Landslide Research in China

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During the spring of 2000 (9 April), a 91 Mm^3 rock avalanche occurred in Linzhi Prefecture, Tibet (the 'Roof of the World'). The event was accompanied by a deafening noise, with the rock mass traveling from a maximum elevation of 5132 m asl and coming to a rest at an elevation of 2163 m asl. It formed a landslide dam in the Yigong Zangbo River of some 55 m high impounding a reservoir of some 2 Gm3 for a period of 62 days after which it emptied in less than 12 hours (Delaney and Evans 2015). The event forewarning of a period of frequent geological disasters in China during the start of the 21st Century. The ensuing Wenchuan earthquake (surface-wave magnitude Ms 8.0; May 2008), Zhouqu debris flow (August 2010) and Ludian earthquake (Ms 6.7; August 2014) urged China to renew its campaign against geological disasters and the Chinese Government has since invested heavily in scientific research to guide efforts to mitigate the impact of such natural disasters. A thematic set on Landslide Research in China was initiated to highlight this research. This paper provides a brief review of three featured subjects and accompanies the five papers published in the thematic set.

Landslides in areas affected by earthquakes

Large earthquakes severely affect the geological environment and also result in the potential for secondary disasters in the days, months and years that follow. There is continued debate on how quickly landscapes recover following a high-magnitude disturbance. Lin (*et al*. 2006, 2009) studied the Chi-Chi Earthquake of 1999 and found that five years after the earthquake, the area experienced a relatively high number of landslides (including debris flows) followed by a trend of gradual decline. Hovius *et al.* (2011) concluded that it took approximately 6 years for the landslide signal to return to pre-1999 levels. Other examples of long-term landscape recovery are discussed in, for example, Nakamura *et al*. (2000) for the 1923 Ms 7.9 Kanto earthquake in Japan and in Huang (2011) for the 2008 Ms 8.0 Wenchuan earthquake, China. The Wenchuan earthquake took place on 12 May 2008 in Sichuan Province resulting in some 200,000 landslide events (Xu *et al*. 2013) and in the following years the province suffered frequently from further landslide activity. According to the first author's statistics, the province experienced 668, 934, 2,161, 1,997, and 3,147 geohazards from 2008 to 2012. The enhanced landslide and debris-flow activity after the 2008 Wenchuan earthquake is highlighted in the Special Issue of Engineering Geology "The long-term geologic hazards in areas struck by large-magnitude earthquakes" (2014, Volume 182, Part B).

On 24 September 2008, Beichuan County, previously destroyed by the Wenchuan Earthquake, experienced yet another debris flows which led to a further 42 fatalities (Tang and Liang, 2008; Tang *et al.* 2011a; Figure 1).

On 13 August 2010, Qingpingxiang (a town in Mianzhu County), Yingxiu (a town in Wenchuan County) and Hongkou Township (in Dujiangyan county), all severely affected by the Wenchuan Earthquake, experienced torrential floods and landslides (dominated debris flows). The total landslide volume for these regions exceeded 13 million m^3 causing the partial or total destruction of roads and houses and the interruption of traffic (Figures 2 and 3).

Another serious debris flow happened on 9 July 2013 in Qipangou. The flood disaster created a barrier lake that blocked the Mingjiang River. This is the largest recorded debris flow in this region.

Conducting rainfall monitoring and the associated provision of timely warnings in seismically-prone regions provide an effective way of limiting the impacts of potential landslides on the local population. However, experience has shown that, as a result of long runout and high relief, the areas most impacted by landslides are not necessarily those affected by the highest intensity of rainstorms. The 7 August 2010 Zhouqu debris flow is an example (see Figure 4, Dijkstra *et al*. 2012). Zhouqu County, which was severely damaged by the debris flow, experienced a rainfall intensity of only 10 mm/h, while the Dongshantai Station, close to the top of Sanyanyu where the debris flow was initiated, registered a rainfall intensities as high as 90 mm/h (Tang *et al.* 2011b; Dijkstra *et al*. 2012; Dijkstra *et al.* 2014). Figure 5 explains the disaster process from the standpoint of a 2,000 m difference in elevation between the area of intense rainfall and the area affected by the debris flow. For this reason, the Ministry of Land and Resources launched a program to implement a warning system used in high, cold mountainous areas that experience dense fog. A remotely-operating video platform was installed in Zhouqu County, with the purpose of transmitting information to the monitoring and warning center on a real-time basis via sensors and communication satellites (Figure 6).

