream. Abundant granular material deposited along channels in the region can easily cause erosion and entrainment of debris by floods, which allows gradual transformation of a flood into a debris flow. Note that landslides are usually the dominant mechanism for conveying large amounts of debris to river channels (Korup et al., 2004); when a landslide is connected with a channel, landslide debris can be transported to the channel (Schwab et al., 2008). Indeed, several studies indicate that much of the sediment produced in upper basins often does not immediately migrate downstream but is instead deposited in a riverbed, resulting in channel aggradation (Kasai et al., 2004; Koi et al., 2008). Furthermore, other studies have reported that large landslides inundate river valleys and overwhelm channels with large volumes of coarse materials, commonly forming stable landslide dams that trigger extensive and prolonged aggradation upstream (Ouimet et al., 2007). Thus, large debris flows are likely caused by the conjunction of many landslide dams of different scales (from bank slides or collapses), bed erosion, and solid transport (Davies, 1986).

The catastrophic debris flows that occurred at Zhouqu in Gansu Province of China on 8 August 2010, are considered to have been induced by upstream flash floods owing to intense rainfall (Hu et al., 2010; Yu et al., 2010; Zhao and Cui, 2010; Tang et al., 2011). Before the disaster, the sloping channels were blocked by clusters of landslide

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dams (cf. Ma and Qi, 1997) that included almost all of the categories summarized and illustrated by Costa and Schuster (1988) based on their various relationships with the valley floor. When upland floodwaters moved downward at high speed and crushed the obstructing landslide dams, the channel blockage was first gradually broken, then rapidly widened the incision (cf. Costa and Schuster, 1988; Chang and Zhang, 2010). Sediment delivery of the landslide debris by the high speed stream flows was quite large, easily forming debris flows (cf. Scott et al., 1995; Iverson, 1997; Chien and Wan, 1999). The debris flows crossed Zhouqu's urban area, destroying streets, houses, and bridges and causing 1765 deaths. Moreover, the debris flows rushed into the Bailong River and formed a dammed lake about 550 m in length and 70 m in width, which flooded half the city.

After the disaster, landslide dams in varying degrees of collapse were observed along the sloping channel. Thus, we can postulate that incoming streams may have caused cascading landslide dam failures. During the process, the magnitude of the sediment flow is believed to have significantly increased because of these dam failures, as the geography downstream from those landslide dams consists of steep canyons with easily erodible granular materials that can be entrained into the flow and can increase flood peaks. There are many case studies of individual natural-dam failure (e.g., Costa and Schuster, 1988; Korup, 2002; Cleary and Prakash, 2004; Korup et al., 2004), but an integrated view of the cascading failure of clusters of landslide dams falling like dominoes along the slope channels does not exist. The mechanisms underlying such a failure process, and the resulting increase in magnitude of downstream debris flows, are still not clear.

To understand this important natural process, a field study was conducted to systematically investigate the debris flows that occurred in Zhouqu. Specifically, we attempt to estimate the size and distribution of the large landslide dams along the gullies. By complementing the documented post-failure morphodynamic histories of each respective site from upstream to downstream, this paper aims to determine the evolution of cascading landslide dam failures initiated by upland flash floods and the variation in flow discharge during the process. Different combinations of landslide dams along the channel that account for the occurrence of flood peaks are then discussed to determine the key modes underlying cascading landslide dam failure.

2. Background of the Zhouqu debris flows

The Zhouqu debris flows occurred in two large gullies, Sanyanyu and Luojiayu, located in the Gannan Tibetan Autonomous Prefecture, Gansu Province of China. The Sanyanyu gully is usually further divided into two large gullies, Dayu and Xiaoyu, which converge at point 'OO' in Fig. 1A, B, and C. The urban area of Zhouqu township is located on the deposited fan (see Fig. 1A and D), and was seriously destroyed by large-scale debris flows from the gullies starting at about 23:40, 7 August 2010 (see Fig. 2A). The debris flows thrust through the urban area, destroying all buildings along the flow as shown in Fig. 2B, then rushed into the Bailong River and formed a dammed lake. The makeshift lake flooded half of the urban area for over 20 days (see Fig. 2C), interrupting electric power, communications, and water supply.

