Environ Earth Sci (2012) 66:1001–1009
DOI 10.1007/s12665-010-0612-5

ORIGINAL ARTICLE

Secondary geological hazard analysis in Beichuan after the Wenchuan earthquake and recommendations for reconstruction

Yu Huang · Wei Chen · Jinyuan Liu

Received: 20 August 2009 / Accepted: 11 June 2010 / Published online: 29 June 2010

Abstract The Wenchuan earthquake, also known as 2008 Sichuan Earthquake, occurred along the Longmenshan fault zone on 12 May 2008 at 14:28:01.42 CST (06:28:01.42 UTC). It caused serious damage to structures in the region. Beichuan is a town which is within these severely damaged areas. According to the earthquake intensity distribution map of 2008 Wenchuan earthquake officially released by the China Earthquake Administration, the earthquake intensity in Beichuan was XI on the China seismic intensity scale. As the earthquake occurred in a mountainous area, there were thousands of landslides, rockfalls, debris flows, and surface ruptures triggered by the earthquake over a broad area. These secondary geological hazards substantially increased the human, social and economic impact of the earthquake. This paper presents a post-earthquake analysis on the secondary geological hazards in Beichuan. The risk analyses associated with construction of the National Earthquake Memorial Museum in Beichuan are assessed and recommendations on risk mitigations for the mass reconstruction over the ruins are also provided based on this field study.

Keywords Wenchuan earthquake · Beichuan County · Geological hazards · Town planning · Post-earthquake reconstruction · Risk assessment

Introduction

Earthquakes normally trigger secondary geotechnical hazards, including landslides, rockfalls, debris flows, barrier lakes, etc. These secondary geotechnical hazards have caused huge casualties and increased the social and economical impacts of the earthquakes (Rodriguez et al. 1999; Parise and Jibson 2000).

An 8.0 Ms earthquake, known as the Wenchuan earthquake, occurred in Sichuan, China on 12 May 2008 at 14:28:01.42 CST (06:28:01.42 UTC). This powerful earthquake was felt all across China and beyond those destroyed communities. As the earthquake occurred in a mountainous area, the earthquake directly caused more than 15,000 geohazards, including landslides, rockfalls, and debris flows (Yin et al. 2009). Many serious secondary damages were caused by these hazards (Wang et al. 2009).

This paper presents an analysis of the post-earthquake secondary geological hazards which occurred in Beichuan. The risk assessments associated with planning and design of the National Earthquake Memorial Museum are analyzed and recommendations on risk mitigations are also provided based on this field study.

Electronic supplementary material The online version of this article (doi:10.1007/s12665-010-0612-5) contains supplementary material, which is available to authorized users.

Y. Huang (✉) · W. Chen
Department of Geotechnical Engineering,
Tongji University, Shanghai 200092, China
e-mail: yhuang@tongji.edu.cn

Y. Huang · W. Chen
Key Laboratory of Geotechnical and Underground Engineering
of the Ministry of Education, Tongji University,
Shanghai 200092, China

J. Liu
Department of Civil Engineering,
Ryerson University, Toronto, ON M5B 2K3, Canada

Outline of the earthquake

On 12 May 2008, a deadly earthquake that measured at 8.0 Ms and 7.9 Mw hit Wenchuan in Sichuan, China (China Earthquake Administration 2008a). The earthquake epicenter was at a latitude of 31.021°N and a longitude of 103.367°E, 80 km west–northwest of Chengdu, the capital of Sichuan, with a focal depth of 19 km (US Geological Survey 2008). Focal depth refers to the depth of an earthquake hypocenter, which is the actual position of initial movement of the earthquake. Generally, this kind of shallow focus earthquakes may induce more damage than deep focus earthquakes of the same magnitude.

