Engineering Geology 123 (2011) 40–59

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

# The formation and breach of a short-lived landslide dam at Hsiaolin village, Taiwan — part I: Post-event reconstruction of dam geometry

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A R T I C L E I N F O

*Article history:*
Received 13 July 2010
Received in revised form 29 March 2011
Accepted 2 April 2011
Available online 12 April 2011

*Keywords:*
Landslide dam
Heavy-rainfall-triggered
Short-lived
Geomorphic characteristic
Overtopping
Failure mechanism

A B S T R A C T

In this paper, technologies from multiple disciplines are used to reconstruct the shape of the Hsiaolin landslide dam, a short-lived landslide dam (SLD), that was triggered by Typhoon Morakot. Here, the formation, failure mode and breaching process of this SLD are investigated. The results indicate that the overtopping time and the debris budget constrained the dam geometry. The inferred volume of the Hsiaolin landslide dam (15.4 million $m^3$) is much smaller than the actual landslide volume (25.2 million $m^3$) even considering the rock-mass dilation and debris entrainment. Meanwhile, a 46% error could be induced if an over-simplified equation (a function of the dam height, length and width) is used to calculate the dam volume. The saddle of the dam crest, which is where overtopping occurred, could be used as a reference to measure the dam height and length. Accordingly, the determined dam dimensions of height (44 m), length (370 m) and width (1500 m) are suggested to be the representative geometrical indices that influenced the stability of the Hsiaolin landslide dam. The flow rate of the dammed river, another variable relevant to dam stability, was determined from a run-off simulation. It is suggested that, instead of the peak flow before the dam formation, the flow rate during the blockage period (2974 $m^3$/s) should be used as the training data for building a statistical model for stability predictions. Finally, the low hydraulic gradient at the toe of the dam's surface and the high safety factor of the dam slope indicate that the piping and slope instability were irrelevant to the failure of the Hsiaolin short-lived landslide dam. It is postulated that overtopping (about one hour after the blockage) dominated the failure process of this heavy-rainfall-induced landslide dam.



## 1. Introduction

### 1.1. Documenting the morphological characteristics of the landslide dam

Landslides may obstruct river flow and result in landslide dams. Such phenomena have occurred in many tectonically active regions of the world (e.g., Swanson et al., 1986; Costa and Schuster, 1988; Casagli and Ermini, 1999; Ermini and Casagli, 2003; Korup, 2004). The generation and disappearance of landslide-dammed lakes are the results of the interactions between a hill-slope and a valley-floor system. Understanding the processes involved in the formation and failure of landslide dams is crucial for the purpose of hazard mitigation, as well as for the reconstruction of ancient events and landscape evolution (Korup, 2002). However, landslide dams usually break down shortly after the formation of a landslide-dammed lake. Based on 63 cases from the literature, Schuster and Costa (1986) noted that "Many landslide dams maintain their integrity for only short periods of time — a few minutes to several days." Consequently, it is difficult to describe quantitatively the formation and breaching processes of a short-lived landslide dam (SLD), for which longevity ranged from a few minutes to several days.

There are two aspects that highlight the importance of completely and precisely documenting the morphological characteristics of an SLD and the related lake. Firstly, the current geomorphic approach is widely used to correlate the dam, river and water-storage characteristics with the stability of a landslide dam (Swanson et al., 1986; Costa and Schuster, 1988; Casagli and Ermini, 1999; Ermini and Casagli, 2003; Korup, 2004; Dong et al., 2009, 2011). However, the geomorphic data are incomplete and underreport small and ephemeral landslide dams while over-representing earthquake-related case studies (Korup, 2004). Therefore, adequate reporting of the formation and failing of a heavy-rainfall-triggered landslide dam is beneficial for understanding the

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doi:10.1016/j.enggeo.2011.04.001

impact of extreme weather on landslide dams. Secondly, detailed documentation of the processes of dam failure remains scarce (Korup, 2002), and any well-documented case example contributes to the field. To understand the breaching process and to simulate the catastrophic disasters caused by the outburst floods that frequently occur soon after the formation of a landslide-dammed lake, reconstructing the pre-failure dam geometry is required. In sum, gathering and restoring the morphological characteristics of a heavy-rainfall-triggered SLD through post-breach investigation are important both from the scientific and from the hazard-mitigation viewpoints.

### 1.2. Typhoon Morakot, the Hsiaolin landslide and the breach of the landslide dam

In 2009, Typhoon Morakot brought intense rainfall to southern Taiwan and caused 17 landslides that resulted in the formation of dams (Chen and Hsu, 2009). One such landslide dam was located at the Hsiaolin village, Southern Taiwan (E120°38′39.1″, N23°10′0.6″; Figure 1). Hourly rainfall records from three nearby rainfall stations (solid circles in Figure 1) are shown in Fig. 2. A total of 2138 mm of accumulated rainfall was recorded at the Jiashian #2 rainfall station. The peak hourly rainfall intensity was 95 mm/h, and the rainfall duration was 99 h.

