THE Ms 8.0 WENCHUAN EARTHQUAKE OF 12 May 2008 RECONNAISSANCE REPORT

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SUMMARY

On 12 May 2008 at 2.28 pm Beijing Time, an Ms 8.0 earthquake occurred in the Wenchuan County of Sichuan province, China. The associated fault ruptured over 240 km on the ground surface. The resulting damage was very severe and widespread, with casualties of almost 70,000, another 18,000 missing and 370,000 injured. The New Zealand Society for Earthquake Engineering reconnaissance team observed the effects and the recovery from this massive earthquake. The team studied the damages caused to the natural and the built environment due to fault rupture, seismic shaking, huge landslides and rockfalls. Maximum shaking intensity of MM XI significantly exceeded design intensity of MM VII for the area**.** Earthquake induced landslides had a major and catastrophic impact on development and infrastructure in this earthquake. Site selection was demonstrated to be critical. Brittle or non-ductile and irregular buildings performed very poorly especially in a seismic overload situation. Well engineered structures and dams performed well. Lifeline facilities were severely damaged, which resulted in interruptions to key transportation routes, inhibited rescue and recovery operations.

1. INTRODUCTION

At 2.28 pm on May 12 2008, an earthquake of magnitude M8.0 occurred along the steep eastern margin of the Tibet Plateau, in Wenchuan County of Sichuan Province, hereafter referred to as the Wenchuan Earthquake. Its epicentre was located at 31.02 degrees N and 103.4 degrees E, about 70 km from Chengdu, the provincial capital (Figure 1). The earthquake had a shallow focal depth of 14 km, and resulted in intense shaking and massive damage. Aftershocks were felt in the months following the earthquake.

This earthquake was the strongest to have occurred in China over 50 years and caused the largest loss of life since the Tangshan earthquake in 1976. The official death toll for the 2008 event stood at over 70,000, with nearly 18,000 missing and over 370,000 injured. The damage was spread over an area of about 30,000 square kms, with a reconstruction cost estimated at 1.2 trillion Chinese RMB (US$ 170 billions).

The New Zealand National Society of Earthquake Engineering (NZSEE) decided to send a reconnaissance team to the earthquake affected area to observe the effects of this massive earthquake, with the intention of reporting on lessons learnt for New Zealand.

The team comprising five members, each in their respective areas of expertise, is:

- Jiashun Yu, Co-leader, Seismology
- Philip Yong, Co-leader, Building Structures & Bridges
- Stuart Read, Engineering Geology and Dams
- P. Brabhaharan, Lifeline & Geotechnology
- Meng Foon, Emergency Management

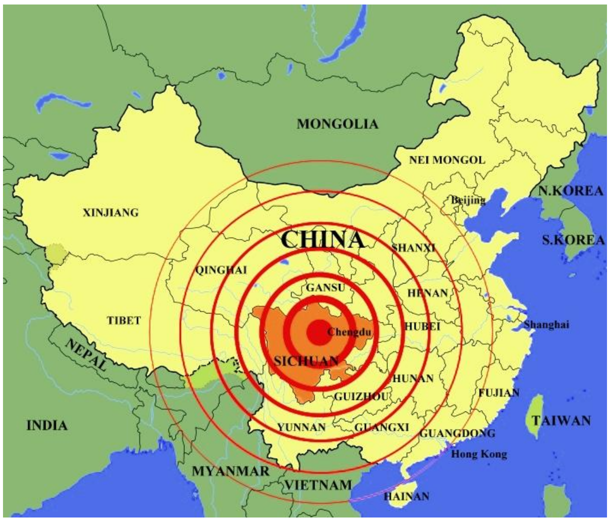

Figure 1: Location of Ms 8.0 Wenchuan Earthquake.

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The reconnaissance activities started immediately after the earthquake and extended over 6 months, with several visits to China.

Jiashun Yu happened to be in Chengdu when the earthquake occurred. Being an eye witness to the disaster he was able to collect first hand information and started his involvement in the relief effort with the locals immediately following the earthquake. In July 2008, Jiashun was invited by the Chinese Academy of Science to attend the Wenchuan Earthquake Reconstruction forum in Chengdu. Taking advantage of the opportunity, Jiashun visited the epicentral area to collect fault rupture and land deformation information, covered in Section 3.2 of this report. These field trips were invaluable, as some of the sites were destroyed later in the rainy season. This visit to China also allowed crucial preparation and arrangements to be made for the subsequent reconnaissance team mission.

From 2 to 11 November 2008, with visas finally granted, the team (Figure 2) visited the earthquake affected area. Although it was then almost 6 months after the earthquake, access into the epicentral area was still under strict control. With permits granted from the local authorities, the team was able to make reconnaissance field trips into the following sites: Dujiangyan, Zipingpu dam, Yingxiu (the epicentre of the earthquake), Beichuan, Hanwang, and Qingping Village (Figures 3 & 4).

The team also visited Chengdu University of Technology (CDUT), the Sichuan Seismological Bureau and the Sichuan Highway Design Institute to meet with local experts of various fields relating to the earthquake. These visits were invaluable in extending the team's knowledge of the earthquake. In addition, the team was also able to meet with Dr Xie Hong, the vice chairman of the reconstruction committee of Sichuan Province. The team found this meeting very informative in learning how the Chinese managed the emergency situation and planned the reconstruction.

This report is a summary of what the team learnt in the above activities.

Figure 2: The team in Yingxiu, the epicentre, 4 November 2008.

Figure 3: Epicentre rock in Yingxiu.

Figure 4: Reconnaissance trips of the team in November 2008.

2. TECTONIC SETTING

The Wenchuan Earthquake occurred in the Longmenshan Fault zone, which lies on the south-east edge of the Tibet Plateau (Figure 5). In Chinese, the name "Longmenshan" consists of three characters: "Long" means dragon, "men" means gate or door, and "shan" means mountain. The names Longmenshan and Longmen Mountain therefore refers to the same place.

The Tibet Plateau is a result of the convergence of the India Plate against the Eurasia Plate. On its south-east margin near the Longmen Mountain range the plate movement is ~15-20 mm/yr (Burchfield *et al.* 2008). This advancing of the Tibet Plateau is brought to a sudden stop on its edge by the Yangzi Crust Block, on the west edge of which lies the Sichuan Basin. The collision of the two geological blocks is accommodated by the uplift of the mountain ranges including Longmenshan and the fractures of the Xuanshuihe, Anninghe and Longmenshan Fault Belts.

The Longmenshan has steep, high-relief margins on its eastern side **(**Figure 6**)** and only modest western slopes. To the west the eastern part of the Tibetan plateau is at an altitude of about 4,000 m, with the Sichuan Basin to the east at ~500 m (Figure 7). Over the 100 km in between, the topography in the Longmen Mountain rises to >5,000 m, with deeply incised river valleys traversing and draining the range. The terrain is consequently steep and mountainous.

The eastern margin of the Tibet Plateau is one of the most rapidly uplifting areas in the world. Figure 8 illustrates the uplift history and the denudation amount from the east Tibet Plateau to the Sichuan Basin. In the Sichuan basin, the amount of denudation is ~2 km, at ~0.1 mm/y. In the Longmen Mountain range, the denudation is much larger, of up to 7 km, at ~0.35 mm per year. Arne *et al.* (1997) and Xu & Kamp (2000) also found that the denudation rate has increased to >1 mm/y in the period from late Miocene to Pliocene (7-2 Ma).

Figure 5: ***Location of the Wenchuan Earthquake (star), the Longmenshan Fault (red line), and the indicative movement of the plate tectonic blocks.***

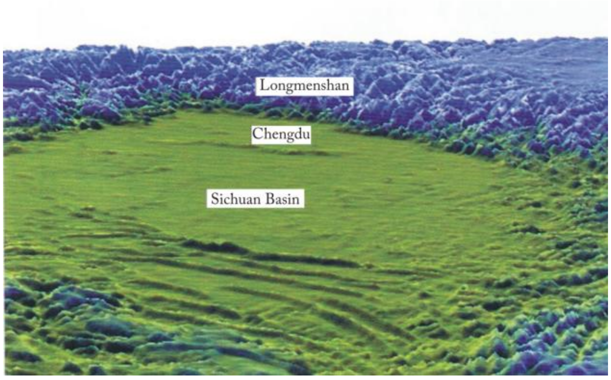

Figure 6: ***Topography of the Longmenshan and the Sichuan Basin. The sudden elevation change marks the boundary of the Tibet Plateau and the Sichuan Basin. (from Li Yong et al., 2009).***

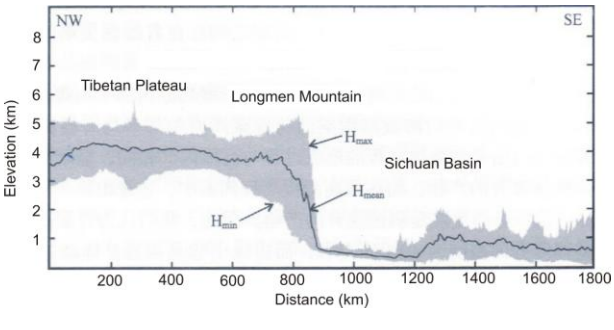

Figure 7: ***Elevation section of Longmenshan (from Li Yong et al., 2009), a synthesis using elevation data over a grid of 1 km by 1 km interval, covering an area of 250 km by 1700 km. H_{mean}, represents the mean elevation, while H_{max} and H_{min} represent the maximum and minimum elevations, respectively.***

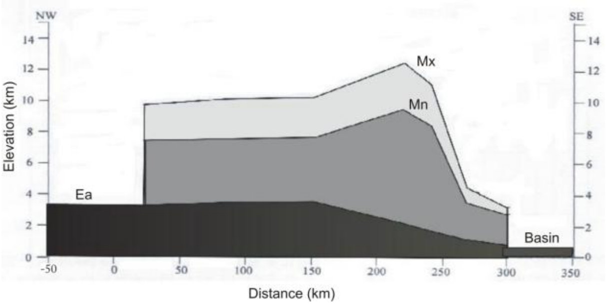

Figure 8: ***Denudation in the Longmen Mountain Region since early Miocene. Ea denotes the average elevation of the current ground surface; Mn and Mx denote the minimum and maximum, respectively, elevations of the ground surface if there were no denudation (Provided by Ganqing Xu, Waikato University, NZ).***

The tectonics in the Longmen Mountain area is dominated by three large imbricate reverse faults (Figure 9), i.e., the Wenchuan-Maowen fault (running through Wenchuan and Maowen), the Yingxiu-Beichuan fault (running through Yingxiu and Beichuan) and the Peng-Guan fault (running through Pengxian and Guanxian, which is now called Dujiangyan). The faults are also referred to by the Chinese geologists as the frontal fault (for the Peng-Guan fault), the mesial fault (for the Yingxiu-Beichuan fault) and the distal fault (for the Wenchuan-Maowen fault). These faults all trend northeast-southwest at ground surface and dip usually 60^o-70^o to the north west. Recent studies found that the faults are not only dip-slip reverse but also have been characterised with a lateral movement component (Li *et al.* 2006). It is right-lateral at many sites but there are also arguments that it is of left lateral (e.g., Luo *et al.* 2008 and Liu *et al.* 2008), reflecting the complex rupture pattern in the faulting history. On a regional scale, these three faults are referred to as the Longmenshan Fault, as they are believed to be branches of the thrust fault beneath the Longmen Mountain range (Figure 10), e.g., Luo *et al.* (2008). This was supported by many geophysical data (Zhu *et al.* 2005, Wang *et al.* 2008).

