AVALANCHES, LANDSLIDES AND QUAKE LAKES INDUCED BY THE WENCHUAN EARTHQUAKE ON MAY 12, 2008

Zhaoyin Wang[1)]
(Professsor, State Key Lab of Hydroscience and Engineering, Tsinghua University,
Beijing 100084, China, Email: zywang@tsinghua.edu.cn)

1. WENCHUAN EARTHQUAKE

A great earthquake measured at 8.0 Ms according to the China Seismological Bureau occurred at Wenchuan (31°01′16″N, 103°22′01″E) at 14:28 May 12, 2008 (Beijing time), 80 km northwest of Chengdu, the capital of Sichuan, with a depth of 19 km. The epicenter is at Yingxiu of the Wenchuan county. According to a report by the state government of China on July 31, 2008, the earthquake killed 68,197 people, injured 374,176 people and left 18,222 missing. According to the British Geological Survey, seismicity in the region is caused by the northward movement of the Indian Plate at a rate of 5 cm/year and its collision with the Eurasian Plate, resulting in the uplift of the Himalaya and the Qinghai–Tibetan plateau and associated earthquake activity (Wikipedia, 2008). This deformation also results in the extrusion of crustal material from the high plateau in the west towards the Sichuan Basin and southeastern China. The earthquake was felt as far away as Beijing (1,500 km) and Shanghai (1,700 km). The earthquake occurred as a result of motion of the Qinghai–Tibet plateau at Longmenshan Mountain along the Yingxiu–Qingchuan fault, as shown in Fig. 1. More than 100 major aftershocks, ranging in magnitude from 4.0 to 6.1, were recorded. The quake-hit area is about 440,000 km^2.

There are many streams in the quake-hit area, which deeply cut the mountains. Figure 1 shows the streams on the east margin of the Qinghai–Tibet Plateau and the locations of 33 quake lakes created by landslides during the Wenchuan earthquake. The Minjiang, Tuojiang, Fujiang and Jialing Rivers are tributaries of the Yangtze River. Other streams are tributaries of the four rivers. The quake lakes are mostly on these streams. Because the Qinghai–Tibet plateau is rising, most of the tributaries flow into the four major rivers from the west side (right side). The Longmenshan fracture belt consists of three faults: in the middle is the major Longmenshan fault, where the Wenchuan earthquake occurred, extends from Yingxiu to Qingchuan, on the left side there are two broken faults called the back fault, and on the right side there are two broken faults called the front fault. The streams in the area are incised channels and the bank slopes are so steep that slope failures readily occur during rainstorm and earthquake events.

The earthquake induced numerous rockfalls, avalanches and landslides and created many quake lakes. Rockfall is the phenomenon of a few huge rocks falling from a cliff or steep slope. An avalanche is the collapse of a cliff and slope under the action of gravity. A landslide is the mass movement of rock and soil down a slope along one or several sliding beds under the action of gravity. Rockfall and avalanches have essentially the same motion mechanism.

The mass movements induced by the Wenchuan earthquake resulted in a large death toll and much damage to infrastructure. In Beichuan county, landslides caused thousands of deaths; the Qushan town landslide killed 1,600, the Jingjia village landslide killed 700, the Liangcun village landslide killed 906, and the Changzhen landslide killed 400. In Qingchuan county, a landslide at Donghekou buried three villages and three tourist buses and killed 260 people. Avalanches also contributed to the death toll; two avalanches at Dalongtan and Xiaolongtan in the Yinchang Ravine of Pengzhou County killed 200 people. The landslides induced by the Wenchuan earthquake were particularly disastrous and may be second only to the landslides at the town of Yungay in Peru in 1970 with an estimated death toll of about 17,000 (Plummer and McGeary, 1996). It is forecast that debris flow, landslides and avalanches will occur at higher intensity and frequency than normal over a period of 10–20 years because the earthquake has broken up rocks and provided a huge amount of solid material for debris flows.

The Wenchuan earthquake triggered landslides created more than 100 quake lakes, 35 of which have been identified as dangerous (33 are shown in Figure 1). The management of quake lakes is a challenge for river engineers.