Geo-hazard Mitigation for the Three-Gorges Project

The Three Gorges Project is the largest hydro-electric complex both in China and the world. However, the area of the reservoir has a significant landslides history. In this area, the hilly and mountainous areas constitute 21.7% and 74% of the total, respectively while the flat surface around the dam is only 4.3%. The river valley in the reservoir area is affected by the geology, its structures and the associated geotechnical parameters. Heavy rainfall and rainstorms are frequent in the reservoir area, and about 70% of the total annual rainfall is concentrated between the months of May to September (Chen *et al.* 2005).

At the beginning of the Three Gorges Project, great efforts were made to prevent geological disasters, including landslides, and significant effort was expended in mitigation and control works. The main experience and achievements are summarized below.

Transition from frequent geological disasters during the initial impoundment stage to the balance and decline stages.

From September 2008 to August 2014, the Three Gorges Project underwent six impoundment trials. The highest water levels in front of dam during the 2010, 2011, 2012 and 2013 trial impoundments were uniform at 175.0 m. By 31 August 2014, the reservoir area of the Three Gorges Project sustained a total of 421 significant ground deformation events and landslides, of which 120 occurred in the Hubei reservoir and 301 in the Chongqing reservoir. The total volume of landslides and collapses reached 350 million m^3 and the total length of the 60 river bank slumps was 25 km. Table 1 clearly shows that in the following years, the number of slope failures declined rapidly although the water level reached the same elevation of 175 m (Zhen 2010).

After the 175m trial impoundment in 2008, the water level rose by 8.32 m from 30 October to 4 November, equivalent to 1.66 m/d. Ten days later, 37 landslides occurred at the peak level of the impoundment. Between 1 August and 6 August 2010, the cumulative decline in water level was 5.57 m, equivalent to 1.15/d, the largest daily rate of lowering since the impoundment. No landslides were generated during the ten days that followed. When the rate of lowering of the water level ranged between 0.40 m/d and 1.15 m/d, there was no correlation between the occurrence of landslides and the lowering of the reservoir water level. The first increase of the water level triggered the majority of the landslides while draw-down had little impact on landslide occurrence.

Adoption of engineering measures against major potential landslide hazards to significantly reduce the threat of geological disasters.

To ensure the safety of more than one million people living in dozens of towns surrounding the reservoir area, potentially hazardous sites were the subject of mitigation works including drainage measures, stressed anchoring cables, anti-slide piles, etc. The hazards associated with 243 landslides sites with the potential to slide into the Yangtze River have been significantly reduced and as a result the risks to 79 towns potentially threatened either directly from landslides or from landslide-induced waves have been reduced to acceptable levels.

The surface of the bedrock landslide in central Fengjie, the Monkey Stone landslide, had an elevation of 90 m at the front-edge and 250 m at the back-edge, a 160 m elevation difference with the water level varying between 145 m and 175 m elevation as shown in Figure 7 (Chen and Feng, 2008) and occupied an area of 12×10^4 m^2 and a volume of 450×10^4 m^3. The engineering mitigation involved two stages (Zou *et al*., 2008). Stage I consisted of water discharge measures, loading the toe of the slope, and erosion protection of the slope surface. Stage II extended the project and consisted of cascaded slide-resistant shear keys at the level of the slip plane, rock fill dumped underwater to further load the toe, and further slope protection and water discharge measures. The project started in May 2006 and was completed in May 2008, enhancing the safety of the population of this densely populated town as shown in Figure 8 (Chen and Feng, 2008)).

Building of systematic landslide monitoring and warning systems

The entire Three Gorges reservoir area has been built with a high-level monitoring and early-warning system that includes three levels (i.e. county, township and village levels) based on mass movement predictions, early warnings of events, and evacuation plans in order to help prevent disasters. The program aims to provide effective monitoring and warning of 3,049 sites of potential collapse, landslide and bank slump within the reservoir area. Over 12,200 people, 5,200 from the Hubei Province and 7,000 from Chongqing, have been evacuated during the period since 2003 when the reservoir was first impounded.

