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# A preliminary study of the failure mechanisms of cascading landslide dams

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ABSTRACT

Landslide dams commonly form when mass earth or rock movements reach a river channel and cause a complete or partial blockage of the channel. Intense rainfalls can induce upstream flows along a sloping channel that significantly affect downstream landslide dams. If a series of landslide dams are collapsed by incoming mountain torrents (induced by intense rainfall), large debris flows can form in a very short period. Furthermore, the failure of these dams can amplify the magnitude and scale of debris flows in the flow direction. The catastrophic debris flows that occurred in Zhouqu County, China on 8 August 2010 were caused by intense rainfall and the upstream cascading failure of landslide dams along the gullies. Incorporating the role of outburst floods associated with the complete or partial failure of landslide dams is an interesting problem usually beyond the scope of analysis because of the inherent modeling complexity. To understand the cascading failure modes of a series of landslide dams, and the dynamic effect these failures have on the enlargement of debris flow scales, experimental tests are conducted in sloping channels mimicking field conditions, with the modeled landslide dams distributed along a sloping channel and crushed by different upstream flows. The failure modes of three different cascades of landslide dams fully or partially blocking a channel river are parametrically studied. This study illustrates that upstream flows can induce a cascading failure of the landslide dams along a channel. Overtopping is the primary failure mechanism, while piping and erosion can also induce failures for different constructed landslide dams. A cascading failure of landslide dams causes a gradually increasing flow velocity and discharge of the front flow, resulting in an increase in both diameter and percentage of the entrained coarse particles. Furthermore, large landslide blockages can act to enhance the efficiency of river incision, or conversely to induce aggradation of fluvial sediments, depending on the blockage factor of the landslide dams and upstream discharge.


## 1. Introduction

A landslide that becomes agitated and disaggregated as it tumbles down a steep slope can usually transform into a debris flow if it contains or acquires sufficient water for saturation. Some of the largest and most devastating debris flows originate in this manner (e.g., Plafker & Ericksen, 1978; King et al., 1989; Scott et al., 1995). It has also been widely reported that large landslides can 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, there has been a growing recognition that landsliding exerts a primary control on the planform development, incision history, and sediment discharge of watersheds (Hovius et al., 1997, 1998; Hewitt, 1998; Strasser & Schlunegger, 2005; Korup et al., 2006, 2010; Hsu & Hsu, 2009).

Landslide dams are a very common phenomenon in mountainous areas, forming when a landslide reaches the bottom of a river valley and causes a complete or partial blockage (Ermini & Casagli, 2003). Unlike an artificial gravity or concrete dam with engineered barriers and filter materials, a landslide dam is formed of an unconsolidated heterogeneous mixture of earth or rock debris in a naturally unstable

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state (Costa, 1985; Li et al., 2011). Freshly deposited landslide soils easily erode, which is a significant factor behind the initiation and development of breaches in landslide dams made from this material (Chang et al., 2011). The longevity of landslide dams depends on many factors, such as rate of inflow into the impoundment, the size and shape of the dam, its geotechnical characteristics, the size of the original landslide deposit (Costa & Schuster, 1988), and the step-pool development degree on the spillway of the landslide dam (Wang et al., 2012). Floods arising from the failure of such natural and constructed dams constitute a widespread hazard to people and property, in part due to the suddenness and unpredictability of dam failures of all types (Walder & O'Connor, 1997). The formation and failure of landslide dams are complex processes that occur at the interface between hill slopes and alluvial plain or valley-floor systems on the earth surface.

Understanding, simulating, and predicting the occurrence, longevity, breakdown, and subsequent debris flows of landslide dams have been the focus of a number of different multidiscipline studies (e.g., Costa & Schuster, 1988; Walder & O'Connor, 1997; Li et al., 2002, 2011; Chen et al., 2004; Korup, 2004; Iovine, et al., 2007; Corominas & Moya, 2008; Crosta & Clague, 2009; Dong et al., 2009, 2011; Nandi & Shakoor, 2009; Peng & Zhang, 2012). An important point is that most of these works have only concentrated on the failure of a single landslide dam. However, large earthquakes can cause clusters of landslide dams of multiple types to develop and be distributed close together in canyons (cf. Keefer, 1999; Korup, 2005; Cui et al., 2009). Despite the common occurrence of such phenomena, little attention has been paid to the cascading failure of clusters of landslide dams, which can fail like dominoes along sloping channels.