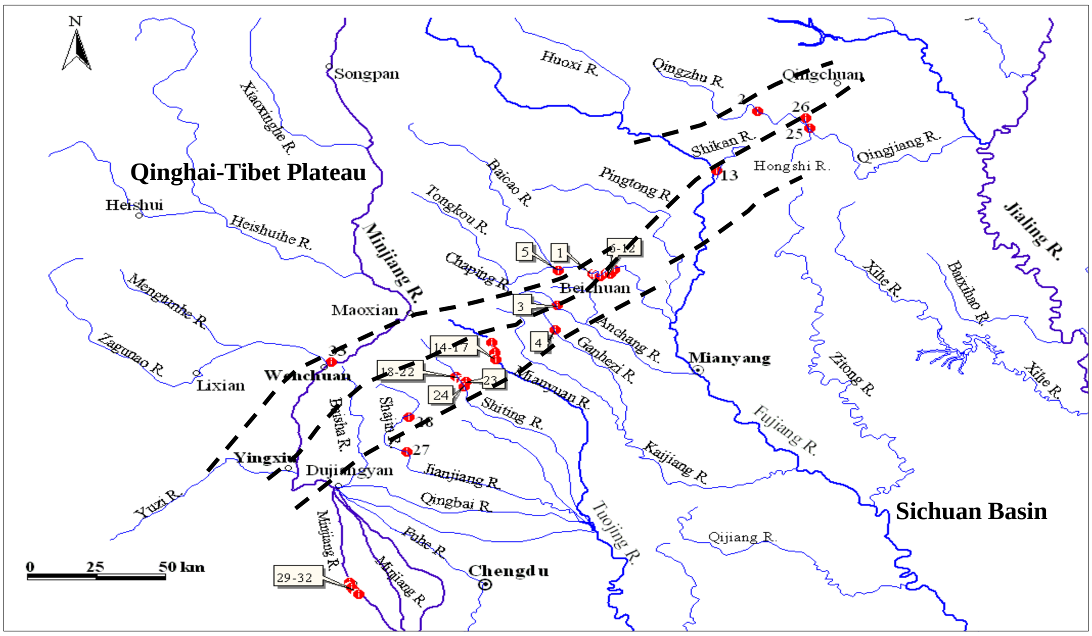

Figure 1 Streams on the east margin of the Qinghai–Tibet plateau, the Longmen Mountain Fault and the locations of the 33 quake lakes. 1 – Tanjiashan quake lake on the Tongkou River; 2 – Shibangou quake lake on the Qingzhu River; 3 – Xiaojiaqiao quake lake on the Chaping River; 4 – Jushuizhen quake lake on the Ganhezi River; 5–12 – Zhicheng, Kuzhuba, Xinjiecun, Baiguocun, Yanyangtan, Sunjiayuanzi, Guanzipu and Tangjiawan quake lakes on the Tongkou River; 13 – Nanba quake lake on the Shikan River; 14–17 – Heidongya, upper Xiaogangjian, lower Xiaogangjian, and Yibadao quake lakes on the Mianyuan River; 18–24 – Ganhekou, Macaotan A, B, C, D, Yanziyan, and Hongcun quake lakes on the Shiting River; 25- Hongshihe quake lake on the Hongshi River; 26 – Donghekou quake lake on the Qingzhu River; 27–28 – Fengmingqiao and Xiejiadianzi quake lakes on the Shajin River; 29–32 – Liudinggou, Zhugendingqiao, Shoshigou, and Haiziping quake lakes on the Wenjing River; 33 – Wenchuan quake lake on the Minjiang River; ▬ ▬ ▪ the Longmenshan faults, with the major Longmenshan fault, where the Wenchuan earthquake occurred, in the middle extending from Yingxiu to Qingchuan.