This extremely heavy rainfall triggered a catastrophic landslide with a volume of more than $20 \times 10^6$ $m^3$ that mainly comprised shale and colluvium (Lee et al., 2009). The huge landslide buried over one hundred houses in Hsiaolin village and entered the Cishan River, where a landslide-dammed lake was formed. Seismic waves induced by the landslide were registered by the Taiwan Central Weather Bureau Seismic Network (TCWBSN), and the occurrence time can be precisely identified as 06:16 a.m. on 9 August (local time) (Tsou et al., 2011). A vivid account was given by the eyewitness: "…a sudden loud rumbling bang and two small bangs were heard, and at this precise moment, the nearby Cishan River became completely dry and not a single drop of water was seen in the riverbed. Following the banging noises, there were only rock boulders scattered about the riverbed…" About an hour, this SLD collapsed. Overflowing floodwater washed away part of the buried village. The Hsiaolin landslide, the breached

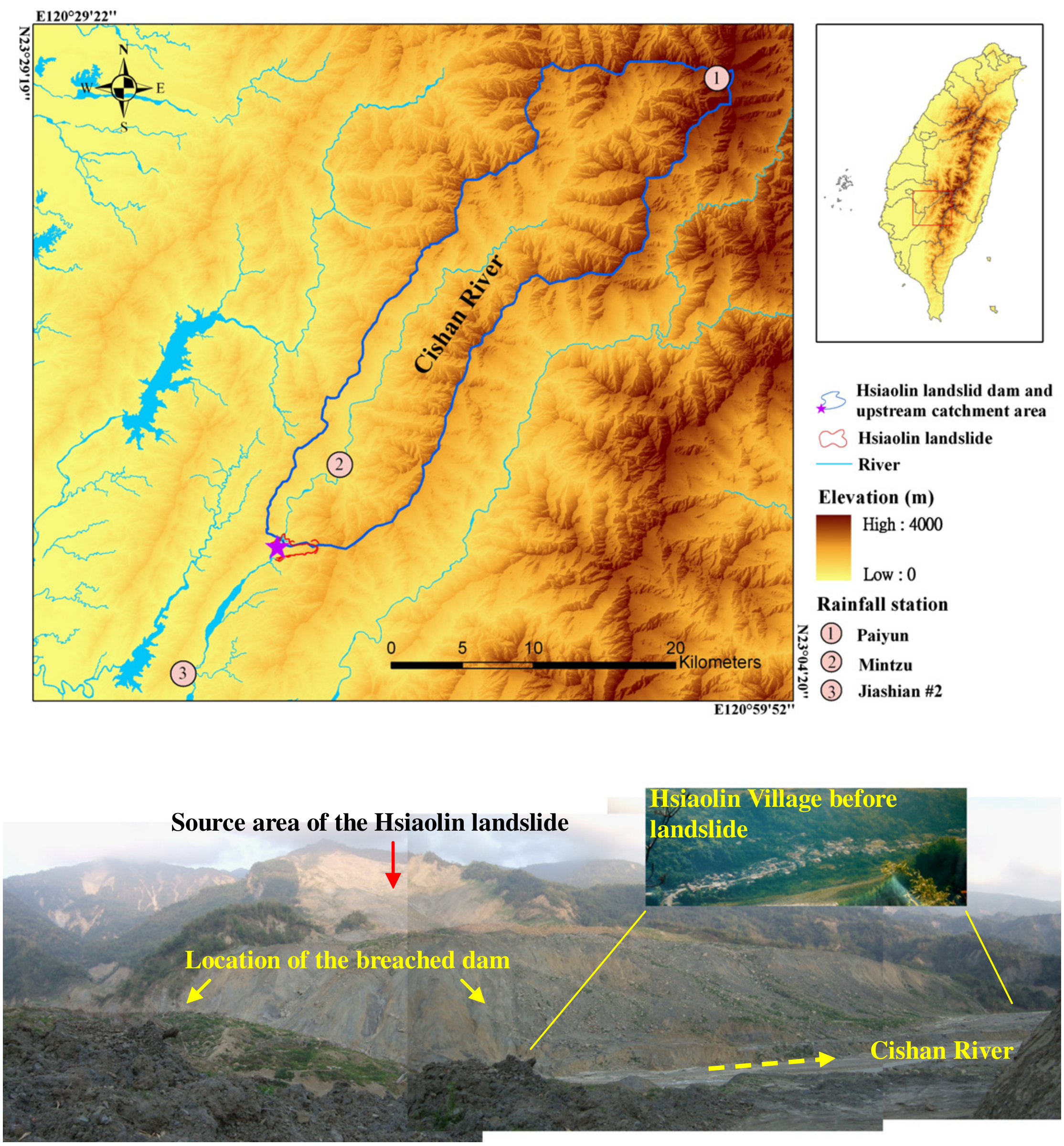


**Fig. 1.** The Hsiaolin landslide, the landslide dam and the buried Hsiaolin village. The landslide blocked the Cishan River and the landslide dam breached soon after the formation of an impounded lake. Blue line shows the drainage basin upstream of the Hsiaolin SLD. The boundary of the upstream catchment area is generated by the ArcHYDRO tool. The photo was taken from the west bank of the Cishan River shows the breached dam.