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ORIGINAL PAPER

Landslide dams triggered by the Wenchuan Earthquake, Sichuan Province, south west China

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Abstract At 14:28 (Beijing time) on 12 May 2008, the catastrophic Ms 8.0 Wenchuan earthquake occurred just west of the Sichuan basin, China, causing severe damage and numerous casualties. It also triggered a large number of landslides, rock avalanches, debris ßows etc. Some of the landslides formed natural dams in the rivers, with the potential secondary hazard of subsequent ßooding. Through the interpretation of a series of aerial photographs and satellite images, 256 landslide dams were identiÞed, although because of limited access, relatively detailed data were available for only 32. The paper presents statistical analyzes of the distribution, classiÞcation, characteristics, and hazard evaluation of these 32 dams. A case study of the 2.04×10^7 m^3 Tangjiashan landslide dam and the emergency mitigation measures undertaken is discussed.

Keywords Wenchuan earthquake · Landslide dam · Barrier lake · Breach · Hazard

Introduction

At 14:28 (Beijing time) on 12 May 2008, the catastrophic Ms 8.0 Wenchuan earthquake occurred on the NEÐSW trending Longmenshan fault zone at the eastern margin of the Tibetan Plateau, just west of the Sichuan basin, China (Fig. 1). The Longmenshan fault zone is a tectonically active region, with three faults: the WenchuanÐMaowen fault, the YingxiuÐBeichuan fault and the Pengguan fault. The YingxiuÐBeichuan fault is the main fault that induced the earthquake. This devastating earthquake was the largest and most destructive movement in this densely populated mountainous area in the last 100 years and caused numerous landslides, rock avalanches, debris ßows etc. One type of natural hazard can induce other hazards (the domino effect), which makes research on natural hazards much more complex and difÞcult. For example, a co-seismic landslide can block a river and form a landslide dam, which may burst and cause a catastrophic ßood.

The impacts of landslide dams can generally be divided into upstream and downstream components. Korup (2005) undertook some research on the geo-hazard assessment of landslide dams in New Zealand and built a sequential path model of geo-hazard associated with the formation and failure of landslide dams. Figure 2 shows the hazards caused by the 32 landslide dams based on a modiÞcation of this model.

Figure 2 shows that a barrier lake generated by a landslide dam will submerge the upstream area and subsequently cause an increase in pore water pressure in the adjacent strata, which may induce secondary landslides into the lake. As a result, a displacement wave might be generated and may force the failure of the dam, in turn producing ßooding in the downstream area and a high potential for the triggering of secondary landslides.

The sudden damming of rivers by landslides creates major hazards hence it is receiving more and more attention in many countries. Costa and Schuster (1988) published a benchmark paper on the formation and failure of

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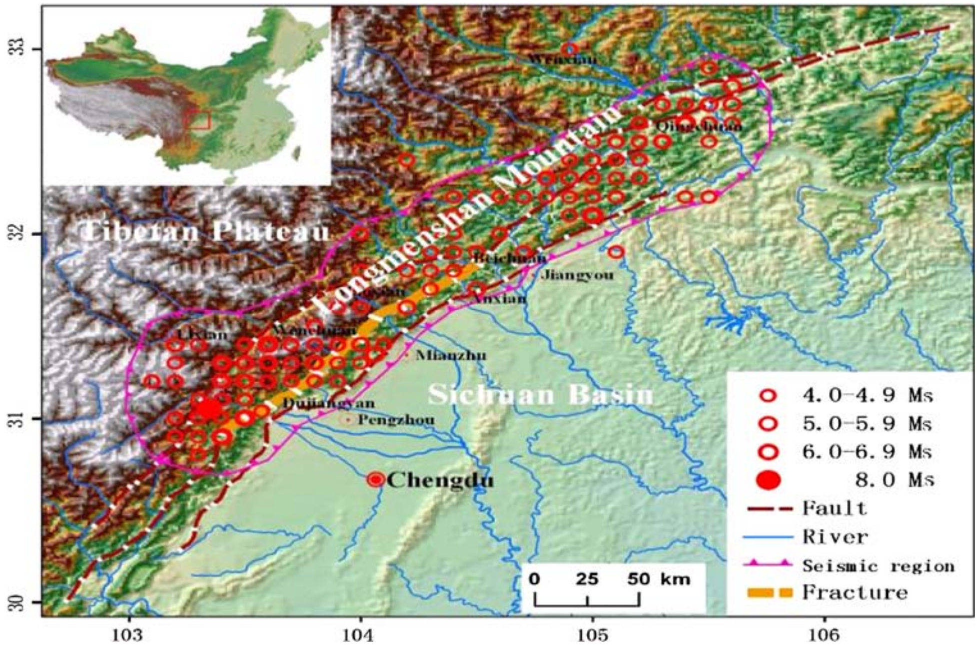

Fig. 1 The Longmenshan fault zone related to the Ms 8.0 Wenchuan earthquake

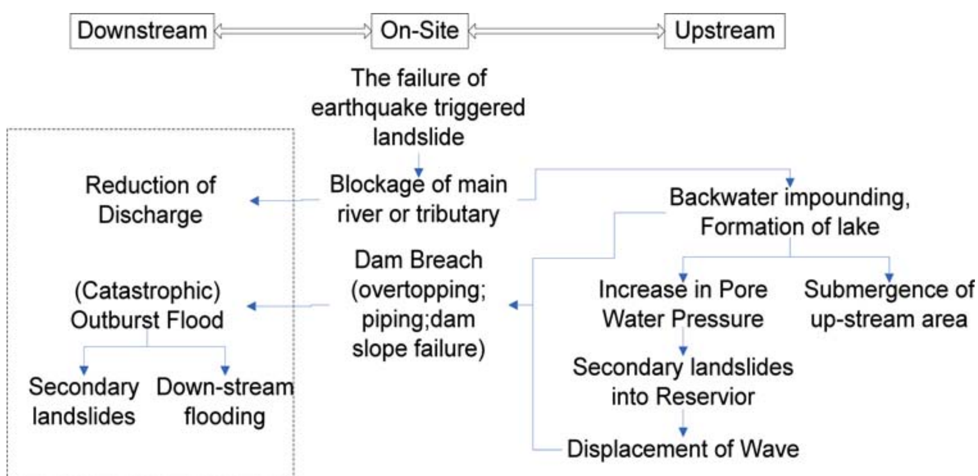

Fig. 2 Hazards caused by the formation and failure of landslide dams triggered by the Wenchuan earthquake using a modified version of Korup's (2005) model; the geomorphic hazard is not included

