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The 1786 earthquake-triggered landslide dam and subsequent dam-break flood on the Dadu River, southwestern China

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Abstract

Chinese historic documents recorded that on June 1, 1786, a strong M=7.75 earthquake occurred in the Kangding-Luding area, Sichuan, southwestern China, resulting in a large landslide that fell into the Dadu River. As a result, a landslide dam blocked the river. Ten days later, the sudden breaching of the dam resulted in catastrophic downstream flooding. Historic records document over 100,000 deaths by the flood. This may be the most disastrous event ever caused by landslide dam failures in the world. Although a lot of work has been carried out to determine the location, magnitude and intensity of the 1786 earthquake, relatively little is known about the occurrence and nature of the landslide dam. In this paper, the dam was reconstructed using historic documents and geomorphic evidence. It was found that the landslide dam was about 70 m high, and it created a lake with a water volume of about 50×10^6 m^3 and an area of about 1.7 km^2. The landslide dam breached suddenly due to a major aftershock on June 10, 1786. The peak discharge at the dam breach was estimated using regression equations and a physically based predictive equation. The possibility of a future failure of the landslide seems high, particularly due to inherent seismic risk, and detailed geotechnical investigations are strongly recommended for evaluating the current stability of the landslide.

Keywords: Landslide dam; Breach; Flood; Discharge; Earthquake

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1. Introduction

Natural damming of rivers by landslides may cause significant hazards in many countries. It presents serious threats to people and property due to possible upstream flooding as the impounded lake water level rises and possible downstream flooding due to dam breach and rapid release of the impounded water. Attempts in recent years to collect and classify data on landslide dams result directly from increasing hazard awareness. Costa and Schuster (1991) presented the most comprehensive inventory and bibliography of 463 landslide dams throughout the world. Clague and

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Evans (1994) described 16 existing and 22 historical landslide dams in the Canadian Cordillera. Casagli and Ermini (1999) presented an inventory of 68 present and historic landslide dams in the northern Apennines. Hewitt (1998) provided an excellent guideline on how to reconstruct landslide-damming events from geomorphic evidence.

In China, Chai et al. (1995) presented an inventory of 147 present and historic landslide dams, although it is by no means complete due to the remote nature of landslide-damming events and the vagaries of reporting such incidents. This inventory and more recent landslide-damming events suggest that at least 5500 deaths have been caused by landslide dams in China since 1900. A few of these incidents are well documented. On August 25, 1933, an earthquake of M=7.5 near Diexi, Sichuan Province, caused the formation of three landslide dams with a maximum height of 160 m on the Min River and nine landslide dams on its tributaries. The three lakes behind the landslide dams merged into a large lake because of the continuous inflow of water from upstream and the higher elevation of the most downstream dam. The dam was overtopped 45 days later, and a flood of water rushed down the valley for a distance of 250 km, killing at least 2500 people (Sichuan Seismological Bureau, 1983; Chai et al., 2000). On June 8, 1967, a huge landslide with a volume of 68×10^6 m^3 occurred at Tanggudong on the Yalong River, Sichuan Province, forming a natural dam with a height of 175 m and a reservoir with a capacity of 680×10^6 m^3. Nine days later, the dam broke by overtopping, lasting 13 h and resulting in a maximum flood discharge of 53,000 m^3/s (Chen et al., 1992), but no loss of life occurred because of precautionary evacuations. More recently, the Yigong River in southeastern Tibet was dammed on April 9, 2000, by a huge landslide with a volume of 300×10^6 m^3. This natural dam, about 130 m high and 1.5 km long, was created in 8 min. The dam partially failed on June 10, 2000 (Shang et al., 2003). The resultant flood traveled more than 500 km downstream, damaged many bridges and created numerous new landslides along both banks of the river. The flooding also resulted in 30 deaths, more than 100 missing people and more than 50,000 homeless in the five districts of Arunanchal Pradesh, India (Zhu and Li, 2001).

Historic records revealed that the 1786 Kangding-Luding earthquake in southwestern China triggered a large landslide that dammed the Dadu River, which, 10 days later, breached suddenly, resulting in over 100,000 deaths due to downstream flooding. In our knowledge, this incident may constitute the world's most disastrous landslide-damming event ever recorded. Although a lot of work has been carried out to determine the location, magnitude and intensity of the 1786 Kangding-Luding earthquake (Wang and Pei, 1987), relatively little is known about the nature of the landslide dam. This paper presents an attempt to address the location and nature of this landslide dam and to reconstruct the peak discharge at the dam breach based on historical documents and geomorphic evidence.

2. Geographic and geological setting

The Kangding-Luding area in Sichuan, southwestern China, is located in the convergence of the NE–SW trending Longmenshan, NW–SE trending Xianshuihe and N–S trending Anninghe active fault zones (Fig. 1). This area is one of the most seismically active areas in China, although seismic activity, in terms of magnitude, at the south extremity of the Longmenshan fault zone is considered to be moderate (Wang and Pei, 1987). The spatial and temporal characteristics of historic earthquakes along the Anninghe fault zone indicate that its seismic activity tends to decrease northward. The seismic activity of the Kangding-Luding area is controlled primarily by the Xianshuihe active fault zone (Wang and Pei, 1998). The zone is one of the most active fault systems in the world and can be divided into five segments: the Moxi fault, Selaha fault, Zheduotang fault, Yalahe fault (Fig. 2) and northwest segment (Allen et al., 1991; Zhou et al., 2001). As the Selaha and Zheduotang faults are at most only 10 km apart and they converge toward their ends, it is possible that they dip steeply toward each other and merge at depth (Allen et al., 1991; Zhou et al., 2001). The northwestern end of the Xianshuihe fault overlaps with the southeastern end of the Ganzi-Yushu fault, with a left end echelon step-over of about 40 km (Fig. 1). The southeastern extremity of the Xianshuihe fault zone connects with the Anninghe fault.