The landslide forecast at Qianjiangping in the Zigui County has proven to be very successful. A landslide occurred on the night of 13 July 2003 ($1{,}542\times10^4$ m^3 volume) and caused a blockage and silting of the Qinggan River, a tributary of the

Yangtze River. However, relying on a timely warning, more than 1,200 people were safely evacuated. Table 2 presents two typical field monitoring schemes taken from a report summarizing this and 12 similar cases.

Emergency response to landslide dams

Combatting the risks associated with barrier lakes created by large-scale landslides has been one of the principal geological disaster prevention programs of China in the past 15 years.

In 2000 the Yigong-Zangbo River formed the Yigong Lake due to a mountain landslide which generated an overtopping flood of two billion m^3 of water having a peak flow of 95,000 m^3/s (Yin 2000). After the Wenchuan Earthquake (Ms 8.0) of 12 May 2008, the main area affected by seismic tremors saw the formation of 34 barrier lakes of different sizes. The Tangjiashan landslide lake had a storage capacity of 316 million m^3 becoming the largest rainwater catchment lake with the highest impoundment and posing the most severe threat (Lin *et al.* 2010). The isograms of seismic intensity are also shown in Figure 9 which reveals a consistent trend in the distribution of earthquake-induced barrier lakes as they are clustered in the area that experienced a seismic intensity of *X* degrees (Cui *et al.* 2009).

In August 2010, Gansu Province was affected by very heavy rainfall with a cloudburst in the mountainous Sanyanyu and Luojiayu catchments above the town of Zhouqu triggering large debris flows. The debris flow deposits blocked the Bailong (White Dragon) river forming a barrier lake that flooded part of the town (Tang et al. 2011b; Yu *et al*. 2010; Dijkstra *et al*. 2012).

In 2014, an earthquake of magnitude Ms 6.5 hit Ludian County of Zhaotong in Yunnan Province and caused mountain collapses on both sides of Hongshiyan Village, blocking the Niulanjiang River and forming a barrier lake that flooded the area upstream of the Hongshiyan hydropower station (Liu 2015).

The emergency response to a barrier lake normally involves evacuating a large number of people and mobilization of large amounts of human and mechanical resources. After the Wenchuan earthquake, the Chinese government issued the

Standard for Classification of Risk Grade of Barrier Lake (SL450-2009; MWS 2009a) to provide a technical and legal basis for emergency response actions. Barrier lake dams were classified into several types, including high dams, narrow dams, short dams, *etc*. According to the standard requirements (MWS, 2009a), the lakes are classified into large size, medium size, small size (1) and small size (2) as shown in Table. 3. They are then rated as extremely high risk, high risk, medium risk and low risk according to Table. 4.

Of the 34 barrier lakes following the Wenchuan Earthquake, the Tangjiashan barrier lake was classified as posing an extremely high risk, the Laoyingyan, Xiaogangjian, Xiaojiaqiao and Nanba barrier lakes were classified as posing high risk, with the remainder posing medium or low risks.

Controlled blasting is a common method of eliminating the hazard and thus reducing the risk associated with barrier lakes as shown in Figure 10 (Liu et al., 2016). It is usually adopted on occasions where the risk posed is judged to be significant and to require urgent action: such situations include those in which recovery construction works are hampered and transportation corridors required by the emergency services are blocked, obstructed field construction and transportation conditions (*Technique guideline for emergency disposal of landslide lake, SL 451-2009*; MWS. 2009b). For instance, the blasting of a drainage channel followed by mechanical excavation was adopted for reducing the risk associated with barrier dam outburst at three barrier lakes on the Shiting River (i.e. Yanziyan, Upper Macaotan and Muguaping barrier lakes), the Shibangou (Jialing River), the Ma'anshi (Fujiang River basin) and the Xiaogangjian (Jinyuan River) barrier lakes. Channel drainage is the most common method of reducing the risk associated with barrier dam outburst both in China and other countries. Other examples include the Yigong, Tangjiashan, Xiaojiaqiao and Hongshiyan barrier lakes as shown in Figure 11 (Liu, et al., 2016).

Landslide Research in China special set

The papers published in this thematic set represent a small part of a large number of scientific reports and publications on landslide research in China.

Tu and Huang (2016) present an analysis of infiltration in embankments constructed in sandy clay and gravel and evaluate the effects of rainfall intensity and duration on the stability of the embankment slopes. Their numerical analyses provide further insights into the differences in behaviour of the two materials, including a lesser sensitivity to rainfall intensity of the stability of the sandy clay slope relative to the gravel embankment slope but a larger and longer lasting reduction in slope stability of the sandy clay embankment slope for longer duration rainfall events.