natural dams, paving the way for further studies on landslide dams. Subsequently, based on information made available by the U.S. Geological Survey, Costa and Schuster (1991) presented a comprehensive inventory of 463 landslide dams throughout the world. Schuster (1993) concluded that 90% of 390 landslide dams he studied were triggered by rainstorms/snowmelts or earthquakes and less commonly by volcanic activities, as reported by Umbal and Rodolfo (1996) and Melekestsev et al. (1999) or anthropogenic activities (e.g Asanza et al. 1992). Since 1995, a considerable amount of work has been undertaken in Italy; Casagli and Ermini (1999) reported an inventory of 68% and historical landslide dams in the Northern Apennines; Casagli and Ermini (2003) analyzed the grain size distribution in the Northern Apennine landslide dams, through sampling and laboratory analysis and showed how these are closely related to the geotechnical characteristics of landslide dams. Chai et al. (1995, 2000) studied and classified 147 recent and historical landslide dams in China. Twenty-one of these 147 were triggered by earthquakes while most of others were triggered by the heavy rainfall.

Landslide dam failures are quite common worldwide. For example, Mason (1929) described the failure of the earthquake-triggered Raikhot landslide dam and lake on the Indus River in Pakistan in 1841; Gesiev (1984) reported the 1911 earthquake-induced Usoi landslide on the Bartang River in the Pamir mountains of Tajikistan involving some 2×10^9 m^3; Nicoletti and Parise (2002) analyzed the origin, morphology and evolution of seven landslide dams in south eastern Sicily; Dunning et al. (2006) made a detailed description of the formation and failure of the Tsatichhu landslide dam in Bhutan; Geertsema and Clague (2006) collected and analyzed the 1,000-year record of landslide dams in Halden Creek, in north eastern British Columbia; Schneider (2008) reported on the Hattian slide which was reactivated by the 2005 Pakistan earthquake. This landslide created a rock avalanche and formed a natural dam impounding two lakes in the Karli river in Pakistan.

As early as 1786, a strong (Ms 7.75) earthquake occurred in the Kangding–Luding area, in Sichuan Province, China, which caused the formation of a landslide dam and the subsequent flooding of the Dadu River when the dam was breached. Historic records document over 100,000 deaths in this event (Dai et al. 2005). On 25 August 1933, an earthquake with an Ms of 7.5 occurred with its epicenter 180 km upstream of Diexi town. The resultant three landslide dams (Dahaizi, Xiaohaizi, and Deixi) extended to a maximum height of 160 m on the Min River. Because of the continuous inflow of water and the high elevation of the downstream Diexi dam, as the water rose the three lakes merged and eventually overtopped on 9 October 1993. Some 45 days later, a flood rushed downstream for a distance of 250 km, killing more than 2,500 people (Sichuan Seismological Bureau 1983; Chai et al. 2000; Huang 2008). On 8 June 1967, a large-scale landslide (9.5×10^7 m^3) moved into the Yalong River in Tanggudong, Sichuan Province within a period of only 5 min. A 175 m high landslide dam was formed and a lake with a capacity of 6.8×10^8 m^3. On 17 June, the dam broke and over a period of 12 h released a catastrophic flood with a peak discharge of 57,000 m^3/s (Chai et al. 1988 and Huang 2008).

Of all the recorded cases, the 3×10^8 m^3 Yigong landslide is the largest. This occurred on 9 April 2000 along the Zhamu Creek in south eastern Tibet. Within 10 min, the landslide material traveled 8 km, creating a natural dam with a maximum height of 100 m, a maximum bottom width of 2,500 m (parallel to the Yigong River flow) and an axial length of 1,000 m (the length of the dam axis, cross the river). At 20:00 (Beijing time) on 10 June, the dam was breached and the water level downstream rose sharply by at least 50 m. On 11 June, the maximum discharge was about 120,000 m^3/s. The terrible flood resulted in 30 deaths and more than 100 people missing (Shang et al. 2003; Huang 2008).

In this review, it has only been possible to mention a few of the studies on landslide dam classification and some important case histories. A more detailed and comprehensive literature review was made by Korup (2002), who takes a critical look at recent trends and developments in international and New Zealand-based research on landslide dams.

Through the interpretation of a series of aerial photographs and satellite images, 256 landslide dams caused by the Wenchuan earthquake were identified. Among them, there are 32 landslide dams which posed a serious threat to people in the area.

Although some work has been carried out to describe and analyze the mechanism of the Wenchuan earthquake and the distribution of earthquake-induced landslides; to date, the research on earthquake-triggered landslide dams is sketchy. The present study concentrates on the statistical analysis of landslides dams, focusing on the distribution, classification, characteristics, and hazard evaluation of landslide dams based on a database of 32 samples and the description of one case study.

Generation of the landslide database

As mentioned above, the Wenchuan earthquake generated at least 256 landslide dams, but due to difficulty of access, to date it has only been possible to collect relatively detailed data for 32 of the comparatively larger landslide dams (Table 1, Fig. 3). After the earthquake, the potential of flooding caused by the breaching of these 32 landslide dams was one of the most serious and urgent emergency problems in the earthquake-hit area. The Chinese government immediately organized a team of geological and hydrological experts to investigate the landslide dams. Some of the first information was collected by helicopter reconnaissance, before the blocked and damaged roads were repaired. Remote sensing and Geographic Information Systems (GIS) were also very useful for these investigations and gave a general idea as to the location and volume of the dams.

As seen in Fig. 3 and Table 1, eight of the landslide dams are along the Jian River in Beichuan; three along the different tributaries of the Pei River in An county; four along the Mianyuan River in Mianzhu; seven along the Shiting River in Shifang; three along the Qingzhu River in Qingchuan; four along the Wenjing stream, a tributary of the Min River, in Chongzhou; two along the Shajin stream, a tributary of the Tuo River, in Penghzhou and one along the Shikan River in Pingwu county. Most of the basic data in Table 1 were obtained from reconnaissance records by many experts and institutes, while the classification of the landslide dam type and the estimated dam failure mode were evaluated by the authors on the basis of the following criteria.