This earthquake took place along the northeast-orientated Longmenshan fault, as shown in Fig. 1 (ESM only), where Beichuan is in the yellow circled area and the red dashed line denotes the fault (Cui et al. 2009a). This thrust fault runs along the base of the Longmenshan Mountain. The strike of the fault plane is approximately NE. This fault separates the active Tibetan Plateau and the latent Sichuan Basin Plateau (Densmore et al. 2007). A study by China Earthquake Administration states: "The late-Cenozoic deformations in this fault (that caused the 2008 Wenchuan earthquake) are concentrated in the Guanxian-Jiangyou fracture (hill-front fracture), Yingxiu-Beichuan fracture (mid-fracture), Wenchuan-Mao County fracture (hill-back fracture), and their related folds. The recent Ms 8.0 earthquake occurred on the Yingxiu-Beichuan fracture, as a result of Longmenshan thrust pushing southeastward combined with clockwise shears" (China Earthquake Administration 2008a).

One of the most prominent features of this earthquake is that many strong aftershocks occurred after the mainshock. There were 26 major aftershocks, ranging in magnitude from 4.0 to 6.1 recorded within 7 days of the mainshock as shown in Fig. 2 (ESM only). According to China Earthquake Administration (2008b), "by 12:00 CST, November 6, 2008 there had been 42,719 total aftershocks, of which 246 ranged from 4.0 Ms to 4.9 Ms, 34 from 5.0 Ms to 5.9 Ms, and 8 from 6.0 Ms to 6.9 Ms; the strongest aftershock measured 6.4 Ms." These strong aftershocks led to severe accumulated damages. As the earthquake occurred in a mountainous area and there were so many strong aftershocks, more than 15,000 geohazards occurred, including landslides, landslips, and debris flows (Yin et al. 2009).

Based on official figures (as of 21 July 2008 12:00 CST), there were a total of 69,197 fatalities, and 374,176 injured, with 18,222 listed as missing (State Council Information Office of China 2008). The earthquake left millions of people homeless. This powerful earthquake was felt all across China and beyond those destroyed communities. Millions of houses and other structures including school buildings, roads, and bridges were seriously damaged in the earthquake.

Outline of earthquake damage to Beichuan

Based on the statistics, Beichuan is the town that suffered the most in this earthquake. There were at least 15,645 casualties in Beichuan (Sichuan Provincial Government 2008). The damages include nearly all kinds of features, direct damages associated with strong earthquakes and the secondary disasters. The ruins in Beichuan have significant scientific value on seismology and seismic design. In addition, Beichuan is of prominently significant in propagating the spirits of earthquake relief and protecting national culture.

The once beautiful Beichuan, as a town of the unique Qiang Autonomous County in China, 50 km north of Mianyang and 140 km northeast of the epicenter, was one of the most affected regions during the 2008 Wenchuan earthquake. Beichuan is scattered in a mountainous area, as shown in Fig. 3 (ESM only).

Beichuan develops mainly on the morphologically flat areas and especially on older and modern river terraces and on slopes that develop on both sides of the river terraces. Slopes and river terraces are composed of unconsolidated formations, particularly river–stream deposits. These formations are characterized by the presence of pebbles, breccias, debris, and slope formations of variable thickness. The above formations cover in a great extent of the Tibetan Plateau formations (Lekkas 2008).

Beichuan is just above the south part of Longmenshan central fault, which is also called the Yingxiu–Beichuan fault. According to initial analysis of Wu et al. (2008), the main damage caused by the Wenchuan earthquake occurred in the hanging wall of the Beichuan–Yingxiu fault. The fierce fault dislocation led to a large number of landslides and devastating damages to buildings, as shown in Fig. 4 (ESM only), Figs. 1 and 2.

In Beichuan region, 80% of the buildings collapsed, while the rest suffered significant structural damages (Xinhua News Agency 2009). Only a few buildings survived without severe damages in the earthquake affected area. The damages in Beichuan can be seen in Fig. 5 (ESM only). Furthermore, all the bridges and road network collapsed, while in general the infrastructure suffered considerable damages within and beyond the urban center. In addition, the large-scale landslides were triggered in many locations which destroyed a lot of buildings.

Secondary geological hazards in Beichuan

Beichuan situates in washes on the long and narrow valley terrace in which the rivers' and streams' growth forms. The area which suffered the earthquake most is 2.0 km distant from the fault. The fault rupture cut Beichuan from

Fig. 1 Building damages at Xinbei Middle School

Fig. 2 Building damages at Beichuan Municipal Office

southwest to northeast, forming an intense thrust deformable zone along the fault zone, which collapsed the buildings along the fault. Half of the old town was destroyed by a landslide called Wangjiayan landslide; the southern part of the new town was destroyed by a rockfall called Jingjiashan rockfall. This rockfall was composed of the megalith, the largest one amounted to several hundred cubic meters. It destroyed several dozens of houses, cut the county main road, and caused huge casualties.

