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Formation, failure, and consequences of the Xiaolin landslide dam, triggered by extreme rainfall from Typhoon Morakot, Taiwan

Abstract An extreme rainfall event on August 9, 2009, which was close to setting a world record for 48-h accumulated rainfall, induced the Xiaolin deep-seated landslide, which was located in southwestern Taiwan and had volume of $27.6 \times 10^6 \text{ m}^3$, and caused the formation of a landslide dam. The landslide dam burst in a very short time, and little information remained afterward. We reconstructed the process of formation and failure of the Xiaolin landslide dam and also inferred the area of the impoundment and topographic changes. A 5×5 -m digital elevation model, the recorded water stage of the Qishan River, and data from field investigation were used for analysis. The spectral magnitude of the seismic signals induced by the Xiaolin landslide and flooding due to failure of the landslide dam were analyzed to estimate the timing of the dam breach and the peak discharge of the subsequent flood. The Xiaolin landslide dam failure resulted from overtopping. We verified the longevity of the Xiaolin landslide dam at about 2h relying on seismic signals and water level records. In addition, the inundated area, volume of the impoundment behind the Xiaolin landslide dam, and peak discharge of the flood were estimated at 92.3ha, $19.5 \times 10^6 \text{ m}^3$, and $17 \times 10^3 \text{ m}^3/\text{s}$, respectively. The mean velocity of the flood-recession wave front due to the dam blockage was estimated at 28km/h, and the peak flooding velocity after failure of the dam was estimated at 23km/h. The Xiaolin landslide provides an invaluable opportunity for understanding the mechanism of deep-seated landslides and flooding processes following a landslide dam failure.

Keywords Deep-seated landslide · Landslide dam · Overtopping · Typhoon Morakot · Xiaolin

Introduction

The formation of a landslide dam results from the natural blockage of the river channels by hillslope-derived mass movements (Costa and Schuster 1988). Most landslide dam disasters due to excessively rainfall or earthquake events (Schuster 1993) occur in landslide-prone countries, including New Zealand (Korup 2004, Korup 2005; Korup and Tweed 2007), Japan (Tabata et al. 2002), China (Chen et al. 1992; Dai et al. 2005; Liu et al. 2010), and especially Taiwan with its frequent torrential rainfall and earthquake events (Chen 1999; Shou and Wang 2003; Hsu and Hsu 2009). The floods resulting from the bursting of a landslide dam can result in serious bank erosion and inundation of populated areas and farmland near the river. The longevity of a landslide dam depends on the discharge into the impoundment, geomorphologic factors, and the composition of the dam (Costa and Schuster 1988). The existence time of a landslide dam directly determines the seriousness of the subsequent flooding. Due to the seriousness of the event and insufficient reaction time, the failure of a landslide dam and the subsequent flooding have often resulted in numerous deaths (Costa and Schuster 1988; Shroder 1998; Chen et al. 1992; Dai et al. 2005; Duman 2009).

There have been many huge landslide dam failure events worldwide, including the failure of landslide dams in Southwestern China in 1786 (Chanson 2005; Dai et al. 2005; Liu et al. 2010; Xu et al. 2009). It has been claimed that at least 5,500 deaths have occurred due to landslide dam failure events in China since 1900. Why the landslide dam events often lead to catastrophic disasters can be explained from two angles. First, some landslide dam events have short longevity, especially in extreme rainfall-triggered cases. Individuals who live along rivers cannot easily detect the formation of a landslide dam during extreme rainfall and, therefore, do not have sufficient time to evacuate. Second, the volume of the impoundment behind an earthquake-triggered landslide dam with long longevity is often too large to be discharged safely. Two very large landslide dams, Tsaoling (Hsu and Hsu 2009) and Chiufenershan (Shou and Wang 2003) and 15 smaller ones (Chen 1999) occurred in Taiwan due to the 1999 Chichi earthquake. Most of these dams were of short longevity, except the Chiufenershan landslide dam, which still exists with remedial engineering measures more than 12 years later.

Detailed information concerning the geomorphologic characteristics, time of formation, and time of failure of rainfall-triggered landslide dams is difficult to collect because of their short longevity. The Xiaolin landslide dam caused by Typhoon Morakot in 2009 in Taiwan was similarly a short-longevity one with little remaining information. This study reconstructs the process of formation and failure of the Xiaolin landslide dam by using the few pieces of remaining information, which include seismic signals, water stage records, and data from field investigations. The 5×5 m digital elevation model (DEM) and geomorphological data from field surveys were employed to infer the location and the original deposited landform of the Xiaolin landslide dam. The size of the landslide dam and the volume of the impoundment lake were also estimated. The seismic signals caused by the Xiaolin landslide and the subsequent flooding were recorded by a regional seismic network 14 km distant from Xiaolin and used to confirm the time of formation and failure of the Xiaolin landslide dam. This study interpreted the detailed geomorphologic information from stereoscopic aerial photo and field investigations to explain the process of the Xiaolin landslide and the formation and failure of the Xiaolin landslide dam. We verified the existence of the Xiaolin landslide dam and explained the flooding process after the failure of the landslide dam. Records from a downstream gauge station were used to check the existence and failure timing of the Xiaolin landslide dam and estimate the possible discharge during the flooding process.

Overview of the Xiaolin landslide

Regional setting

The Xiaolin landslide dam was located to the west of Xiaolin Village in the watershed of the Qishan River, which is a tributary

of the Kaoping River in Southwestern Taiwan (Fig. 1). The area of the sub-watershed upstream of the Xiaolin landslide dam is about 353 km². The terrain along the river reach near Xiaolin Village consists of river terraces; this area is known as the Xiaolin Gorge featuring an active river down cutting (Kung and Chyi 2004). Before the landslide, Xiaolin Village was located on a fluvial terrace on the left hand side of the river; this terrace had a drop height of 5–10 m to the riverbed and a gentle slope of less than 15°.

The geological setting of the Xiaolin landslide (Tsou et al. 2011; Wu et al. 2011) is shown in Fig. 2. The upslope portions of the Xiaolin landslide are chiefly located in Miocene/Pliocene Tangenshan sandstone. The downslope portions are mainly located in Pliocene Yenshuikeng shale. The Tangenshan sandstone consists of thick inter-bedded sandstone and clayey sandstone and has a thickness of 450–500 m. The Yenshuikeng shale consists of massive shale with a thickness of 200–250 m. The fluvial terraces and alluvial formations in the vicinity of Xiaolin Village chiefly consist of gravel and sand. Three active faults, including the Qishan fault, Wulipu fault, and a newly discovered fault (Lee et al. 2009), are close to or in the landslide. Three folds also pass through the landslide area, namely the Xiaolin syncline, the Jiaxian anticline, and the Shihchangeli syncline. The flanks of the three folds dip gently with angles of 10°–20°; however, the flanks occasionally have high dipping angles of 30°–40° (Keng 1965).

Rainfall distribution

According to 15-year records from four nearby rainfall stations, including Minsheng (the station number is C1V160), Biaohu (CoV150), Jiaxian (o1P660), and Xinfu stations (C1V240), the mean annual rainfall at Xiaolin is about 2,440–3,270 mm (Fig. 3a). The average rainfall during the rainy season is about 2,620 mm (approximately 90 % of the annual rainfall); frequent typhoon events, typically occurring from May to October, contribute to the rainfall amount. In contrast, average rainfall during the dry season is normally about 280–300 mm.

The torrential rainfall brought by Typhoon Morakot was concentrated in Southern Taiwan and caused 17 landslide dams in mountainous areas (Chen et al. 2011a, b). Torrential rainfall during Typhoon Morakot (August 6–10, 2009) was equivalent to roughly 75 % and 72 % of average annual rainfall at the Jiaxian Station (2,839 mm, Fig. 3) and Xinfu Station (3,305 mm, Fig. 3). The accumulated rainfall at Xiaolin Village during Typhoon Morakot was about 1,998 mm, which was estimated based on rainfall records at 18 nearby rainfall stations, and was equivalent to roughly 85 % of the total rainfall in 2009.