2. AVALANCHES AND LANDSLIDES INDUCED BY THE EARTHQUAKE

Although rockfalls, avalanches and landslides were directly triggered by the Wenchuan earthquake, the riverbed incision was the essential cause of these mass movements. There are many rivers in the quake-hit area and most of them are subjected to incision (Figure 1). On a continental scale, the rising Qinghai–Tibet plateau is a result of the northward convergence of the Indian Plate against the Eurasian Plate. The streams in the quake-hit area flow from west to east and have been incising for a million years as the tectonic motion increases the gradient of the river channels. Many streams have cut the channel bed more than 1000 m deep. As shown in Figure 2, as the river cuts into the bed below the sliding surface, the sliding body loses the support of the sediment and rock at the toe of the sliding body and the sliding body slides along the slip surface into the river. It is the bed incision that makes the bank slopes very steep and the potential energy for avalanches and landslides very high. The energy released from the mass movements is due to and proportional to the riverbed incision.

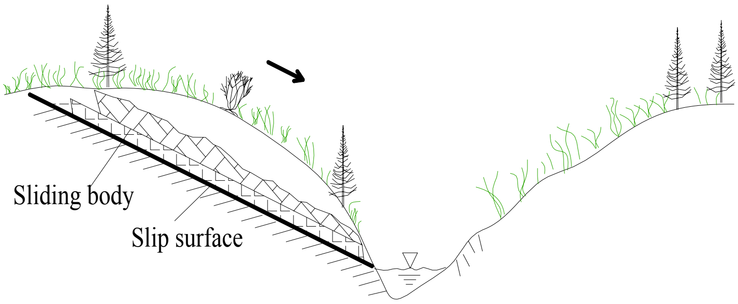

Figure 2 A stream cutting the bed below the slip surface and causing a landslide.

After the Wenchuan earthquake, investigations were conducted using Beijing No. 1 and IKONOS satellite images with identification scales of 32 and 1 m, respectively (Di, 2008). The earthquake caused in total 11,700 avalanches and landslides on the steep bank slopes of numerous streams in the quake-hit area. The total area of avalanches and landslides is 2260 km^2, which changed from green vegetation to naked rock and soil. It is estimated that the average thickness of soil and rock mobilized by the avalanches and landslides is about 2–3 m. Thus, the total mobilized sediment volume is about 4.5–6.8 billion m^3.

For the rivers with different geological and morphological conditions, six kinds of mass movements directly triggered by the Wenchuan earthquake can be recognized: granite rockfalls, granite avalanches, sedimentary rockfalls, sedimentary rock avalanches, sedimentary rock landslides, and quaternary deposit and slope-debris landslides. The volume of moving solid materials increases in the order from rockfalls and avalanches to landslides: rockfalls of $10^{0–1}$m^3; avalanches of $10^{2–3}$ m^3; sedimentary rock landslides of $10^{4–5}$ m^3, quaternary deposits and slope debris landslides of $10^{6–7}$ m^3.

By the Minjiang River from Wenchuan to Xuankou, the lithology consists mainly of granite. There is no sliding interface within the granite rock and therefore numerous avalanches and rockfalls occur but almost no landslides occur in the area. Along a 135 km long reach of the Minjiang River from Zipingpu Dam to Maoxian, 334 avalanches occurred; of which 199 occurred in a 29 km long reach around the epicenter from Yingxiu to Caopo (Huang, 2008). Local bedrock lithology controls the cohesive strength of hill-slope material and determines the size of the material within the avalanche deposits, largely as a function of how massive, fractured, or layered is the bedrock in the area. Figure 3 shows a comparison of the naked mountain area along the Minjiang River before and after the earthquake. The slopes along the Minjiang River were green before the earthquake and become naked after the earthquake mainly because of the avalanches.

Figure 4 (a) shows rockfall on the Baisha River, a tributary of the Minjiang River, where the main lithology is thick limestone. The interface between layers inclines to the downstream of the river. There are no landslides but many avalanches and rockfalls. The Baisha River cuts deep into the bed rock and forms a narrow and deep channel. The earthquake induced rockfalls and avalanches on slopes steeper than 40 degrees. Because the river is very narrow and deep, some avalanches blocked the river and created small quake lakes with only 1–2 meters water depth.