Surface fracture

The earthquake took place in the Longmenshan fault, which is a famous reverse fault belt in the northwest of Sichuan, China. Seismic activities concentrated on its mid-fracture, also known as Yingxiu–Beichuan fracture. The rupture lasted approximately 120 s, with the majority of energy released in the first 80 s. Starting from Wenchuan, the rupture propagated at an average speed of 3.1 km/s at

Fig. 3 Example of earthquake surface ruptures

49° toward the northeast, rupturing a total of about 300 km. The maximum displacement amounted to 9 m. The depth of the surface rupture extended more than 10 km deep (China Earthquake Administration 2008c).

Damages distributed mainly along the Longmenshan fault region. After the earthquake, the surface fractures were investigated in Beichuan and Yingxiu, as shown in Fig. 3. It was found that the Beichuan–Yingxiu earthquake fracture zone extends northeastward, dipping to the northwest (Fu et al. 2008). The earthquake fracture zone is mainly characterized by thrust faulting with a small strike-slip movement, and demonstrating various complexities for different areas. The phenomena related to dextral strike-slip displacement were found in the Beichuan and those related to left-lateral strike-slip movement were found in Yingxiu. The compressive shortening of the two surface fracture zones in Beichuan was 2.8–3.9 m and the left-lateral strike-slip displacement of the surface fractures in Yingxiu was 0.52 m (Deng et al. 2008).

Beichuan had two main surface fractures, the trend was northeast with an angle of 30°–50° to the north. The first fracture burst in a southwest direction from Beichuan Middle School and extended 10 m through the old town. The other one extended 8 m from the east part of Beichuan to the Jingjiashan rockfall, as shown in Fig. 6 (ESM only) (Huang et al. 2009).

Landslide and rockfall

Figure 7 (ESM only) shows a series of landslides and rockfalls on the very steep hill slopes in Beichuan, where the landslides were noted in the yellow patterns. The damages from Wangjiayan landslide were among the most severe ones, which caused 1,600 deaths and destroyed half of the old town. It was at the west side of the Beichuan. The Xinbei Middle School landslide buried at least 1,000

Fig. 4 Xinbei Middle School landslide at the new town in Beichuan

Fig. 5 Rockfalls on the road from Renjiaping to the old town in Beichuan

students and teachers, as shown in Fig. 4 (Xinhua News Agency 2008).

The external causes of landslides and rockfalls were the high level strong ground motion and surface rupture. The internal causes were topography of Alpine mountain-canyon cutting in joints and beddings severely in the rock body, deposition and weathering of overburden soil layer on the rock (Zhao et al. 2008).

The mainshock landslides blocked the routes to the towns and villages in the mountainous area. The landslides blocked the traffic, submerged or demolished residential houses, and caused a lot of casualties and property loss. The secondary landslides continued to impede the deployment of aid and reconstruction several weeks, even months in a certain area, after the mainshock.

There were different scale landslides and rockfalls in Beichuan's peripheral mountains. The consequences of these landslides and rockfalls were river course jamming, vegetation deterioration, mountain massif bareness, and the geological crisp pine, which further initiated the secondary disasters. The main landslides include: Wangjiayan landslide, Xinbei Middle School landslide (shown in Fig. 8, ESM only), and Tangjiashan landslide. The largest rockfall is the Jingjiashan rockfall.

The landslide that caused the most casualties was Wangjiayan landslide in the old town. This landslide massif fell as high as 300 m and destroyed nearly the half of the old town. The Tangjiashan landslide was the biggest landslide, which completely blocked the upstream of the Jianjiang river in Beichuan and formed the largest barrier lake of this earthquake, Tangjiashan barrier lake. This lake seriously threatened the safety of the people living in the downstream.