The landslide dams were classified into six types according to the classification proposed by Costa and Schuster (1988):

Type I dams which do not span the valley from side to side;

Type II dams which do span the valley and may run up the opposite slope;

Table 1 Key features of the 32 landslide dams and barrier lakes associated with the Wenchuan earthquake

No.	Name	County	Dammed river	H_D (m)	V_D (10^4 m^3)	V_L (10^4 m^3)	Landslide type	Landslide dam type	Main geologic materials making up the dam	Estimated dam failure mode
1	Tangjiashan	Beichuan	Jian	82Ð124	2,040	30,000	Rock slide	II and III	Boulders and blocks with fragmented rocks and soil	Overtopping with erosion
2	Kuzhuba	Beichuan	Jian	60	165	200	Rock slide	II and III	Blocks and fragments only with a little soil	Overtopping with erosion
3	Xinjie village	Beichuan	Jian	20	70	200	Soil slide	III	Unconsolidated soil with fragments and blocks	Piping
4	Baiguo village	Beichuan	Jian	10Ð20	40	80	Rock slide	II and III	Unconsolidated blocks and fragments with a little soil	Piping
5	Yanyang-tan	Beichuan	Jian	20Ð30	160	400	Rock slide	II and III	Loose soil and blocks	Piping
6	Sunjia-yuanzi	Beichuan	Jian	50	160	560	Rock slide	II and III	Loose blocks and fragments with soil	Piping
7	Guanzipu	Beichuan	Jian	60	Ð	585	Rock slide	II and III	Unconsolidated blocks with soil	Piping
8	Tangjia-wan	Beichuan	Jian	30	400	1,520	Rock slide	III	Unconsolidated fragments (40%) and soil (30%) with blocks (20%)	Overtopping with strong erosion
9	Xiaojia bridge	An county	Chaping	61.5Ð73	390	2,230	Rock slide	II and III	Rock fragments (45%) with boulders (15%) and blocks (35%)	Overtopping with strong erosion
10	Guantan	An county	Ganhezi	60	120	1,000	Soil slide	III	Soil with rock blocks	Overtopping with strong erosion (9Ð11 m^3/s)
11	Laoying-yan	An county	Jushui	106Ð140	470	1,010	Rock slide	III	Boulders (15%) and blocks with fragmented rocks (60Ð70%)	Overtopping with strong erosion
12	Heidong-ya	Mianzhu	Mianyuan	50Ð80	40	180	Ð	Ð	Ð	Overtopping with strong erosion (1Ð3 m^3/s)
13	Upstream Xiaogang-jian	Mianzhu	Mianyuan	62Ð72	160	1,100	Rock slide	III	Rock blocks (60Ð70%)	Overtopping with strong erosion
14	Downstream Xiaogang-jian	Mianzhu	Mianyuan	30	45	700	Rock slide	II and III	Rock blocks	Overtopping with strong erosion
15	Yibadao	Mianzhu	Mianyuan	25	10	50	Rock slide	II	Rock blocks	Piping
16	Ganhekou	Shifang	Shiting	10	1	50	Rock slide	II	Rock blocks	Overtopping with erosion
17	Muguaping	Shifang	Shiting	15	20	4	Soil slide	IV	SuperÞcial accumulative soils	Overtopping with erosion
18	Macaotan-upsteam	Shifang	Shiting	40Ð50	100	60	Rock slide	II	Blocks and rock fragments	Overtopping with erosion and break immediately
19	Macaotan-site	Shifang	Shiting	40Ð50	20	25	Rock slide	II and III	Boulders and blocks with rock fragments	Overtopping

Table 1 continued

No.	Name	County	Dammed river	H_D (m)	V_D (10^4 m^3)	V_L (10^4 m^3)	Landslide type	Landslide dam type	Main geologic materials making up the dam	Estimated dam failure mode
20	Macaotan-downstream	Shifang	Shiting	30	14	10	Rock slide	II and III	Boulders and blocks with fragmented rocks	Overtopping
21	Yanziyan	Shifang	Shiting	10	0.6	3	Rock slide	II	Blocks and fragmented rocks	Overtopping and formed a natural channel
22	Hongcun	Shifang	Shiting	40Ð50	40	100Ð150	Rock slide	III	Blocks and fragmented rocks with soil	Overtopping and formed a natural channel
23	Shibangou	Qing-chuan	Qingzhu	30Ð75	1,500	1,100	Rock slide	III	Blocks and fragmented rocks	Overtopping and formed a natural channel (20Ð30 m^3/s)
24	Hongshihe	Qing-chuan	Qingzhu	30Ð50	400	120	Rock slide	II	Blocks and fragmented rocks with soil	Overtopping and formed a natural channel (20-30 m^3/s)
25	Donghekou	Qing-chuan	Qingzhu	20	1,200	1,000	Rock slide	III	Fragmented rocks with soil	Overtopping with erosion (30Ð40 m^3/s)
26	Liuxianggou	Chong-zhou	Wenjing	60	150	300	Ð	Ð	Ð	Overtopping and formed a natural channel
27	Zhugen bridge	Chong-zhou	Wenjing	90	300	450	Ð	Ð	Ð	Overtopping and formed a natural channel
28	Huoshigou	Chong-zhou	Wenjing	120	240	150	Ð	Ð	Ð	Overtopping and formed a natural channel
29	Haiziping	Chong-zhou	Wenjing	8	67	300	Ð	Ð	Ð	Overtopping and formed a natural channel
30	Fengmingqiao	Pengzhou	Shajin	10		180	Ð	Ð	Ð	Overtopping
31	Xiejiadianzi	Pengzhou	Shajin	10		100	Ð	Ð	Ð	Overtopping with erosion
32	Nanba	Pingwu	Shikan	25Ð50	532	686	Rock slide	II	Blocks and fragments (70Ð80%)	Overtopping

H_D is the height of landslide dam, V_D is the volume of landslide dam, V_L is the maximum capacity (the impounded water volume at lake full level) of barrier lake