Figure 4 (b) shows a granite avalanche on the Minjiang River at Yingxiu. The slope for the avalanche area is still high and the slope may move again during a rainstorm. In general, the erosion rate in an earthquake-hit area increases because huge amounts of loose materials are produced by avalanches and landslides. Nevertheless, in the Minjiang River the solid materials from avalanches are rather coarse and the river flow cannot carry the materials in suspension. The sediment concentration in the river flow does not obviously increase. The sediment concentration in the Minjiang River on June 6, 2008 was measured, and was found to have an average of only 0.12 kg/m^3. As a comparison, the average suspended sediment concentration in the period 1991–2005 was 0.447 kg/m^3 (a high concentration occurred mainly during high floods).

Figure 4 (c) shows a sedimentary rock landslide on the Mianyuan River, a tributary of the Fujiang River, where there are thick dolomite rock layers with a shale interlayer. The shale interlayer became the sliding surface. Coincidently, the sliding surface inclines to the river bed. The stream bed incision of the Mianyuan River cut off the sliding surface and caused erosion of the toe of the sliding body. The seismic excitation during the earthquake triggered the landslide and a large volume of rock lying on the sliding surface slid into the river. There are quite a few such landslides on the Mianyuan River, Shiting River, and many other streams.

Figure 4 (d) shows a huge landslide at Donghekou on the Qingzhu River, a tributary of the Jialing River, consisting mainly of quaternary deposit, eluvial soil and clastation rocks. The interface between these solid materials and the hard rock below became a sliding surface. The sliding volume was estimated at 10 million m^3 and the sliding distance was measured at 1,700 m. The sliding body moved across two small streams (both tributaries of the Qingzhu River), climbed a small slope and made a 60^o turn to the left, and finally dumped into the Qingzhu River.

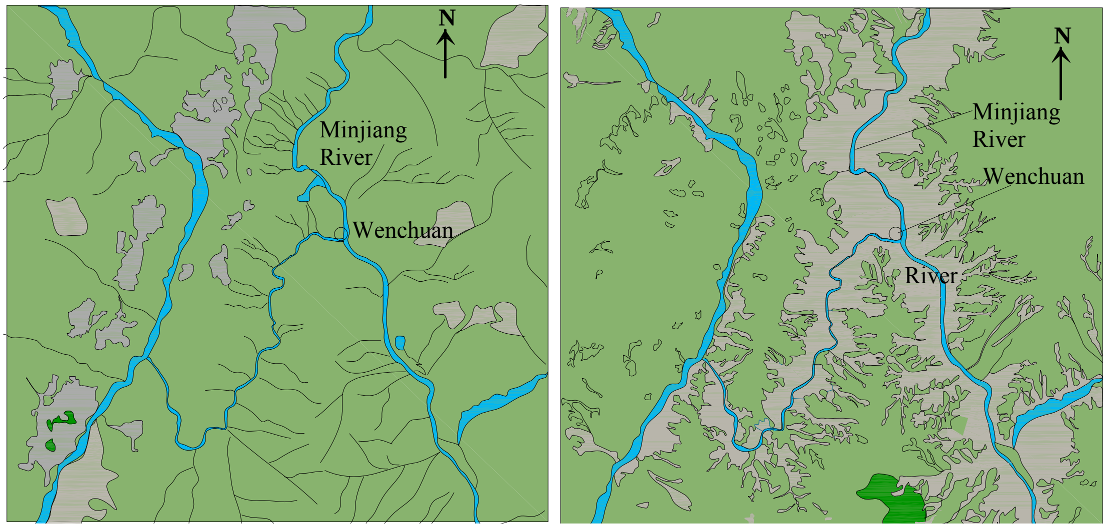

Figure 3 Comparison of naked slope areas before and after the earthquake near Wenchuan County town and along the Minjiang River in June 2003 (left) and after the earthquake in June 2008 (right) (green indicates vegetation and grey indicates naked slopes).

Figure 4 (a) A limestone rockfall on the Baisha River; (b) a granite avalanche on the Minjiang River near the epicenter of Yingxiu; (c) a sedimentary rock landslide on the Mianyuan River; (d) a quaternary deposit landslide on the Qingzhu River at Donghekou.