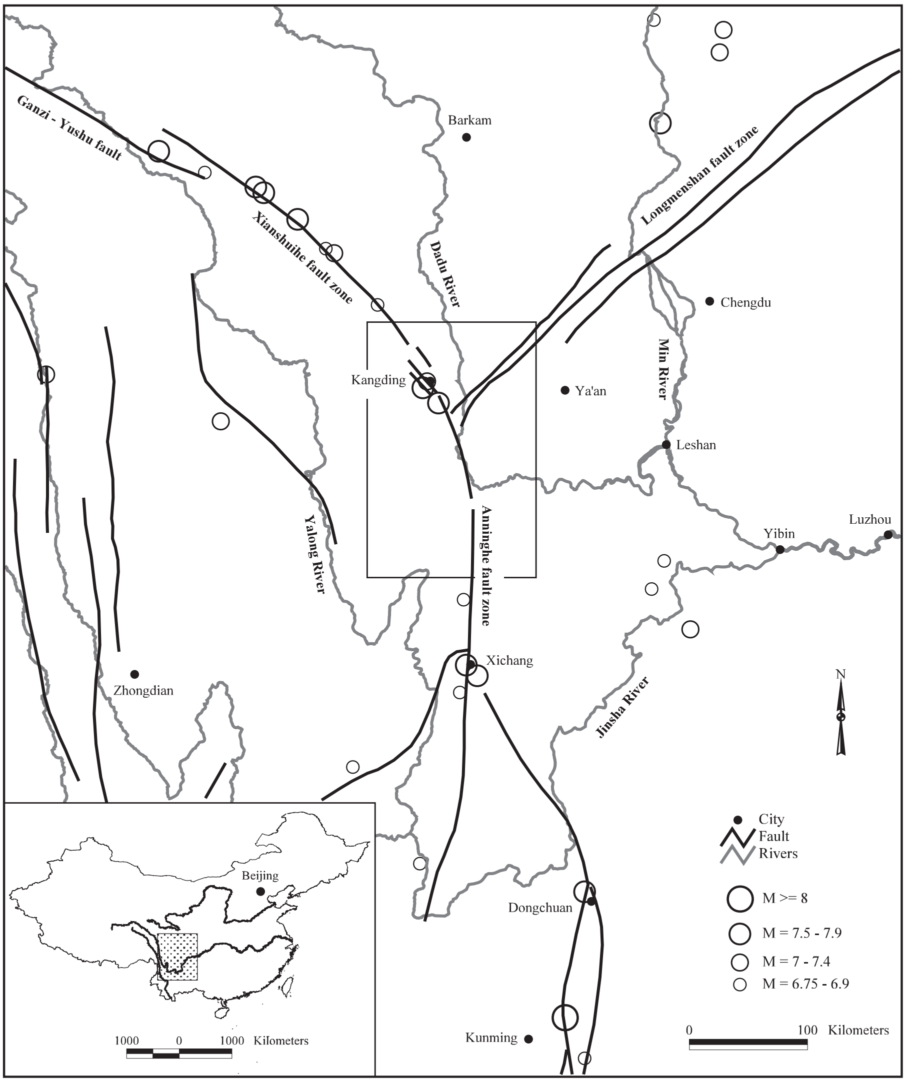

Fig. 1. Map showing major faults of western Sichuan and epicentres of large earthquakes since 1467, based on Allen et al. (1991). Box in the centre shows location of Fig. 2.

Based on a detailed study of fault landforms, historical and paleo-earthquakes, coseismic slip and geochronology, Zhou et al. (2001) found that the average horizontal slip rates of the Yalahe, Selaha, Zheduotang and Moxi faults during the late Quaternary are 2.0±0.2, 5.5±0.6, 3.6±0.3 and 9.9±0.6 mm/year, respectively, and that the recurrence intervals of strong earthquakes ($M \geq 6.0$) are over 1000 years for the Yalahe fault, 230 to 350 years for the Selaha and Zheduotang faults and about 300 years for the Moxi fault.

Fig. 1 shows large historic earthquakes on the Xianshuihe and associated faults of southwestern China. It can be seen that the major earthquakes tend to occur on the major faults. It should be noted that the historical seismic records in this sparsely populated part of China are very short compared to those of more densely populated areas. The earliest record of large earthquakes on the Xianshuihe fault zone dates back to 1725. Among the recorded major earthquakes, the following three events are of particular significance to the Kangding-Luding area (Table 1): the 1725 Kangd-

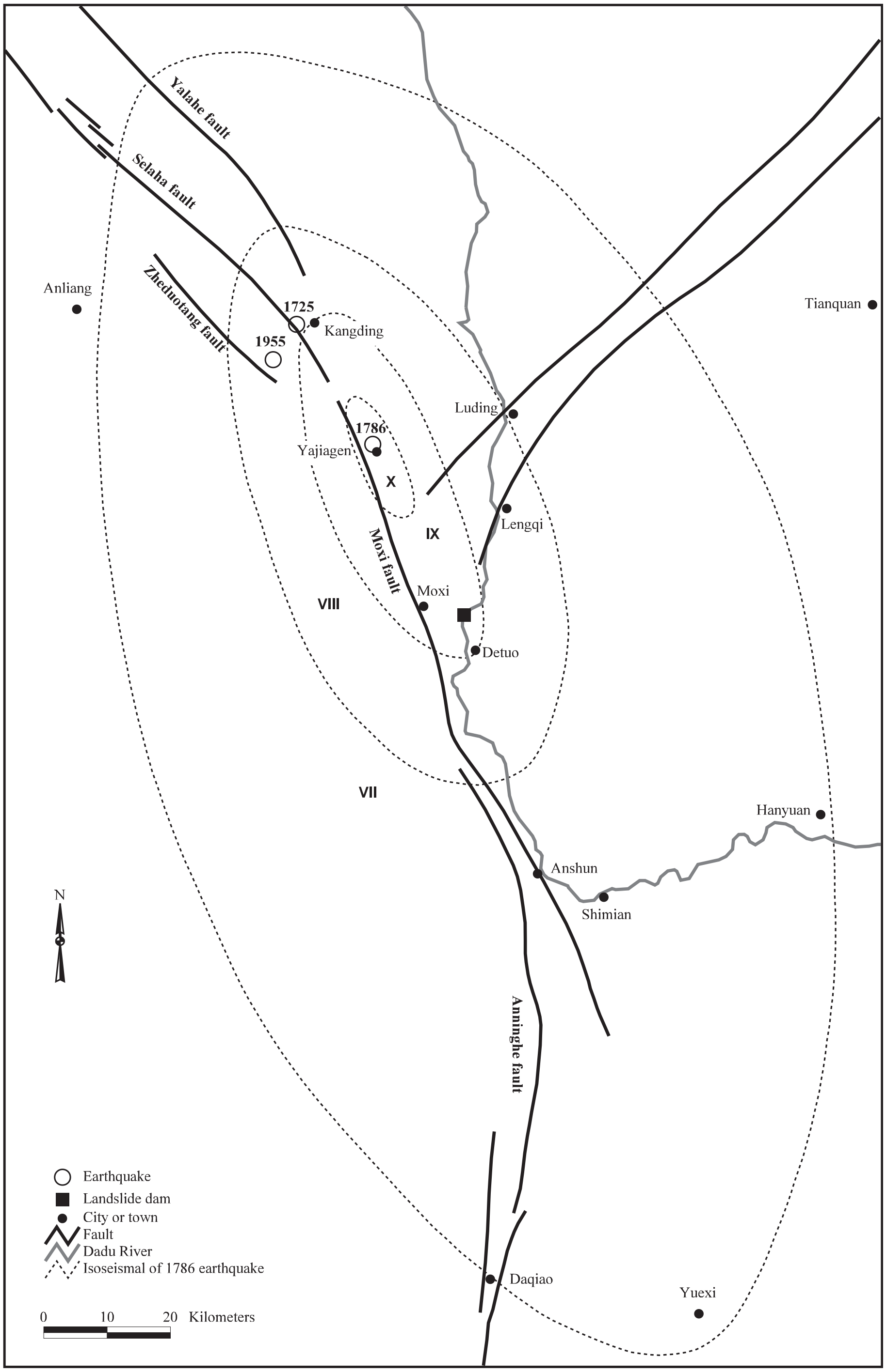

Fig. 2. Isoseismal map of the 1786 Kangding-Luding earthquake, based on Wang and Pei (1987). Modified Mercalli intensities assigned to the different isoseismal zones are shown with Roman numerals.

Table 1
Historic large earthquakes in the Kangding-Luding area, southwestern China

Date	Name	Coordinates	Fault	MMI at the epicentre	Magnitude	Focal depth (km)
August 1, 1725	Kangding earthquake	30°03′ N, 101°56′	Selaha fault	IX	7.0	–
June 1, 1786	Kangding-Luding earthquake	29°53′ N, 102°01′	Moxi fault	≥X	7.75	20
April 14, 1955	Zheduotang earthquake	30°00′ N, 101°54′	Zheduotang fault	IX	7.5	20

ing earthquake; the 1786 Kangding-Luding earthquake; and the 1955 Zheduotang earthquake, which killed 70 people, injured 217 persons and caused extensive damage to property (Wang et al., 1996).