Two papers provide a contribution to landslide research in the Three Gorges area. Shi *et al*. (2016) discuss landslide stability evaluation using High-Resolution Satellite SAR (Synthetic Aperture Radar) data and Huang *et al*. (2016) describe a case study of a pillar-shaped rock mass failure. Shi *et al.* (2016) used TerraSAR-X InSAR data pairs with short normal baselines and temporal baselines to map landslide-prone areas and the point-like target offset tracking (PTOT) approach to identify large displacements to characterize potential landslides. Their methods provide a clear way forward to evaluate landslide stability in this geodetically challenging terrain characterized by steep slopes and dense vegetation. Huang *et al.* (2016) describe in detail a case study of an unstable pillar-shaped rock mass in the Three Gorges area. Their calculations show that this rock mass is only marginally stable (FoS 1.08) and that the collapse of the pillar is related to local failure in a slowly deteriorating block at the foot of the pillar that is periodically affected by the 175 m impoundment level of the reservoir. Were this rock mass to fail, an estimated 360,000 m^3 is likely to catastrophically enter the Yangtze forming a substantial threat to local residents and passing tourists.

The effects of the magnitude 8.0 Wenchuan earthquake on the performance of engineered interventions of the reinforced right abutment slope of the Zipingpu Dam are analysed by Ren *et al*. (2016). This 156 m high rockfill dam experienced peak ground acceleration in excess of 2g. The nearby natural slopes were severely affected by the earthquake. However, the reinforced abutment slope coped very well and a stable slope was maintained. The paper describes how this abutment slope experienced stresses and strains during the earthquake as these were monitored through multiple extensometers and load cells.

Zhou *et al*. (2016) provide a further example of monitoring and stability analysis and discuss this using a case study of the left bank slope at the Jinping-I hydropower station. This complex 530 m high excavated rock slope was instrumented with a monitoring system comprising surface deformation observations, multi-point extensometers and graphite bar extensometers. The complex geology of the site provided challenging conditions for the construction of a safe slope, particularly as it transpired that a large central section of the slope could potentially become unstable. Detailed 3D slope stability analyses assisted with the design of a stable slope and the observations from the monitoring network support the results from these design analyses.

These five papers provide a further showcase and snapshot of research currently being carried out on this topic in China and compliment the earlier thematic set on Geohazards in China (Dijkstra et al. 2014).

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Tables

Table 1 Annual landslide events as a result of 175m trial impoundments from September 2008 until September 2014.

Table 2 Two case studies of typical geological disasters as a result of a 175m impoundment in the Three Gorges reservoir (Lu *et al*. 2014; Chen *et al*. 2014).

Tab. 3 Classification of barrier lakes by size.

Tab. 4 Risk factors of barrier lakes.

Figures

Fig. 1 A view of Beichuan County town shortly after it was buried by the Weijiagou landslide of the 24th of September 2008

Fig. 2 Aerial photo of the August 13th landslide in Qingpingxiang Town, Mianzhu. Along a 3km section through Qingpingxiang more than ten valleys saw the outbreak of simultaneous mudslides and debris flows.

Fig. 3 The market town of Qingpingxiang covered by silt and buried by the “8.13” torrent and mudslide. The mudslide volume reached 6,000,000m^3 and far exceeded that of the Zhouqu mudslide (i.e. 1,800,000m^3) (Extracted from www.nandu.com).

Fig. 4 Cumulative rainfall recorded at the rainfall stations in Zhouqu and Dongshantai (from Dijkstra *et al.* 2012).

Fig. 5 A longitudinal section of the Dayu valley, one of the tributaries to the Bailong River draining the Sanyanyu catchment where the Zhouqu debris flow originated. Steps in the longitudinal profile are predominantly formed by palaeo-rock avalanches. The critical change in behaviour occurred at an altitude of 2300 m; above this level discharge is characterized by turbulent flow and large bedload transport, while below this step in the terrain the torrent regime changed, eroded substantial quantities of valley-based deposits and took on the characteristics of a debris flow (modified after Dijkstra *et al.* 2012)

Fig. 6 Geological disaster monitoring and warning apparatus used in cold alpine and densely-fogged mountainous areas.