Based on the four rainfall stations closest to Xiaolin, the heaviest rainfall period, which had total rainfall of 578–787 mm with a mean intensity of 48–66 mm/h, occurred from 12:00 to 24:00 on August 8, 2009 (Fig. 3). The accumulated rainfalls for 24-h, 48-h, and 72-h periods at the Jiaxian Station during Typhoon Morakot were 1,040, 1,614, and 1,915 mm, respectively. The corresponding rainfall

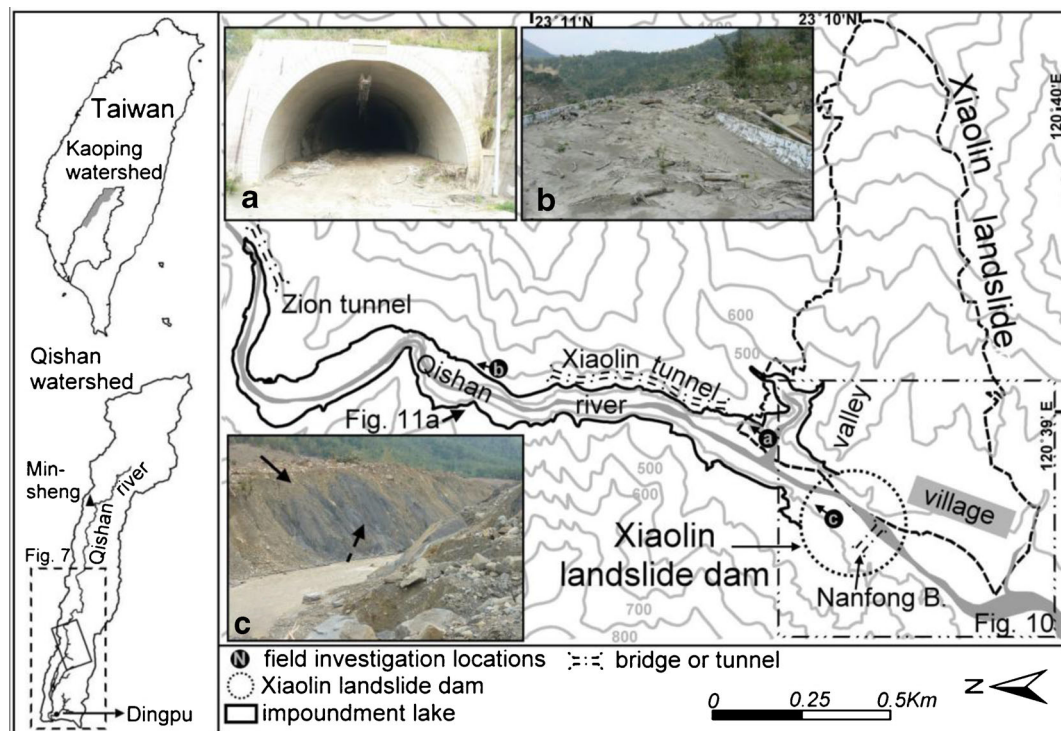
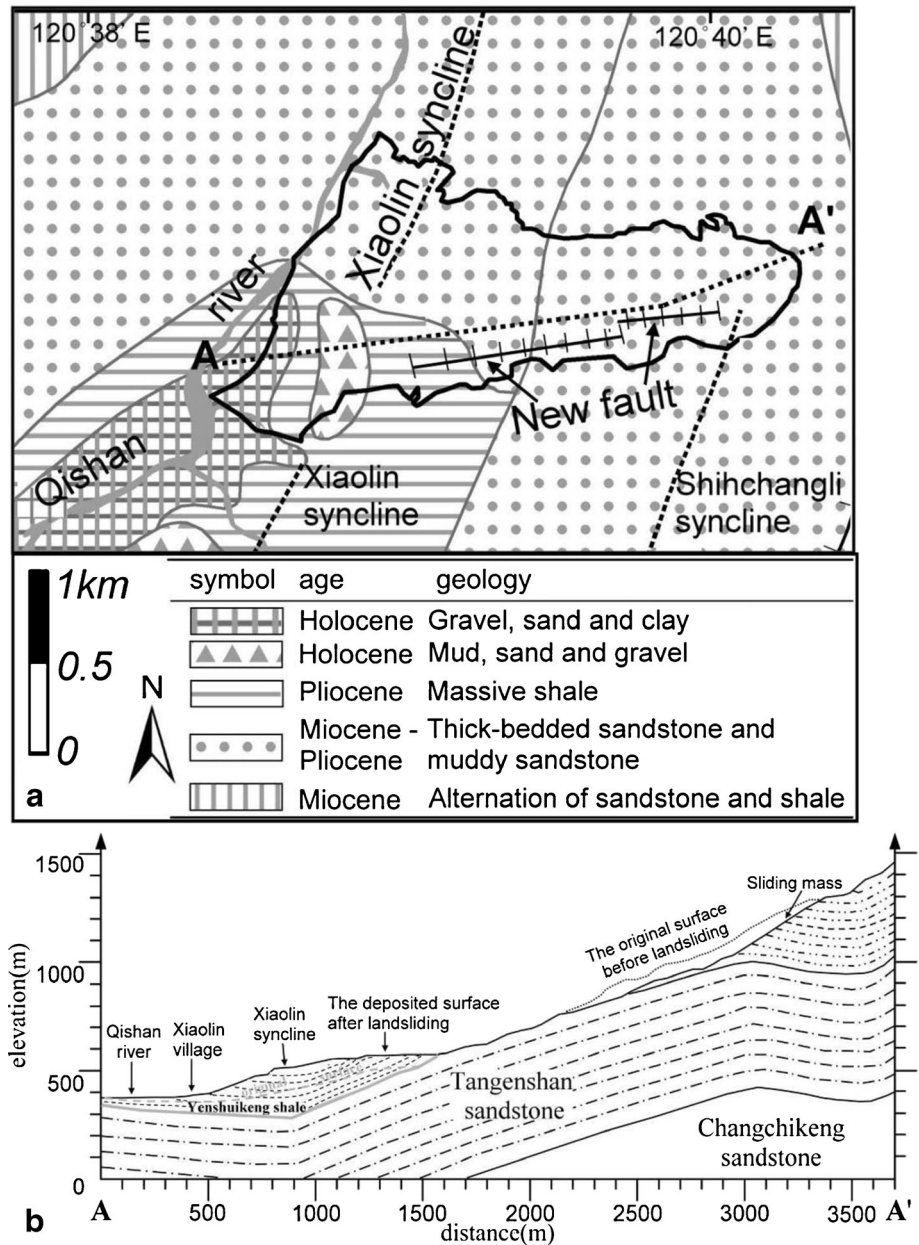


Fig. 1 Location of the Xiaolin landslide dam on a contour base map of the area before the Xiaolin landslide. Field survey pictures taken after the failure of the Xiaolin landslide dam and impoundment lake with an estimated depth of 52.4 m are shown in Fig. 1a, b, and c. a Large amounts of fine sediments were deposited to a thickness of 1.3 m on the road, and grass was found on the lamps hanging in the Xiaolin tunnel. It is conjectured that the Xiaolin tunnel was completely submerged during the impoundment after the landslide and before failure of the landslide dam. b Large amounts of fine sediment were found on the road along the upstream Qishan River, but no obvious fine sediment was found near the Zion tunnel. It is inferred that the impoundment lake, with an estimated elevation of about 422 m, submerged the area from the Zion tunnel (upstream) to the location of the Xiaolin landslide dam (downstream). The submerged area and volume of the impoundment behind the Xiaolin landslide dam are estimated to have been 92.3 ha and $19.5 \times 10^6 \text{ m}^3$. c The burst section of the Xiaolin landslide dam eroded by the overtopping floodwaters. Some of the collapsed materials, the yellow surface soil (black arrow) were even deposited on the original bank hillslope and the black surface soil (dashed arrow) opposite to that of the Xiaolin landslide

Fig. 2 a The geological setting (Wu et al. 2011) and b the geological section map (Lee et al. 2009) of the Xiaolin landslide. The new fault within the Xiaolin landslide area was found by Lee et al. (2009)