The Xinbei Middle School landslide was a complex of ancient landslide and cliff with a length of 650 m, a breadth of 200 m, an average thickness of 20 m with some places reaching a thickness of 40 m, and an altitude difference of 300 m. The volume of this landslide was approximately 2,400,000 m^3. This landslide had the characteristics of rockfalls and was composed mainly of blocks and stones with some having a volume of 1,000 m^3 (Yin et al. 2009). Its impulsive force was huge and totally destroyed a three-storied school building in the Xinbei Middle School and adjacent buildings and took the lives of nearly 500 people. In the leading edge of the landslide, there was ground ballooning along the former main street, it might be related to the break thrust formed by the seism tectonic line.

The rocks fell down under strong ground motion and surface rupture. Figure 5 shows Jingjiashan rockfall on the road from Renjiaping to Beichuan, which is situated on the Longmenshan central fault. The fall blocks were round or angular. The joints and beddings were full-fledged and the interfaces among block–block and block–soil were very clear.

Debris flow

The earthquake-struck areas were also prone to debris flow. There were a total of 501 debris flow disasters reported in the Wenchuan earthquake, among them 24 were in Beichuan (Cui et al. 2008).

A heavy rainstorm occurred in the early morning on 24 September 2008 with a daily rainfall of 370 mm at the rainstorm center and 190 mm in Leigu Town. According to Tang et al. (2009), before the debris flow happened, the 3-day antecedent precipitation was accumulated to be 350–380 mm with a single day rainfall of 272 mm on 24 September 2008 recorded at Tangjiashan. This heavy rainstorm caused a heavy flood in the region. The vast

Fig. 6 Debris flow at the old town in Beichuan

stretches of farmlands and temporary dwellings were submerged and many roads and bridges were destroyed by the flood. This rainstorm also triggered numerous debris flows in the central part of Beichuan. There were 42 people killed and many roads in this area were damaged by this flood (Tang et al. 2009).

There were several serious ravines in the mountain behind the Xinbei Middle School, which took debris flow place simultaneously; it caused 20 residents to be killed or missing. The large-scale debris flow in Weijiagou almost completely buried the nearby old town as shown in Fig. 6. The thickness of this debris flow varied from 5 to 8 m. The original drainage channel system in the ruins of Beichuan old town was destroyed completely. It became more difficult for the construction of the Earthquake Memorial Museum. If there were another heavy rainstorm, a larger debris flow would occur and destroy the old town and even endanger the new town.

The debris flow induced by the earthquake was sloping debris flow. Its hazards were lower than those large-scale landslides and rockfalls. The considerable hazards always occurred in continuous heavy rain after the earthquake, but it had certain hysteresis quality. Without doubt, the earthquake provided the massive incoherent material for debris flow.

The Wenchuan earthquake made the regional geology environment very frail, massive incompact substance deposited in the slope and ravine, so the secondary geological disaster is extremely easy to occur. Because almost all the roads were destroyed, more than 4,000 people were stranded in the mountains. At the same time, the debris flow threatens the safety of the residents in the resettlement areas.

Barrier lake

The Longmenshan river system includes the Minjiang river system, the Tuojiang river system, and the Jialingjiang river system. The rivers were filled up with mud due to the massive landslides, rockfalls, and debris flow triggered by the earthquake. There was a close relationship between the distribution of barrier lakes and the Longmenshan fault. According to Cui et al. (2009b), the barrier lakes distributed along the fault, especially along the Jianjiang river, the Mianyuan river, and the Shitingjiang river. The necessary condition for the landslides to form a dam is that there must be enough water volume. However, it was certain that massive landslides along the fault were large enough to form the barrier lakes.

Cui et al. (2009b) reported that there was a string of nine barrier lakes along the Jianjiang river in Beichuan. Among them, the most dangerous lake was the Tangjiashan barrier lake, which was 5 km from Beichuan, as shown in Fig. 9 (ESM only). This bedding landslide was composed of weathered schist and slate with sand, the height difference of the anterior and the posterior reached 650 m, the horizontal distance was approximately 1,250 m. The Tangjiashan barrier lake had a length of 610 m and a width of 800 m and a barrier dam height of 80–120 m. The lake's volume was approximately 20 million m^3. The outburst of this barrier lake, as shown in Fig. 7, would initiate a series of barrier dam bursts in the downstream. This would enlarge the flood and severely threaten the safety of approximately 110,000 people in many counties and villages downstream. The small-scale barrier lakes distributed in the ditches were unable to be identified in the remote sensing images due to the cloud influence. Although these small-scale barrier lakes could not cause major disasters like the large-scale ones, they might still initiate a large-scale debris flow and endanger the infrastructures, the villages, and the cities in the downstream.