Fig. 7 The Monkey Stone landslide prevention and control projects and relocated households in Fengjie County. The red line indicates the outline of the landslide.

Fig. 8 Layout profile of the prevention and control project of the Monkey Stone landslide (See also Figure 7).

Fig. 9 Diagram showing the location of the barrier lakes related to the Wenchuan Earthquake. The Roman numerals represent the earthquake intensity.

Fig. 10 The large volume of material generated by the Zhouqu debris flow blocked the Bailong river, causing extensive upstream flooding. Explosives were used to enlarge drainage channels during the first phase of the emergency response mission.

Fig. 11 Excavation of a drainage channel at the Hongshiyan barrier lake during the first phase of the emergency response mission.

Figure 1

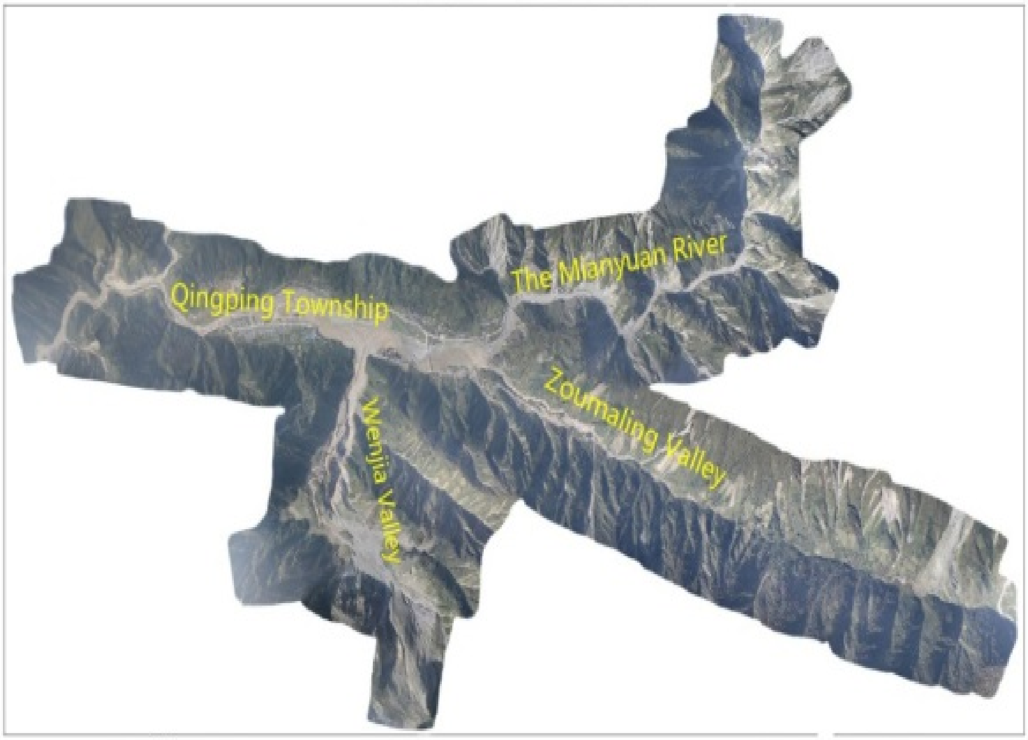

Qingping Township
The Mianyuan River
Zoumaling Valley
Wenjia Valley

Figure 2.

Figure 3.