The catastrophic debris flows that occurred in the county of Zhouqu, in Gansu Province of China, (Aug. 8, 2010) are generally considered to have been induced by upstream flash floods due to intense rainfalls (Yu et al., 2010; Zhao & Cui, 2010; Tang et al., 2011). Before the disaster, the sloping channels of two gullies (Sanyanyu Gully and Luojiayu Gully) were blocked by clusters of landslide dams advancing from side valleys. These landslide dams consisted of almost all of the landslide categories as summarized and illustrated by Costa and Schuster (1988) based on their different orientations with the valley floor. When upland floods moved downwards at high speed and crushed the obstructive landslide dams, the channel blockage was first gradually broken, then followed by a rapid incision. The sediment delivery of the land-
slide debris by the high-speed stream flows was quite large, easily forming debris flows. The flows crossed Zhouqu's urban area, destroying streets, houses, bridges, and causing 1765 deaths. Moreover, the debris flows rushed into the Bailong River, forming a dammed lake about 550 m in length and 70 m in width (across the river), which flooded half of the city. As demonstrated by Tang et al. (2011), the failure of check dams and natural rockfill dams (landslide dams) in the torrent must have contributed to the considerable increase in peak flow discharge (cf. Tang et al., 2011).

After the disaster, there were many collapsed landslide dams of varying degrees along the sloping channel (Fig. 1). There were some large landslide dams with long run-out distances, which may have fully blocked the sloping channel before the debris flow event (Fig. 1a). Meanwhile, many landslide dams and rock dams combined together to fully block the sloping channels (Fig. 1b). These landslide dams were mainly composed of loosely contacted coarse particles that remained quite unstable. In addition to the landslide/rock dams fully blocking the channels, many clusters of other landslide dams only partially blocking the wide sloping channels could be found in the debris flow gullies (Fig. 1c). Based on post-flood field observations, we can postulate a cascading of landslide dam failures caused by upstream flows may have occurred. A breach of one of the landslide dams may have caused an anomalous flood wave to propagate downstream, inducing more breaches of downstream landslide dams.

This cascading failure effect can significantly amplify the magnitude of the outflow when there are multiple landslide dams distributed along a gully. Moreover, huge amounts of sediment (from the landslide dams and erodible channel beds) can be entrained into the flow to form debris flows. It is likely that large debris flows are due to the conjunction of many landslide dams of different scales (ranging from bank slides to full collapses of a channel wall), bed erosion, and solid transport (Davies, 1986). There are many case studies of individual natural-dam failures (e.g., Costa & Schuster, 1988; Korup, 2002; Korup et al., 2004; Cleary & Prakash, 2004), but an integrated view of the cascading failure of clusters of landslide dams failing like dominoes along slope channels does not exist. The mechanisms behind the cascading failure of different types of landslide dams are still not clear.

To understand this important natural process, we conducted physical experiments to systematically investigate the failure mechanisms of different cascading landslide dams caused by upstream flows. By analyzing the results from these experiments, this paper aims to infer the failure modes and the evolution of natural cascading landslide dams of different types and simulate those failure modes in modeled experiments.

## 2. Experimental method

### 2.1. Test site and soil properties of landslide dams

All experiments were conducted in the Jiangjia Ravine and on a debris fan of the Chaqing Gully, which are located near the Dongchuan Debris Flow Observation and Research Station (DDFORS) (Fig. 2), in the Dongchuan District, Yunnan Province of China (N26°14′, E103°08′). In previous years, most debris flows occurring in the Chaqing Gully and in the Jiangjia Ravine deposited on the fans with an inclined angle of approximately 6° and 4°, respectively. Fig. 3 shows the modeled sloping channels constructed on the floodplain of the Jiangjia Ravine and on the debris fan of the Chaqing Gully. To simulate the cascading failures of large landslide dams that fully block sloping channels, two model tests (No. 1 and No. 2) were conducted on the floodplain of the Jiangjia Ravine. The length of the channel was 15 m long, with a rectangular cross section 1.0 m wide and 0.5 m deep. A third model test (No. 3) was conducted on the deposition fan of the Chaqing Gully to take into account the failures of landslide dams triggered by local rock avalanches or collapses that only partially block sloping channels. The channel was 15 m long, with a rectangular cross section 0.5 m wide and 0.7 m deep. Local farmers had previously excavated a relatively straight aqueduct for irrigation that stretched from the main channel of the Jiangjia Ravine to downstream farmlands. This aqueduct was used to direct the sediment flows from the Jiangjia Ravine to the artificial sloping channel (Test No. 3) for modeling upstream flows, and to crush the downstream landslide dams distributed along the two banks of the channel. The sediment flows in the aqueduct move gently as the declination of the channel bed is quite small, which means discharge $Q_0$ can be controlled and kept relatively constant (Fig. 3). The densities of the sediment flows in the three modeling tests were measured to be about 1050 kg m$^{-3}$.

To clarify the processes involved in landslide dam failure, and to provide information on the effect of upstream flows and cascading landslide dam failures on the likely downstream peak discharge, we also constructed physical models of the rock/landslide dams. These dams were designed to be dynamically similar to the rock/landslide dams found in Zhouqu using similarity theory (Yalin, 1971). To emulate the poorly sorted soil properties of existing landslide dams, and to sufficiently reproduce the grain-size distribution in the models,