The landslide mass hit the mountain on the left bank. As a result, a loose deposit of rock debris was accumulated in the north side of the landslide. The total storage capacity of

Fig. 7 Tangjiashan barrier lake

the barrier lake was 240 million m^3; the backwater length was 10 km. At the beginning of June 2008, the excavation measures were taken in the dam with a slotting depth of 20 m. The upstream water level of the Tangjiashan barrier lake achieved the highest water level of EL. 743.10 m at 1:30 AM CST on 10 June 2008 and then fell back to EL. 719.48 m at 8:00 PM CST on 10 June 2008 and met the safety design standards (Hu et al. 2009).

Engineering geological risk assessment

In addition to the massive reconstruction, there will be four main memorial projects planned in the region: (1) the Beichuan Earthquake Memorial Museum; (2) the Wenchuan Epicenter Commemoration Place in Wenchuan; (3) the Industry Ruins Commemoration Place in Hanwang factory site; and (4) the Earthquake Vestige Commemoration Place in Hongkou in Dujiangyan.

For planning these memorials, seismic safety was evaluated to minimize the risks due to serious secondary geological hazards. It consisted of analyses for four typical secondary geological disasters in Beichuan.

Site analysis

According to Code for Seismic Design of Buildings (Ministry of Construction of China 2001), the selection of construction sites should meet the project needs, keep track of the relevant seismic activities, including engineering geology, and earthquake geology, make the quality evaluation of low risk area, medium area and hazard high risk area.

A stable site should be selected so that it will keep away from the hazardous area. If it is unable to avoid fully, certain effective actions should be taken to provide a reliable prevention from the risk.

If a fault exists in the site, an engineering influence of the fault should be assessed, and it should meet the following requirements:

(a) The earthquake resistance fortification intensity is lower than VIII.
(b) It is not a Holocene fault.
(c) When the earthquake resistance fortification intensity is VIII or IX, the thickness of former Quaternary bedrock underlying break's soil layer cover is more than 60 and 90 m, respectively.
(d) If it does not meet all the criteria listed in requirement (a), the master fault should be avoided. Its distance is not smaller than the stipulated values in Code for Seismic Design of Buildings (Ministry of Construction of China 2001). The minimum distance to avoid the fault is 200 m.

Risk level assessment

Deciding on the risk levels involves complex technical, social and economical issues and requires value judgements. Because this work mainly serves a conceptual planning purpose related to the reuse of land in Beichuan, to simplify the following analysis, the risk levels are determined by the geological environments in the paper.

Regarding the National Earthquake Memorial Museum, the engineering risks are assessed based on Beichuan's engineering geology conditions and the characteristics of the area. Based on Technical Guidelines for Investigation of Urban–Rural Planning and Siting in Strong Earthquake Mountainous Regions (China Institute of Geotechnical Investigation and Surveying 2008), the risk levels are listed in Table 1.

According to the town planning standards, Beichuan is strongly influenced by dynamic geological process. The environmental engineering geology conditions are severely degraded. The site is unstable. The engineering geology condition is poor and the geological stability of site is also weak. So, it is essential to carry out risk assessment in Beichuan. Beichuan is divided into three different regions: the risk level-I area (high risk area), the risk level-II area (medium risk area), and the risk level-III area (low risk area), as shown in Fig. 8.

(a) Risk level-I area (high risk area)

The area has a distance of 50 m away from the fault and/or is directly affected by landslides, rockfalls, debris flows.