The bedrock of the region is made up primarily of quartzites, marbles, slates and phyllites of the Late Triassic Xikang group; diorite of the Archean to early Proterozoic age; and Mesozoic and Precambrian granites (Sichuan Bureau of Geology and Mineral Resources, 1991). Quaternary deposits are limited to small basins, particularly along the fault, in addition to local fluvial terraces and glacial deposits. Rocks along the fault zone are intensely sheared, with many tight folds, as well as abundant mylonite and gouge. Such crushed zones, which are easily erodible, control the drainage pattern of the region.

The terrain is typically steep and mountainous. The region affected by the 1786 earthquake is situated in the transitional zone between the Longmenshan mountains and the Qinghai–Tibetan plateau. This area has a very large relief with rivers flowing at approximately 1100–1300 m a.s.l., while the mountain peaks rise to above 6000 m. The mean annual rainfall at Luding is 637 mm. The major rivers flowing through the study area include the Dadu River and its tributaries. The Dadu River has a U-shaped and steep-sided valley. The maximum discharge of the river generally occurs during the summer season between June and September. A maximum peak discharge of 5500 m^3/s was recorded at Luding in 1992, while the average flow varies from 100 to 1500 m^3/s. The valleys have five levels of paired river terraces, which support agriculture and the main villages.

3. Methodology

With the aim to determine the location and nature of the 1786 landslide dam and subsequent dam-break flood, the methodology used in the present study can be summarized as follows:

- Initially, the published materials associated with the 1786 earthquake were collected and analysed to provide the background information on the epicentre, magnitude and seismic intensities.
- Next, historic records were collated to define the possible locations, the nature of the landslide dam and the consequence of dam-break flood.
- Reconnaissance fieldwork was carried out to identify the location of the landslide dam. Diagrammatic mapping was then conducted to determine the nature of the landslide dam from the geomorphic evidence, after identifying the landslide site.
- Based on the dam crest height estimated in the field, the former lake created by the landslide dam was reconstructed, and the peak discharge at the dam breach was estimated from empirical regression equations that relate the observed peak discharge to some measure of the landslide dam and the impounded water volume and a physically based model developed by Walder and O’Connor (1997).

4. The 1786 Kangding-Luding earthquake

At noon on June 1, 1786, the Kangding-Luding area was shocked by a strong earthquake, which caused extensive damage in the affected area. Historic documents showed that the main shock was followed by a series of aftershocks during the next 12 days. Damage to buildings was reported from the affected area to the Emperor Qianlong of the Qing Dynasty. This report was prepared by Bao Ning, the governor of the Shaanxi–Sichuan region at that time and will be termed as the Bao Ning report hereafter. The Bao Ning report can be accessed from the *Atlas of Historic Earthquakes in China for the Qing Dynasty period* (Institute of

Geophysics at the National Seismological Bureau and Institute of Historic Geography at Fudan University, 1990). Based on the damage description in the report, Wang and Pei (1987) adopted the following classification system with regard to structures or buildings: A-type buildings simply constructed using mud and dry grass; B-type structures with stone slabs piled upon each other with small chips filling the voids and supporting the large stones or those with thick slabs of uniform stones cemented with mud plaster or woods of poor quality; and C-type, other types of construction with either an integral wooden frame or with brick masonry normally used for temples and museums.

We conducted a detailed analysis of the Bao Ning report, field surveys and visual interpretation of available aerial photographs and satellite images. As a result, a very recent surficial fault rupture that extended for at least 70 km from south of Moxi to northwest of Kangding was identified, and an isoseismal map (Fig. 2) was produced on the basis of modified Mercalli intensity (MMI) scale by Wang and Pei (1987). Each intensity contour in Fig. 2 shows a NW–SE trend for its major axis and a NE–SW trend for its minor axis. The tectonics of the region, the isoseismal trend and the pattern of ground fractures resulted from the earthquake indicate that the causative fault of this earthquake was trending NW–SE, which follows the regional orientation of the Xianshuihe fault. The major and minor axes of the isoseismal for MMI IX or above are 20 and 6 km long, respectively. The zone with MMI X or above thus covers an area of approximately 95 km^2 and is confined to a relatively sparsely populated area. It was found that, in this zone, the ground failure occurred mainly along the major faults and was characterized by the distribution of numerous sag ponds, faulting scarps and secondary surface ruptures with subsidence along the faults. MMI zone IX extends from Kangding in the north to Detuo in the south and covers an area of approximately 720 km^2. In this zone, the majority of the A- and B-type structures and 24–26% of the C-type buildings collapsed. Within MMI zone VIII, more than 50% of the A- and B-type structures were tilted or even damaged, and a minority of the C-type buildings were tilted. Within MMI zone VII, only a few of the A- and B-type houses were either collapsed or damaged.

The epicentre of this earthquake was located in Yajiagen along the Moxi active fault, and the focal depth was estimated to be 20 km (Wang and Pei, 1987). The magnitude of this earthquake was estimated to be M=7.75 because the length of the major axis of MMI zone VIII is equivalent to that of other earthquakes with M=7.5–8.

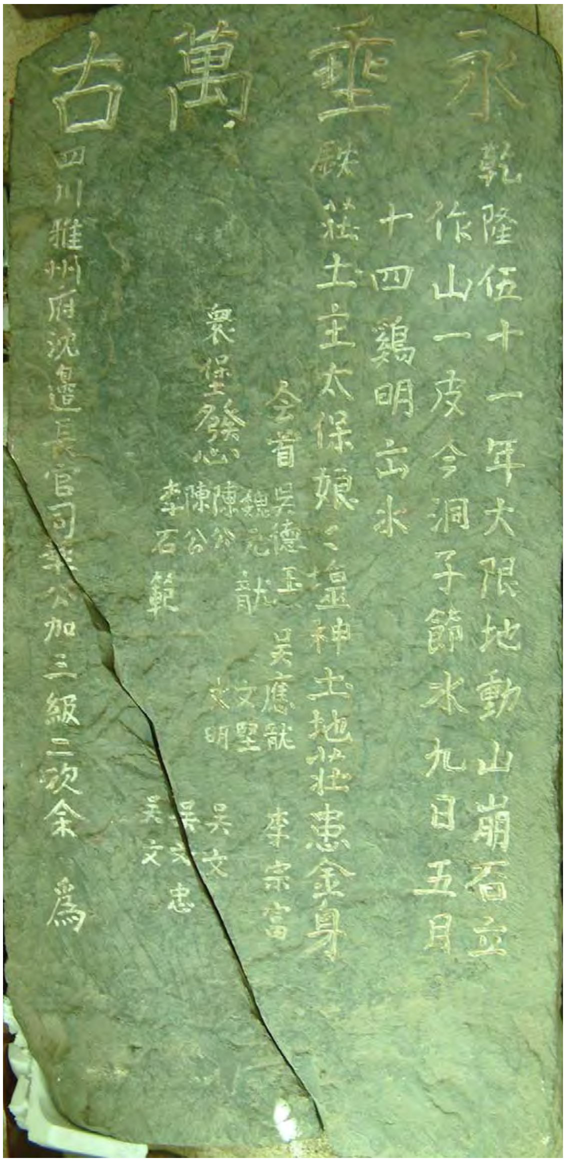

Fig. 3. The monument created by local residents in memory of the landslide-damming event. For interpretation, refer to the main text.

Available historic records revealed that the violent prolonged shaking from this earthquake gave rise to extensive small-scale rock/block falls and landslides in MMI zones VIII to X, and the majority of these events were confined to intensely jointed and crushed rocks on steep slopes. Historic records also mentioned that a large landslide occurred and dammed the Dadu River.