The northeast – southwest trending Longmenshan area has a complex geology resulting from superposition of Cenozoic tectonic deformation on intense Mesozoic deformation. In the Mesozoic two distinct structural sequences (upper and lower) were deformed and then juxtaposed by thrust faulting, with refolding and further thrusting in the Cenozoic (Li *et al*., 2009, Burchfield *et al.*, 2008, Wang & Meng, 2009).

The distribution of the sequences may be simply divided into tectonic zones associated with three major northeast – southwest striking Longmenshan faults (Li *et al*. 2009). North-west of the Wenchuan-Maowen fault are Triassic sedimentary (flysch) rocks that have been tightly folded and imbricated. East of it are highly metamorphosed Paleozoic sedimentary rocks including Precambrian mixtites (conglomerates). South-east of the Yingxiu-Beichuan fault are pre-Cambrian basement rocks overlain by an incomplete sequence of Paleozoic to Mesozoic sedimentary rocks that form the lower structural sequence, with the sediments also grading eastward into the Sichuan Basin.

The Mesozoic sequences were refolded and thrust eastward, including deformation of Eocene (Tertiary) red beds along the margin of the Sichuan Basin. Vertical uplift associated with crustal shortening is estimated to be in the order of 0.7 – 1.2 mm/year with formation of the modern high topography of the Longmen Mountain established in the late Miocene (Burchfield *et al.*, 2009, Wang & Meng, 2009) accompanied by rapid river incision and deposition of alluvial deposits on the Chengdu plain.

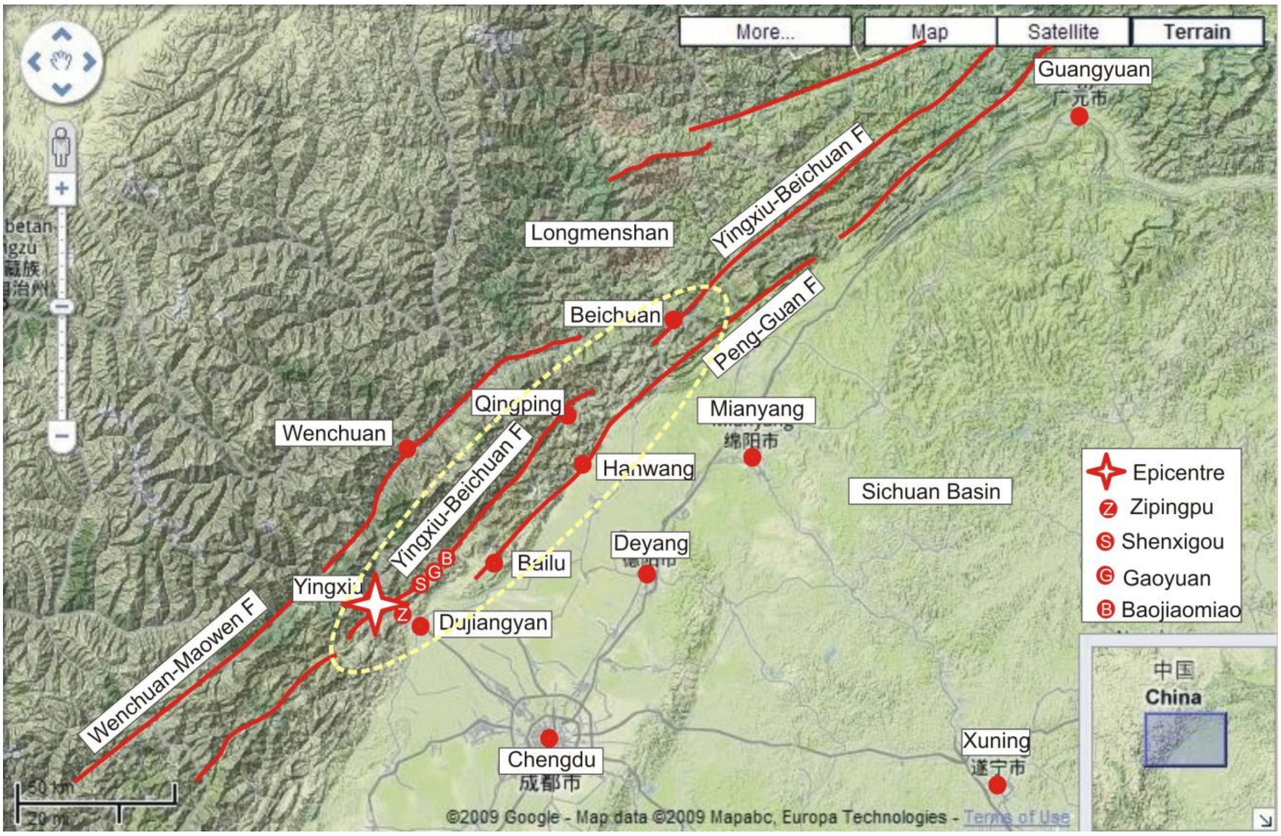

Figure 9: ***The Longmen Mountain Fault Belt. Marked within the dotted golden line is the area the reconnaissance field trips cover.***

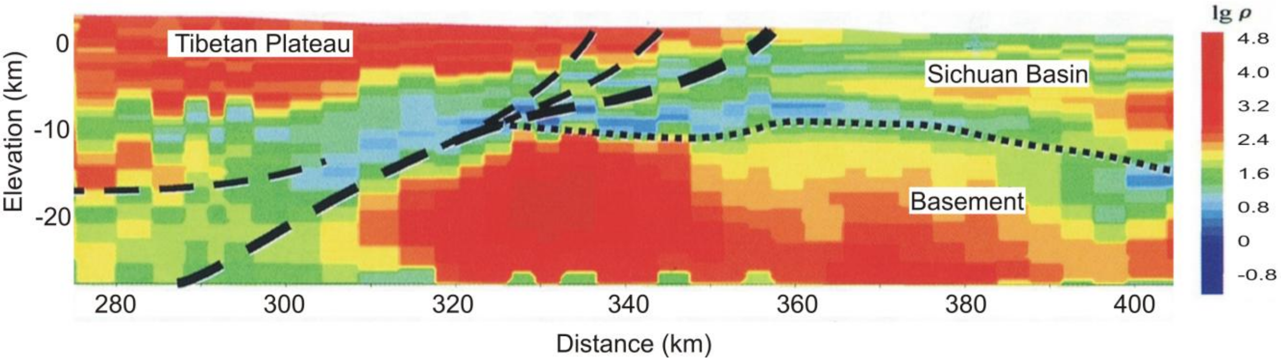

Figure 10: ***An MT cross section of the tectonics of the Tibet Plateau and the Sichuan Basin. (from Wang Xuben, CDUT).***

3. SEISMOLOGY

The Wenchuan Earthquake occurred at 14:28:01.42 CST (06:28:01.42 UTC) on May 12, 2008. The epicentre was located at 31.021^{o}N, 103.367^{o}E, with a focus depth of 14 km. Immediate measurements of the size of the earthquake were of Ms 7.8 by the Chinese Earthquake Administration (CEA), and Mw 7.8 by the United States Geological Survey (USGS). A few days after the earthquake, official magnitutes of Ms 8.0 by CEA and Mw 7.9 by USGS were published, based on more accurate calculations using seismic data recorded world wide. The earthquake was named Wenchuan because the epicentre was located in Yingxiu, a town of the Wenchuan County, although the surface fault rupture did not occur along the Wenchuan-Maowen fault. This will be discussed in Section 3.2.

3.1 EYE WITNESS

When the earthquake occurred, Jiashun was in his guest house apartment, on the sixth level of the Waizhuanlou building at CDUT, 70 km from the epicentre. He experienced the earthquake and many aftershocks in the following days.

The first jolt was moderate, but soon became very strong. He stumbled and crouched on the floor, which felt wobbly to him. The shaking seemed endlessly long. Cracking and creaking noises of the building structure sounded terrifying.

When the shaking finally became less violent, Jiashun rushed down the stairs, went outside the building and in the nearby tennis court he joined many others who had just escaped. Some of these people were only in under-garments, showing a hurried escape, just after an afternoon nap.

Aftershocks occurred frequently in the following hours. The terrified crowd stared at an antenna at the top of a nearby building for warning signals and screams broke out when it started to move again.

Large crowds remained in the open space for the afternoon, the night and the following days as well. Jiashun managed to pop into the guest house building in that late afternoon to retrieve his camera. Hence he was able to record his observations in the following days. Showing in Figures 11-14 are the conditions at the CDUT campus after the earthquake.

Figure 11: 12 May 2008. Sports ground track field, CDUT. Students who had escaped from the earthquake.

Figure 12: 13 May 2008, am. Sports ground track field, CDUT. People staying in the open for the night.

Figure 13: 13 May 2008. CDUT. The Museum Building badly damaged.

Figure 14: 12 May 2008. Library, CDUT. Fallen computer terminals and chairs.

3.2 FAULT RUPTURE

Fault surface rupture mainly occurred along the Yingxiu-Beichuan fault, which extended for a distance of 240 km. The fault surface rupture, initiated at Yingxiu, propagated towards the north-east for about 200 km and reached beyond Qingchuan. The rupture also propagated for a small distance towards the south west. According to the inversion analysis of seismic recordings by Chen *et al* (2008), total length of the underground rupture was about 300 km. The average speed of the rupture was approximately 3.1 km/s. The energy of the earthquake was released in about 80 seconds, while the rupture was in progress.

There was also a surface rupture on the Peng-Guan fault for 72 km on the ground surface. Rupture displacements along the Peng-Guan fault are smaller than the Yingxiu-Beichuan fault. No rupture was found along the Wenchuan-Maowen fault.

On the reconnaissance trips, the team was able to visit several surface rupture sites as follows.

Yingxiu-Beichuan fault

Figure 15 shows the surface rupture of the Yingxiu-Beichuan fault in the north suburb of Yingxiu (see Figure 9 for location), close to the epicentre of the earthquake. The broken river bank demonstrated a large right-lateral oblique movement. The vertical and horizontal components were 3+ and ~1.7 metres, respectively.

Surface rupture and land deformation sites in Shenxigou, Gaoyan and Bajiaomiao (see Figure 9 for locations), 12 to 20 km to the north-east of Yingxiu, are separately shown in Figures 16-23.

At the Shenxigou site where the Yingxiu Beichuan fault runs through, there was a large scale of land deformation. The concrete pavement of the country road was tilted and broken into pieces (Figure 16). Trees on the right hand side of the picture leaned 20 to 30 degrees, indicating an extension of the land deformation from the road into the land covered by the forests.

The Yingxiu-Beichuan fault is mainly dip-slip reverse in Gaoyuan. As shown in Figure 17, a country road was suddenly uplifted ~1.5 m in the earthquake. No lateral movement was observed at the site. About 300 m away from the uplifting site there was a Kiwi fruit farm, where there was a crack of ~0.8 m wide caused by the earthquake, (Figure 18).

Further towards the north east in Bajiaomiao (see Figure 9 for location), a two story building sat across the Yingxiu-Beichuan fault line (Figure 19). The south-east wing of the building on the foot wall was brought down, while the other wing on the hanging wall remained standing. The leaning trees behind the building indicate land deformation on the footing wall.

The surface rupture plane was exposed in Bajiaomiao (Figure 20**,** also see Figure 9 for site location). The dip of the plane was near vertical. Striations on the mudstone recorded the direction of the movement. Vertical displacement was ~4 m, with a ~1.7 m right-lateral component.