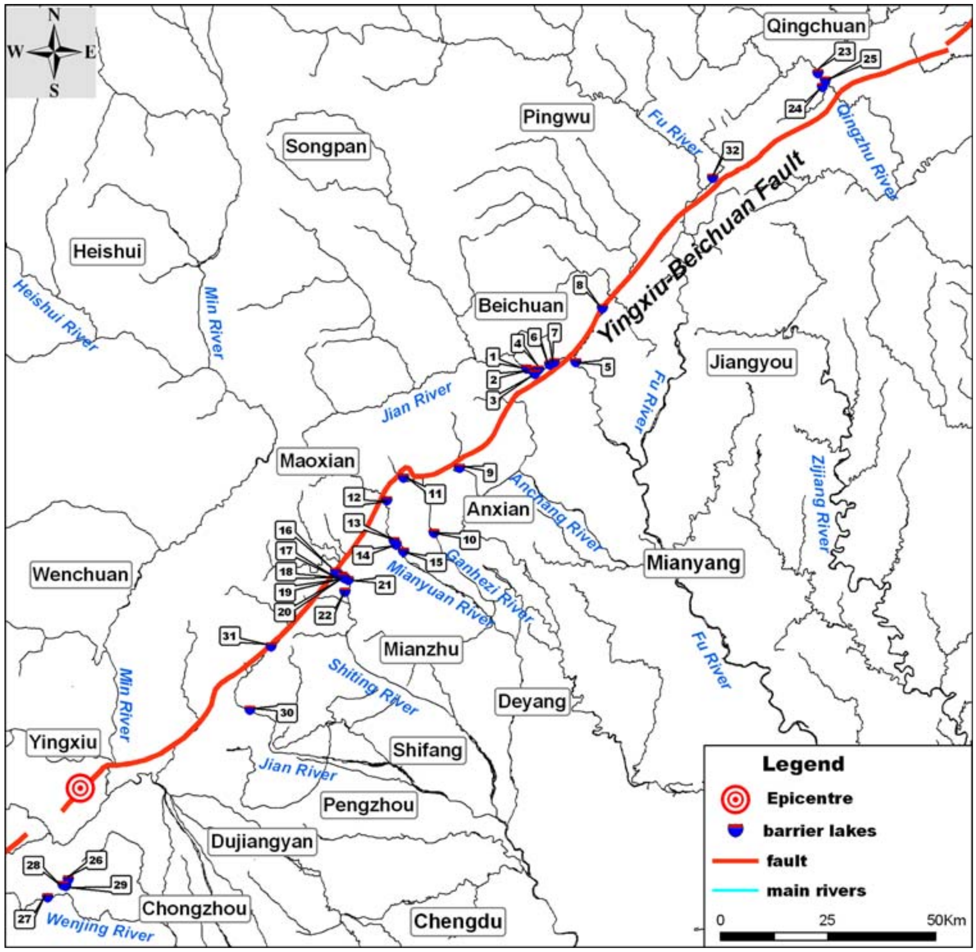

Fig. 3 Locations of the 32 earthquake-induced landslide dams and surface expression of the YingxiuÐBeichuan fault

Type III dams which span the valley and, in addition, move considerably up and down the valley;

Type IV dams which are formed by contemporaneous failures from both valley sides, followed by frontal or slide contact between the two masses;

Type V dams which are caused by multiple lobes of a given landslide;

Type VI dams which occur when the failure surface(s) extend(s) under the stream bed, which is then raised when the landslide moves.

The six types are not mutually exclusive. A landslide could be Type II, Type III, and Type V or other types at the same time. The failure mechanism, evolution process, and the stability analyzes of landslide dams are very complex (Costa and Schuster 1988). In this study, the possible failure modes of landslide dams were divided into three types: overtopping, internal seepage, and dam slope failure.

(a) Overtopping is further divided into two sub-types:

with erosion (water in a lake overßows the crest of a dam, erodes and incises the dam, forming a natural channel that will probably cause the dam to fail) and

without erosion (although water overßows the crest of a dam, it only causes slight erosion of the dam, forming a stable natural channel).

(b) Internal seepage can also be divided into two sub-types:

with erosion-piping, deÞned as water that ßows through the dam and washes out the Þnest soil particles, increasing the volume of voids such that progressively larger particles can be moved to create a pipe (Waltham 2002) and

without erosion (which probably occurs when a dam is composed of rock boulders and blocks with little soil).

It is difÞcult for overtopping and internal seepage without erosion to cause a dam failure, although this is possible in some extreme conditions, such as a sharp increase of river discharge of the blocked river in the monsoon season.

Although the basic failure mechanism of natural dams is commonly studied, very little is known about the actual processes involved with their failure, as there are only a few direct observations of and data on dam failures. Table 1 shows some landslide dams that failed naturally, including the Donghekou, Hongshihe, Guantan, Heidongya, Fengmingqiao, Laoyingyan and Ganhekou landslide dams. Their failure modes were defined on the basis of field survey reports. For the artificial breached dams, the failure mode was estimated based on comprehensive analysis of the composition of the dam material, the grain size distribution, the discharge of the blocked river and the records on dam failure time and phenomena given by the policemen who carried out the emergency measures.

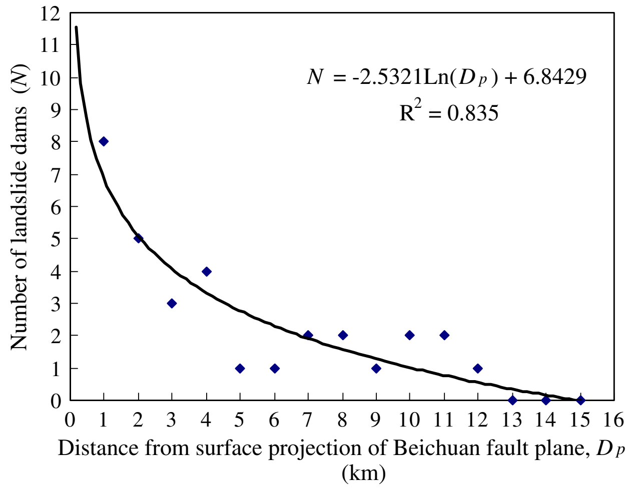

Fig. 4 Landslide dam concentration (N) versus distance from the Yingxiu–Beichuan fault (D_p). The *solid line* is the best-fit regression line, which has a logarithmic form

Statistical analysis of landslide dams

Landslide dam distribution

The statistical analysis undertaken was related to the 32 landslide dams for which relatively complete data were available (Fig. 3). The landslide dam concentration (N) is defined as the number of landslide dams for a sequence of concentric parallel bands 1 km wide, extending outward from the surface projection of the fault plane. Figure 4 shows the relationship between the landslide dam concentration and the distance from the surface projection of the Yingxiu–Beichuan fault plane (D_p). The figure shows that the highest concentration values are close to the fault (8 at $D_p = 1$ km), decreasing to 0 at ≥13 km. Without a theoretical basis for choosing a particular function form for the relation between N and D_p, it as found that the relation between N and D_p empirically fits best with a regression equation with a logarithmic form (see Fig. 4). Keefer (2000) undertook a similar statistical analysis of an earthquake-induced landslide distribution in California in 1989.