2.1. Geomorphic and geological properties

As a part of the southern area of Gansu Province (which is located in the northern section of the Chinese north–south seismic belt), Zhouqu is located in the west tectonic zone of the Qinling Mountains and is significantly influenced by the Indo-China orogeny and Yanshan movements. New tectonic movements in the area are frequent: hills strongly uplift, gullies rapidly incise, and mountainous areas of high relief are usually formed. The tectonic activities in the late Quaternary period were quite intensive in this region, inducing developed faults and frequent earthquakes. All of the recorded, closely correlated earthquakes—e.g., the Wudu earthquake (M_S 7) in B.C. 186, the Tianshui earthquake (M_S 8) in 1654, and the Wenxian–Wudu earthquake (M_S 8) in 1879—caused serious losses in Chinese history. All three of the above-mentioned earthquakes occurred near Zhouqu (see Fig. 3A), triggering large collapses and landslides that were instrumental in depositing loose solid materials in the gullies of the area. As illustrated by Keefer (1999), high magnitude earthquakes play an important role as preparatory and triggering variables for landslides, reducing slope stability through rock shattering, fault zone weakening, slope tilting, and topographic amplification of ground shaking (cf. Hancox et al., 1997; Korup, 2005). Those landslides usually accumulated in sloping channels, gradually forming the multiple landslide dams as shown in Fig. 1B and C. Those landslide dams are natural barriers, blocking the granular material of upstream debris flows and causing a large volume of solids to accumulate at these points.

Previous investigation by Ma and Qi (1997) illustrated that eight large slope failures (with a total area of 0.88 km^2) had developed in the Sanyanyu gully, with a total sediment volume of 1.30×10^7 m^3. The area had a total of 58 potential collapse areas encompassing 2.83×10^7 m^3 of debris, with additional solids deposited on the channel bed amounting to about 1.03×10^7 m^3. Ma and Qi estimated that 2.51×10^7 m^3 of the total available debris (amounting to 5.16×10^7 m^3) could be entrained and involved in debris flows (Ma and Qi, 1997). The geomorphic properties of Luojiayu gully are quite similar to that of Sanyanyu gully, except for a narrower sloping channel. Although the scale of the landslide dams in Luojiayu gully is relatively smaller, the distribution of the landslide dams along the channel is much denser (cf. Fig. 1B and C). At least two large landslide dams (higher than 10 m) are located in each section with an average 500-m channel length (totally about nineteen landslide dams, as illustrated by Fig. 1C), with lots of sediment accumulation. The landslide dams are usually stable under low rainfall conditions but react quite differently with intense rainfall. Large flash floods induced by these intense rainfalls can mobilize the deposited sediments behind the landslide dams and initiate downstream debris flows.

The fault zone of the Bailong River possesses the major active faults of the basin (see Fig. 3B). Moreover, this fault zone is also composed of a cluster of secondary faults, mainly characterized by reversed faults and left-lateral strike-slip faults. Tectonic activity from the late Quaternary period was quite intensive, leaving obvious changes to the geography of the region. The Bailong River further divides the fault zone into north and south branches (see Fig. 3B). Both branches of the fault zone are fully developed in Zhouqu, and the north branch even penetrates through the downtown area. Fig. 3B shows that the north branch consists of three parallel faults: the Animaqing fault, the Pingding-Huama fault, and the Zhouqu fault, with the Zhouqu fault the most southern of the three. The branch's eastern and middle parts are basically distributed along the valleys of the Bailong River; they twice cut into the river and penetrate into the city from the west, and are the most dangerous to Zhouqu township. The direction of the Zhouqu fault is N.60°W., inclined to the southwest with a steep angle (60–70°). The total penetration length of the fault inside Zhouqu county is about 50 km. Typically, the Zhouqu fault is considered to have been an active fault into the late Pleistocene period. The geomorphic characteristics of the Zhouqu fault are the terraces, whose activities and properties can be described as follows: (i) the morphology terraces are well developed

Fig. 1. Sequential air photography showing massive aggradation on the lower town and Bailong River following the Zhouqu debris flow on 8 Aug. 2010. (A) The satellite image shows the gully morphology where Dayu gully and Xiaoyu gully converge at 'OO'; (B) locations of the landslide dams and sections of field investigation along Dayu gully; (C) locations of the landslide dams and sections of field investigation along Luojiayu gully; (D) Zhouqu township located on the deposited fans (the area bracketed by d_1–d_2 and A′-A″). Image courtesy of the Chinese State Bureau of Surveying and Mapping.