5. Landslide dam

5.1. Historic records

As a direct result of the 1786 earthquake, a large landslide occurred along the bank of the Dadu River. The sliding materials blocked the river and formed a

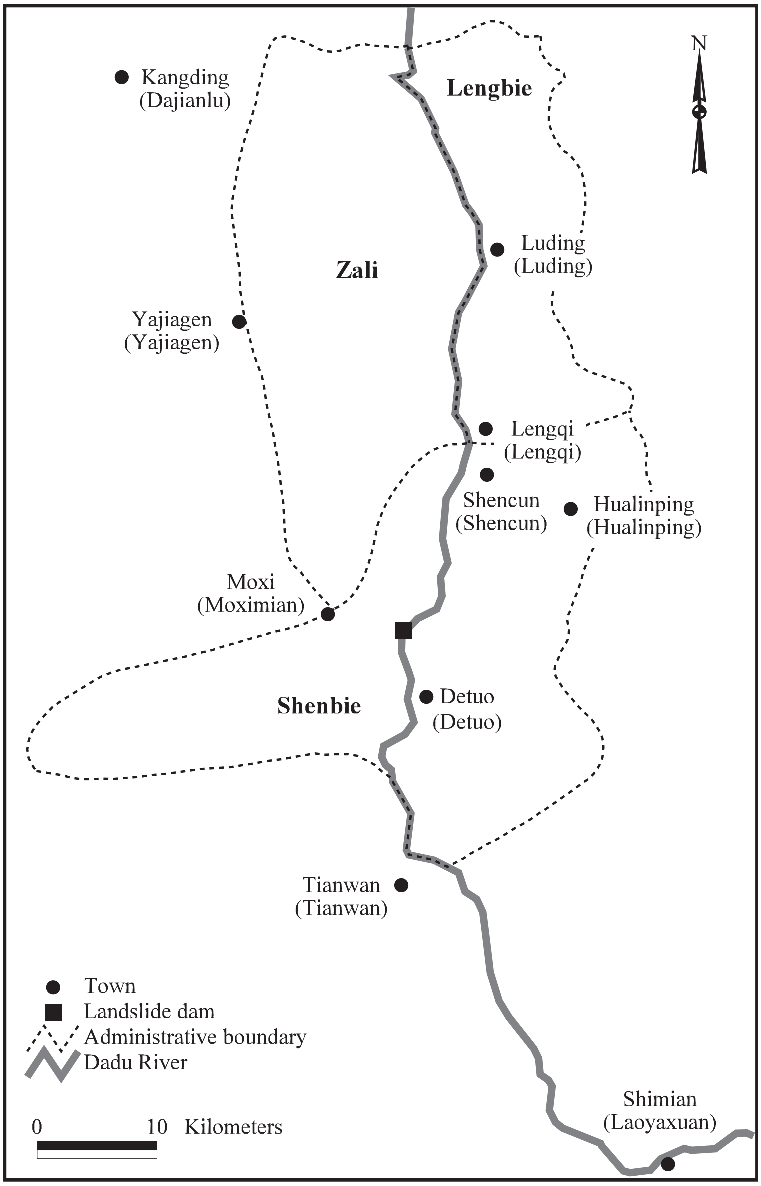

Fig. 4. Location of the Shenbie administrative zone regard to the Dadu River in the period governed by the Emperor Qianlong of the Qing Dynasty. The names of the towns used in the Qing Dynasty are given in parentheses (after Wang and Pei, 1987).

dam. The Bao Ning report offered the following description of this landslide-damming event: "... In Tiger Cliff, the mountain fractured and fell due to the June 1 earthquake and dammed the river, causing submergence of the majority of the river-side agricultural land behind the dam. The water level in the lake behind the dam exceeded 66 m above the original river level. On June 10, the dam breached suddenly, washing away the agricultural land. . ." (Institute of Geophysics at the National Seismological Bureau and Institute of Historic Geography at Fudan University, 1990).

Apart from the Bao Ning report, a monument was created by local residents in memory of this event. The monument (Fig. 3), now kept at the Luding Seismological Office, is a stone tablet with the following inscription in Chinese (Zheng, 1998): “In 1786, the ground shook and the rocks collapsed. The mountain at Jindongzi collapsed and a landslide dam blocked the Dadu River for nine days. In the early morning on June 9, water in the lake overflowed the crest of the dam.”

Although this landslide-damming event has been cited to illustrate the catastrophic effects of landslide dams (e.g., Li et al., 1986; Li, 1990; Allen et al., 1991; Korup, 2002), there has been little consensus on the location and nature of the landslide dam. In fact, it has been a subject of debate among some Chinese seismologists and geologists (e.g., Wang and Pei, 1987; Zheng, 1998). Although Tiger Cliff and Jindongzi were mentioned as the landslide locations in the Bao Ning report and the monument, respectively, it is now difficult to find these precise locations. In all likelihood, the names of some locations might have been changed with time.

However, the Bao Ning report stated that Tiger Cliff was located in the Shenbie administrative zone at that time. Wang and Pei (1987) collected historic documents and presented a figure showing the geographical location of the Shenbie administrative zone (Fig. 4). This means that the landslide-damming events occurred on the Lengqi–Tianwan section of the Dadu River.

Fig. 5. Photograph showing the location which was interpreted as the landslide site by the Institute of Geophysics at the National Seismological Bureau and Institute of Chinese Historic Geography at Fudan University (1990) (view is to the west). The location of the site is shown in Fig. 7.

5.2. Geomorphic features

We searched all published materials associated with the possible location of the landslide and found a photograph taken in 1984, which was considered to represent the landslide site, in the *Atlas of Historic Earthquakes in China for the Qing Dynasty Period* (Institute of Geophysics at the National Seismological Bureau and Institute of Chinese Historic Geography at Fudan University, 1990). The location, as then photographed, was found in the field in August 2003 (Fig. 5). A detailed walkover survey was then carried out, and it was found that the landslide could not have taken place there on the grounds that (a) a gentle terrace surface with slope angles less than 5° can be seen, and it seems to be composed of glacial deposits (Sichuan Bureau of Geology and Mineral Resources, 1991), although slope deposits originating from small-scale rockfalls occur on steep slopes behind the terrace; (b) the bedrock, although heavily fractured, was consistently exposed along the ephemeral streamlines on slopes; and (c) no remnants of the landslide debris can be found on the opposite bank. We then checked all other possible locations, conducting a walkover survey from Lengqi to Qianwan along the Dadu River (Fig. 4). We found that although numerous small-scale rockfalls and landslides could readily be observed on both banks of the Dadu River, a site on the right bank (Fig. 6) was the only sizable landslide that could dam the Dadu River. This landslide is adjacent to the site in Fig. 5 and lies within MMI zone IX of the 1786 earthquake.