Table 1 Criteria for different risk levels

Levels	Arrangements	Acceptance criteria
I	Immediately stop, need alternative plans	High risk, unacceptable
II	Need the decision of policy-maker, need controlling measures	Medium risk, tolerable
III	Call for great attention, need prevention, and monitoring measures	Low risk, broadly acceptable
IV	No need for management and supervision	Safe, negligible

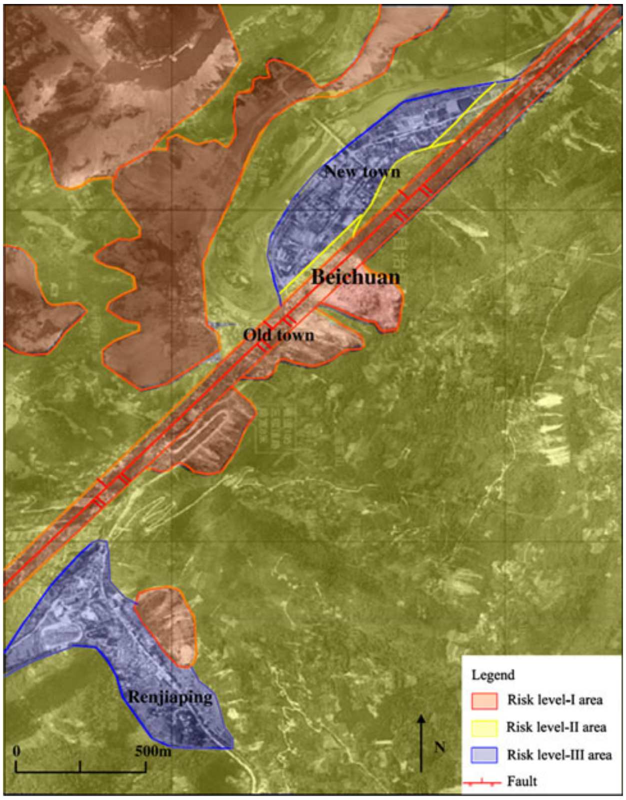

Fig. 8 Distribution of areas of different risk levels in Beichuan

It corresponds to the red areas in Fig. 8; its measures include immediately stops and alternative plans.

The majority of the large-scale geological disaster distributes in the distance of 0–5 km to the fault. Therefore, the fault zone should be avoided.

Because Beichuan's intensity is XI, the minimum distance to avoid the fault is 200 m. So the risk level-I area nearly concludes all of the old town and a part of the new town. Considering the significance of the National Earthquake Memorial Museum, there must be countermeasures implementation to reduce the risks.

According to China Code for Seismic Design of Buildings, the faults and the places which are prone to secondary geological hazards, including landslides, rockfalls, surface fracture, and debris flows, are the hazardous areas to be avoided, because the landslides, rockfalls and debris flows are so powerful to seriously threaten to the properties and the residents.

(b) Risk level-II area (medium risk area)

The area has the influence from landslides and rockfalls. It corresponds to the yellow areas in Fig. 8; the decision of policy-maker and controlling measures are needed in this area.

In order to avoid the significant geological disaster hidden spots, the support and protection projects should be established in these areas.

The safe distance and the protection measure should be determined. The natural slopes which have the potential risk in the construction site shall be reinforced and the critical facilities shall be guaranteed. The reinforcement measures shall be taken according to the slope's actual situation and the coefficient of seismic effect. The reinforcement measures include: (1) anti-slide pile, anchor cable plus frame; (2) trellis plus anchor rod; and (3) the ordinary trellis, drifts net plus spraying.

Risk level-III area (low risk area)

It is the landslides and rockfalls surrounding areas, which covers the entire earthquake ruins area except the risk level-I and risk level-II areas. It corresponds to the blue area in Fig. 8. In this area, prevention and monitoring measures are required.

The geology disaster monitoring network, the information system, the early warning system and the immediate response system should be established in the construction area.

On the basis of a comprehensive geological survey, secondary geological hazards should be monitored, including landslides, rockfalls, debris flows, surface fracture, and other hidden dangers. The local government should set up a geological monitoring station, instruct and train the local monitoring worker specifically.

For the risk level-IV area (safe area), it does not exist in Beichuan.