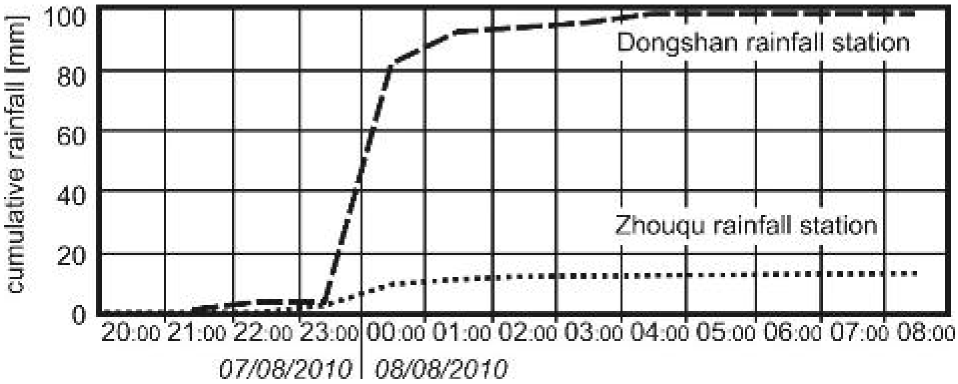
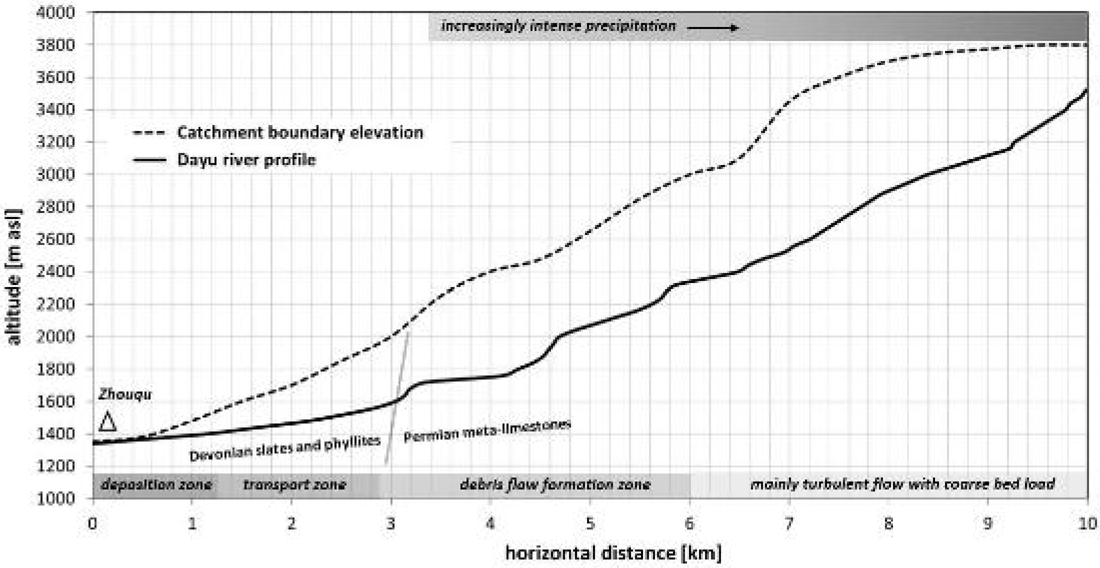

cumulative rainfall [mm]
100
80
60
40
20
0
Dongshan rainfall station
Zhouqu rainfall station
20:00 21:00 22:00 23:00 00:00 01:00 02:00 03:00 04:00 05:00 06:00 07:00 08:00
07/08/2010
08/08/2010

Figure 4



increasingly intense precipitation
Catchment boundary elevation
Dayu river profile
altitude [m asl]
4000
3800
3600
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
Zhouqu
Devonian slates and phyllites
Permian meta-limestones
deposition zone
transport zone
debris flow formation zone
mainly turbulent flow with coarse bed load
0
1
2
3
4
5
6
7
8
9
10
horizontal distance [km]

Figure 5

Figure 6.