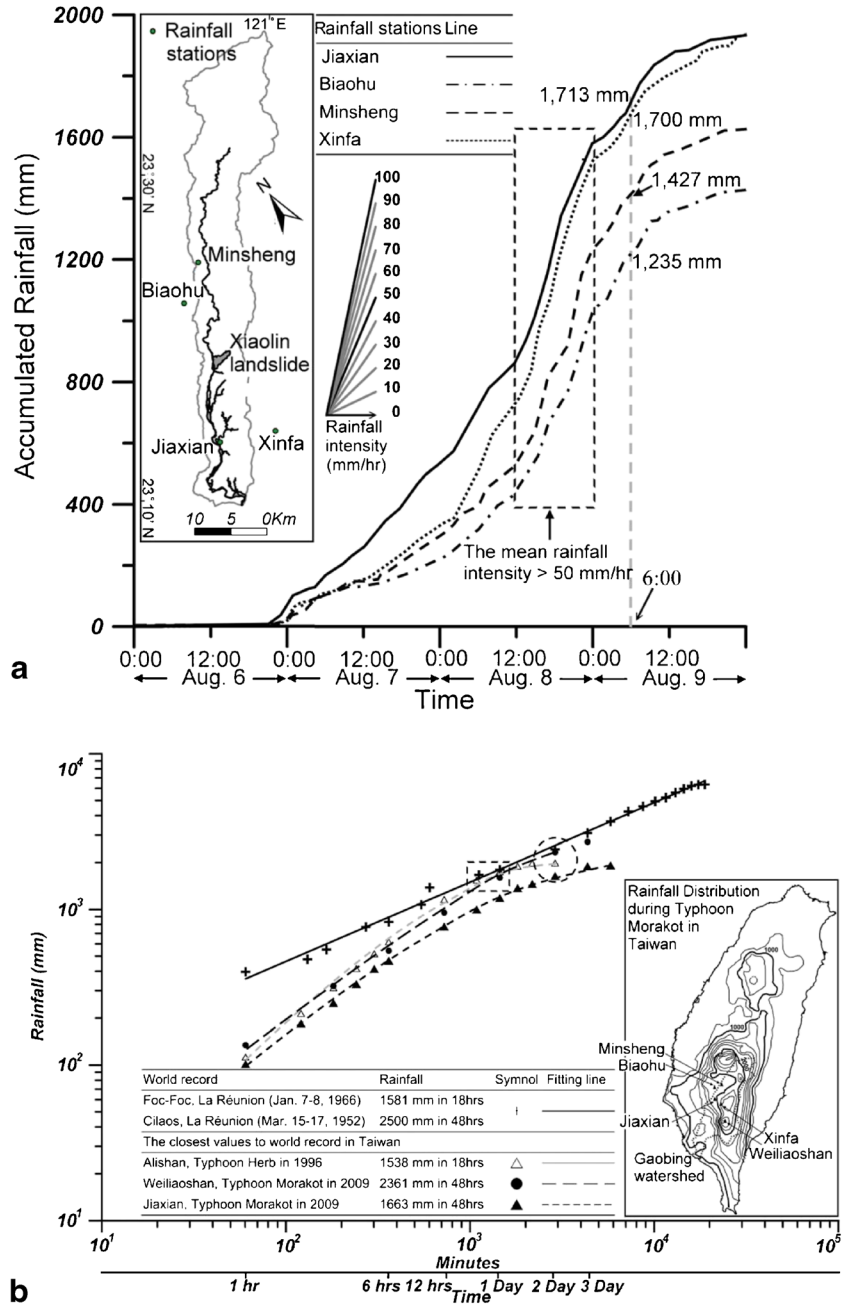
amounts for the three durations over 200-year return periods are 967, 1,436, and 1,761 mm (Wu et al. 2011), respectively. The high-accumulated rainfall records during Typhoon Morakot were 1,931 mm in 24 h, 2,361 mm in 48 h, and 2,748 mm in 72 h at Weiliaoshan station, also in Southwestern Taiwan. Here, the 2,361 mm rainfall in a 48-h period is only 139 mm less than the world record of 2,500 mm during the same duration (Quetelard et al. 2009; The Ohio Weather Library 2012; Hydrometeorological Design Studies Center 2012; see the black dashed circle in Fig. 3b). Heavy rainfall exceeding the 200-year return period forecast and close to the world record rainfall at Xiaolin triggered the serious disasters during Typhoon Morakot. This rainfall was characterized by high intensity and a long duration, while torrential rainfall during the 1996 Typhoon Herb was high-intensity and short-duration (Lin and Jeng 2000; see the black dashed rectangle in Fig. 3b). This change of the rainfall characteristics in Taiwan during the past two decades is a worthwhile subject for further study.

The Xiaolin deep-seated landslide

The Xiaolin landslide resulted in 465 deaths in Xiaolin Village and the Xiaolin landslide dam blocking the Qishan River. The Xiaolin landslide source area was separated by a ridge (shown in Fig. 4; Wu et al. 2011) into two zones, including Zone A and Zone B (shown in Fig. 4). Because the displaced volume in Zone B did not contribute to the formation of the Xiaolin landslide dam, this study chiefly discusses the incision and deposition in Zone A with the landslide area and volume of 1.9 km² and 26 × 10⁶ m³.

This study estimated the landslide depth along the D profile lines in the depletion area with an elevation above 800 m (Wu et al. 2011) and the deposition depth along the E profile lines in the deposition area with an elevation under 600 m (Wu et al. 2011) by employing the 5 × 5 m DEMs before and after Typhoon Morakot (Figs. 4, 5, and 6). The deepest incised depth along D profile lines is 73 m in profile D3, and the deepest incised area is located at the

Fig. 3 The characteristics of heavy rainfall events in Taiwan, including Typhoon Herb in 1996 and Typhoon Morakot in 2009. **a** Hourly rainfall intensity near Xiaolin landslide during Typhoon Morakot. The heaviest rainfall intensity, shown in the *dashed rectangle* in (a), was in the afternoon and night of August 8, 2009. **b** Comparison of cumulative rainfall records in Taiwan with world's cumulative rainfall records (Quetelard et al. 2009; The Ohio Weather Library 2012; Hydrometeorological Design Studies Center 2012). The heavy rainfall during Typhoon Herb in 1996, shown in the *dashed rectangle* in (b), was characterized by high intensity and short duration. Rainfall during Typhoon Morakot in 2009, shown in the *dashed circle* in (b), was characterized by high intensity and long duration



areas with original elevation of 880–980 m in profile D3 (the dashed rectangle in Fig. 5). The landslide mass was mainly deposited along profiles E1 to E4 (Fig. 6), i.e., the valley uphill from Xiaolin Village (Fig. 1), and the maximum deposited depth was roughly 50 m in profile E3 (shown in Fig. 6). The landslide mass from this deep-seated landslide heavily modified the original topography in the downslope area (the gray dotted rectangles from profiles E6 to E9 in Fig. 6). The slopes from profiles E1 to E4 near the Qishan River (the gray dotted circles in Fig. 6) were very steep after Typhoon Morakot, but those in the upper deposited area were gentle. This study inferred that the original deposited surface should be gentle both in the upper deposited area and in the downslope area from profiles E1 to E4. The landslide mass of Zone A was transported along

the original valley and deposited at the intersection of the valley and the Qishan River, forming the Xiaolin landslide dam. The steep slope from profiles E1 to E4 near the Qishan River is an indication of the erosion of the dam body by the overtopping flow. The flood also washed away much of the deposited landslide mass further down the river.

Landslide dam and reservoir

Water stage records

The water stage records at Shanlin Bridge with the subscript S and Nanfong Bridge with the subscript N in Fig. 7 were used to estimate the occurrence time of the Xiaolin landslide and the failure time of the Xiaolin landslide dam. The stream lengths from