Figure 15: ***The Yingxiu-Beichuan fault cut through the river bank road north of the Yingxiu Township. The earthquake caused vertical and horizontal displacements of 2 m and 1.7 m, respectively, across the fault. (From Chen Yuntai, Chinese Academy of Sciences.)***

Figure 16: ***Land deformation due to the underground rupture of the Yingxiu-Beichuan fault in Shenxigou.***

Figure 17: ***The Yingxiu-Beichuan fault rupture created a sudden uplifting of the road in Gaoyuan. The vertical displacement is ~1.5 m. No significant oblique movement was observed at this site.***

Figure 18: ***Cracks of ~0.8 m wide caused by the earthquake in the Kiwi fruit farm in Gaoyuan.***

Figure 19: ***In Bajiaomiao, a two story building sitting on top of the Yingxiu-Beichuan fault line was cut in half. The south-east wing of the building, on the right hand side of the picture, was brought down in the earthquake.***

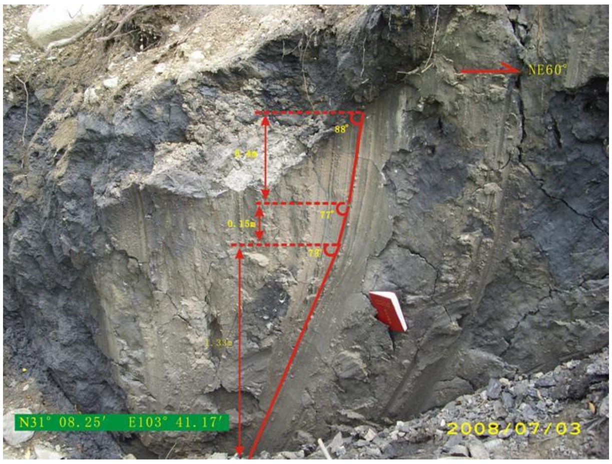

Figure 20: ***A rupture plane of the Yingxiu-Beichuan fault in Bajiaomiao. Striations on the fault plane in mudstone indicate a right-lateral oblique reverse offset.***

North of Qingping, the fault displaced a road with a vertical displacement of ~4 m, (Figure 21). The centre line of the road was laterally shifted by about 1 m, see Figure 22. As the road is not perpendicular to the strike of the fault, this distance of the centre line shift is only a projection of the lateral displacement of the fault. Using the angle and the centre line shifting distance, our calculation yielded a horizontal displacement component of ~1.2 m at the site.

Figure 23 shows the deformation profile of the Yingxiu-Beichuan fault running through Beichuan city at the intersection of the old and new townships. No proper measurement of the fault rupture offsets was made as the permitted time to stay inside the city was very limited, due to the risk of infection, but were estimated to be >2 m, by right-lateral oblique reverse movement.

The maximum vertical and horizontal displacements along the fault line were reported to be of 6.2 m and 4.9 m, respectively (Li *et al.* 2008).

Figure 21: ***The displacement of the Yingxiu-Beichuan fault near Qingping Village. The vertical displacement is of ~4 m.***

Figure 22: ***Horizontal displacement of the surface rupture of the Yingxiu-Beichuan fault near Qingping Village. Jiashun Yu is indicating the right lateral offset based on the road centre line.***

Figure 23: ***The Yingxiu-Beichuan fault surface rupture in Beichuan city. A dip-slip reverse displacement can be seen.***

Peng-Guan fault

The Peng-Guan fault, lies to the east of the Yingxiu-Beichuan fault, close to the boundary between the Longmen Mountain range and the Sichuan basin (Figure 9). The surface rupture was mainly characterised as dip-slip reverse faulting.

Figure 24 shows surface rupture at the Bailu Middle School. The faulting uplifted the ground by ~2 m. This resulted in the top of the three story classroom block (on the left hand side) to be at the same level as the roof of a four story classroom building (on the right hand side). In the foreground of the photo is the remains of a building that straddled the fault, which collapsed in the earthquake. At the distance along the fault was the ruin of the teacher’s dormitory, which also used to sit across the fault. Two teachers were killed in the collapsed building in the earthquake. The surviving classroom buildings located only a few metres away from the fault line and the collapse of the other two buildings straddling the fault, demonstrate the importance of site selection, as will be discussed in later sections.

The other surface rupture site seen along the Peng-Guan fault was near Hanwang, at the Mianyuan River outlet into the Chengdu Basin. The rupture displacement observed at the site was only about ~ 0.5 m, significantly smaller than the Bailu site.

Figure 24: ***The Peng-Guan fault rupture in the Bailu School campus. The vertical displacement was ~2 m. Two buildings used to sit on top of the fault line were brought down by fault rupturing and only ruins were visible in the frontal and distal parts of the photo.***

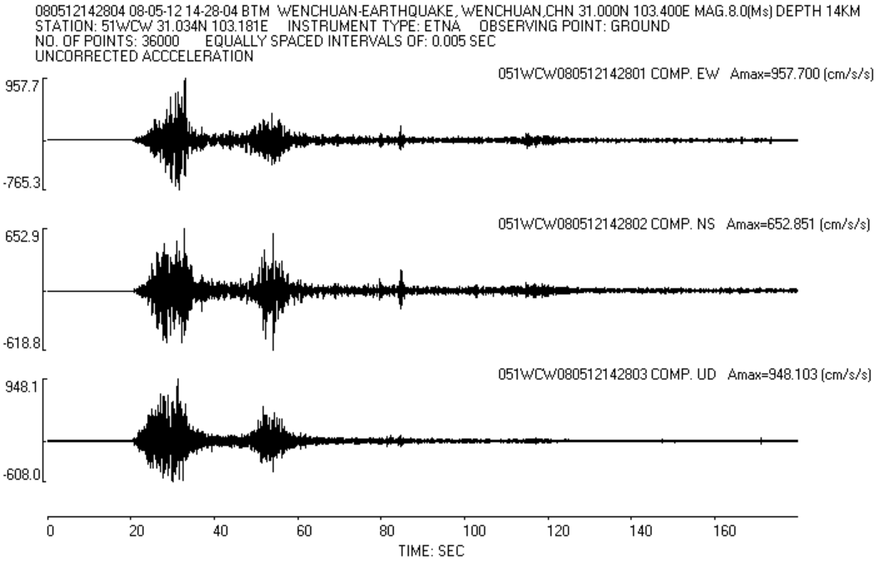

Figure 25: ***Time history of the three dimensional ground motion recorded by a strong motion station at the Wolong site. The maximum PGA of 957.7 cm/s^2 was recorded in the horizontal NS component (from NSMONS of CEA).***

3.3 GROUND MOTION

Strong motion recordings and PGAs

The Wenchuan earthquake ground motion was recorded by strong motion stations of the National Strong Motion Observation Network System (NSMONS) of China Earthquake Administration (CEA) (Li Xiaojun *et al*, 2008). The maximum peak ground acceleration (PGA) of 957.7 Gal (i.e., cm/s^2) was recorded at the Wolong site (see Figure 25). The station was only 1.09 km from the Yingxiu-Beichuan fault, and 22.2 km from the epicentre. Another strong motion station in Qingping, 0.74 km from the Yingxiu-Beichuan fault, recorded the second largest PGA of 824.1 Gal. Figures 26 to 28 show the isoseismal maps of the three peak acceleration components of the ground motion in the area. The PGAs in the earthquake largely exceeded the building design intensity for the area, as will be discussed in Section 5.

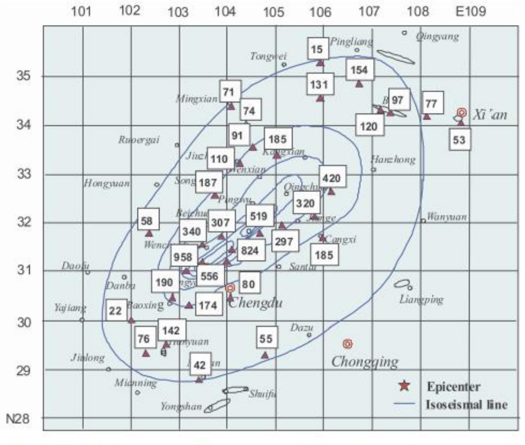

Figure 26: ***E-W component PGA of the Wenchuan Earthquake (Institute of Engineering Mechanics & China Earthquake Administration. 2008).***

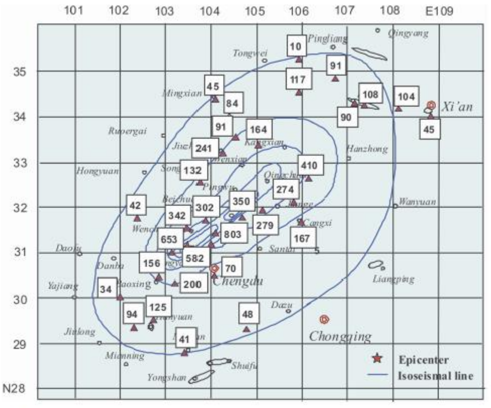

Figure 27: ***Distribution of the N-S component PGA of the Wenchuan Earthquake (Institute of Engineering Mechanics & China Earthquake Administration. 2008).***

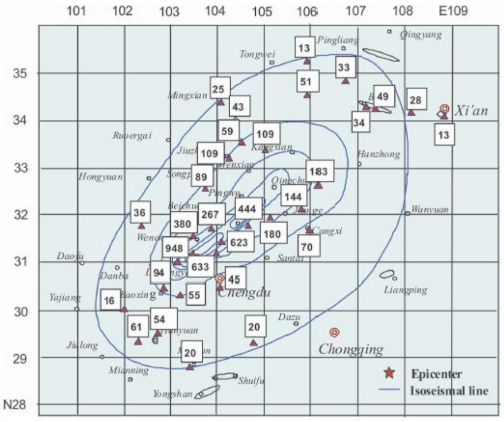

Figure 28: ***Distribution of the vertical component PGA of the Wenchuan Earthquake (Institute of Engineering Mechanics & China Earthquake Administration. 2008).***

MM Intensity

The Modified Mercalli Intensities (MMI) of the earthquake are shown in Figure 29. The distribution pattern is very similar to the three peak acceleration component maps in Figures 26 to 28. The maximum felt intensity of the earthquake is MM XI, in two separate narrow zones, centred at Yingxiu, the epicentre of the earthquake and Beichuan County (see Figure 29). These MM XI zones cover an area of 2,419 km^2, in which damage to buildings was extremely severe. The MM X and MM IX zones are also narrowly located along the Yingxiu-Beichuan fault and also cover part of the Peng-Guan fault.

The comparatively less destructive zones of MM VIII, VII and VI take the shape of eclipses, with a maximum long axis of 936 km, and short axis of 596 km (see in Table 1 for details). An area of 440,442 km^2 experienced a strong shaking intensity of >MM VI. This area is about ~1.6 times that of the New Zealand land territory. There are a few abnormal sites, in which the intensity is significantly higher than the surrounding area (see Table 2 for details). These sites are normally one intensity degree higher, except Huanyuan County, which is two intensity degrees higher than the surrounding area. The Hanyuan site is separated from the main MM VIII zone for a large distance.