The 256 landslide dams identified after the Wenchuan earthquake were combined with a digital elevation model (DEM), generated by the Institute of Mountain Hazards and Environment in Chengdu (Fig. 5). Statistical analysis indicates that 43% of the dams are located in areas less than 5 km from the Yingxiu–Beichuan fault and 26% 5 to 10 km away from the fault.

As ground motion records are not available, the variation of the concentration of landslide dams with peak ground acceleration (PGA) values could not be analyzed at this time.

Analysis of the size of landslide dams and barrier lakes

The size and shape of the dam depends on the landslide type, material and size, and on the relationship between these and such valley characteristics as cross-section at the dammed site, area of the watershed and its hydrologic regime (Nicoletti and Parise 2002). The volumes of the 32 landslide dams studied and the lakes behind them are very variable. The possible natural maximum capacities (the impounded water volumes at full lake level) of the barrier lakes given in Table 1 have been estimated from the heights of the landslide dams and the upstream topography. As seen in the table, the Tangjiashan landslide dam is the largest with a volume of 2.04×10^7 m^3 while Yanziyan is the smallest with a volume of 6×10^3 m^3. There are three landslide dams with volumes larger than 1×10^7 m^3 and six barrier lakes with an estimated maximum capacity of more than 1×10^7 m^3. The landslide dams vary widely in height, from 8 to 124 m (Fig. 6).

Casagli and Ermini (1999) developed a method of rapid assessment of stability "domains" using the compound geomorphometric indices of landslide dams and lakes. They proposed an Impoundment Index:

$$I_i = \log\left(V_D V_L^{-1}\right), \quad (1)$$

where V_D and V_L are the volume of landslide dam and lake in "m^3", respectively.

$I_i = 1$ roughly separates two empirical "domains" of stable (existing) and potentially unstable landslide dams in New Zealand. When this method was used to evaluate the stability of the dams listed in Table 1, all of them appeared to be unstable, which is not helpful and seems to be inconsistent with the real situation.

Analysis of landslide dam type, dam material and failure mode

As mentioned above, the landslide dams triggered by the Wenchuan earthquake have been classified into six types.

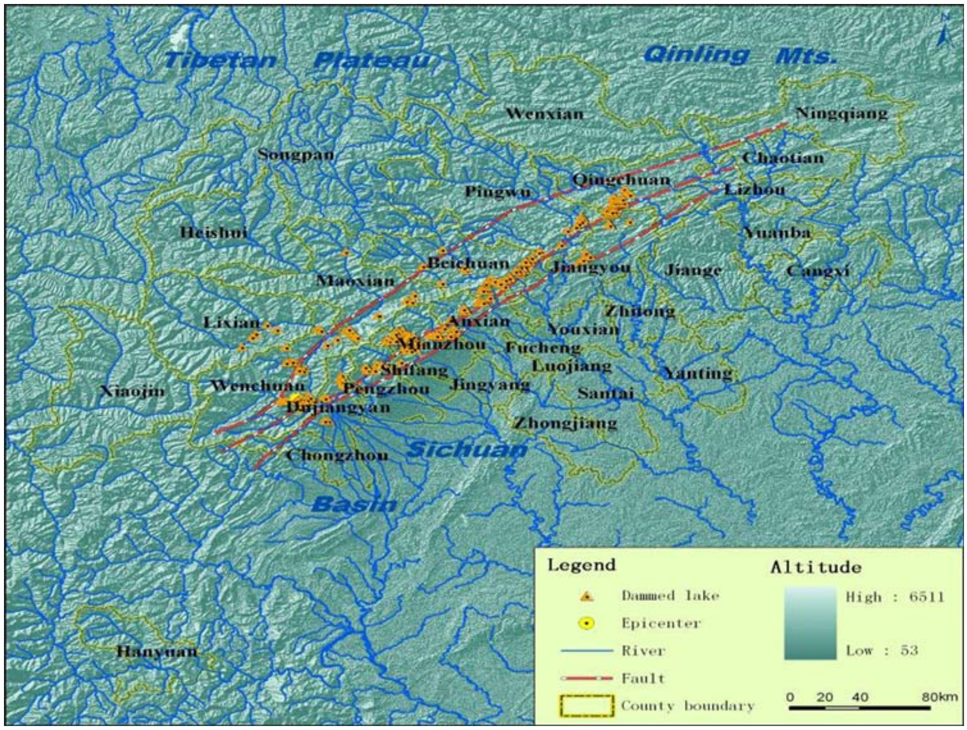

Fig. 5 The distribution of some of the landslide dams triggered by the Wenchuan earthquake (source: Institute of Mountain Hazards and Environment in Chengdu)

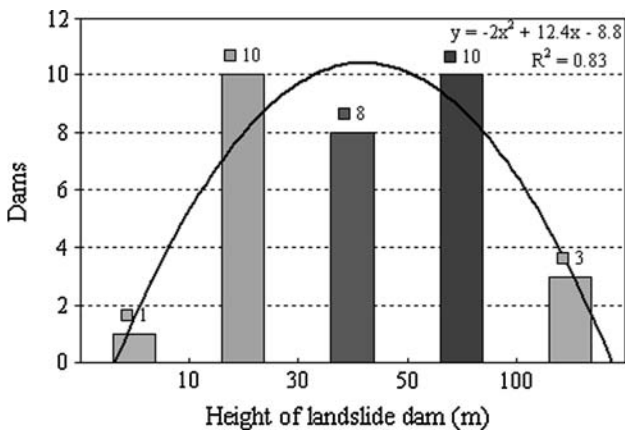

Fig. 6 Variation of the height of the landslide dams

Nearly all the landslide dams shown in Table 1 belong to Type II and III, while only one is identiÞed as Type IV. Costa and Schuster (1988) also concluded that Types II and III are the most common worldwide, accounting for 61 and 28% of the total number of landslide dams studied, respectively. From a consideration of the Þeld investigation and aerial photography data, the type of landslide dam appears to be closely related to the volume and speed of the landslide mass as well as to the valley ßoor geometry. In this study, Type II and Type III both occurred with high speed rock slides moving into a narrow valley such that the material spread either up the side of the valley and/or up- and downstream, e.g the Tangjiashan landslide dam.