Comparing with storm-triggered landslides, the earthquake-triggered avalanches and landslides mobilize much coarser sediment. The storm-triggered landslides result primarily from local pore water pressure gradients and are likely to be most pronounced in the shallow subsurface. The seismic ground motion affects local stress fields well below the topographic surface and may trigger a relatively large number of deep-seated, bedrock-involved avalanches and landslides. Such mass movements are likely to produce coarse debris with diameters of up to several meters. The mobilized sediment is, therefore, difficult to transport. A large volume of mobilized debris deposits at places where the potential for onward transport is low. Because seismic ground motion is strongest at ridge crests, earthquake-induced avalanches and landslides often cluster around high points and deposit debris on hillslopes rather than on channel floors (Hovius and Stark, 2006).

The mass movements induced by the Wenchuan earthquake released different degrees of potential energy. Figure 5 shows the occurrence and deposition slopes for avalanches and landslides. Avalanches occurred on steep slopes and also deposited on steep slopes. Landslides, especially the landslide with quaternary deposit, occurred on a relatively shallow slope and the deposition slope was almost flat. The vertical distance from a plotted point on the graph to the 45^{o} straight line, S_1, is the energy released during the mass movement and the vertical distance from the point to the horizontal axis, S_2, is the residual potential energy after the movement. The ratio, S_1/S_2, may be used to represent the stability or safety of the deposit of the mass movement. The landslide of quaternary deposit has the largest S_1/S_2 value and the highest stability and safety. The avalanche deposits along the Minjiang River have the smallest S_1/S_2 value and the lowest stability. The deposits are dangerous because the slope is steep and rainstorms and aftershocks may trigger secondary mass movement.

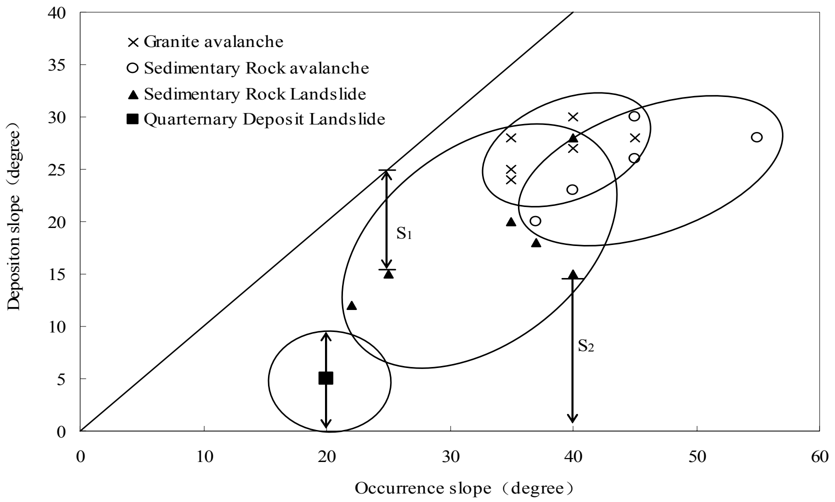

Figure 5 Occurrence and deposition slopes of avalanches and landslides, in which S_1 is the energy released during the mass movement and S_2, is the residual potential energy. S_1/S_2, represents the stability or safety of the deposit.

3. QUAKE LAKES AND MANAGEMENT STRATEGIES

Large landslides inundate river valleys and overwhelm channels with large volumes (> 10^5 m^3) of coarse material, commonly forming landslide dams and quake lakes. As shown in Figure 1, 33 large quake lakes were created by landslides during the Wenchuan earthquake in Sichuan. Some of the lakes were regarded dangerous because massive amounts of water were pooling up at a very high rate behind the landslide dams, which might eventually fail under the action of dam-outburst flood flushing, potentially endangering the lives of thousands of people in the downstream reaches. On the other hand, the quake lakes are a feedback of the natural system to the riverbed incision. The quake lakes may form knickpoints on the river profile and trigger extensive and prolonged aggradation upstream. They act as a primary control on river morphology and longitudinal bed profiles, inhibiting incision and further preventing the complete adjustment of rivers to regional tectonic and climatic forcing. The feedbacks among hill-slope processes, river morphology and incision are prevalent throughout this landscape and are characteristic of transient landscapes in the quake area and the eastern margin of the Qinghai–Tibetan plateau experiencing large increases in local relief (Ouimet et al., 2007). The abrupt change in slope associated with the transition from the upstream, low-gradient lake section to steep, dramatic rapids through the landslide dams creates significant knickpoints with drops in elevation of up to 80 m.