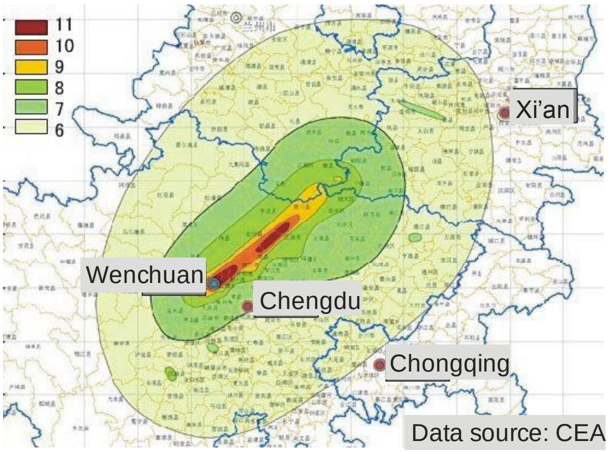

Figure 29: MM Intensity of the Wenchuan Earthquake published by the Chinese Earthquake Administration (CEA).

Table 1. Area of the MM Intensity Zones

Intensity	Area (km^2)	Long axis (km)	Short axis (km)
XI	2,419	66 and 82	22 and 15
X	3,144	224	28
IX	7,738	318	45
VIII	27,786	413	115
VII	84,449	566	267
VI	314,906	936	596
>VI	440,442		

Table 2. Abnormal Intensity zones

Abnormal zones	MMI	MMI of surrounding	MMI difference
Kangxian	XI	VIII	+1
Zhongjiang	VIII	VII	+1
Tongjiang	VII	VI	+1
Hongya	VII	VI	+1
Baoji-Qishan-Meixian	VII	VI	+1
Si'an	VI	Outside	+
Hanyuan County	VIII	VI	+2

3.4 AFTERSHOCKS

There were thousands of aftershocks following the major earthquake. In the following 18 months from 12 May 2008 to 30 October 2009, 116 aftershocks of magnitude ≥ 5.0 were recorded, with their distributions shown in Figure 30. Among these, 8 earthquakes had a magnitude ≥ 6.0 (See **Table 3** for details). These larger aftershocks were also destructive, mainly occurred in the following weeks after the major earthquake. Their locations also lined up well along the Yingxiu-Beichuan fault (Figure 31). The largest aftershock was M6.4, on 25 May 2008. The locations of these aftershocks demonstrate the separation of theYingxiu-Beichuan fault in two sections.

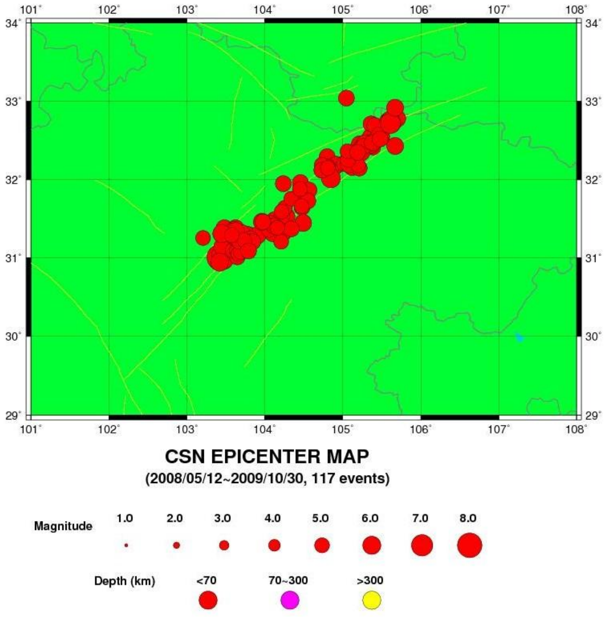

Figure 30: Locations of the Wenchuan Earthquake and 116 aftershocks of magnitude greater than 5.0 from 12 May 2008 to 30 October 2009. All these events occurred along the Yingxiu-Beichuan and the Peng-Guang fault lines. There is an obvious discontinuity in the location distribution south west of Beichuan, indicating the separation of the Yingxiu-Beichuan fault in two sections.

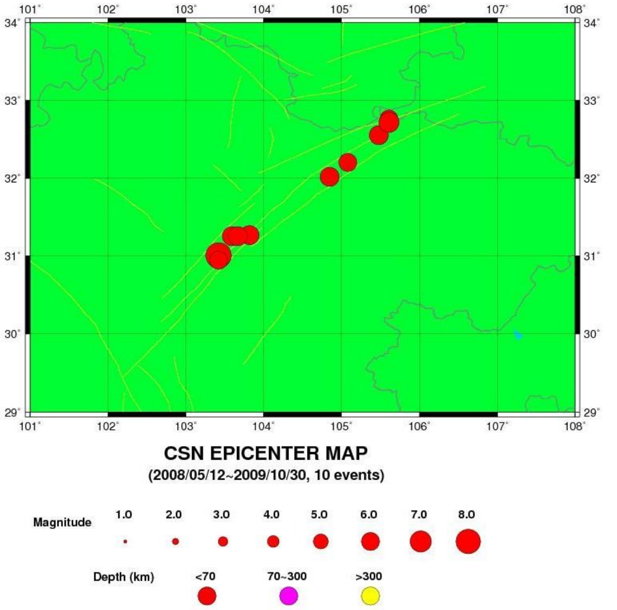

Figure 31: Locations of the May 12 Wenchuan Earthquake and 8 earthquakes of magnitude greater than 6.0. All these events occurred along the Yingxiu-Beichuan fault line.

Table 3. Information of aftershocks of M ≥ 6.0

Date	Time	Lat. (degree)	Long. (degree)	Depth (km)	Mag. (Ms)
5/08/2008	49:18.7	32.8	105.5	10	6.1
1/08/2008	32:44.6	32.1	104.7	20	6.1
24/07/2008	09:28.6	32.8	105.5	10	6.0
25/05/2008	21:47.0	32.6	105.4	33	6.4
18/05/2008	08:23.4	32.1	105	33	6.0
13/05/2008	07:11.0	30.9	103.4	33	6.1
12/05/2008	10:58.4	31.4	103.6	33	6.0
12/05/2008	43:15.0	31	103.5	33	6.0

3.5 SEISMIC HISTORY

Seismicity was low in the Longmen Mountain area immediately before the earthquake. In the first months before 12 May in 2008 there were only 3 small earthquakes of M3.0 or slightly larger along the Longmenshan Fault (Figure 32).

Regionally the area was active in its seismic history. As can be seen in Figure 34, there were many historic earthquakes occurred in the area (Marked in red circles). These earthquakes were mainly caused by the movement of a **Y** shape active fault system, including the Longmenshan fault (the red line), the Xuanshuihe fault (top left branch of the **Y**), and the Anninghe Fault (foot of the **Y**).

Xuanshuihe and Anninghe are very active faults. Large earthquakes occurred associated with these faults include the M7.9 Helu Earthquake of 6 Feb 1973, the M7.5 Kangding Earthquake of 14 April 1955, and the M7.5 earthquake occurred in Sichang on 12 September 1850.

The Longmenshan fault was less active in the last centuries. An M6.5 earthquake in Wenchuan in 1657 and an M6.2 earthquake in Beichuan in 1958 were recorded in the historic literature. However, in a larger time scale, there is geological evidence of large earthquake events along the fault, eg. Figure 33. There were also two large earthquake events associated with the surface rupture of the Peng-Guan fault 3,830 ± 200 and 930 ± 40 years ago, separately (Li *et al.* 2006).

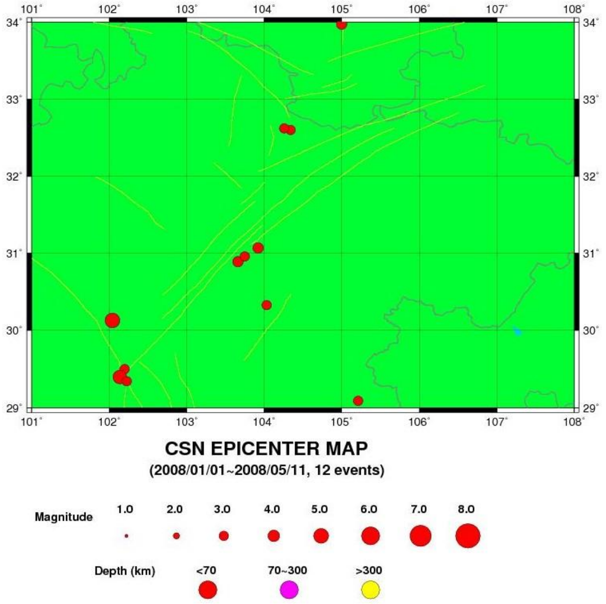

Figure 32: There were 3 earthquakes of, or slightly greater than, magnitude 3.0 along the Longmenshan fault zone in 2008 before the Wenchuan Earthquake.

Figure 33: A lenticel in the Yingxiu-Beichuan fault zone in Leigu. The large dip and the compressive structure of the coal fragment in the lenticel suggest a high angle reverse rupture of the fault in the past.

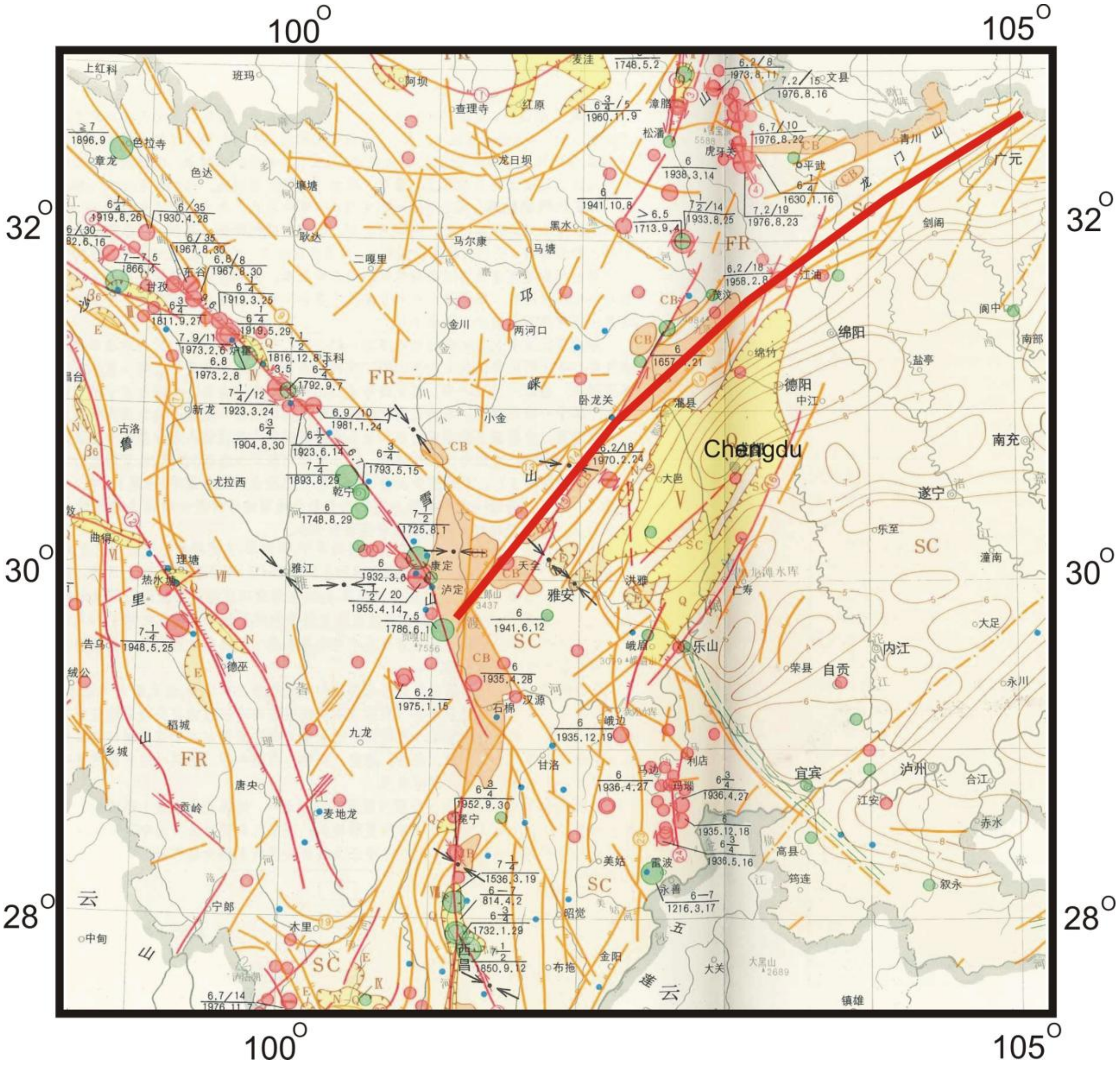

Figure 34: ***Historic earthquakes in the West-Sichuan area (Ma et al. 1989). A Y-shaped fault system dominates the tectonics in the area. The thick red line represents the Longman Mountain fault Belt. To its left, the top left branch of the Y is the Xuanshui River Fault Belt. The footing section of the Y is the Anninghe Fault Belt. Marked by red solid circles are historic earthquakes of magnitude ≥ 6.***