The composition of the landslide dam materials plays a crucial role in controlling the longevity, stability, and

Fig. 7 Hydropower station upstream of the Kuzhuba landslide dam along the Jian River. a Before the Wenchuan earthquakeb After the Wenchuan earthquake

failure mechanism of a landslide dam. Dams formed from large rock boulders or cohesive clays are less likely to fail than dams composed of permeable soil or unconsolidated barriers (Schuster 1993, 1995). Most of the dams considered here were the result of rock slides; only three being formed of soil (Table 1). The dams were categorized according to the different materials they contained:

1. soil and fragments of rock, which consists of more than 50% of soil and rock fragments with the grain size varying from 20 to 200 mm;
2. soil and fragments of rock with a few boulders and blocks, which consists of more than 50% of soil and rock fragments with the grain size varying from 20 to 200 mm; the grain size of boulders and blocks is larger than 200 mm;
3. boulders and blocks with little soil and rock fragments, which consists of more than 50% of boulders and blocks with the grains larger than 200 mm;
4. boulders and blocks, where the grain size of the boulders and blocks is larger than 200 mm.

The study indicated 75% of the 32 landslide dams failed by overtopping while 25% failed by piping.

Impacts and hazard assessment of landslide dams

Impacts of landslide dams

The theoretic peak discharge is recognized as an important parameter to express the potential impact of the catastrophic breaching of a landslide dam. Dai et al. (2005) claimed that the peak discharge could be estimated by two methods: (a) regression equations that are related to the observed peak discharge and some measure of the impounded water volume and (b) computer-based physical modeling. Although regression equations have many limitations and disadvantages, e.g generating much larger peak discharges than the real values, they still provide useful information in general. Costa (1985) has suggested the following regression equation (Eq. 2) for a rapid assessment of peak discharge from outburst floods from landslide dam lakes:

$$Q_p = 181(H_D V_L)^{0.43} \quad (R^2 = 0.76) \tag{2}$$

where Q_p is the peak flood discharge in (m^3/s), H_D is the dam height in (m), and V_L is the maximum volume of the barrier lake in 10^6 m^3. H_D and V_L values are given in Table 1 and the calculated peak discharge of landslide dams in some typical catchments in Table 3. The estimated peak discharge of the Tangjiashan landslide dam is huge—15,474 m^3/s.

A barrier lake generated by a landslide dam will submerge the upstream area; an example of the impact of landslide dams in the upstream area is shown in Fig. 7.

Hazard assessment of landslide dams

Numerous methods have been developed to assess landslide hazard. Aleotti and Chowdhury (1999) made a summary review of landslide hazard assessment and also gave a detailed description of the various approaches to landslide susceptibility and hazard assessment including empirical, heuristic, statistical, deterministic approaches etc. It is extremely difficult to make a hazard assessment of potential sites where landslide dams can occur. After an earthquake, the hazard assessment of new landslide dams that have occurred is extremely important for the emergency preparedness planning and in making rational decisions to carry out suitable mitigation measures to reduce the risk. In times of emergency, with limited data available, the empirical approach is the most suitable for individual landslide dam hazard assessments. As speed is of the essence to save lives at such times, some experts put forward a matrix to allow a quick qualitative assessment of landslide dam hazard (Table 2). The height and constituent material of the landslide dam as well as the virtual volume (the maximum capacity) of the barrier lake were selected as the criteria on which to classify the risk as very high, high, moderate or low. For each of the three criteria a

Table 2 Matrix for a quick qualitative assessment of the individual landslide dams induced by the Wenchuan earthquake

Hazard classification	Criteria		
	Height of dam (m)	Maximum capacity of barrier lake (10^4 m^3)	Composing materials of dam
Very high	>100	>10,000	Group 1
High	>50 and ≤100	>1,000 and ≤10,000	Group 2
Moderate	>25 and ≤50	>100 and ≤1,000	Group 3
Low	≤25	≤100	Group 4

The dam composing materials are roughly categorized into four groups: Groups 1–4 as mentioned above hazard class is defined and the majority of the classes define its overall hazard class.

The hazard posed by 32 landslide dams has been evaluated; Table 3 shows the evaluation for some of the dams along the Jian and Shiling rivers. It indicates the Tangjiashan landslide dam is the most dangerous while most of the others were assessed as having moderate hazard.

Case study: the Tangjiashan landslide dam

The Tangjiashan landslide dam, located in the upstream section of the Jian River in Beichuan county was the largest and most dangerous landslide dam created by the Wenchuan earthquake. The dam crest extended approximately 600 m across and 800 m along the valley (Figs. 8, 9). The height of the dam varied from 82 to 124 m; from a rough calculation using the profiles its volume was estimated to be 2.04×10^7 m^3.

The Tangjiashan landslide dam was caused by a rock slide in interbedded soft rock and hard rock strata, which were formed from grayish black siltstone of the Qingping Formation of Cambrian age. According to the eye witnesses' description, the landslide occurred almost at the same time as the earthquake and traveled for a vertical distance of 540 m within 1 min, i.e with an estimated speed of 10 m/s. The very large, steep scarp can be observed in Figs. 8 and 10. Another characteristic of the landslide is that it ran up the other side of the valley. With reference to the aforementioned classifications, it fits both Type I and Type II. The dam basically has a three-layered structure (Fig. 11). The top layer is composed of fragmented rocks with soil; the middle layer contains mainly boulders and blocks while the bottom layer consists of very weathered strata which retain their original structure. The average size of the boulders is 2 to 3 m with a maximum of 5 m. The blocks vary from 0.2 to 1.5 m. The top layer and middle layers comprise approximately 10% boulders, 60% blocks, 20% fragmented rocks, and 10% soil. Consequently, the bottom layer is relatively more consolidated and has a lower permeability than the middle and top layers.

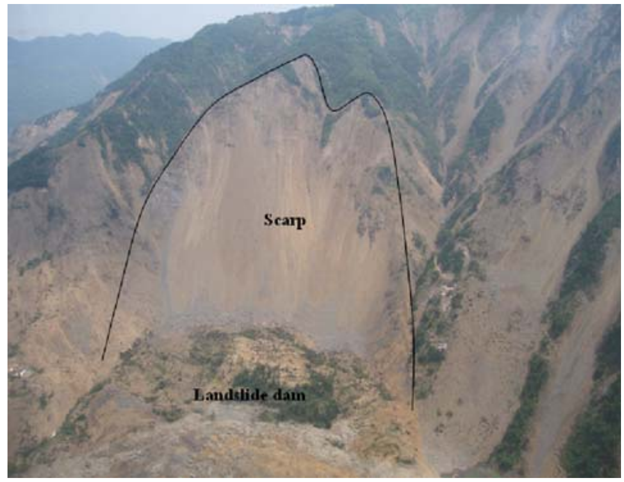

Fig. 8 Helicopter view of the Tangjiashan landslide dam

According to Hu (2008) it was estimated that the volume of the barrier lake behind the dam on 9 June 2008 would be 2.4×10^8 m^3, approaching the maximum capacity of the barrier lake which was estimated to be 3×10^8 m^3. As there were seven relatively smaller landslide dams downstream, the breaching of the Tangjiashan landslide dam would have induced the failure of several other landslide dams, posing a severe threat to more than 1 million people.