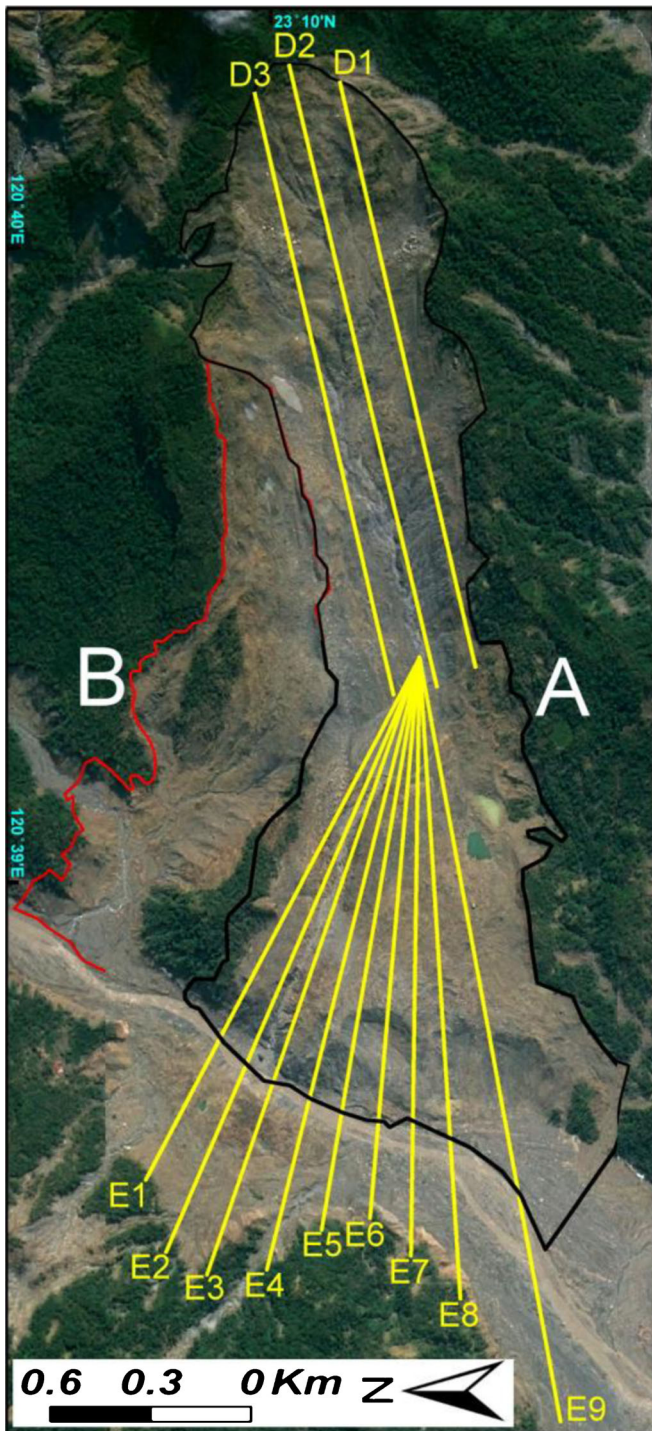


Fig. 4 Survey profiles of the Xiaolin landslide, which was separated by a ridge into landslide A and landslide B. The landslide B is not studied in the study because the formation of Xiaolin landslide dam mainly resulted from the landslide volume of Landslide A. The yellow lines are the profile lines in Fig. 5 (*D* profile lines) and Fig. 6 (*E* profile lines)

Nanfong Bridge to Jiaxian and from Jiaxian to Shanlin Bridge are 10.7 and 17.1 km, respectively. Water stage records and the rainfall intensity near the Xiaolin landslide are shown in Fig. 7. Three apparent peaks (B_N and B_S , D_N and D_S , and I_S in Fig. 7) can be observed in the water stage records.

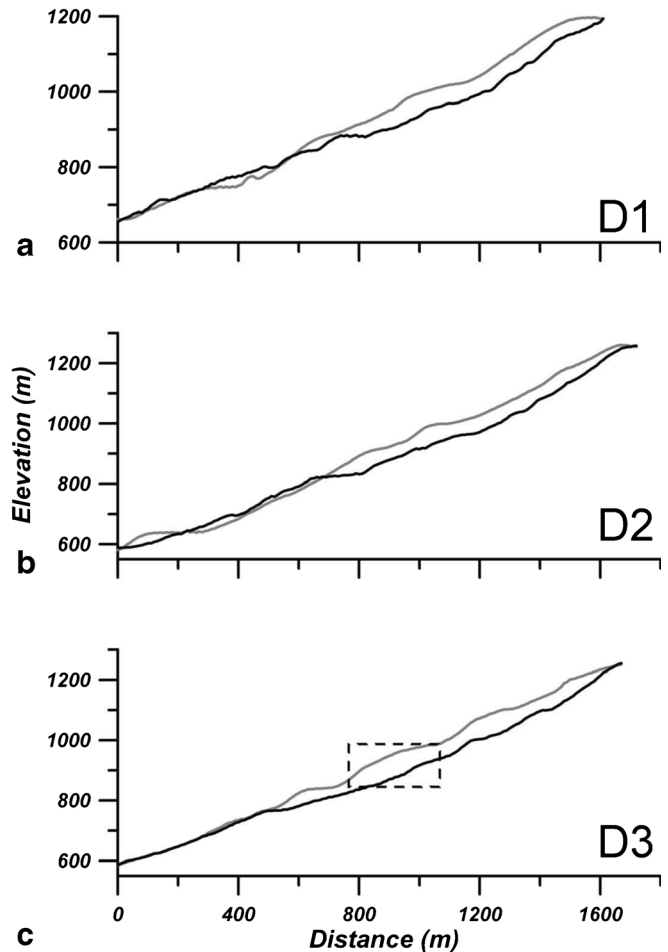
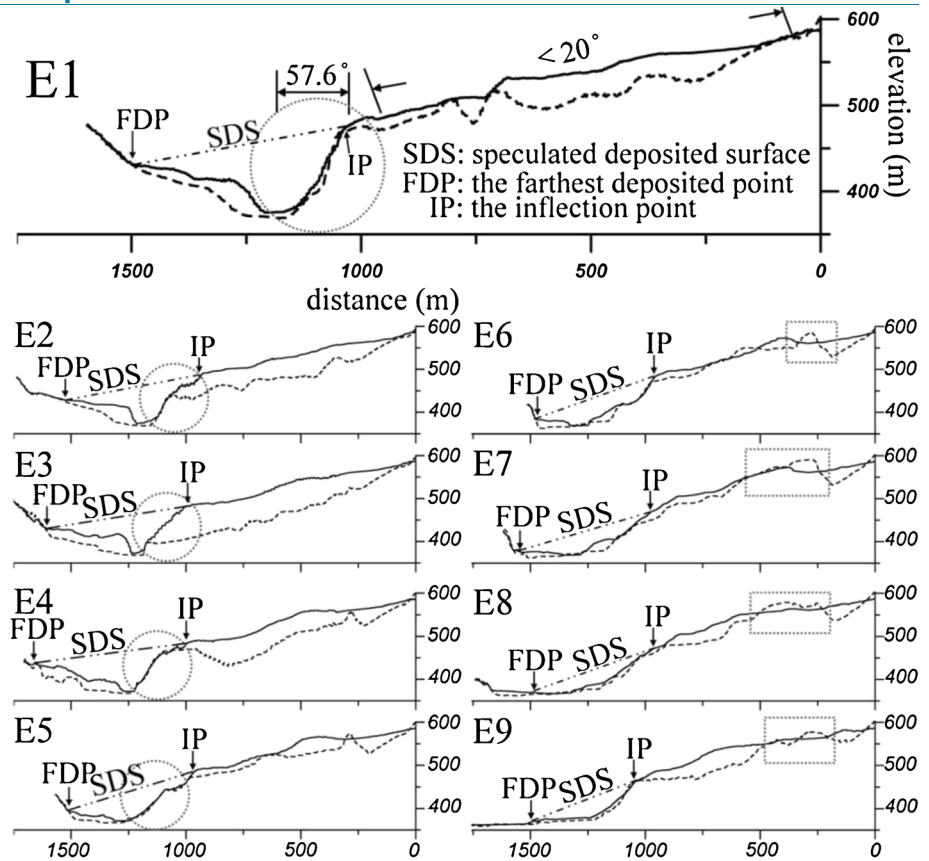


Fig. 5 Elevations along the longitudinal direction (*D1* to *D3* profile lines, shown in Fig. 4) of the Xiaolin landslide before (gray line) and after (black line) Typhoon Morakot. The dashed rectangle in Fig. 5c is the deepest incised area

The water elevations at Nanfong Bridge and Shanlin Bridge were 368.8 and 116.1 m, respectively, before Typhoon Morakot. The first peak (B_S and B_N in Fig. 7) had an average water stage increasing rate of 0.61 m/h and was caused by the heavy rainfall, which had a mean intensity of 26–37 mm/h from 10:00 to 16:00 on August 8. The second peak (D_N at 23:20 on August 8 and D_S at 0:40 on August 9, Fig. 7) had an average water stage rising rate of 0.77–0.83 m/h and was caused by the torrential rainfall, which had a mean intensity of 60 mm/h from 20:00 to 23:00 on August 8. The accumulated rainfall of 261 mm within 3 h was observed at Minsheng station. The flood, with an estimated water depth of 7 m at 0:30, destroyed the gauge station at Nanfong bridge on August 9. Based on the official investigation report of the Water Resources Agency (2009), the water stage diminished rapidly at a rate of 0.92 m/h at Shanlin Bridge after the second peak, and this resulted from decreasing rainfall intensity and the broken levee at Dingpu (Fig. 7) from 0:00 to 0:30 on August 9.

The water stage at Shanlin Bridge station should have decreased gradually in view of the accumulated rainfall of 150–197 mm at the four rainfall stations (Fig. 3) from 0:00 to 6:00 on August 9, but it instead dropped at a rate of 3.94 m/h in 50 min and rose at a rate of 8.05 m/h in 1 h. We inferred that the

Fig. 6 Elevations of sediment deposits from the Xiaolin landslide before (dashed line) and after (solid line) Typhoon Morakot along the E profile lines (shown in Fig. 4)



unexpected drop and rise of the water stage were due to the formation and failure of the Xiaolin landslide dam. The changes in the gauge were also consistent with the survivors' accounts.