In addition, the risk assessment on Tangjiashan barrier lake is listed as follows:

(a) Tangjiashan barrier lake lies in the area of influence of the fault. The interaction between the barrier lake and the fault should be considered when the earthquake intensity is greater than or equal to VIII.
(b) Under the earthquake intensity VIII condition, Tangjiashan behind side slope has a low possibility to have large-scale landslides. But it is still possible to develop large-scale landslides at earthquake intensity IX, so the landslides influence must be considered (Hu et al. 2009).
(c) Under the earthquake intensity VIII condition, potential rockfalls should be considered.
(d) The earthquake causes the accumulation of debris, so the debris flows are very likely to happen, especially during a continuous precipitation.

Based on the above analysis, the National Earthquake Memorial Museum is suggested to be constructed at

Renjiaping in Beichuan, which lies in the risk level-III area as shown in Fig. 8.

Conclusions

This paper presents an analysis of the secondary geological hazards in Beichuan after the Wenchuan earthquake. There were thousands of landslides, debris flows, and barrier lakes reported after the earthquake. These secondary geological hazards caused serious damages in the region. Beichuan is among severely damaged towns during the earthquake. Beichuan, which is scattered in a mountainous area, has two parts: the old town and the new town. A half of the old town was totally destroyed by the Wangjiayan landslide. The southern part of the new town was destroyed by the Jingjiashan rockfall. The disaster level in the new town was lower than the one in the old town.

According to town planning standards and specifications, the dynamic geological process in Beichuan is intensive. The engineering geological conditions are seriously deteriorated and not easy to improve after the earthquake. The site engineering geologic conditions are instable and soil is extremely poor. The engineering ground conditions are incapable for construction.

Based on this study, it is clear that the secondary disasters should be considered seriously for the construction of the Earthquake Memorial Museum in Beichuan. A geology disaster monitoring network shall be established in earthquake ruins area, including an information system, an early warning and forecast system, and an emergency response safeguard system. The safety of people should be put first and natural law is respected. Ultimately, a balance between the speed and the quality can be reached in reconstruction over the earthquake ruins.

Acknowledgments This work is supported by the National Natural Science Foundation of China (Grant Nos. 40802070 and 40841014), the Shanghai Municipal Education Commission and Shanghai Education Development Foundation (Shu Guang Project No. 08SG22), and the Shanghai Leading Academic Discipline Project (No. B308). The constructive comments from Prof. Wanghua Sui of China University of Mining and Technology are greatly appreciated.

References

China Earthquake Administration (2008a) Analysis of the cause of the M8.0 Wenchuan earthquake. http://www.cea.gov.cn/manage/html/8a8587881632fa5c0116674a018300cf/_content/08_05/30/1212119940937.html. Last accessed 29/07/2009 (in Chinese)

China Earthquake Administration (2008b) Distributions and statistics of aftershocks of the M8.0 Wenchuan earthquake. http://www.cea.gov.cn/manage/html/8a8587881632fa5c0116674a018300cf/_content/08_05/30/1212117488687.html. Last accessed 29/07/2009 (in Chinese)

China Earthquake Administration (2008c) Seismic intensity map of the M8.0 Wenchuan earthquake. http://www.cea.gov.cn/manage/html/8a8587881632fa5c0116674a018300cf/_content/08_08/29/1219979564089.html. Last accessed 29/07/2009 (in Chinese)

China Institute of Geotechnical Investigation and Surveying (2008) Technical guidelines for investigation of urban–rural planning and siting in strong earthquake mountainous regions. China Architecture and Building Press, Beijing (in Chinese)

Cui P, Wei F, Chen X, He S (2008) Geo-hazards in Wenchuan earthquake area and countermeasures for disaster reduction. Bull Chin Acad Sci 23(4):317–323 (in Chinese)

Cui P, Chen X, Zhu Y, Su F, Wei F, Han Y, Liu H, Zhuang J (2009a) The Wenchuan earthquake (May 12, 2008), Sichuan Province, China, and resulting geohazards. Nat Hazards. doi:10.1007/s11069-009-9392-1

Cui P, Han Y, Chen X (2009b) Distribution and risk analysis of dammed lakes reduced by Wenchuan earthquake. J Sichuan Univ (Engineering Science edition) 41(3):35–42 (in Chinese)

Deng Z, Yang Z, Sun Z, Chen G, Ma W, Sun Q (2008) Complicated phenomena of the Beichuan–Yingxiu surface fracture zone during Wenchuan Ms8.0 earthquake in Sichuan Province, China. Chin Sci Bull 53(24):3891–3896 (in Chinese)