Geomorphic and geologic features of the landslide site are illustrated in a diagrammatic map of the landslide area (Fig. 7). Two adjoining hummocky slide masses can be seen above the steep right bank of the Dadu River. The landslide area is bush covered, marked by an active debris avalanche scar. The landslide is bounded to the north and the south by two ephemeral drainage lines and separated into two parts by a drainage line along which the recent debris avalanche moved downslope (Fig. 6). It can be

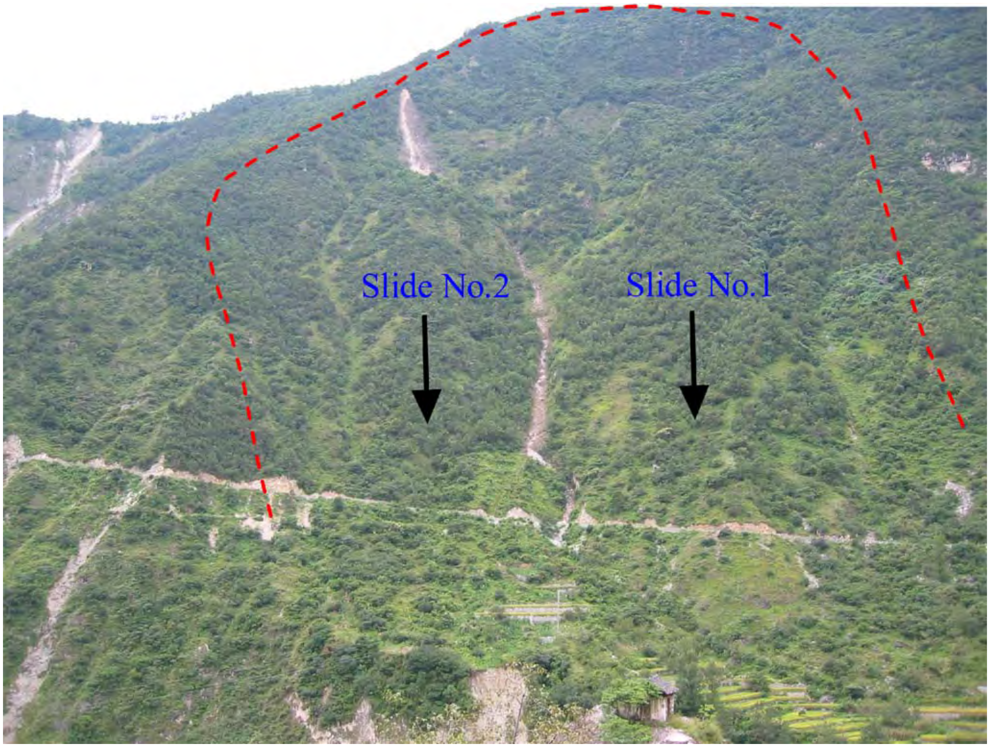

Fig. 6. Photograph showing the landslide site (view is to the west). The failure main scarp is marked with a dashed line, and the location of the site is shown in Fig. 4.

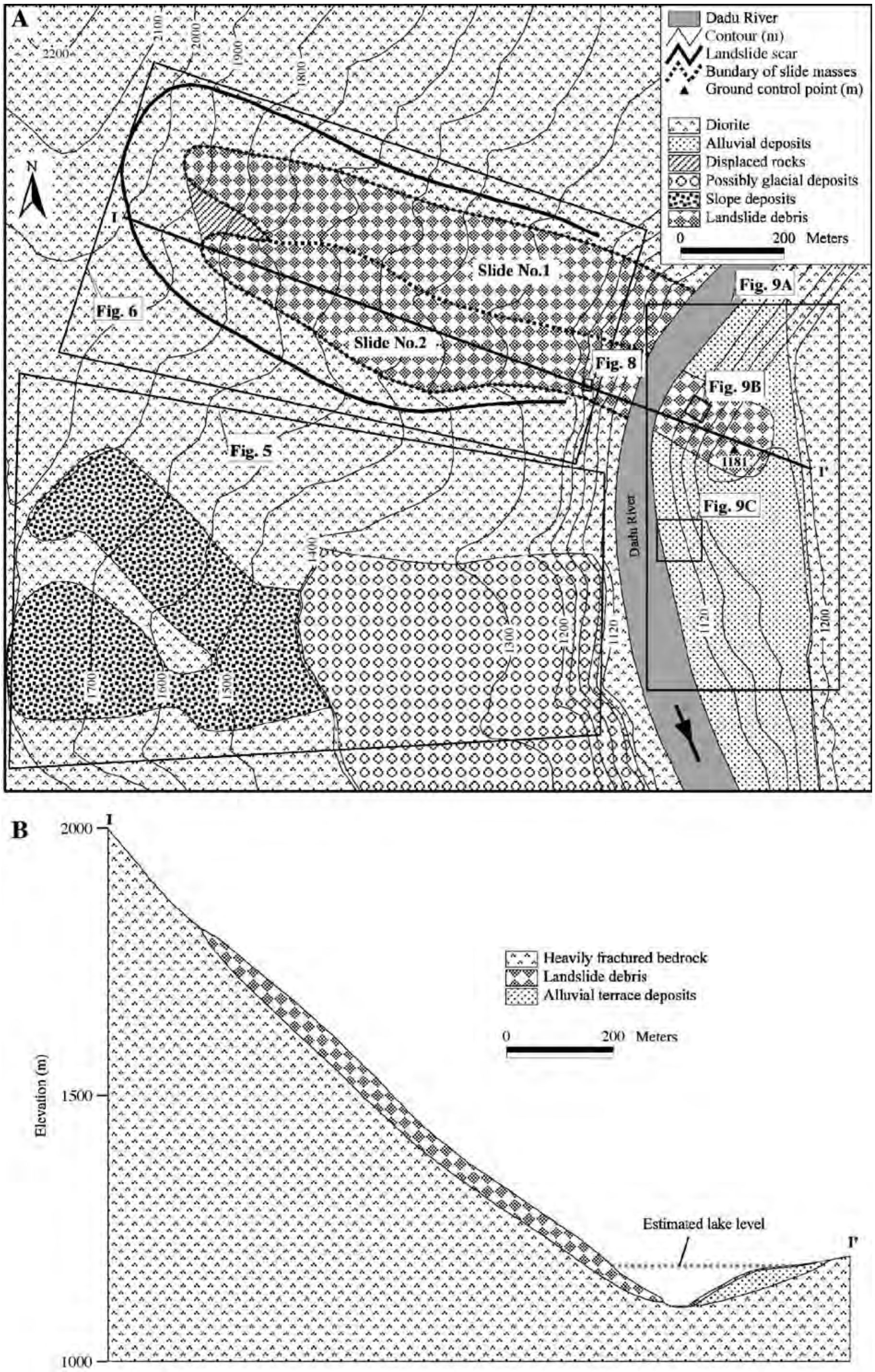

Fig. 7. Sketch map showing the geomorphology and geology of the landslide site and the spatial relation of Figs. 5, 6, 8 and 9, (A) plan; (B) cross-section of I–I'.

observed that the loose materials deposited along the drainage line were entrained during debris movement, exposing the underlying bedrock. It may be reasonable to divide the landslide into Slide no. 1 and Slide no. 2 as possibly two phases of movement (Fig. 7) because both slides are inferred to have a deep shear surface from the geomorphic features of the main landslide scar and the exposed bedrock on the drainage line. At the back of the landslide mass, a huge displaced rock block was sandwiched between these two slide masses. Apart from the minor erosion scar that constitutes the source area of the recent debris flow, no scarp shows evidence of active slope movements.

The slope of the landslide area ranges from 35° to 40°, whereas the Dadu River has a gradient of about 1%, traversing a narrow and steep-walled valley. The width of the riverbed at the landslide site is estimated to be about 80 m. The geology of the landslide area is comprised mainly of diorite of the Archean–early Proterozoic age (Fig. 7). The bedrock is heavily fractured due to structural and weathering effects. On the left bank, two terrace levels composed of alluvial sands, gravels and boulders can be distinguished. The river turns right and erodes the toe of Slide no. 2. The intense undercutting and lateral erosion of the river water makes the riverbank very steep, with an estimated slope angle of 50°–60°. The landslide debris consists predominantly of extremely crushed materials, ranging in particle size from clays to boulders and rock fragments (Fig. 8). It appears that both Slide no. 1 and Slide no. 2 occurred within heavily fractured diorite and slid along a steeply inclined slip surface (Fig. 7B). The volume is approximately 5×10^6 m^3 for Slide no. 2, and 6×10^6 m^3 for Slide no. 1, if the average failure depth is assumed to be 35 m based on the topographic features of the main landslide scar.