4. LANDSLIDES

One of the most striking feature of the Wenchuan Earthquake is the extent of landslides caused by the earthquake, their effects on the landscape and consequential effects on the built environment. The impact was still evident some six months after the earthquake and is expected to be there for years. This section gives an overview of landslides, primarily based on examples seen during the fieldtrip (e.g. Figures 35 – 38), followed by some notable examples and landslide-dammed lakes.

The terrain in the epicentral area of the Longmenshan is steep and mountainous with deeply incised rivers that have up to 1,000 m of relief along their valley sides. The widespread occurrence of landslides in the epicentral area (MM >VIII) is simply a consequence of the combination of steep slopes and strong ground shaking.

The landslides were often damaging, disrupting infrastructure, burying parts of towns and villages and causing greater than 20% of the 70,000 deaths. In some cases they blocked river valleys, forming landslide dams that impounded lakes behind them (often referred to as ‘quake lakes’, in particular by the press).

The landslides occurred in a wide range of sizes from <10 m^3 to >10 x10^6 m^3, with a variety of types / mechanisms (e.g. rockfalls, block slides, rock avalanches, debris flows), and affected an area of over 30,000 km^2. In many cases the landslides were shallow, resulting in a stripping of the landscape (Figure 35). There were also notable large individual landslides, some of which have been discussed by other authors (e.g. Wang *et al.*, 2009).

Figure 35: ***Shallow landslides stripping slopes beside the Zipingpu reservoir.***

Figure 36: ***Wenjiagou debris avalanche near Qing Ping village. Landslide with volume > 20 x 10^6 m^3 started as a block slide at the ridge crest, followed by 1500 m vertical drop as a debris avalanche with super-elevation. Fan in foreground is from post-landslide alluvial deposition.***

Figure 37: ***Rockfall from slope near Yingxiu. Rockfall is a symbolic epicentral marker.***

Figure 38: ***Tian Chi rock avalanche between Hanwang and Qing Ping. Coarse-grained debris overwhelmed the highway and a landslide-dammed lake formed behind.***

The epicentral area geology is complex, dominated by Mesozoic and Paleozoic age well-indurated or metamorphosed sedimentary rocks, with Pre-Cambrian basement granites also present. Reflecting the ongoing uplift invariably present in a high (>2,000 m) mountain range, weathering profiles on these hard rock lithologies do not tend to be very deep. Consequently there was widespread occurrence of shallow ‘stripping’ landslides, in some cases resulting in near total devastation of valley walls (Figure 39). This is consistent with landslide effects in mountainous areas (e.g. Fiordland in 2003, Hancox *et al*. 2004) and also reflects a reasonably high underlying rock mass strength.

Figure 39: ***Extensive damage to slopes northwest of Hanwang. Steep slopes almost stripped by landslide debris trails.***

Figure 40: ***Less intense landslide damage with partial reactivation of previous shallow landslide. Location closer to Hanwang than Figure 39.***

Figure 41: ***Ridge failure in bedded sandstones beside the Mianyuan River with landslide debris covering lower part of the slope.***

In many areas the landslides gave the appearance of being first-time failures. In some cases reactivation within a previous landslide scar could be seen, or indeed no reactivation at all (Figure 40). Many had head (initiation) scarps in the upper parts of slopes, where stress relief effects and ground motion amplification are more likely (e.g. Figure 41). With long slopes it often meant that landslide debris buried the middle and lower parts of slopes where infrastructure is more likely to be located.

Most of the larger, more complex, landslides exhibited a structural control in their source area. This is well shown by the Wenjiagou debris avalanche (Figure 36), which initiated as a block slide in a sedimentary sequence dipping obliquely into towards the catchment headwaters. The debris then followed the valley course as an avalanche with super-elevation on corners. Super-elevation, reflecting rapid movement and long runout of debris was seen elsewhere in the epicentral area (e.g. Niujuangou debris flow - Figure 42) and has been a feature of earthquake effects in mountainous areas (e.g. Huascaran landslide in the May 1970 earthquake in Peru).

Source area structural control is also apparent in less mobile landslides that only buried the slope below. An example is the landslide just upstream from Yingxiu (Figure 43) that buried the abutment of the bridge across the Minjiang or Min River.

A feature of the landslides was rapid movement, independent of their size and material. On a smaller scale rockfalls, which were more common where rock mass jointing spacing was wider, and as a consequence slopes often steeper (e.g. dolomites), were widespread. Individually rockfall blocks could be >50 m^3 (Figures 37 & 44) and the effects of these ‘evil dancing rocks’ were widespread, and particularly hazardous in aftershocks with recovery operations underway.

Lithological controls on landslide mechanisms and distribution were apparent in many parts. A good example is in the vicinity of the Qushan Town in Beichuan County. The view in Figure 45 shows the difference in the performance of slopes on either side of the Beichuan fault that passes through the city, along which there was a 3 m surface rupture offset. Landslides are more widespread in the shale-dominated sequences on the left and centre of the photo compared with the dolomite-dominated sequences, with more common scarp slopes, on the right hand side.

The city itself was hit by two major ($>1 \times 10^6$ m^3) landslides during the earthquake, one from either side of the valley (Figure 46). The mechanisms of the two landslides, which are studied further in Yin *et al*. (2009) and Yang *et al*. (2009) had contrasting mechanisms. The Wangjiayan landslide, pushing buildings in front of its debris, and the Jingjiashan landslide originating from on a steeper slope burying them.

Figure 42: ***Super-elevation along the path of Niujuangou debris flow avalanche near Yingxiu.***

Figure 43: *Fault scarp and deep seated landslide at Yingxiu. Rapids formed by the vertical fault offset (Figure 15) and the bridge over Minjiang River made serviceable after being skewed off piers when hit by the landslide. The bridge structure alongside the river on the other bank was also completely destroyed, (Figures 92 & 93).*

Figure 44: *Rockfall blocks on road near Hanwang.*

Figure 45: *View along Yingxiu-Beichuan fault that passes through Beichuan. Shales and mudstones dominate on the left hand side of the fault and dolomites on the right. The source of the September debris flow was from the shale slopes in the left foreground.*

Figure 46: *View of Beichuan New Town. Debris of the Wangjiayan landslide is on the left and Jingjiashan landslide above hairpin in road on the right. Debris from the September debris flow is in the left foreground.*

The earthquake occurred at the end of the dry season, just before the higher rainfall rainy season, which would typically raise piezometric levels in many slopes. Ongoing and/or increased landslide activity and sediment redistribution in wet seasons that follow an earthquake have been documented elsewhere (e.g. following the September 1999 Chi Chi earthquake in Taiwan, Petley *et al*, 2009). These effects also followed the Wenchuan earthquake. For example, debris flows sourced in the shale slopes above Beichuan buried the Town as well the older gate village above it (Figures 46, 47), and alluvial fans were seen building in front of other landslides (e.g. Wenjiagou debris flow in Figure 36).

Figure 47: ***Debris flow in September 2008 in gate entry village to Qushan Town. Steep dolomite scarp slopes on opposite side of the valley.***

Landslides that blocked the bottoms of river valleys forming dams were a widespread feature of the epicentral area. The dam heights and impounded lake volumes covered a wide range and several were seen on our trip. Landslide-dammed lakes had also formed on the Minjiang River some 100 km north of Yingxiu after the 1933 M7.5 Deixi earthquake and breaches followed in 1933 and 1986 (Chai *et al*., 2000). In 2008, after a hazard assessment including size height, material and shape of the barrier and volume of the lake) and likelihood of failure and downstream effects (e.g. Yin *et al.*, 2009), several with extremely dangerous ratings were treated to form a breach.

The best known example was the 2.4 x 10^9 m^3 Tangjiashan landslide-dammed the lake immediately upstream from Beichuan. A 20 m deep channel was cut into the 150 m high dam by equipment flown in by helicopter to promote a breach before full impoundment of the lake (Figure 48).

Figure 48: ***Breach of 150 m high Tangjiashan landslide dam formed in mudstone dominated lithologies (after Chen et al, 2009).***

Figure 49 shows the Yi Ba Dao landslide-dammed lake on the Fujiang river tributary near Hanwang. The landslide was a kinematically-controlled block slide and a channel had been cut through debris on one side to lower the impounded lake by 30 m. In some cases the lakes behind dams had not filled (e.g. Tianchi landslide – Figure 39) due to permeable nature of the debris.

Although not able to be studied in the field, several studies (e.g. IEM/CEA Report, 2008) indicate that over 75 % of the landslides occurred within 15 km of the fault surface rupture. This reflects the MM IX isoseismal, which in China is dominantly prepared on the basis of building effects rather than a combination of building and environmental effects, like in New Zealand (Hancox, *et al*. 2002).

The isoseismal distribution also reflects the majority of the landslides being on the hanging wall of the fault, which coincides with the steep topography of the Longmenshan. Such a distribution reflects that for other recent earthquakes associated with reverse movement (thrust) faults (e.g. Chi Chi in September 1999; Kashmir in October 2005), although the distribution for the Kashmir event was concentrated in a band closer to the fault (Dellow *et al*., 2005, and Petley *et al*., 2009). In New Zealand the M7.8 Murchison earthquake in May 1929 provided proxy for similar landslide effects in the steep terrain of northwest Nelson (Hancox *et al*., 2002).

Figure 49: ***Yi Ba Dao landslide dammed lake between Hanwang and Qingping. The landslide was a rock block slide from the right bank and the 60 m deep lake has been lowered by 30 m.***

Overall observations by the team include:

- Landslides have a major effect on damage from large earthquakes in mountainous terrain. Their impacts are greater with higher levels of population and infrastructure.
- Landslide distribution is influenced by topography and distance from the fault, and is reflected by MM intensity.
- Landslides have a wide range of sizes including a number of movement mechanisms, most of which are rapid including large individual rocks.
- Landslide dams can be mitigated, with suitable equipment available, but which dam to treat (e.g. downstream population, high certainty of failure and access available) needs to be carefully selected.
- Landslide hazards in mountainous areas are often underestimated and as a major landscape forming process their effects can be felt for years after the earthquake.