There are two strategies to manage the quake lakes. The first strategy is to preserve the quake lakes by: 1) water flows through a spillway, which may be shaped by scouring of the overspill flow itself or digging by manpower and then 2) the spillway is stabilized with huge stones or clusters of big stones, generally forming a step-pool system within the spillway. Cobbles and boulders generally compose the steps, which alternate with finer sediments in pools to produce a repetitive, staircase like longitudinal profile in the stream channel. The strategy is applied if a landslide dam consists of a high percentage of large boulders. Once the quake lake level reaches the entrance of the spillway and the flow over the landslide dam deposits begins, erosion-resistant boulders overlap and construct a step-pool system, naturally or with the aid of manpower. This process reduces the original landslide dam material to a smaller mass composed of boulders and cobbles, stabilizing the dam and protecting the top of the initial deposit from further erosion. The step-pool system is not easily moved in even large floods, and serves to maximize the roughness of the channel (Wang and Xu, 2004). Finally, the spillway becomes a narrow and steep reach cutting through the landslide dam but with a step-pool system to consume the flow energy. Figure 6 shows a preliminarily developed step-pool system in the spillway of a quake lake on the Qingzhu River. Boulders of diameter larger than 1 m play a key role in the development of step-pool system. The tight interlocking of particles in steps gives them an inherent stability that only extreme floods are likely to disturb, which suggests that step-pools are a valid equilibrium form, especially when coupled with their apparent regularity and their role in satisfying the extreme condition of resistance maximization.

Figure 6 Preliminarily developed step-pool system in the spillway of a landslide dam on the Qingzhu River

Upstream of the landslide dams, river gradients are low, and fine-grained lake sediments and alluvial gravels accumulate. In this way the quake lakes can be preserved, which in turn stabilizes the river, controls new landslides, and improves the landscape and ecology. However, this method is subject to some risk. If the spillway cannot be stabilized before the flood season, or the step-pool structure is not strong enough to resist a big flood, the landslide dam may fail at high flood and cause great flood disaster.

The second strategy is to remove the quake lakes by 1) removing all boulders in the spillway before a flood arrives and 2) helping the flowing water to scour the spillway bed, if necessary, by explosion. Thus the water volume stored in the lake is released and thus the pool level is reduced to a minimum and the flood risk downstream is minimized. The strategy is often applied to quake lakes where there is high population density in the downstream reaches. In many cases the risk is high because 1) the dam break floods occur infrequently and local people usually do not expect them, 2) the warning time is very short, which limits the potential for evacuation, and 3) the peak discharge may be many times greater than any normal rainfall flood, potentially placing “normally safe” infrastructure and lives at risk (Becke et al., 2007). The discharge and erosion of a landslide dam cannot be easily controlled. Humans are used to having everything under control in hydro-projects. The landslide dams are naturally formed structures and the spillway develops following natural laws. The compositions, structures and mechanisms of landslide dams are not well understood. Therefore, people are more willing to remove quake lakes.