From the geomorphic features of the landslide area, it appears that the distal part of Slide no. 2 released a significant volume of landslide debris into the valley of the Dadu River and dammed the river completely, whereas the remainder of the debris remained stuck on the valley side, forming a hummocky accumulation.

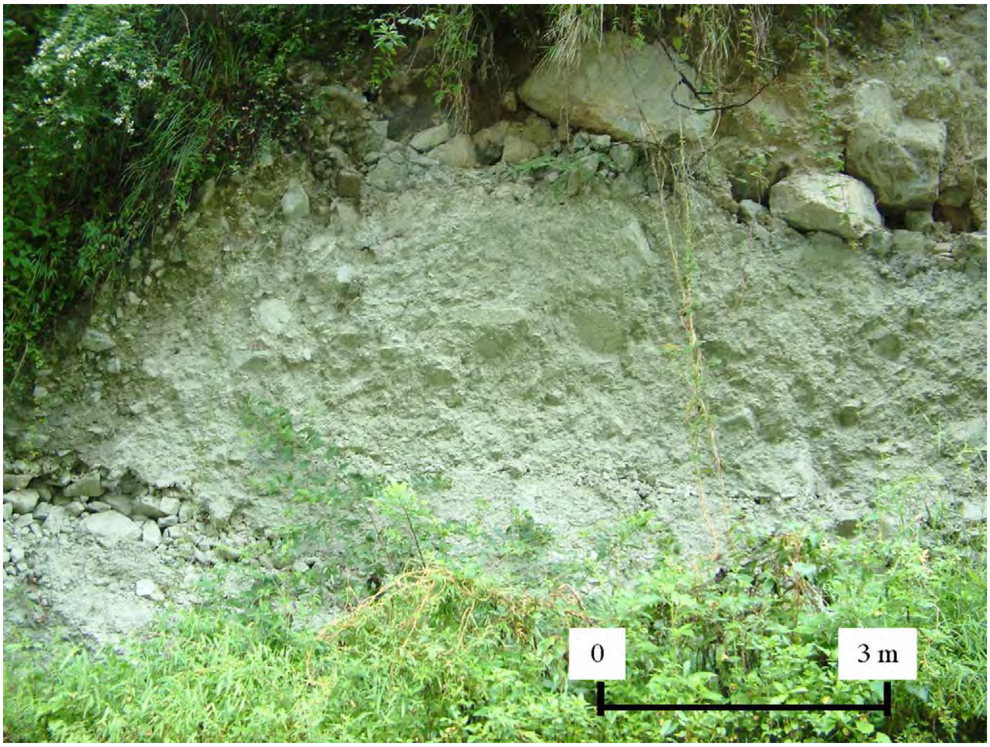

Fig. 8. Photograph showing the landslide debris on the right bank (view is to the west).

This can be verified by the fact that on the opposite bank of Slide no. 2, the remnants of landslide debris can be clearly observed, which can be distinguished from the upstream and downstream boulders and sands of alluvial origin (Fig. 9). The remnants of landslide debris can be found on the terraces of the left bank, implying that the landslide dam had a height equivalent to the elevation of the terrace. An official ground control point (GCP) for surveying at an elevation of 1181 m is located where the remnants of the landslide debris were observed (Fig. 7). Judging from the deposits, the landslide dam had a length of 320 m at the crest and 80 m at the river level. Schuster and Costa (1986) concluded that in steep-walled narrow valleys, there is no room for the landslide mass to spread out. The width of the landslide dam can therefore be estimated from the geometry of the landslide and the width of remnants of landslide debris deposited on the terraces of the left bank and should be less than 150 m. In addition, it can be inferred from the topographical map that the riverbed has an elevation of 1110 m. Therefore, this landslide dam had a height of about 70 m. This figure is in agreement with that recorded in the Bao Ning report. In as much as the landslide dam spanned the river valley floor and deposited materials on the opposite side of the valley, it belongs to Type II in the classification system proposed by Costa and Schuster

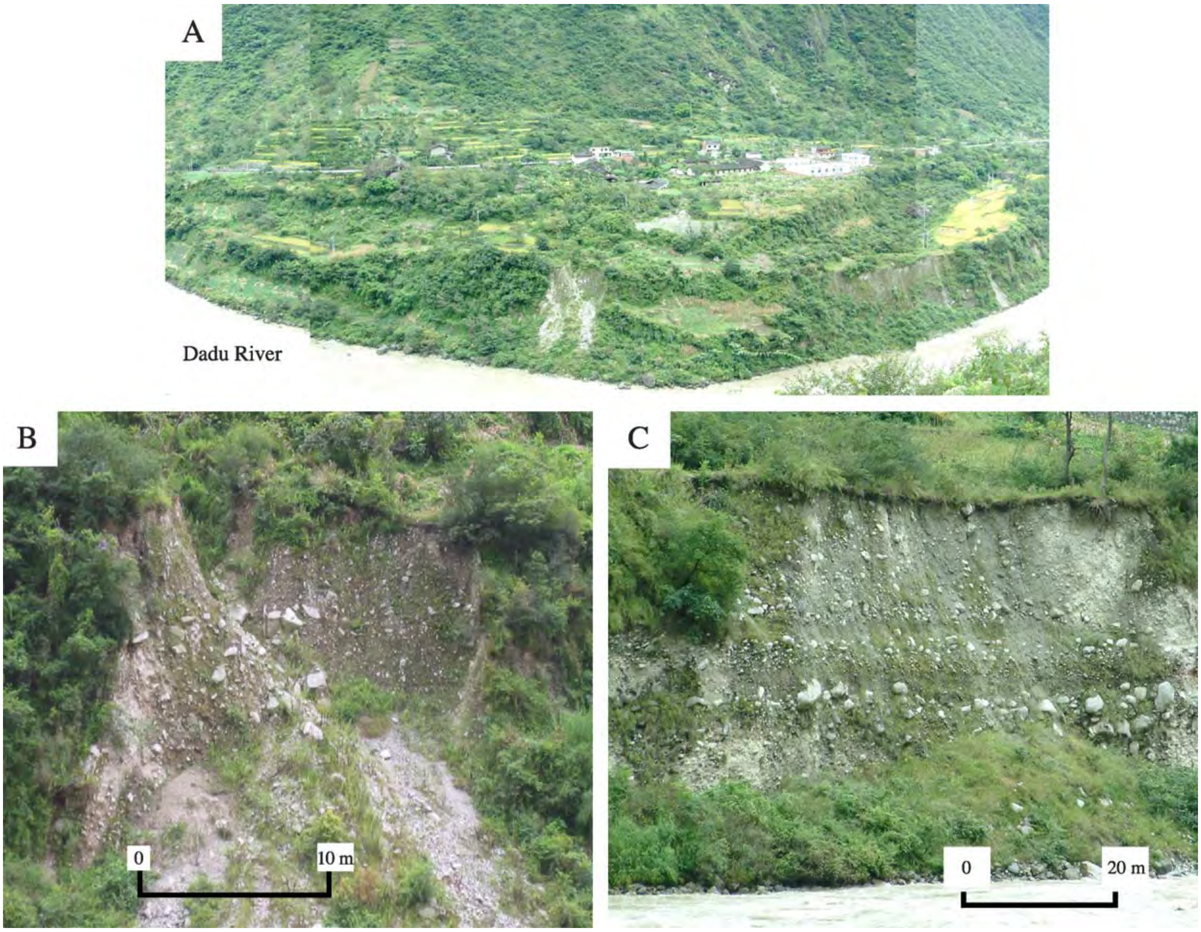

Fig. 9. (A) View of the opposite bank of the landslide (view is to the east). A small fresh bank failure can be observed on the steep-walled bank; (B) remnants of landslide debris on the opposite steep-walled bank exposed due to the small fresh bank failure (view is to the east); (C) alluvial deposits on the opposite steep-walled bank downstream the landslide dam site (view is to the east).