The formation of the Xiaolin landslide dam

This study reconstructed the original deposited landform of the landslide dam before its failure. The inflection point (IP in Fig. 6) is the intersection point of the gentle deposition slope and the steep slope in the deposition landform. The farthest deposited point (FDP in Fig. 6) is the point on the hillslope opposite to the Xiaolin landslide and closest to the Qishan River without change before and after Typhoon Morakot. The line which links the IP and FDP is termed the speculative deposited surface (SDP in Fig. 6). The landform composed by the gentle deposition surface and SDP in each profile line is considered to be the original deposition surface before the failure of the landslide dam. This study estimated the depositional area and volume of the Xiaolin landslide dam to be 0.18 km^2 and $10.5 \times 10^6 \text{ m}^3$. The maximum deposited height from the riverbed before the landslide to the SDP and width of the dam are around 107 and 348 m, respectively, on Profile E3. We classified the Xiaolin landslide dam as a rock-avalanche dam and deduced that the dam was formed around 6:16–6:17 on August 9, 2009 (Tsou et al. 2011; Feng 2012).

Dam failure and river discharge

Water level variation

This study used the water stage records at Shanlin Bridge (Fig. 8a) and the time-frequency spectra of the Jiaxian broadband seismic

signals from 6:00 to 10:00 on August 9, 2009 (Feng 2012) to estimate and verify the formation and failure time of the Xiaolin landslide and the resulting dam. The time-frequency spectral magnitudes of the Jiaxian broadband seismic signals were calculated using the Hilbert-Huang transform (HHT; Huang, et al. 1998). The occurrence of the Xiaolin landslide was indicated around 6:16 (Lin et al. 2010, 2010b; Feng 2012) and can be observed in the spectral magnitude at 2.94 Hz (the spike at roughly 6:16 with the maximum averaged value of 0.0157 during 6:10–25 in Fig. 8b). In addition, we can see that the spectral magnitudes gradually decrease from 6:40 to 7:00, remained almost constant from 7:00 to 8:00, increased rapidly from 8:00 to 8:45 and decreased again from 8:45 to 9:30.

The flood-recession period caused by the blockage of the river by the Xiaolin landslide dam began at 6:16 at Nanfong Bridge (Fig. 8b) and between 7:00 and 7:50 at Shanlin Bridge (Fig. 8a). The flood-recession period at Jiaxian began at 6:33 and ended at 6:52 (Fig. 9), which can be seen in Fig. 8b around 6:30–7:00. The velocity of the flood-recession wave front at the start and end of the flood-recession period can be estimated at about 38 and 17.7 km/h, respectively, and the mean velocity of those was 28 km/h. Furthermore, we hypothesize that the spectral magnitude can serve as an analog signal indicating the seismic signature of the landslide and flood, and we use the moving average values (Fig. 8b) of the seismic signals to indicate the formation and failure processes of the Xiaolin landslide dam event. The increase and decrease of the spectral moving average magnitude reveals the passing of the flood in Fig. 8b. The maximum moving average of the spectral magnitude, which had a value over 0.030 at 8:43–47 in Fig. 8b, can be inferred to be the peak flood after failure of the

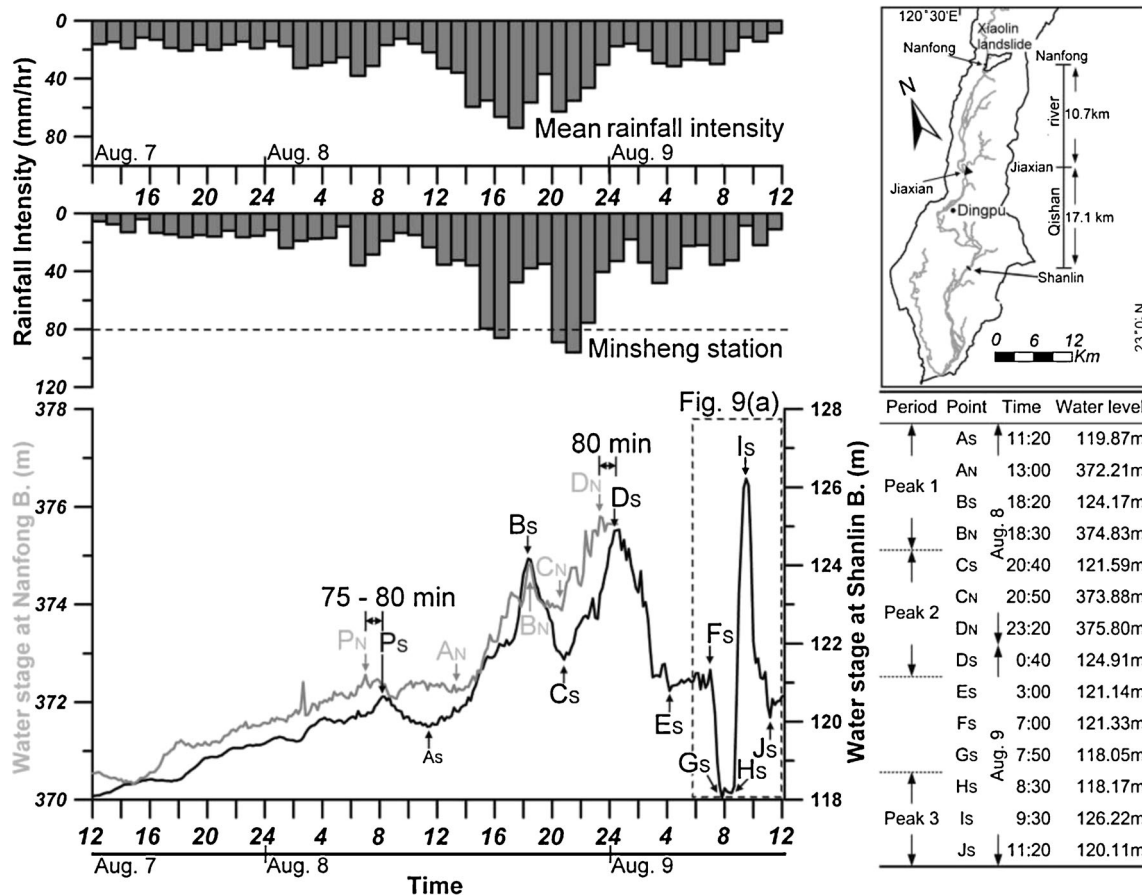


Fig. 7 Water stage records and rainfall intensity (top) in the Qishan watershed during Typhoon Morakot. The mean rainfall intensity was calculated from the rainfall records of the Minsheng, Jiaxian, and Yumei stations

landslide dam. The peak flood took about 45 min to travel from Jiaxian (8:45) to Shanlin Bridge (9:30 with the moving averaged spectral magnitude of 0.011 in Fig. 8a), implying that the velocity of the peak flood was 22.8 km/h. The time at which the peak flood reached Nanfong Bridge can be estimated at 8:20, which also has a maximum averaged spectral magnitude of 0.020 from 8:10–25 in Fig. 8b, by using the velocity of the peak from Jiaxian to Shanlin.

The “convolution effect” of the seismic signals induced by the whole flooding process after the failure of Xiaolin landslide dam. A large dam breach flow will transmit a considerable amount of outgoing energy that shall register seismic signals on a sensitive broadband seismic device in the Jiaxian broadband station; even the flow source is far away. Therefore, when a dam breaches, the seismic waves will be transmitted out continuously along the river while the flood travels down the river, especially, the peak flood will produce most significant seismic signals. The seismic levels of any position will be accumulated and contributed by the flood flows continuously from upstream to downstream. This is the convolution effect concept we point out. To better explain this convolution effect concept and how the spectral magnitude curve shall be interpreted and corresponding to discharge, we choose three representative discharge curves with three respective peaks depicted in Fig. 8c, d.