Table 3 Qualitative hazard assessment of the individual landslide dams along the Jian and Shiting Rivers

No.	Name	Location	Dammed river	Dam material group	Hazard	Peak discharge (m^3/s)
1	Tangjiashan	Beichuan	Jian	Group 3	Very high	15,474
2	Kuzhuba	Beichuan	Jian	Group 4	Moderate	1,418
3	Xinjie village	Beichuan	Jian	Group 1	Moderate	884
4	Baiguo village	Beichuan	Jian	Group 2	Low	527
5	Yanyang-tan	Beichuan	Jian	Group 2	Moderate	1,311
6	Sunjia-yuanzi	Beichuan	Jian	Group 3	Moderate	2,042
7	Guanzipu	Beichuan	Jian	Group 3	Moderate	2,250
8	Tangjia-wan	Beichuan	Jian	Group 2	High	2,518
16	Ganhekou	Shifang	Shiting	Group 4	Low	362
17	Muguaping	Shifang	Shiting	Group 1	Low	145
18	Macaotan-upsteam	Shifang	Shiting	Group 3	Moderate	747
19	Macaotan-site	Shifang	Shiting	Group 3	Moderate	512
20	Macaotan-downstream	Shifang	Shiting	Group 3	Moderate	290
21	Yanziyan	Shifang	Shiting	Group 3	Low	108
22	Hongcun	Shifang	Shiting	Group 3	Moderate	1,024

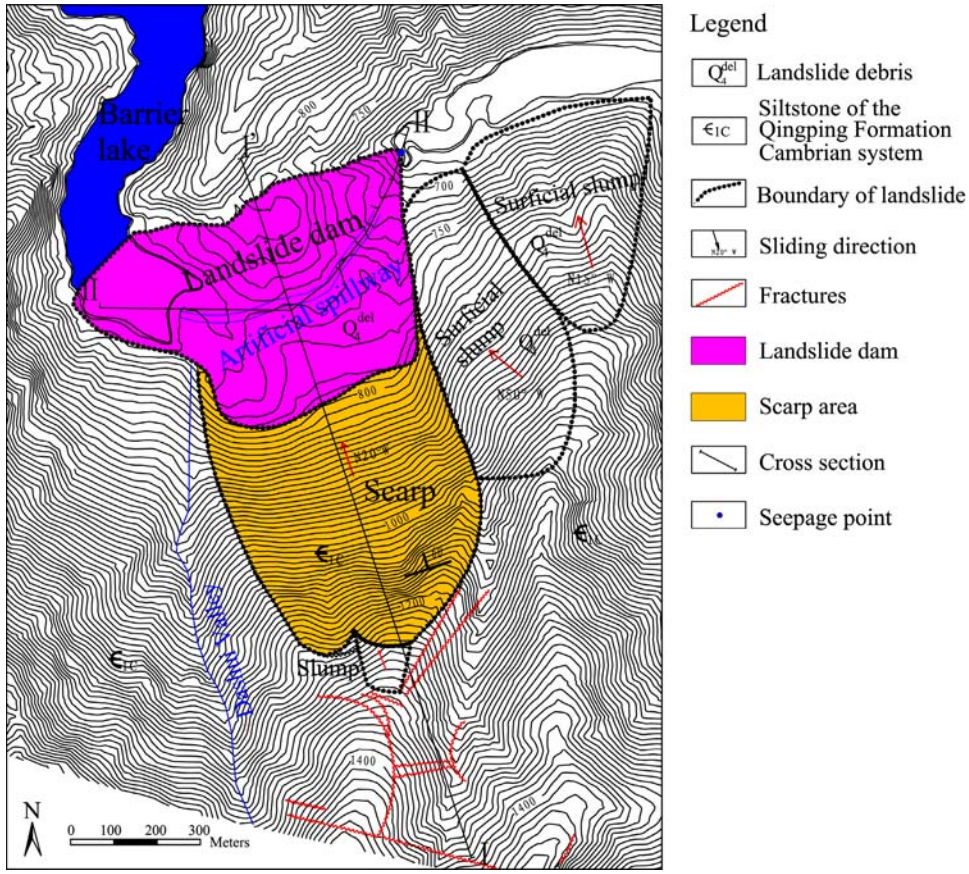

Fig. 9 Engineering geological map of the Tangjiashan landslide (modified from Hu 2008)