(1988) and the “main valley lake” type of Crozier and Pillans (1991). There is no evidence to confirm that Slide no. 1 also completely blocked the Dadu River.

It can be envisaged that after the landslide dam was formed, a reservoir began to develop behind the dam. The 1:50,000-scale topographic map covering the landslide area and its upstream area was digitised and then used to generate the digital elevation model (DEM) data with a resolution of 20 m so that the volume of the reservoir water can be reasonably estimated. Based on the ground control point in Fig. 7, it is reasonable to set the maximum elevation of the lake water as about 1180 m a.s.l. Thus, the reservoir behind the landslide dam at this elevation was about 6.8 km long along the main valley; the volume and area were estimated to be about 50×10^6 m^3 and 1.7 km^2, respectively (Fig. 10).

As described on the monument, the lake water overflowed the top of the landslide dam in the early morning of June 9. On June 10, the landslide dam breached suddenly, and the river valley downstream of the dam was flooded. This dam failure was triggered by an aftershock, rather than by overtopping or seepage and piping that are the most common mechanisms of natural dam failures, as described in the *Memoirs of Tianquan Prefecture*

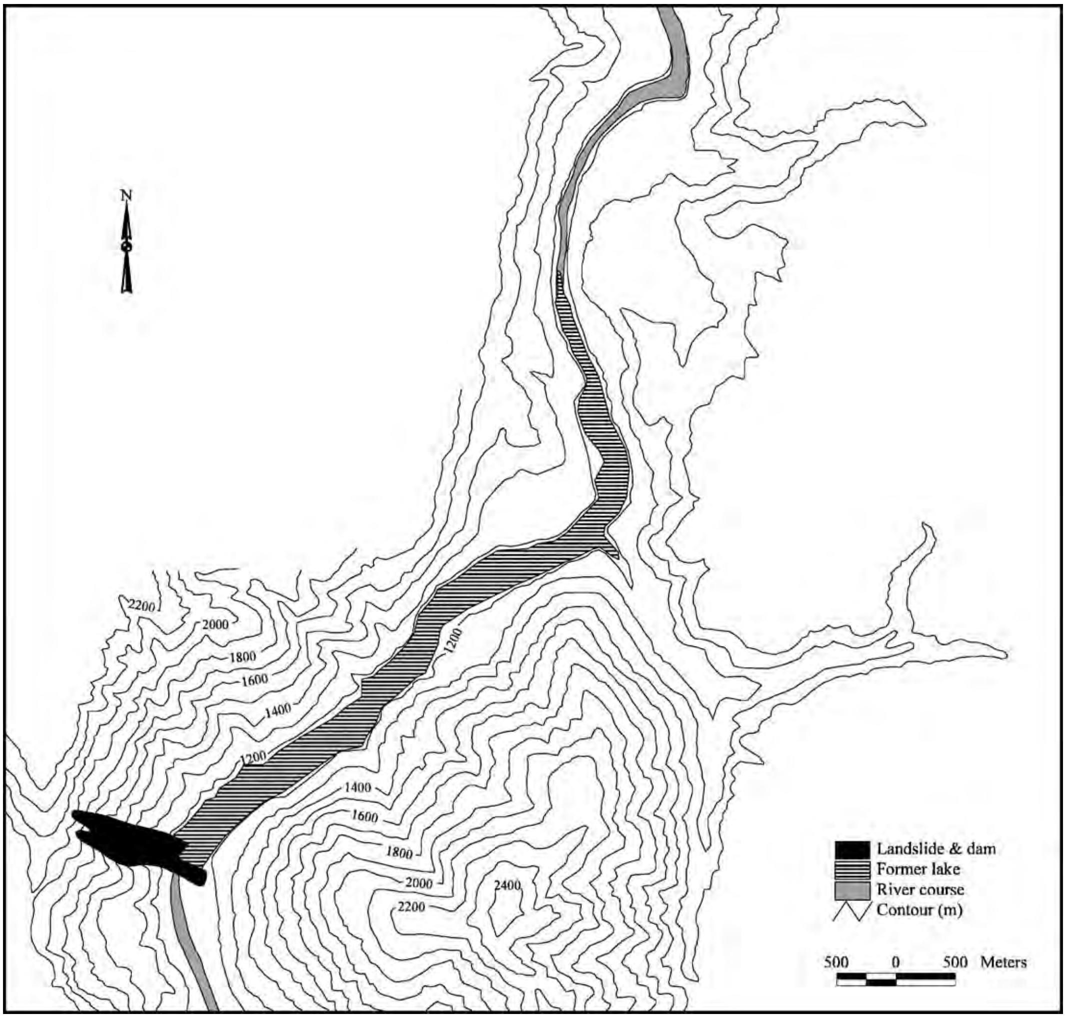

Fig. 10. Map showing the landslide dam site and the lake behind the landslide dam. The lake was reconstructed for a dam crest height of 70 m.

(Editorial Group of Sichuan Earthquake Information, 1980): "... on June 10, a major aftershock triggered the dam failure ..."

If compared to the size of many landslide dams observed elsewhere in the world, the size of this landslide dam on the Dadu River is not spectacular. What makes this landslide dam interesting is its catastrophic consequence downstream that will be subsequently described.

6. Consequences of the dam break

Based on the Bao Ning report, this landslide dam created damage due to two different types of flooding: (1) submergence of agricultural land due to upstream flooding as the reservoir impounded and (2) downstream flooding as a result of the failure of the dam. The Bao Ning report provided the following description: "...between Shimian and Hanyuan downstream of the landslide dam, the river levees, agricultural land, encamps and houses on both banks of the Dadu River were swept away by the flooding water..." There are other historic documents kept in the local governmental archives that recorded the damage downstream caused by this dam failure flood. The *Memoirs of Tianquan Prefecture* (Editorial Group of Sichuan Earthquake Information, 1980) recorded that "...the flooding caused by sudden dam breaching swept away the residents on both banks downstream. One day later, the flooding reached Leshan City. In the morning of June 11, a lot of people crowded on the east gate of the city wall and watched the flood. The wall collapsed suddenly and numerous people dropped into the flood water..." The *Memoirs of Leshan County* (Editorial Group of Sichuan Earthquake Information, 1980) recorded that "...the flood wave looked like a moving mountain; more than 10,000 people were drowned to death..." A written document by Qi Zhong, a scholar in the Qing Dynasty, reported that "...in Leshan, Yibin and Luzhou along the River, at least 100,000 people were drowned to death..." (Editorial Group of Sichuan Earthquake Information, 1980; Lou, 1996). As a result, 100,000 deaths were counted into the damage of the 1786 earthquake (Lou, 1996, p. 193).