Densmore AL, Ellis MA, Li Y, Zhou R, Hancock GS, Richardson N (2007) Active tectonics of the Beichuan and Pengguan faults at the eastern margin of the Tibetan Plateau. Tectonics 26(4): TC4005. doi:10.1029/2006TC001987

Fu B, Shi P, Wang P, Li Q, Kong P, Zheng G (2008) Geometry and kinematics of the 2008 Wenchuan earthquake surface ruptures around the Qushan Town of Beichuan County, Sichuan: implications for mitigation of seismic and geologic disasters. Chin J Geophys 52(2):485–495 (in Chinese)

Hu X, Huang R, Zhu H, Lu X, Zhang X, Shi Y (2009) Earthquake reactivation effects and stability study of Malingyan landslide in Tangjiashan dammed lake. Chin J Rock Mech Eng 28(6):1270–1278 (in Chinese)

Huang J, Guan H, Song Y (2009) Characteristics of ground ruptures in Beichuan County caused by the Wenchuan earthquake. J Inst Disaster-Prevent Sci Technol 11(1):62–65 (in Chinese)

Lekkas EL (2008) Wenchuan earthquake (M_W 7.9, 12 May 2008) Sichuan, China. Geotectonic regime and damage macro-distribution. In: Proceedings of the 14th world conference on earthquake engineering. Mira Digital Publishing, St. Louis, Paper ID: S31-015

Ministry of Construction of China (2001) Code for seismic design of buildings (GB 500011-2001). China Architecture and Building Press, Beijing (in Chinese)

Parise M, Jibson RW (2000) A seismic landslide susceptibility rating of geologic units based on analysis of characteristics of landslides triggered by the 17 January, 1994 Northridge, California earthquake. Eng Geol 58(3–4):251–270

Rodriguez CE, Bommer JJ, Chandler RJ (1999) Earthquake-induced landslides: 1980–1997. Soil Dyn Earthq Eng 18(5):325–346

Sichuan Provincial Government (2008) Casualties of the Wenchuan earthquake in Beichuan County. http://www.china.com.cn/news/txt/2008-06/23/content_15875239.htm. Last accessed 29/07/2009 (in Chinese)

State Council Information Office of China (2008) Casualties of the Wenchuan earthquake. http://news.sina.com.cn/c/2008-07-21/170415971186.shtml. Last accessed 29/07/2009 (in Chinese)

Tang C, Zhu J, Li W, Liang J (2009) Rainfall-triggered debris flows following the Wenchuan earthquake. Bull Eng Geol Environ 68(2):187–194

US Geological Survey (2008) Magnitude 7.9. Eastern Sichuan, China. http://earthquake.usgs.gov/eqcenter/eqinthenews/2008/us2008ryan/#details. Last accessed 29/07/2009

Wang F, Cheng Q, Highland L, Miyajima M, Wang H, Yan C (2009) Preliminary investigation of some large landslides triggered by the 2008 Wenchuan earthquake, Sichuan Province, China. Landslides 6(1):47–54

Wu F, Fu B, Li X, Liu J (2008) Initial analysis of the mechanism of the Wenchuan Earthquake (Southwest China), 12 May 2008. Bull Eng Geol Environ 67(4):453–455

Xinhua News Agency (2008) At least 1,000 students buried in China county worst hit by quake. http://news.xinhuanet.com/english/2008-05/13/content_8157648.htm. Last accessed 29/07/2009

Xinhua News Agency (2009) Chinese county in sorrow: the bereaved mourn in Beichuan on quake anniversary. http://news.xinhuanet.com/english/2009-05/13/content_11366190.htm. Last accessed 29/07/2009

Yin Y, Wang F, Sun P (2009) Landslide hazards triggered by the 2008 Wenchuan earthquake, Sichuan, China. Landslides 6(2):139–152

Zhao J, Zhou Z, Wu J (2008) Investigation of landslide and rockfall caused by Wenchuan earthquake of Ms8.0. In: Proceedings of the 14th world conference on earthquake engineering. Mira Digital Publishing, St. Louis, Paper ID: S31-050