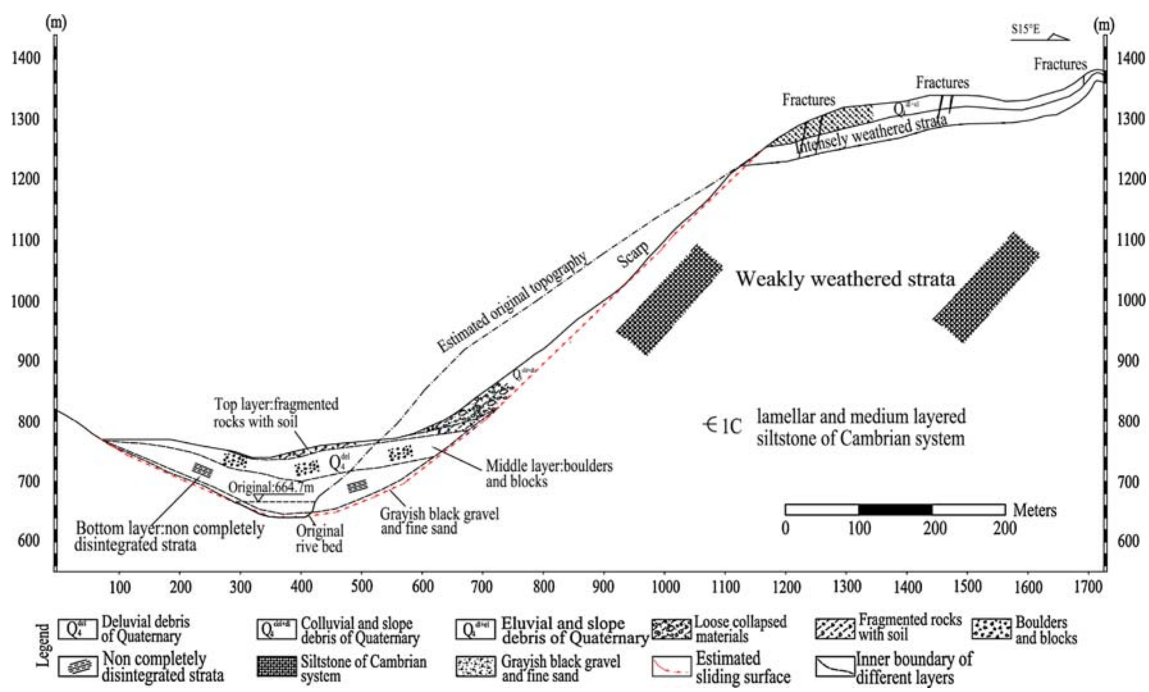

Fig. 10 Engineering geological profile I–I′ through the Tangjiashan landslide and landslide dam. The dam has a three-layered structure. The original water table of Jian River at the dam site was 664.7 m. Some fractures can be seen at the top of the slope, c. 1,300 m. (modified from Hu 2008)

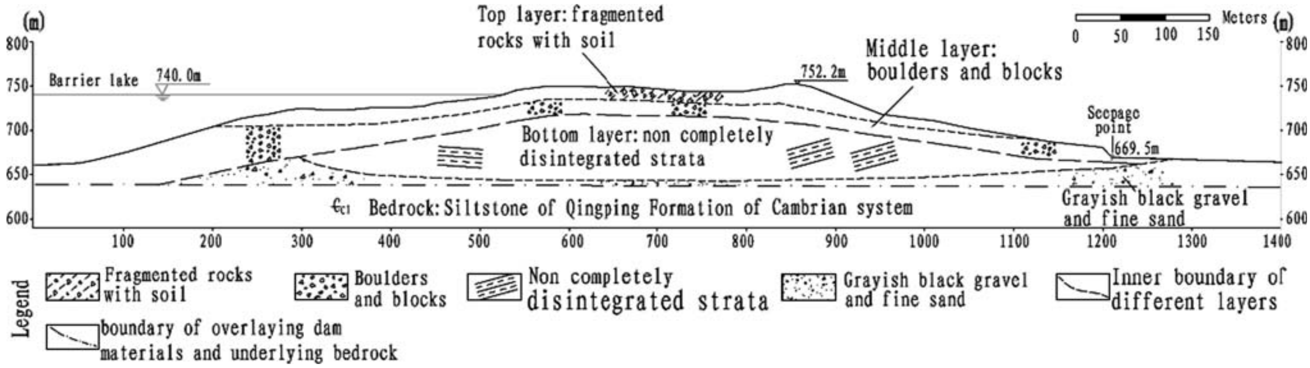

Fig. 11 Cross-section II–II′ of the Tangjiashan landslide dam: note three-layered structure (modified from Hu 2008)

Fig. 12 Helicopter view of the artificial spillway in the Tangjiashan landslide dam

Fig. 13 Impounded water flowing through the artificial spillway. Taken at 11:00 (Beijing time) 10 June 2008 when the discharge reached its maximum (source: Li 2008)

In this crucial situation, the Chinese government made the decision to build an artificial spillway by excavation and blasting. Artificial breaching was considered to be the only means of avoiding uncontrolled outburst flooding (Korup 2002). In order to alleviate the dam-break flood risk, artificial spillways were created by excavator or blasting to release some of the impounded water. On the basis of the information provided by Liu (2008), the emergency engineering was carried out by the army, from 25 May 2008 onwards. After 7 days and 6 nights of continuous work, a 475 m long and 12–13 m deep spillway had been created (Fig. 12). The elevation of the spillway was 740 m near the entrance and 739 m near the exit. On 7 June 2008, the water level of the barrier lake rose to 740.4 m, a little above the elevation of the entrance of the spillway, so the water began to overflow through it. At that time, the volume of the lake was about 2.29×10^8 m^3. The discharge of the spillway changed dynamically with the change of the water level of the barrier lake. The maximum discharge was 6,500 m^3/s on 11 June (Fig. 13).

The spillway had a very positive effect on releasing the impounded water; by 1400 hours (Beijing time) on 11 June the water level had been reduced from 743.1 (the highest value) to 714.3 m. The corresponding volume of the barrier lake decreased from 2.47×10^8 m^3 to 0.86×10^8 m^3 and the people who had been evacuated returned to their homes.

The smaller landslide dams located downstream of a big landslide dam were affected when the upstream dam failed. For example, the seven landslide dams downstream of the Tangjiashan landslide dam along the Jian River failed when impounded water was released through an artificial spillway.

Conclusions

Interpretation of satellite imagery indicated at least 256 landslide dams were triggered by the Wenchuan earthquake, although relatively detailed data was only available for 32 of these. On the basis of this sample of 32 landslide dams, a statistical analysis of the distribution, classification, characteristics, and hazard evaluation of landslide dams was undertaken. The results showed that the highest landslide dam concentration was close to the main Yingxiu–Beichuan fault. The relation between the landslide dam concentration and the distance from the main fault fits best a regression equation with a logarithmic form.

The size of the landslide dams and barrier lakes was very variable. The maximum capacity of the barrier lake was estimated by the height of the landslide dam, which is a crucial parameter for evaluating the landslide dam hazard.

The landslide dams were classified into six types following Costa and Schuster. In addition, they were categorized into four types on the basis of the constituent materials. In this study, 75% of the 32 landslide dams failed by overtopping and 25% by piping.

The impacts and hazards of landslide dams were assessed through a rapid empirical approach, due to the urgent emergency situation and limited available data. Three parameters (dam height and constituent material and maximum capacity of the barrier lake) were selected as the criteria for a qualitative hazard assessment. The results showed most of landslide dams present a moderate hazard but the Tangjiashan landslide posed a very high risk. A brief description of the mitigation measures is given.

Although the results of this hazard assessment are crude and probably not accurate, they are still very useful for elucidating mitigation measures particularly in an emergency situation. Clearly, many research problems need to be solved, such as the formation mechanism and process, the failure mode, the stability analysis and the hazard assessment of the landslide dams triggered by the Wenchuan earthquake. Further and deeper studies are being undertaken.

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