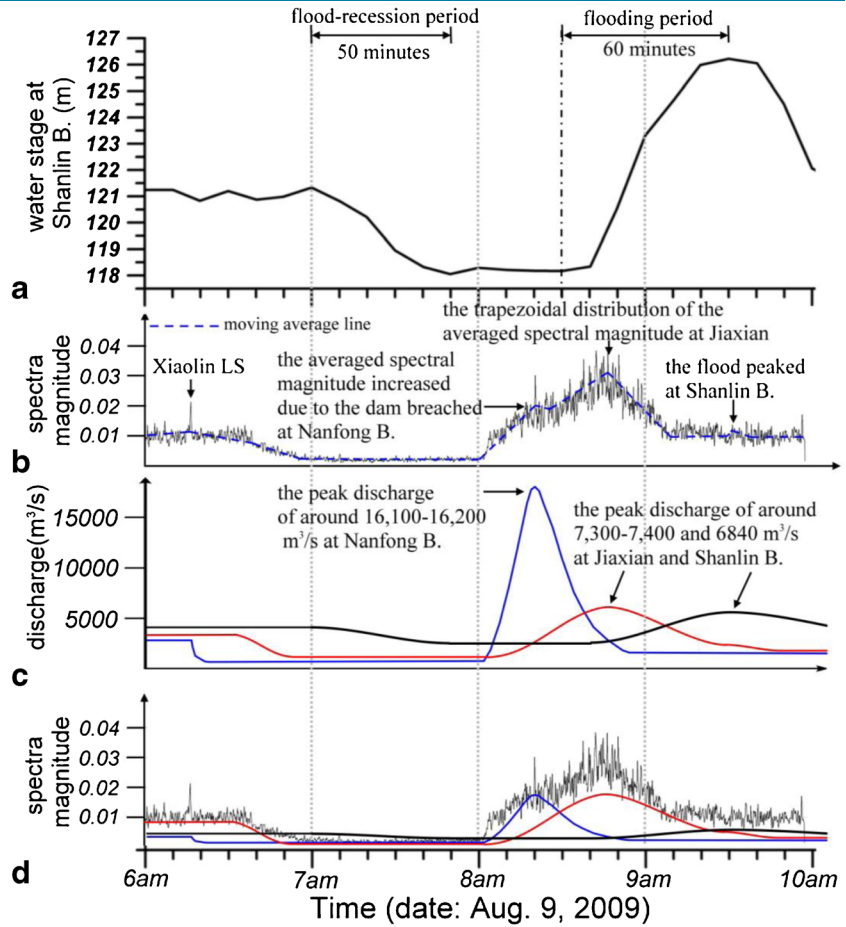
The seismic signals decayed at a rate of $1/\sqrt{d}$ (Lin et al. 2010), where d is the shortest distance from the location of the landslide or flood to the Jiaxian broadband station. Feng (2012) suggested that the

seismic signals around 2.75 and 2.94 Hz of the Jiaxian broadband station are the most obvious signals to show the seismic signals caused by the flooding due to failure of Xiaolin landslide dam. The study also used the amplitudes of the 2.5–5.5 Hz bandpass-filtered seismic signals of the Jiaxian broadband station to correlate the river discharges. The shortest distances from Nanfong Bridge and Shanlin Bridge to the Jiaxian broadband station are 10.4 and 10.5 km, respectively. Averaged from the spectral magnitudes of 2.75 and 2.94 Hz, the spectral magnitude contributed by the peak flood at Nanfong Bridge can be estimated as 0.1811 based on the distance of 10.4 km from Nanfong Bridge to Jiaxian, the spectral magnitude of 0.0561 at 8:20 (Fig. 8b), and the decay rate. Similarly, the spectral magnitude contributed by the peak flood at Shanlin Bridge can be estimated as 0.0772 from the spectral magnitude of 0.0238 at 9:30 (Fig. 8b).

We correlate and scale the spectral magnitudes with the peak discharge for the dam break flooding process. We therefore estimate the peak discharge at the Jiaxian station is set as Q_p ; the peak discharge at Nanfong Bridge and Shanlin Bridge can be estimated as $2.19 Q_p$ and $0.93 Q_p$ respectively, based on the averaged spectral magnitudes 0.1811 from 2.75 and 2.94 Hz around 8:20 at Nanfong station, 0.0827 around 8:45 at the Jiaxian station, and 0.0772 around 9:30 at Shanlin Bridge.

Q_p can be estimated at around 7,300–7,400 m³/s based on the measured peak discharge of 6,840 m³/s at Shanlin Bridge during Typhoon Morakot (Water Resources Agency 2009). The peak discharge at Nanfong Bridge can be also estimated at around 16,100–

Fig. 8 a The water stage record at Shanlin Bridge, b the time-series HHT spectra graph, c the inferred time-series river discharge at Nanfong B (blue line), Jiaxian station (red line), and Shanlin Bridge (black line), and d a comparison of the spectral magnitude and the decayed/scaled river discharge at Nanfong Bridge (blue line), Jiaxian station (red line), and Shanlin Bridge (black line) during Typhoon Morakot



16,200 m³/s. The river discharge time series at Nanfong Bridge, Jiaxian station, and Shanlin Bridge are illustrated in Fig. 8c and are scaled with the distance-decay rate in Fig. 8d. We verified our assumptions by comparing the spectral magnitude and the decayed/scaled river discharges.

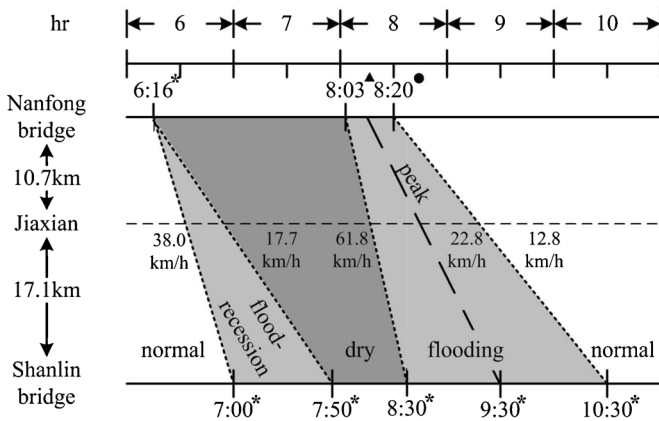


Fig. 9 A schematic diagram of the estimated times of the starting and ending of waves of flood-recession at Jiaxian due to the formation and failure of the Xiaolin landslide dam. The times indicated with a superscript asterisk or filled triangle have been determined from water stage records and seismic signal records, while times indicated with a superscript filled circle have been estimated from water stage records and the seismic signal records

Furthermore, we adopt the derived discharge at Nanfong Bridge to estimate the flood flow velocity when the Xiaolin landslide dam breached to validate the estimated discharge. The flood flow velocity at E2 profile is estimated at 15 to 17 m/s as the failure of the Xiaolin landslide dam, while that at E7 profile is estimated at around 10 m/s. The study also infers that the failure process of Xiaolin landslide dam, which is explained in following paragraph, is pertaining to gradual failure resulting from scouring the boundary of the Xiaolin landslide dam.

We cannot directly validate the estimated river discharge at Nanfong Bridge as the failure of Xiaolin landslide dam at 8 to 10PM on August 9, 2009 because the gauge station was destroyed around 1AM on August 8, 2009. Although, some literatures (Newman and Bennell 2002; Feng 2012) have shown that the proportionality between the vibration magnitude and river flow condition exists, this relationship between the flood discharge and the spectral magnitude presented in the study is only suitable for Qishan River at Jiaxian.

Morphological changes in the river and the disaster caused by the Xiaolin landslide dam failure

This study found vestiges of the dam and pieced together the dam failure process (Fig. 10a) based on stereoscopic aerial photos and field investigations. The yellow arrows in Fig. 10a indicate the Xiaolin landslide and the ensuing deposition, while the white lines and arrows in Fig. 10a indicate the subsequent sediment transport