Figure 7

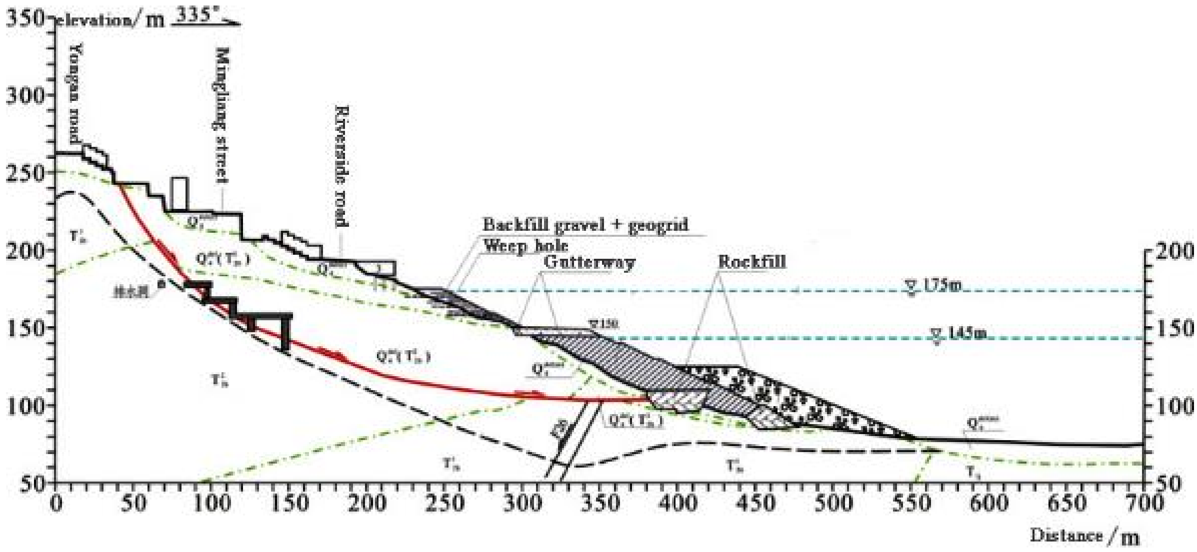
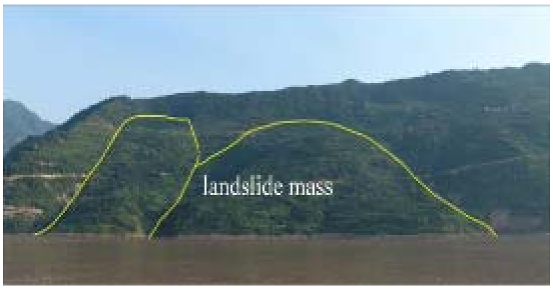
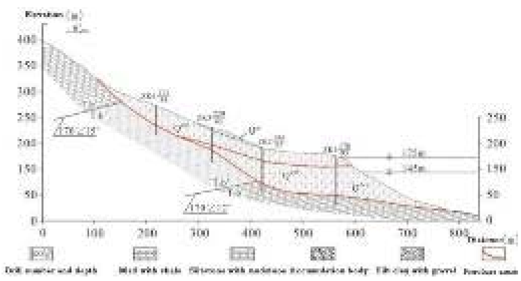
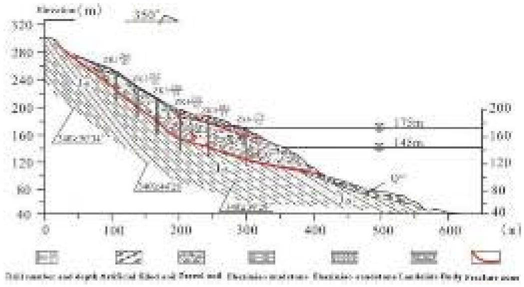
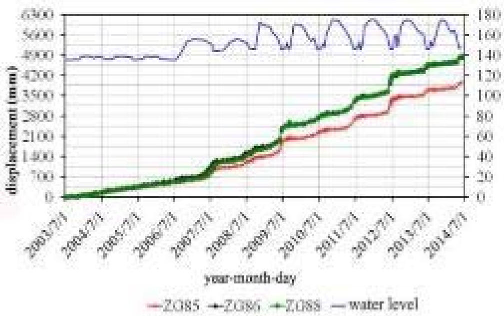
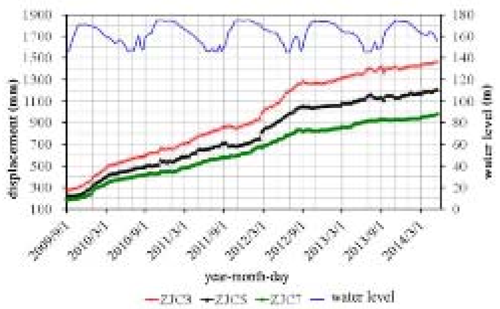

elevation/ m
335°
Yongan road
Mingjiang street
Riverside road
Backfill gravel + geogrid
Weep hole
Gutterway
Rockfill
175m
145m
150
Distance / m
350
300
250
200
150
100
50
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700