The longevity of individual landslide dams is a function of dam geotechnical stability and the spillway incision into the landslide deposit and depends on a number of factors, most important of which are the size of the original landslide deposit, the percentage of large boulders within that deposit, and the geometry of the valley filled (Costa and Schuster, 1988). The failure risk of the landslide dams soon after the earthquake depends on the size composition, the width of the dam and the water head of the lake. If a landslide dam is composed mainly of fine materials, such as soil and fine gravel, it is likely that the materials are soon flushed away by the overspill flow and the landslide dam may collapse. If a landslide dam is composed of stones of different sizes, including big boulders, a structure like a step-pool system may develop and the quake lake may stabilize. If a landslide dam is composed of much fine materials, and also many big stones, the time needed for the step-pool structures in the spillway to develop and stabilization of the dam will be long, during which the risk of dam failure is high. Figure 7 shows the size distributions of the landslide deposits on the Qingzhu River, Shiting River and Mianyuan River, which created quake lakes, and those of avalanches on the Minjiang River and Baisha River for comparison. The clastic materials of landslides of quaternary deposits are rather fine and the avalanches on the Minjiang and Baisha Rivers are rather coarse. All the materials partially consist of stones larger than 1m, which is of the greatest importance for the final stabilization of the quake lakes.

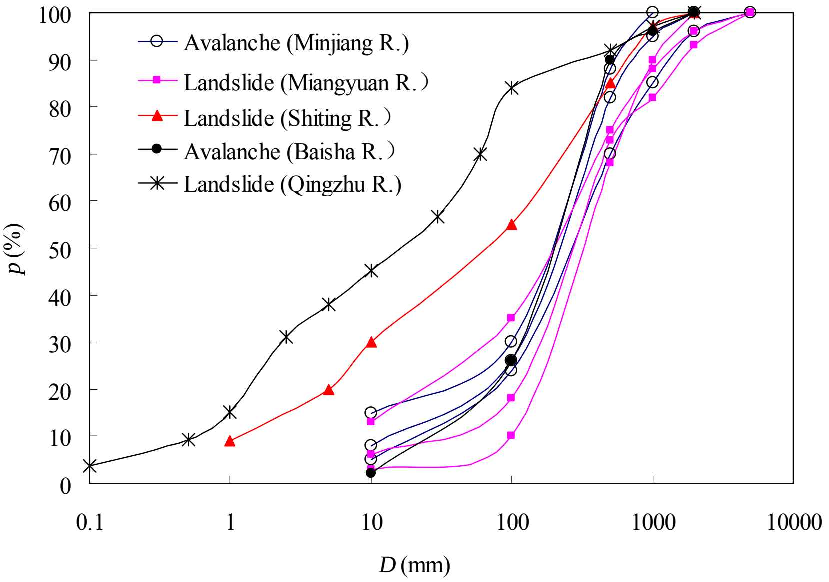

Figure 7 Size distributions of the deposits of landslide dams and avalanches.

Seepage occurs at almost all newly created landslide dams. The seepage discharge through some landslide dams is rather high—more than 10% of the total discharge. Figure 8 shows the seepage at a landslide dam on the Mianyuan River. Whether a landslide dam will soon fail can be determined by observing the sediment movement in the outflow and seepage through the landslide dam. If there is continuous and increasing bed load transportation through the spillway and the seepage water is turbid, the landslide dam will soon fail. For most of the landslide dams induced by the Wenchuan earthquake, the seepage water is clear and bed load transportation was observed through the spillway initially and then reduced to zero soon after. For the landslide dams consisting of quaternary deposit, the bed load transportation continued until the dams were scoured down to an elevation near the original riverbed.

Figure 8 Clear seepage and overspill flows through a landslide dam on the Mianyuan River.

Both the removal strategy and the preservation strategy have been applied for management of the quake lakes formed during the Wenchuan earthquake. The most precarious of these quake lakes is the Tangjiashan quake lake, which is located in extremely difficult terrain in Qingchuan County, accessible only by foot or air. The quake lake was formed by a huge landslide from Tangjiashan Mountain. The volume of the sliding body is about 20.37 million m^3 and the landslide dam is 612 m long (across the river), 803 m wide (along the river), and 82–124 m high. It consists mainly of quaternary deposit, eluvial soil and clastation rocks (china.com.cn, 18.07.2008). The size distribution is similar to that of the landslide on the Qingzhu River. The total storage capacity was about 316 million m^3. There was a high risk of dam-break flooding when 200 million m^3 of water had stored in the lake. A spillway was first dug and then the water began releasing through the spillway. To help the water scour the spillway bed to a low level, large boulders were removed or exploded. The channel inlet bottom elevation was cut down from 740 m to about 714 m, and the channel bed was cut wider from about 10 m to 100 m, as shown in Figure 9. The lake water reduced from 246 million to 86 million m^3. More than 160 million m^3 of lake water was drained out of the lake. Although the peak discharge rate was high at 6420 m^3/s during the course of channel cutting and lake-water draining, no casualties or damage were caused by the draining flood.