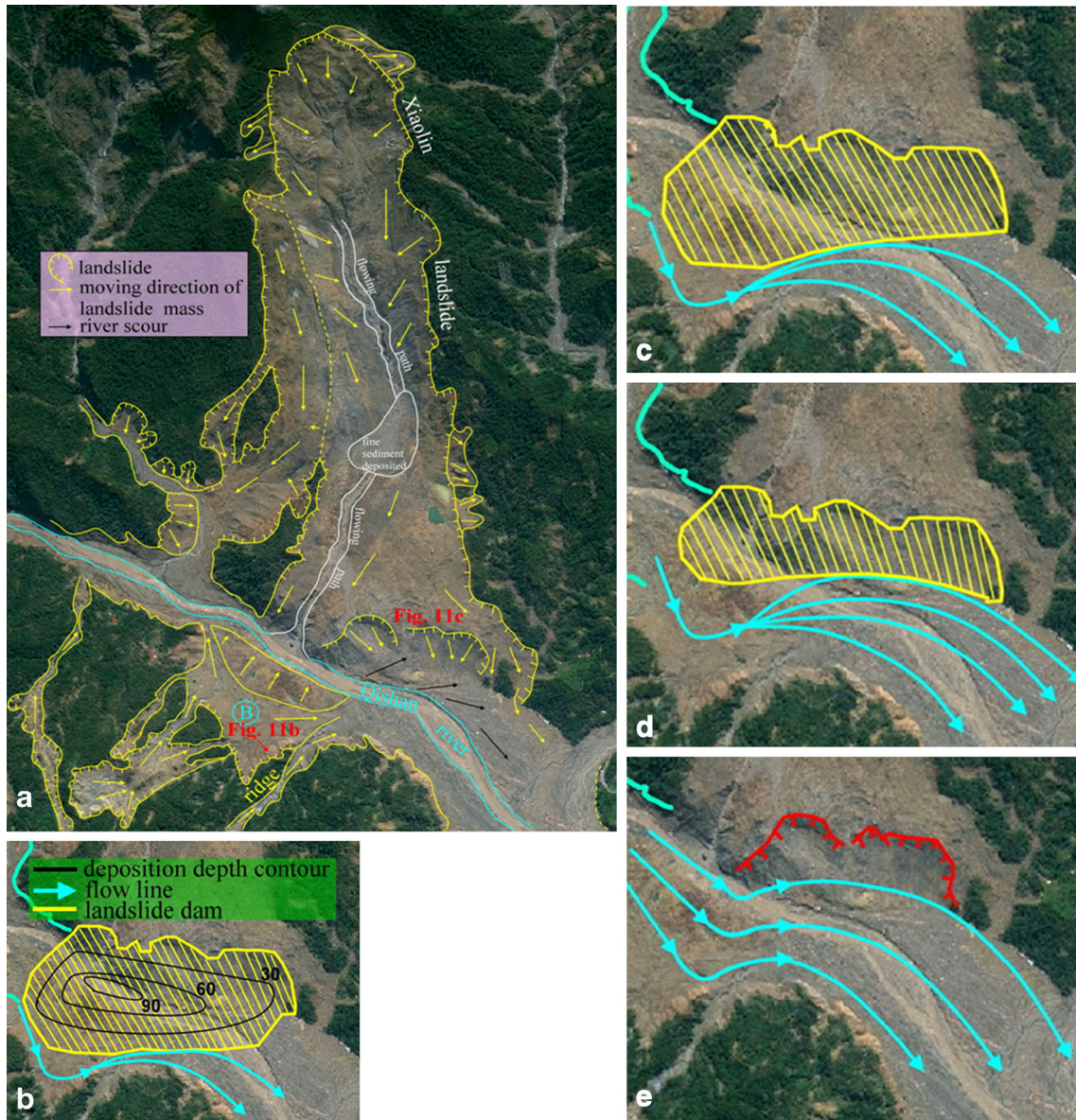


Fig. 10 Interpretation of aerial photo of the landslide scar after the Xiaolin landslide (a) and reconstructed flood flow paths after failure of the Xiaolin landslide dam (b, c, d, e). When the Xiaolin landslide dam started to fail due to overtopping from the impoundment, the overtopping flow started to run around the dam and scoured the dam boundary (b). As the flow gradually scoured the boundary of the landslide dam, the volume of the landslide dam was gradually reduced, and the outburst water gradually increased (c and d). The outburst water also scoured the downslope side of the deposited sediment and formed two concave surfaces (e) due to the diversion of water by the ridge. The overtopping flow ultimately destroyed the landslide dam, and all the impounded water surged downstream. The local geomorphology after the end of flooding, including vestiges of the dam, are shown in Fig. 1c

caused by surface runoff originating from the source area of the watershed after the landslide. The blue lines in Fig. 10a indicate the Qishan River, while black arrows indicate scouring (Fig. 10b, c, d, and e) of the downslope side of the sediment deposited near the Qishan River. This study inferred that the landslide mass flowed in two directions: One portion of the landslide mass buried the original Xiaolin Village (Fig. 1), and the other portion flowed along the original valley (Fig. 1).

When the water depth of the impoundment behind the landslide dam was higher than the minimum deposit thickness of around 52 m in Profile E3 (Fig. 6), i.e., equals to the elevation of 442 m, the floodwaters would begin to flow around the boundary

of the deposit fan and scoured the boundary of the landslide dam. We found several evidences to proof the water depth of the impoundment behind the landslide dam. Firstly, the withered trees hanged in the lamp of the Xiaolin tunnel with the estimated elevation of 428 m (Fig. 1a) stands for the Xiaolin tunnel had been totally submerged under the impoundment behind the landslide dam. Secondary, a mass of the withered trees deposited on the top of the hillslope with the elevation of 439 m (Fig. 11a) also indicates that the water stage of the impoundment behind the landslide dam should be over 439 m. Furthermore, the key information used to reconstruct the failure process of the Xiaolin landslide dam is the concave surface of the original downslope sediment deposit area

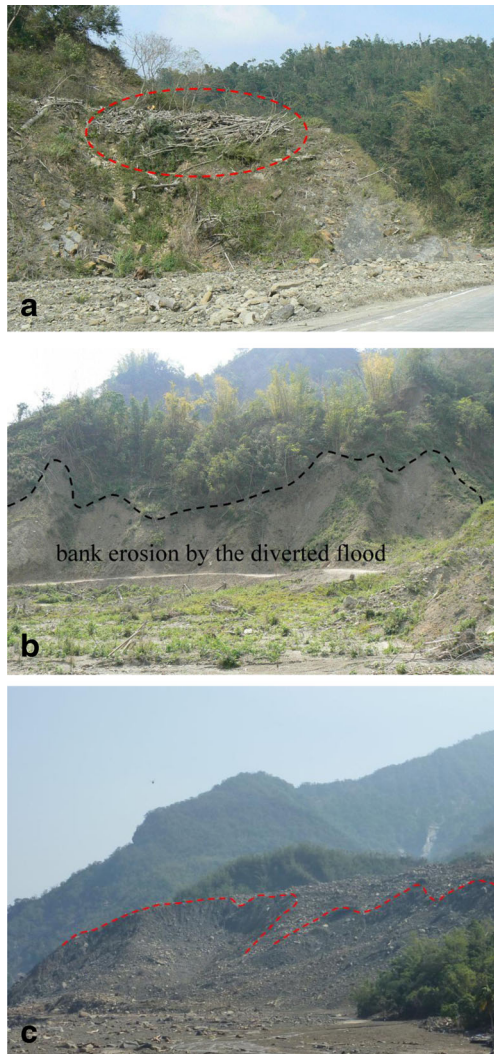


Fig. 11 The vestiges of the impoundment behind the Xiaolin landslide dam. **a** A mass of withered trees (*red dashed circle*) deposited on the top of the hillslope with the elevation of 439 m. The picture-taken location is shown in Fig. 1. **b** The vestiges of bank erosion (*black dashed line*) by the scour due to the diverted flood in the hillslope of the ridge (Fig. 10). **c** The concave surface (*red dashed line*) with the maximum hollow depth of around 15 m located in the downslope side of the original downslope sediment deposited by the Xiaolin landslide. The picture-taken location is shown in Fig. 10

(Fig. 10e), which was where Xiaolin Village was located, and the vestiges of the bank erosion in the opposite bank of Xiaolin landslide (Fig. 11b). This study infers that a concave surface should have been formed by scouring from the flood, and we also found that a key ridge (Fig. 10a) on the hillslope opposite from that of the Xiaolin landslide would have served to divert the flood during the failure of the dam. As the water from the impoundment behind the landslide dam gradually scoured the boundary of the landslide dam, the flow direction was diverted by the ridge. The diverted flood gradually scoured the toe of the ridge (Fig. 11b) and the deposit fan of the landslide dam (Fig. 10b, c, and d), and the route of scouring became the outlet for the about-to-fail impoundment lake. The landslide mass deposited in the streambed of the Qishan River by the Xiaolin landslide was ultimately washed away, and the diverted flood also scoured the downslope side of the original

downslope sediment deposited by the landslide, forming a concave surface (Figs. 10e and 11c). The maximum hollow depths in the two concaves were estimated at around 15 m by using the 5 m Dem after Xiaolin landslide.

This unpredictable catastrophic deep-seated landslide was caused by the extreme rainfall with the high intensity of >50 mm/h and lasting over 12 h, from 13:00 to 24:00 on August 8, 2009. It happened so fast that villagers had no time to respond and evacuate. The loss of life, 465 deaths, is what made this event a disaster. The volume and speed of the Xiaolin landslide made it too large and fast for people to survive. Deep-seated landslides have been reported since 70 years ago (Stini 1941), but the definition and understanding of these landslides remain difficult to clarify. Although typical characteristics and quantifiable definition of deep-seated landslides have been proposed, such as by Agliardi et al. (2001) and Uchida et al. (2011), it is still extremely difficult to predict where and when a deep-seated landslide will occur. The characteristics of rainfall in Taiwan have been gradually changing to heavy rainfall with high intensity or long duration during recent years (Shiu et al 2009). The maximum hourly rainfall intensity of 181.5 mm during Typhoon Megi in 2010 is a good example of the changing characteristics of rainfall in Taiwan. Due to its fragile geological conditions, steep slopes (Chen et al. 2011a, b) and the increasing intensified-rainfall events with long duration (Chiang and Chang 2011; Wu et al. 2011), Taiwan is especially prone to deep-seated landslides.