5. EARTHQUAKE DAMAGE TO STRUCTURES

5.1 BUILDINGS

The Wenchuan Earthquake caused massive damage to building structures, estimated to be in excess of 5 million, given the proximity of the earthquake to major towns and cities along the 300 km long and about 40 km wide fault rupture zones.

The earthquake effects, causing damage to buildings, include the following;

- Massive landslides resulting in large rock and land slides destroying and burying buildings directly, e.g. Beichuan.
- Damage from fault rupture.
- Damage from intense horizontal and vertical shaking.
- Possible site effects resulting in amplification of the ground movement.

The following sections only report on damage to buildings due principally to earthquake shaking.

The catastrophic damaging effects due to landslides and fault rupture in townships such as Beichuan are covered in Sections 3 and 4, and possible site effects are discussed in Section 7. The geohazards due to landslides and fault ruptures are impossible to design for, the best strategy here is to select an appropriate site to avoid these hazards. This is recognised by the Chinese Authorities in their reconstruction plan reported in Section 9.

Much of the severely damaged development in the rural areas and in the epicentral areas, are located at the base of deep valleys, founded on alluvial river deposits or fan materials from historical land slips. As a result, the founding materials for most of the structures in these areas are various mixtures of clay, boulders, gravel and sand.

The predominant material, used for the construction of building structures in Sichuan, is brick masonry. This has been used for building structures in a number of ways, details are as follows:

- Type 1 Masonry Construction: Un-reinforced masonry (URM) used in load bearing wall structures, typically with pre-cast hollow core planks with no topping, bearing on walls in both the transverse and longitudinal directions, sometimes with many openings. The totally URM construction was outlawed in 1976 by the Chinese seismic Code, presumably after the Great Tangshan Earthquake. However, many can still be found in the rural areas, being a common and economic form of construction for low rise buildings.

- Type 2 Masonry Construction: Hybrid brick masonry-reinforced concrete structures, with reinforced concrete framed or wall structure at the bottom story and with all structure above totally constructed of unreinforced brick masonry. They typically are in the range from three to eight story high structures. This is currently a permitted structural form by the Chinese Seismic Code, however there had been very specific provisions in the seismic code about this form of construction in China.

- Type 3 Masonry Construction: Restrained masonry construction. These are generally three to eight story high buildings. These are constructed as brick masonry load bearing wall structures, with reinforced concrete ring beams at floor levels on which the precast hollowcore planks are seated, with no topping.

  The ring beams are connected to columns at the junction of the brick walls. There are no positive connections between the floor planks and the ring beams, except by friction. Typically these beams and columns, match the brick masonry wall thickness, about 250 mm x 250 mm with 4/D12 bars at the corners and R6 stirrups at 300 mm c/c.

  This is a permitted construction type by the current Chinese Seismic Code, with restrictions on height depending on seismicity.

The masonry form of construction is not relevant to the modern construction in New Zealand, given that this has been outlawed since the mid 1960s. However, we still have a significant stock of URM construction in New Zealand, the reconnaissance findings reported in the following sections do reinforce the poor performance of this type of structures. It also explains the cause of such high casualties due to collapse of many of the houses, school buildings, apartments and also hospitals in the Wenchuan earthquake. Reports available show as much as 90% of casualties in this earthquake were due to building collapse.

Of particular relevance to New Zealand are the observed performances of buildings built using modern materials, such as reinforced concrete and structural steel.

In the major cities such as Chengdu, Mianyang and Deyang, more modern structural forms and materials have been used for building construction. These cities had been subjected to shaking intensities of MM VII to MM IX, considerably more than the code specified design intensity of MM VII.

The following subsections describe the observations made by the team on sites visited:

Epicentre – Yingxiu Township (MM XI)

The Yingxiu township is located a few kms from the epicentre of the Wenchuan Earthquake and had a measured ground shaking intensity of magnitude MM XI. When the reconnaissance team visited the township with an estimated population of 20,000, they found the entire township was totally devastated and abandoned. (Figure 50)

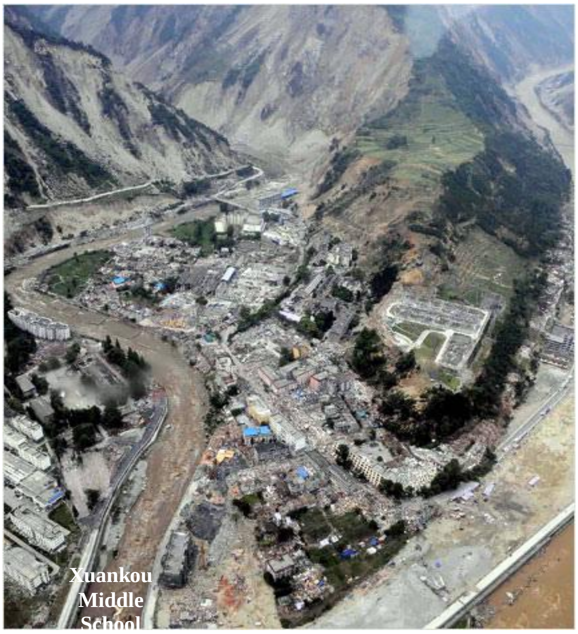

Figure 50: ***Yingxiu Township, totally devastated after the earthquake. Xuankou Middle School is located at the left bottom corner.***

A significant proportion of the building structures in Yingxiu township, is constructed in the three types of masonry construction described above. These are brittle buildings and as expected they performed very poorly, as shown in Figures 51 & 52. Figures 53 & 54 show reinforced concrete buildings observed in Yingxiu.

Figure 51: ***Type 1 Masonry Construction in Yingxiu, complete collapse.***

Figure 52: ***Type 2 Masonry Structure: Hybrid with reinforced concrete structure at the bottom level and URM above. Note the complete failure of the URM floor.***

Figure 53: ***Reinforced concrete framed structure with masonry in fill with soft story failure at the bottom level.***

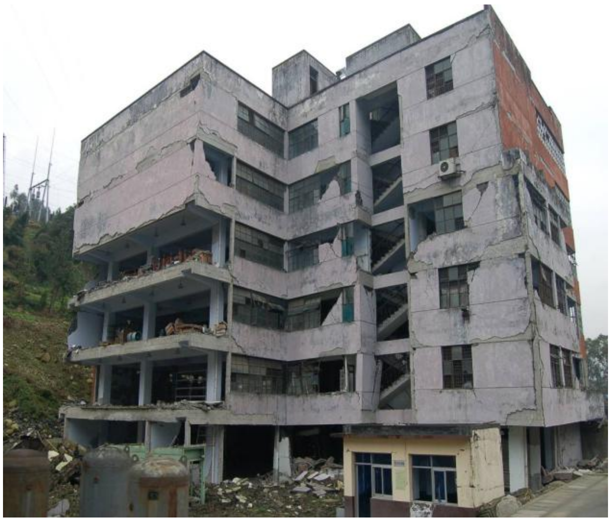

Figure 54: ***Shear wall building in Yingxiu; good performance observed.***

Xuankou Middle School (MM X-XI), Yingxiu

The Xuankou Middle School is just outside the main township of Yingxiu, but located close to a river, refer Figure 50. An aerial view of the school complex in the aftermath of the earthquake is as shown in Figure 55.

Figure 55: ***Overview of Xuankou Middle School, Yingxiu.***

The school complex comprises of buildings with a range of height, two to six stories high and constructed in a mixture of materials and structural forms, and these include:

- Main Administration Block, Classroom Blocks and Link between the Classroom Blocks: reinforced concrete framed structure with in-situ concrete slab.
- Dining Room: reinforced concrete frame with some brick infill panels.
- Dormitory: pre-cast hollow core slab, with no structural topping, supported on un-reinforced masonry (URM) walls in both direction, Type 3 masonry construction as described above.

A number of the dormitory structures, being constructed in URM, suffered the most severe damage, with complete collapse of an entire block causing total loss of life of the students. A number others had also suffered partial collapse at the ground floor. The dormitory buildings were scattered within the school compound, but all with the similar principal orientation and of similar size and construction. It was noted by the reconnaissance team that the dormitory building closest to the river suffered a lot more severe damage than the similar dormitory buildings set back at some distance from the riverbank. This may be due to local site effects, being ground amplification due to softer ground conditions next to the riverbank.

Figures 56 to 61 show photographs of the extent of the damage to the various buildings. The following observations were made, with particular relevance to New Zealand concrete structures.

The Classroom Blocks (Block 1, 2 & 3), located on each side and opposite the link structure had all suffered total collapse. The structural system of the Classroom Block consists of typically reinforced concrete frames, beams & columns and cast in-situ slabs. The collapse was attributed to the formation of a column sidesway mechanism, due to deep spandrel beams and relatively smaller columns and poor detailing from inadequate transverse reinforcement (Figure 62).

Figure 56: Link structure - bracing effect of stair.

Figure 57: Administration Block – complete collapse.

Figure 58: Dormitory Block – partial collapse.

Figure 59: Dormitory Block – complete collapse.

Figure 60: Column Hinging - Classroom Block 1.

Figure 61: Soft story - Classroom Block 2.

Figure 62: Lack of column transverse reinforcing.

Hanwang (MM X)

The team also visited Hanwang, a township of 50,000 population. The township suffered severely, with damage to buildings, to such an extent that the entire township had to be abandoned, see Figures 63 to 66. The severity of the damage may have been caused by site effects, especially for the buildings on the alluvial flats next to the river. This effect is covered in the geotechnical section of this report.

Figure 63: ***Hanwang township - note the collapse of the buildings.***

Figure 64: ***Hanwang township – partial collapse of precast hollowcore floors.***

Figure 65: ***Hanwang township, these buildings survived and performed relatively well.***

Figure 66: ***Mianzhu No.3 Hospital in Hanwang township – near complete collapse.***

Dujiangyan (MM X)

The historic town of Dujiangyan is located about 10 km from the epicentre, and 60 km from the city centre of Chengdu. It has a population of 200,000, and is home to a 2,000 year old irrigation system that still functions today.

This city suffered severe damage from earthquake shaking, with reports of up to 60% of the residents still in temporary accommodation when the team visited. There were reports of schools and hospital collapses causing thousands of casualties, (Figures 67 & 68).

Figure 67: ***Collapse of an entire floor in Dujiangyan (MM X), Type 2 Masonry Construction.***

Figure 68: ***Collapse of a school building in Dujiangyan (MM X). Note the precast hollowcore floor units hanging with no topping and no tie bars.***

Beichuan (MM XI)

Beichuan, with a population of 30,000, was the worst hit township in the Wenchuan earthquake. When the team visited Beichuan, the town was sealed off and all residents ordered to abandon the township, see Figure 23.

As discussed in other sections of this report, Beichuan suffered the sequential devastating events, intense ground shaking, fault rupture, landslides during the earthquake, deluge from the draining of the Tangjiashan quake lake a few weeks later and debris flows burying half of the town some four months after the earthquake.

The team were able to see part of Beichuan, where there was a secondary school complex and saw the evidence of the aftermath of the earthquake and the debris flow. Refer Figures 69 to 73.

Figure 69: Beichuan old township, totally abandoned.

Figure 70: The school dining hall, minor structural damage but severe damage to the architectural fixtures.

Figure 71: Debris flow inside the school dining hall.

Figure 72: Beichuan school building totally collapsed - URM construction.