It was impossible to record the exact number of deaths at that time. It can be concluded, however, that the number of deaths was already large in Leshan City and that the number of deaths increased drastically, as the flood routed downstream and more people were drowned. Historic records on this flooding event in the *Memoirs of Leshan County* (Editorial Group of Sichuan Earthquake Information, 1980; Xie, 1991) denied the possibility of additional flooding from the Min River, and thus, the high number of fatalities should be attributed mainly to downstream flooding from this landslide dam break.

If it is accepted that 100,000 people were drowned by this landslide dam break flood, this event should be the most disastrous in the world, in terms of the number of deaths caused by downstream flooding from landslide dam breaching.

7. Peak discharge estimate for the dam-break flood

The peak discharge of a natural dam-break flood can be estimated by the following two methods. One of them relies on regression equations that relate the observed peak discharge to some measure of the impounded water volume: depth, volume or some combination thereof (Evans, 1986; Costa and Schuster, 1988). Regression equations are expedient but generally provide no better than order-of-magnitude predictions of probable peak discharge (Evans, 1986; Costa and Schuster, 1988; Walder and O'Connor, 1997; Cenderelli, 2000). The other method employs computer implementation of physically based models (Fread, 1996; Singh, 1996). Such models have been developed to simulate breach formation, lake drainage and the peak discharge at the dam breach based on lake volume, water depth, lake geometry, breach geometry and the rate of erosion at the dam breach (Fread, 1996). The models generally account for hydraulic constraints not reflected by regression equations but may be cumbersome to use and often require detailed information on dam structure and material properties, which may be poorly known for natural dams (Cenderelli, 2000).

Despite the limitations of the regression equations, they do provide useful information on general trends in the peak discharge at the dam breach for landslide dam failure floods. Cenderelli (2000) provided the following regression equations for landslide dams:

$$Q_p = 24d^{1.73} \tag{1}$$

$$Q_p = 3.4V^{0.46} \tag{2}$$

$$Q_p = 1.9(Vd)^{0.4} \tag{3}$$

where Q_p is the peak flood discharge (m^3/s), d is the drop in lake level depth (m), and V is the volume of water drained from the lake (m^3).

The peak discharge estimation generally involves a breach that erodes rapidly to the base of the dam to calculate the possible maximum discharge (Walder and O'Connor, 1997). Therefore, we assume that the drop in lake level depth (d) is 70 m, and the volume of water drained from the lake (V) is 50×10^6 m^3. The peak discharge at breach is therefore 37,345 m^3/s based on Eq. (1), 11,831 m^3/s based on Eq. (2) and 12,485 m^3/s based on Eq. (3).

Walder and O'Connor (1997) developed the following physically based predictive equations for estimating the peak discharge at dam breach:

$$Q_p = 1.51(g^{0.5}d^{2.5})^{0.06}(kV/d)^{0.94} \text{ if } kV(gd)^{-0.5}d^{-3} < 0.6 \tag{4}$$

$$Q_p = 1.94g^{0.5}d^{2.5}(D_c/d)^{0.75} \quad \text{if } kV(gd)^{-0.5}d^{-3} >> 1 \tag{5}$$

where g is gravitational acceleration (m/s^2), k is the erosion rate at the breach (m/s), V is lake volume drained (m^3), d is the lake level decline during the flood (m), and D_c is the height of the dam crest relative to the dam base (m). The erosion rate at the breach is determined by

$$k = d/t \tag{6}$$

where t is the time for the breach to form (s).

In as much as the landslide dam failure in this study was triggered by a major aftershock, it may be reasonable to assume the time for the breach to form was very short, and Eq. (5) should be applied. Accordingly, the peak discharge at the dam breach is estimated to be 248,977 m^3/s, if D_c=70 m and d=70 m.

The above analyses indicate that the peak discharges at the dam breach, estimated using the regression equations and the physically based predictive equation, are very variable at least on an order of magnitude. As shown in Fig. 7, the landslide dam with a 70-m-deep flow has a cross-sectional area of about 9800 m^2. Based on the hydraulic continuity, the estimated discharges from Eqs. (1), (2) and (3) divided by the cross-sectional area yield mean velocities of 3.5, 1.2 and 1.3 m/s, respectively. The value of 1.2 or 1.3 m/s seems unreasonably small. However, the estimate from Eq. (5) implies a mean velocity of 25.4 m/s, which is impossibly large and close to the critical velocity to achieve cavitation at that flow depth. Therefore, the values of 3.5 and 37345 m^3/s may be acceptable as the mean velocity and peak discharge at the dam breach, respectively.

The best way to estimate the peak discharge at the dam breach may be to collect information on the flood water levels downstream and then back analyse the peak discharge at the breach, based on flood routing models for unsteady flow (Fread, 1996). This requires detailed information on downstream topographic data and hydraulic constraints. A preliminary study by Xie (1991) concluded that the maximum flood level in Leshan City was 376.9 m a.s.l (Xie, 1991), but the maximum flood depth is not known, and the accuracy of this estimation remains to be evaluated. Further study is needed in this regard.

8. Discussion and conclusions

Landslide dams are significantly hazardous, especially in an area of high seismicity, because of their possible catastrophic damage on downstream settlements and infrastructures. A full development of the hydropower potential of the Dadu River is now on the agenda. However, the risks of extreme, if rare, hazards from future landslide-damming events may be seriously underestimated. The ability to identify the occurrence of such events and interpret the consequence is necessary for estimating future risks.

Although there is no geomorphic evidence indicating that this landslide is still active, it has not yet reached the position of minimum potential energy

(Fig. 7). Hence, it is possible for the landslide to be reactivated under strong shaking conditions. These are the following four external and internal factors that may contribute to the future reactivation of the landslide. The first factor is the erosion of flowing water at the toe of the landslide. The Dadu River continuously and directly erodes the toe of Slide no. 2, removing the lateral support from an oversteepened slope. The second factor is that the shear strength of the sheared surface has been drastically reduced to the residual state due to past landsliding, increasing the possibility of future reactivation, as the heavily fractured bedrock has been extremely crushed or even powdered during the past movement. The third factor is that the head scarp of the landslide seems to show, albeit minor, symptoms of instability, and the possibility of new rockfalls from the cliffs should be considered, particularly under seismic conditions. The last factor is the possibility of future earthquakes. Based on seismological study, there are three near-site potential seismic sources that may produce strong earthquakes: (a) the Zheduotang and Selaha faults, (b) the Yalahe fault, and (c) the Moxi fault. For the Yalahe fault, the recurrence interval of strong earthquake with $M \geq 6.0$ exceeds 1000 years, and the last strong earthquake on this fault is estimated to have occurred in 1380±60 AD (Zhou et al., 2001). The possibility of strong earthquakes on this fault in the coming 100 years is thus very low. The same applies to the Zheduotang and Sehala faults because the strong earthquake ($M \geq 6.0$) recurrence interval of these faults is 230 to 350 years (Zhou et al., 2001), and the last strong earthquake occurred in 1955. However, the Moxi fault will induce a strong earthquake in the coming 100 years because the strong earthquake recurrence interval on this fault is about 300 years, and the last strong earthquake occurred in 1786, which generated the landslide dam under study. In conclusion, it is possible for the landslide to be reactivated in the near future.

Reactivation of the landslide, if it does occur, will block the Dadu River again, as the oversteepened distal part of Slide no. 2 has already reached the riverbed, and the river course is narrow. Elements at risk include the residents and buildings on the opposite bank, as well as those in upstream and downstream areas. Detailed geotechnical investigations for evaluating the stability of the landslide are strongly recommended with due consideration for future seismic risk.

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