Conclusions

We reconstructed and verified the existence of the failed Xiaolin landslide dam using topographic change data, water stages, seismic signals caused by the landslide and flood, and the results of a detailed field investigation. We also explain the new concept of “convolution effect” for the seismic signals induced by the landslide dam breach. Also, new information such as the timing and discharge of the dam breach flooding process is provided.

The Xiaolin landslide was triggered by a rainfall event with a 200-year recurrence period and formed the Xiaolin landslide dam on August 9, 2009. This study used the seismic signals caused by Xiaolin landslide and the subsequent breach flooding to estimate the timing of the Xiaolin landslide, the peak discharge, and the flooding process resulting from the failure of the dam. The Xiaolin landslide dam with the deposition area and volume of 0.18 km^2 and $10.5 \times 10^6 \text{ m}^3$ was resulted from the deep-seated Xiaolin landslide with the landslide area and volume of 1.9 km^2 and $26 \times 10^6 \text{ m}^3$. The Xiaolin landslide dam with the maximum deposition height of 50 m was a rock-avalanche dam, formed at 6:16AM on August 9, 2009 and started to fail from 8:03AM due to overtopping by the impounded water. The landslide dam claimed 465 deaths in Xiaolin village and existed for approximately 107 min. As the water depth of the impoundment behind the landslide dam exceeded the minimum deposited depth, the flood began to scour the boundary of the deposit fan. A ridge on the hillslope opposite side to Xiaolin landslide and the concave surface of the original sediment deposit area where Xiaolin Village was located are the two key information allowing the reconstruction of the dam failure process in this study. The concave surface was formed due to scouring by the flood, had been diverted by the ridge after the flood gradually washed out the landslide mass of the dam, and the impoundment lake finally burst. We reconstructed the flooding process of the Xiaolin landslide dam based on information of the seismic signals,

the water stage records, and the remaining landforms after the failure of the landslide dam. In addition, the result of the study not only contributes to develop a better warning system for the deep-seated landslide and predict the possible location of landslide dams, but also draw attention to deep-seated landslide events caused by extreme events, especially in mountainous countries, in view of the changing rainfall characteristics observed in recent decades.

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References

Agliardi FG, Crosta G, Zanchi A (2001) Structural constraints on deep-seated slope deformations kinematics. *Eng Geol* 59:83–102

Chanson H (2005) The 1786 earthquake-triggered landslide dam and subsequent dam-break flood on the Dadu River, southwestern China. *Geomorphology* 71:437–440

Chen SC (1999) Failure mechanism and disaster mitigation on landslide-dammed lakes. *J Chin Soil Water Conserv* 30(4):299–311

Chen YJ, Zhou F, Feng Y, Xia YC (1992) Breach of a naturally embanked dam on Yalong River. *Can J Civ Eng* 19:811–818

Chen H, Lin GW, Lu MH, Shih TY, Horng MJ, Wu SJ, Chuang B (2011a) Effects of topography, lithology, rainfall and earthquake on landslide and sediment discharge in mountain catchments of southeastern Taiwan. *Geomorphology* 133:132–142

Chen SC, Hsu CL, Wu TY, Chou HT, Cui P (2011b) Landslide dams induced by typhoon Morakot and risk assessment. 5th International Conference on Debris-Flow Hazards Mitigation: Mechanics, Prediction and Assessment, Padua, Italy, pp. 653–660

Chiang SH, Chang KT (2011) The potential impact of climate change on typhoon-triggered landslides in Taiwan, 2010–2099. *Geomorphology* 133:143–151

Costa JE, Schuster RL (1988) The formation and failure of natural dams. *Geol Soc Am Bull* 100:1054–1068

Dai FC, Lee CF, Deng JH, Tham LG (2005) The 1786 earthquake-triggered landslide dam and subsequent dam-break flood on the Dadu River, southwestern China. *Geomorphology* 65:205–221

Duman TY (2009) The largest landslide dam in Turkey: Tortum landslide. *Eng Geol* 104:66–79

Feng ZY (2012) The seismic signatures of the surge waves of the 2009 Xiaolin landslide-dam breach in Taiwan. *Hydrol Processes* 26:1342–1351

Hsu YS, Hsu YH (2009) Impact of earthquake-induced dammed lakes on channel evolution and bed mobility: Case study of the Tsaoling landslide dammed lake. *J Hydrol* 374:43–55

Huang NE, Shen Z, Long SR, Wu MC (1998) The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis. *Proc R Soc Lond A: Math Phys Eng Sci* 454:903–995

Hydrometeorological Design Studies Center (2012). "World record point precipitation measurements." NOAA's Weather Service, <<http://www.nws.noaa.gov/oh/hnds/index.html>> (Apr. 9, 2012)

Keng WP (1965) Geology of the Minsheng-Chiahhsien area, Southern Taiwan. *Bull Geol Surv Taiwan* 16:3–15

Korup O (2004) Geomorphometric characteristics of New Zealand landslide dams. *Eng Geol* 73:13–35

Korup O (2005) Geomorphic hazard assessment of landslide dams in South Westland, New Zealand: fundamental problems and approaches. *Geomorphology* 66:167–188

Korup O, Tweed F (2007) Ice, moraine, and landslide dams in mountainous terrain. *Quat Sci Rev* 26:3406–3422

Kung CL, Chyi SJ (2004) River terraces and landscape evolution in the Nantzuhsien drainage basin. *J Geogr Sci* 38:47–62

Lee CT, Dong JJ, Lin ML (2009) Geological investigation on the catastrophic landslides in Xiaolin village, southwestern Taiwan. *Sino-Geotech* 122:87–94

Lin ML, Jeng FS (2000) Characteristics of hazards induced by extremely heavy rainfall in Central Taiwan—Typhoon Herb. *Eng Geol* 58:191–207

Lin CH, Kumagai H, Ando M, Shin TC (2010) Detection of landslides and submarine slumps using broadband seismic networks. *Geophys Res Lett* 37:L22309–L22314

Liu N, Zhang JX, Lin W, Cheng WY, Chen ZY (2010) Draining the Tangjiashan Barrier Lake. *J Hydraul Eng* 136:914–923

Newman JD, Bennell JD (2002) A mountain stream flowmeter. *Flow Meas Instrum* 13:223–229

Quetelard H, Bessemoulin P, Cervený RS, Peterson TC, Burton A, Boodhoo Y (2009) World-record rainfalls during tropical cyclone gameade. *Am Meteorol Soc* 90:603–607

Schuster RL (1993) Landslide dams—a worldwide phenomenon. *Proceedings Annual Symposium of The Japanese Landslide Society, Kansai Branch, 27 April, Osaka, 1–23*

Shiu CJ, Liu SC, Chen JP (2009) Diurnally asymmetric trends of temperature, humidity and precipitation in Taiwan. *J Clim* 22:5635–5649

Shou KJ, Wang CF (2003) Analysis of the Chiufengershan landslide triggered by the 1999 Chi-Chi earthquake in Taiwan. *Eng Geol* 68:237–250

Shroder JF Jr (1998) Slope failure and denudation in the western Himalaya. *Geomorphology* 26:81–105

Stini J (1941) Unsere Täler wachsen zu. *Geol U Bauw, Wien* 13(3):71–79

Tabata S, Mizuyama T, Inoue K (2002) The disasters of natural dam. Kokon Shoin, Tokyo

The Ohio Weather Library (2012) World point rainfall records. Ohio Weather Library Inc, <<http://weatherrecords.owlinc.org/RainfallRecords1.html>> (Accessed Apr. 9, 2012)

Tsou CY, Feng ZY, Chigira M (2011) Catastrophic landslide induced by Typhoon Morakot, Shialin, Taiwan. *Geomorphology* 127:166–178

Water Resources Agency (2009) The analysis of the rainfall and river discharge during Typhoon Morakot. Water Resources Agency, Ministry of Economic Affairs, Taipei, Taiwan, pp 24–25

Wu CH, Chen SC, Chou HT (2011) Geomorphologic characteristics of catastrophic landslides during typhoon Morakot in the Gaobing Watershed, Taiwan. *Eng Geol* 123:13–21

Uchida T, Yokoyama O, Suzuki R, Tamura K, Ishizuka T (2011) A new method for deep catastrophic landslide susceptibility. *Int J Erosion Cont Eng* 4:32–42

Xu Q, Fan XM, Huang RQ, Westen CV (2009) Landslide dams triggered by the Wenchuan Earthquake, Sichuan Province, south west China. *Bull Eng Geol Environ* 68:373–386

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