Figure 73: Classroom Block of the school Beichuan, regular structure, minor damage.

The key observations on building structures are:

- Unreinforced masonry (URM) construction performed very poorly, especially when the earthquake is many times the design capacity of the building, i.e. under an overload condition. Failure is sudden and catastrophic, with serious casualties.
- In reinforced concrete frame construction, poor detailing and lack of adequate transverse reinforcement in the columns, resulted in brittle shear failure of the columns, often resulting in either partial or total collapse. There were buildings that performed well, even at the Epicentre, these were generally structurally regular, and of reinforced concrete construction, (Figures 74 & 75).
- A column hinging mechanism in reinforced concrete framed structure was observed to be a common failure mode. It had resulted in the total collapse of a number of the classroom blocks at Xuankou Middle School. This is due principally to inappropriate structural form with deep spandrel beams and small columns, (Figures 76 & 77).
- Lack of separation in the secondary elements, such as stairs, results in modification of the behaviour of the reinforced concrete framed structure.
- Lack of separation of the non-structural components, such as infill brick panels in all the reinforced framed structures, resulted in the primary structure attracting considerably significant higher earthquake loading.
- Shear failure of short columns due to lack of separation of the primary structure from the panels, (Figure 78).

Figure 74: Public Security Bureau in Dujiangyan (MMX), some structural damage but intact, reinforced concrete frame - shear wall structure.

Figure 75: Dong Fang Steam Turbine Factory in Hanwang (MMX), basically intact with minor damage, shear wall structure.

Figure 76: Soft story at the bottom, large change in structural stiffness vertically.

Figure 77: Inadequate transverse reinforcement in the columns.

Figure 78: Short column effect.

5.2 BRIDGES

A large number of highway bridges were damaged by the large magnitude of the earthquake. Information made available to the NZSEE reconnaissance team by the Sichuan Highway Design Institute, shows that over 226 bridges suffered severe damage or collapse, making significant sections of the highway system un-useable, resulting in difficulties for subsequent rescue and recovery efforts.

Table 4 shows the data from the damage survey carried out by the Sichuan Highway Design Institute soon after the earthquake.

Table 4. Survey of Damage to Highway Bridges

Road System	Number of Bridges	No Damage	Minor Damage	Medium Damage	Severe Damage	Collapse
Expressway	576	39.26%	45.68%	2.97%	11.45%	0.53%
Provincial Route	1081	40.98%	31.27%	11.26%	11.55%	3.10%
Total	1657	40.38%	36.28% (1292)	8.38% (139)	11.5% (190)	2.2% (36)

A significant number of these bridges would have been damaged due to landslide effects, these are covered elsewhere in this reconnaissance report. This section of the report is focused on damage due to ground shaking or movement.

The team had inspected a number of bridges accessible in the reconnaissance trip, of particular significance are a number of major bridges that cross the Mingjiang River or its tributaries.

The following subsections report on these bridges in details:

Baihua Bridge (MM XI)

The Baihua Bridge is located about 2 km from the epicentre town of Yingxiu, on the provincial highway route 213, the only road linking Wenchuan to Dujiangyan. The later is a major township 60 km out from the provincial capital Chengdu.

It was completed towards the end of 2004, as part of the hydro dam development of Zipingpu Dam.

The bridge is 496 m long, 8 m wide viaduct, about 30 m maximum height, curved at each end of the bridge. The bridge superstructure is of reinforced concrete construction and was made up of 6 continuous sections and 20 bridge spans, with each section made up of spans as: 4x25 m, 5x25 m, 1x50 m, 3x25 m, 5x20 m, and 2x20 m. With the exception of the 50 m span constructed in simple spanning T-girders, the remaining sections of upper structure were continuous box girders.

The substructure comprise a total of 19 slender twin reinforced concrete piers, with cross beams providing the portal actions for cross directional stability. The continuous box girder sections of the bridge were supported on steel bearing plates, on the top of the twin piers.

The earthquake resulted in the collapse of Section 5 of the bridge, a curved section of 5x20 m span of continuous box girder upper structure. Available reports attributed this to a local fault movement across this section of the bridge. Significant structural damage was also reported and documented.

Figures 79 to 87 show the extent of damage to the bridge. When the team visited the bridge site it had been demolished by blasting to allow safe passage of vehicles across the site.

Available information from the Sichuan Highway Design Institute reveals the following observation for this major bridge:

- Of the total of 38 piers (19 sets of twin piers), 8 piers had collapsed and 16 piers had suffered major structural damage.
- Large displacements of the bridge deck relative to the supporting piers or abutment were recorded: in excess of 900 mm in the transverse direction and over 600 mm longitudinally.
- Unseating of the bridge deck due to fault movement caused the partial collapse.
- Major structural damage resulted from inadequate transverse steel to provide the shear and confining effect to main bars, resulting in brittle shear failure and buckling of the main reinforcing.
- Inadequate main reinforcing in the cross beams had caused fracture of the main bars, resulting in loss of effective portal action and large deformation at the top of the piers, contributing to the failure, (Figure 88).

Figure 79: Baihua Bridge after the earthquake.

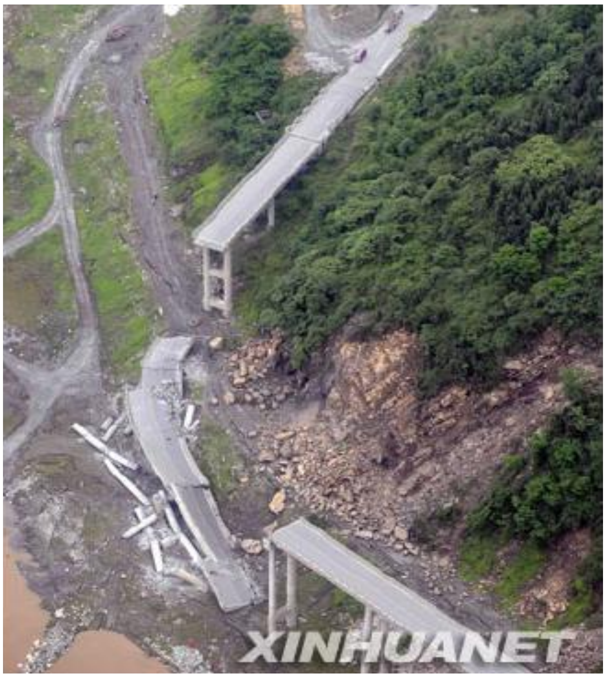

Figure 80: Close up view of the collapsed bridge section.

Figure 81: Collapse span end seating – note the lack of restraint bolts and loss of vertical support.

Figure 82: Large lateral displacement (800 mm) of the bridge deck and damage to bridge pier.

Figure 83: Buckling of main reinforcing bars, spacing of stirrups well in excess of 300 mm.

Figure 84: Shear failure, buckling of main reinforcing bars, spacing of stirrups in excess of 400 mm.

Figure 85: Longitudinal movement at abutment in excess of 600 mm.

Figure 86: Fracture of main bars in the cross beam, large cracks and ineffective portal action.

Figure 87: Lateral displacement of bridge deck at bridge Section 3.

Failure Mechanism

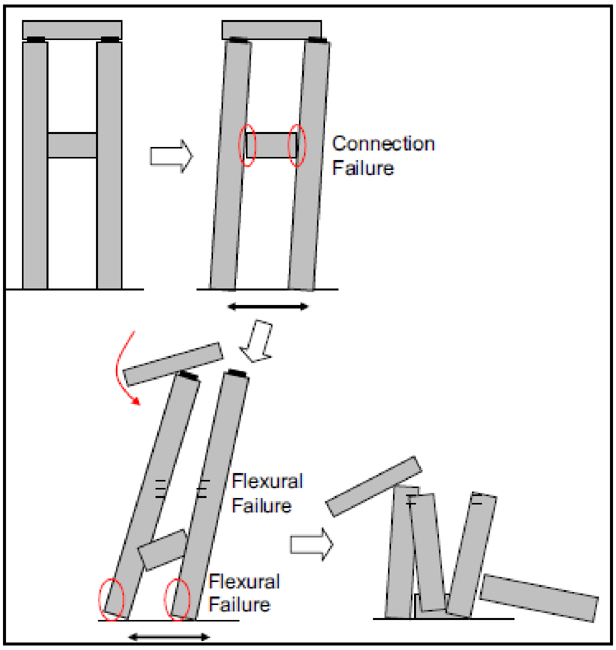

Figure 88: Baihua Bridge – Possible failure mechanism.

Miaoziping Bridge (MM X)

The Miaoziping bridge was under construction when the earthquake struck. This major bridge is situated within the reservoir area of the Zipingpu Hydro Dam, located within 20 km of the epicentre. When completed, it would provide an expressway road link from Dujiangyan to Wenchuan.

The bridge is 1,440 m long, with a maximum pier height of 108 m, with a general arrangement of the superstructure as follows: 2 spans of simply supported 50 m long T beams, 3 continuous box girder spans of 125 m, 220 m and 125 m, and 17 spans of 50 m long T beams.

The bridge suffered damage as follows:

- Loss of seating at approach span No.10, a simply supported span.
- Report of lateral displacement of the piers with associated minor structural damage below the waterline.
- Movement of the simple spanning bridge deck, relative to the piers, both transversely and longitudinally.
- Shear key damage resulting from deck movement.

Figure 89: Loss of seating at span no. 10.

Figure 90: Close up view, no linkage bolts.

Figure 91: Impact damage of external shear key.

Bridges at Epicentre (MM XI) and on Highway 213

The team observed varying degrees of damage to the bridges at the epicentre at Yingxiu and also along state highway 213, the link between Wenchuan and Dujiangyan.

The damage to the bridges on key highways meant that rescue and recovery work was made extremely difficult. The impact is covered in the Lifelines section of this report.

Figure 92: Complete collapse of a bridge across the fault rupture at Yingxiu near the epicentre.

Figure 93: ***A bridge that runs parallel to the fault rupture near the Epicentre, suffered considerably less damage, large movement of the deck, up to 1 m horizontally .***

Figure 94: ***Damage to shear key due to the horizontal inertia force from the deck.***

The key observations are:

- Lack of effective restraints both longitudinally and transversely for the bridge superstructure.
- Inadequate transverse reinforcement in the bridge columns, resulted in shear failure and buckling of the main bars.
- Poor beam/column connections and detailing was a major contribution to the failure of Baihua Bridge.
- Use of simple plate bearings or pot bearings for a typical bridge deck, meant that the substructure was subjected to the full inertia force of the bridge deck generated by the earthquake. This is in contrast to the common use of lead rubber bearings in New Zealand.
- Inadequate or no allowance for longitudinal movement generated by earthquake at the abutments for simply supported bridges.
- Structurally integral bridges had performed well

5.3 SEISMIC DESIGN INTENSITY

China has had a seismic design code for building structures since 1974. This code has since undergone a number of revisions in 1978, 1989 and in 2001.

At the time of the occurrence of the Wenchuan Earthquake, the seismic design code is GB50011-2001. The code defines peak acceleration according to Seismic Design Intensity. The areas affected in the Wenchuan Earthquake are designated as Seismic Design Intensity VII, with the design peak ground acceleration designated as 0.10g.

This design intensity zoning applies to cities and townships in the earthquake area including Chengdu, Mianzhu, Mianyang, Qingchuan, Beichuan, Pengzhou, etc., some of which were devastated totally by the earthquake.

The Design Intensity in the seismic code for structural design is related to the envisaged intensity of shaking according to the Modified Mercalli scale.