For quake lakes with low risk of dam failure, the preservation strategy was applied. Figure 10 shows a small quake lake on the Mianyuan River. The landslide dam consists of mainly clastic rocks and there are many huge stones. In the naturally formed spillway, there was no bed load motion and the dam and the spillway became stable. The quake lake and landslide, a small waterfall and seepage, and several avalanches around the lake have formed a landscape that has become a tourist attraction.

Figure 9 Lake water flows through the enlarged spillway from the Tangjiashan quake lake and scours the landslide dam.

Figure 10 A quake lake with low risk of dam failure is preserved.

Figure 11 shows the longitudinal profile of the Minjiang River. The landslide dams and the quake lakes at Diexi formed a knickpoint on the profile; the slope below it is steep but the slope upstream is remarkably gentler. The integrated effects of the Diexi landslides and quake lakes on river channels completely prohibit rivers from eroding their bed and incising over the length of the landslide mass and the reach upstream of the quake lakes. This period of local non-incision continues if the landslide dams are not broken and scoured away. The long-term evolution of the river profiles and landscape evolution are affected by the preserved quake lakes. The downstream reaches are still steep and continue to incise, and in the meantime the upstream reaches and the whole profile upstream of the landslide dam have a new, unchanging base level that halts all further adjustment. As shown in the figure, the avalanches occurred mainly at an elevation near that of the river bed, because the continuous bed incision of the river steepens bank slopes of the lower part. This suggests that if the bed incision is controlled avalanches may be prevented during a future earthquake event.

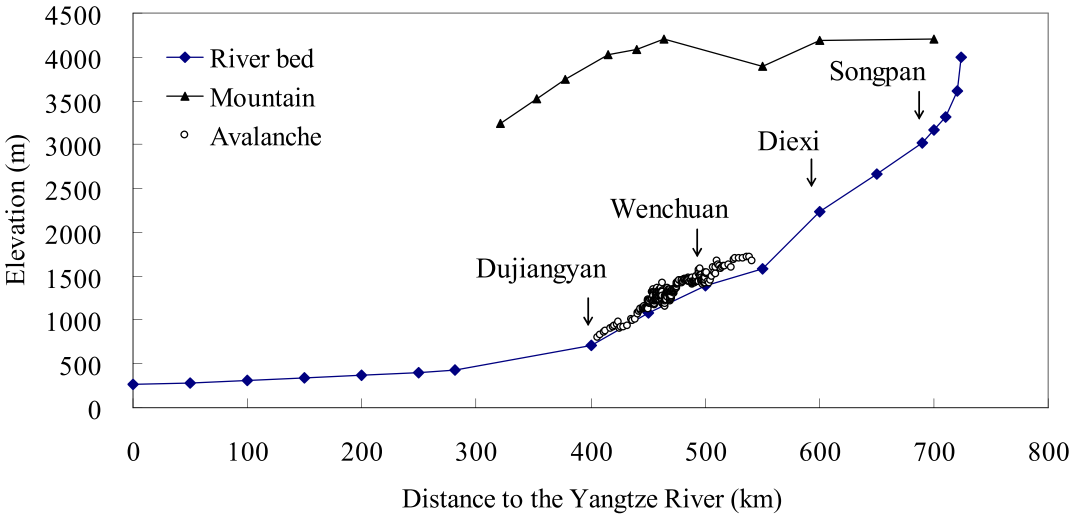

Figure 13 Longitudinal bed profile, relative difference in elevations of the bed and adjacent mountain, and elevations of avalanches that occurred along the Minjiang River.

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