Figure 8

Figure 9

Zigui Shuping landslide	Yunyang Liangshuijing landslide
	
(a) Panoramic image	
	
(b) Profile	
	
(c) Horizontal displacement monitoring and water impoundment levels	

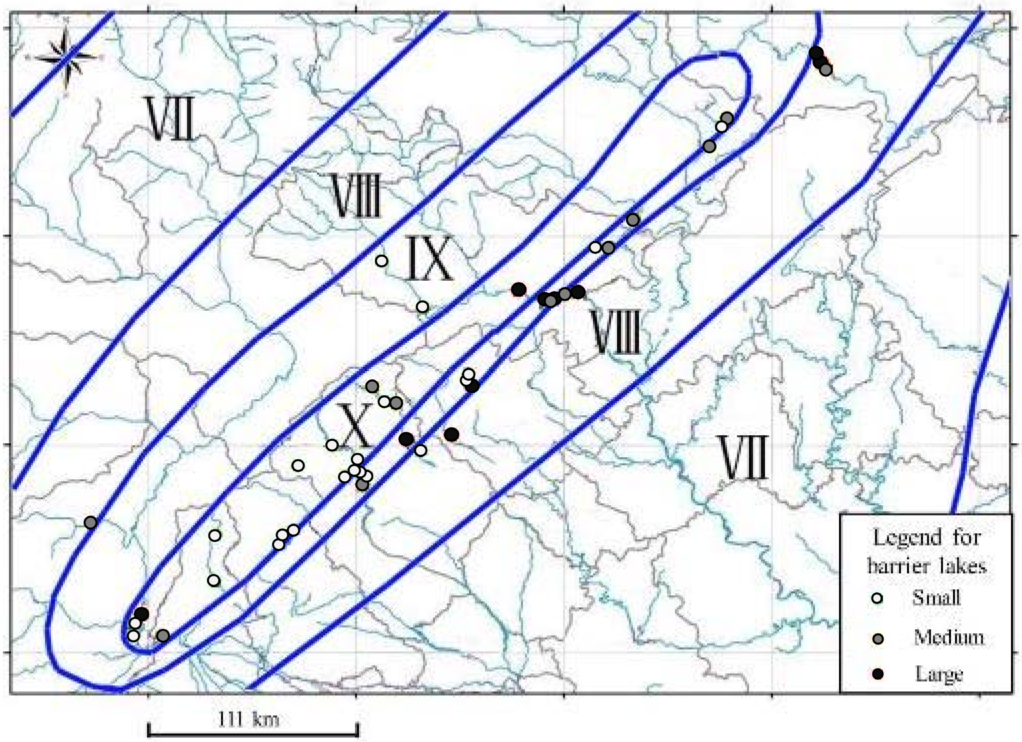

VII
VIII
IX
X
VIII
VII
Legend for
barrier lakes
Small
Medium
Large
111 km

Figure 10.

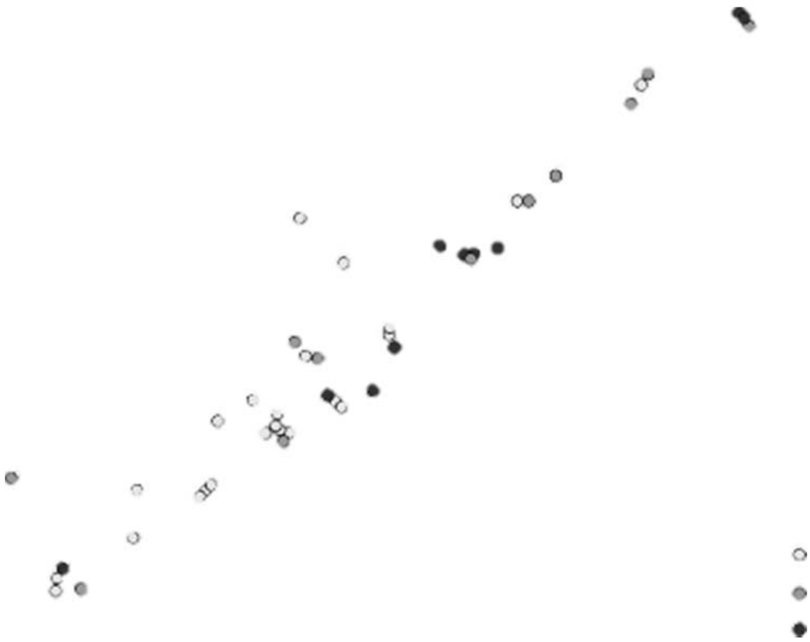


Figure 11

Figure 12