The code also defines the three key objectives on the performance of building structures:

- No damage under a minor earthquake.
- Repairable damage under a moderate earthquake.
- No collapse under a major earthquake

Figure 95 shows the Design Response Spectra in the Chinese Seismic Code GB50011-2001, where α_{max} corresponds to the maximum acceleration to be adopted for the Design Basis Earthquake. For the areas in the Wenchuan Earthquake area, $\alpha_{max} = 0.10g$.

The design acceleration, therefore the design base shear, to be applied to the design of a building structure, varies with the fundamental period of the structure, in line with the spectra curve, (Figure 95).

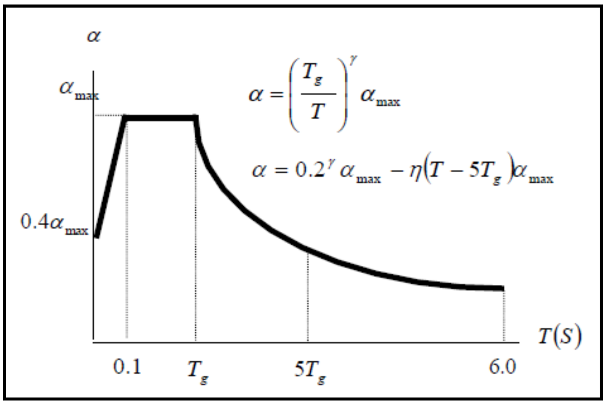

Figure 95: ***Response Spectra from Chinese Seismic Design Code GB50011-2001, $\alpha_{max} = 0.10g$.***

The measured earthquake intensity, in terms of the Modified Mercalli scale, is as shown on the isoseismal map in Figure 29, in Section 3.3 of this report.

It is evident that the actual ground shaking intensity experienced is many times the design intensity in the seismic zoning map of the code. The maximum actual shaking intensity of the Wenchuan Earthquake being MM XI, compared to the area being designated by the seismic code as MM VII for the design of structures.

In Chengdu and Mianyang the measured peak ground acceleration was close to the design intensity (MM VII), and this was also reflected in the considerably less structural damage observed in these cities.

Note the following key characteristics in the isoseismal map shown in Figure 29:

- The shaking intensity at the epicentre reached MM XI.
- The areas with intensity larger with MM IX, are located in a relatively narrow belt, along the length of the fault rupture.
- This intensity decreases very rapidly in the direction perpendicular to the fault, for example, at the provincial capital Chengdu with a population in excess of 5 million, the felt intensity was rated at MM VII.
- Some site effects resulting in anomalous intensity at some sites remote from the rupture zones, in the adjacent provinces such as Gansu, Shaanxi, and Yunnan etc.

Figures 26 to 28 show the peak ground accelerations measured in the earthquake areas by 478 seismic strong motion data recording stations, with over 140 stations located in the Sichuan province. Of these, about 12 stations are located less than 20 km from the epicentre, 11 stations between 20 km and 50 km, and 22 stations between 50 and 100 kms.

The strong motion data show that the measured peak ground accelerations (PGAs) are many times larger than the design intensity in many of the areas designated as VII, where a modern structure would have been designed to a maximum ground acceleration of 0.10g, if it was designed to the 2001 version of the Chinese Seismic Code.

In comparison, the maximum PGAs are as follows:

E-W Directions :	0.98g	(957.7 cm/s^2)
N-S Direction:	0.67g	(652.9 cm/s^2)
Vertical:	0.97g	(948.1 cm/s^2)

The Wenchuan Earthquake had resulted in major casualties and injuries from poor performance of building structures, this can be attributed to the following:

- The large difference between the magnitude of the earthquake and the design earthquake for structures is a major cause of the extensive damage of structures observed by the reconnaissance team.
- The poor choice of materials such as masonry, poor detailing and lack of seismic separations, resulted in buildings which are brittle or not ductile. When these buildings were subjected to seismic loads well in excess of the design intensity, they did not survive, with the consequential major casualties and injuries.
- This is compounded by the failures of non-engineered and poorly constructed structures, such as the residential buildings in the rural or semi-rural areas.

6. DAMS

Water together with its use and control has been important in Sichuan Province for thousands of years. A notable example is the Dujiangyan irrigation system (Figure 96), which naturally diverted part of the Minjiang or Min River flow over 2,200 years ago and irrigating over 100,000 hectares. It is a World Heritage site and continues to operate today in a slightly modified form with control gates on the Minjiang River providing irrigation to over 600,000 hectares of the Sichuan Basin.

Figure 96: ***Dujiangyan irrigation system headworks. Original scheme used the central levee to divert the river into the channel in the foreground with the race intake.***

Dams, for power generation, irrigation and water supply are widespread in Sichuan Province, with over 5,000 reservoirs of all sizes and including six >100 m in height. Figure 97 shows the major dam and hydro-electric plant development the Minjiang or Min River. The river flows through the epicentral area, with a mean annual flow of 470 m^3/sec close to where it enters the Sichuan Basin at Dijiangyan. Damage requiring repair works was reported at several of these dams (Figure 97), with nearly 2,000 of the 6,500 reservoirs in Sichuan Province suffering some level of damage, though with the majority (>1,600) not affecting operating safety (IEM/CEA Report, 2008). Damage impacts were reported as greater on the smaller dams/reservoirs (< 5,000 m^3 capacity), but few specific site visits to these were made (some cracking in the Dujiangyan weir had been repaired).

The major dam visited was Zipingpu, a 156 m high concrete-faced rock fill dam approx 17 km from the epicentre (Figures 97 & 98). The main purpose of the dam, which was completed in 2004, is water conservancy for irrigation, but it also has a 760 MW powerhouse. The dam is founded on steeply dipping Tertiary-age, moderate strength, sedimentary rocks (Figure 99). At the time of the earthquake, which was at the end of the dry season, the reservoir was 50 m below nominal design flood level (Figure 99). Ground accelerations gave pga values between 0.5g and 0.7g at its toe and >1.5g at crest level.

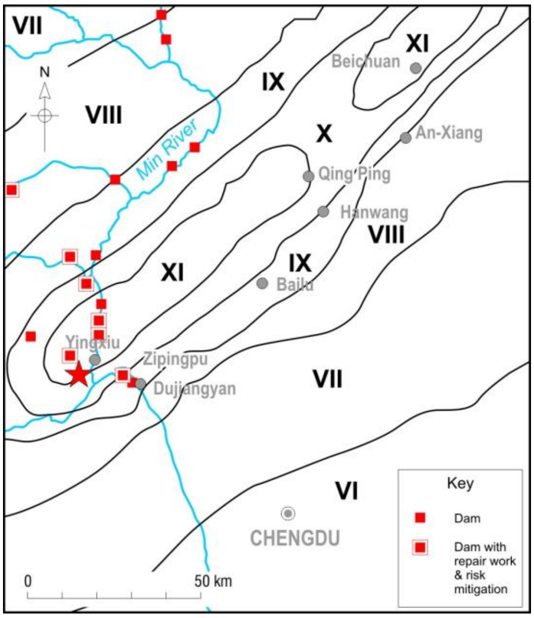

Figure 97: Major dams on Minjiang or Min River and tributaries (after Wang et al., 2009).

Figure 98: Google image of the Zipingpu dam.

Damage to the dam included up to 730 mm settlement at the crest (Figure 99 – with lesser lateral shift - Figure 100). There was also jostling of the upstream concrete facing panels and edge damage, though without any significant increase in seepage (Guan, 2009). Gate structure towers suffered some damage (Figure 101), and along with reservoir dewatering using the low level outlet tunnels, power generation was restored in five days. The ground motions had much higher accelerations than the design level of 0.26g (MM VIII equivalent), and while landslides were common on the reservoir margin (Figure 35), none were of sufficient size to block the reservoir.

Other major dams close to the epicentre were not visited during the trip. Three dams in the epicentral area are >100 m high) e.g. Shapai - a 130 m high roller compacted concrete (RCC) arch gravity dam 12 km from the epicentre, to which routine access had not been restored at the time of our visit.

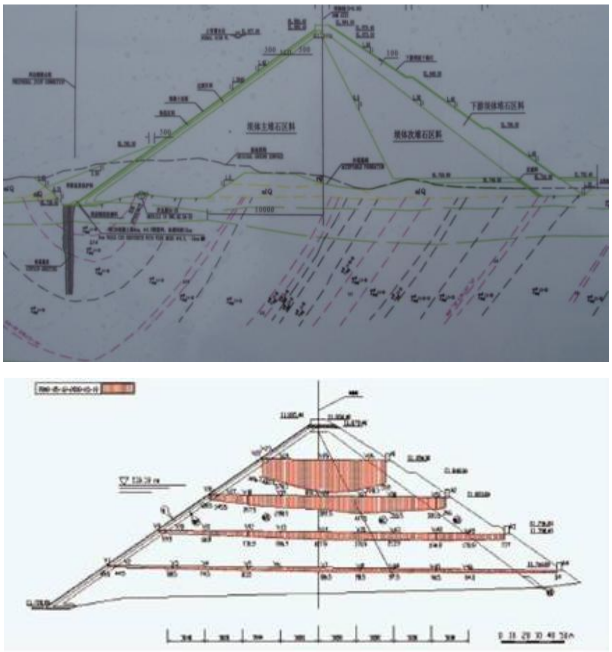

Figure 99: Cross section of 156 m high Zipingpu dam showing foundation geology and settlement (max. 730 mm - Wang et al., 2009) as a result of the earthquake.

Figure 100: Deformation of Zipingpu dam downstream face reflecting settlement during earthquake.

Figure 101: Intake structures low level outlet tunnels. Some damage to tower superstructures is apparent, but tunnels operated after earthquake.

Figure 102: ***Shapai powerhouse showing damage from 'evil dancing rock' impacts (photo from Charlewood et al., 2009).***

At Shapai ground motions during the earthquake were again significantly higher than design level (0.35g v. 0.14g at MM7 equivalent). The reservoir was full at the time of the earthquake and it was successfully lowered after the earthquake (Jia *et al*., 2008). There was, however, notable rockfall damage to power plant buildings and equipment (Figure 102). Like many other places with steep surrounding slopes, these 'evil dancing rocks' highlighted safety from a personal point-of-view.

Smaller dams and associated appurtenant structures, by their size and nature, were often dwarfed by the scale of the topography in the mountainous areas. In many cases, along with roads and other access ways, they suffered extensive damage, including burial by landslides or impact from falling rocks during the earthquake and aftershocks, or in some cases damaged by landslide breakout floods, (Figure 103).

Figure 103: ***Irrigation control structure on Mianyuan River upstream of Hanwang. Much of damage believed to be from partial breach of Yi Ba Dao landslide-dammed lake.***

Overall observations by the team include:

- Major dams in the epicentral area performed well, in spite of loadings well in excess of the design criteria.
- Smaller dams suffered greater levels of damage, largely because of the scale of the terrain.

7. GEOTECHNICAL ISSUES

The Wenchuan Earthquake affected a very large area and there were a variety of important geotechnical issues. The reconnaissance mission was undertaken six months after the earthquake and visited a relatively small proportion of the earthquake affected area. In this section of the report, an overview of the geotechnical issues is presented, from the reconnaissance observations and discussions with various institutions in Sichuan, supplemented by available literature where appropriate.

The geotechnical issues are:

- Possible site effects
- Fault rupture ground damage
- Liquefaction and lateral spreading
- Impact of slope failures
- Retaining walls
- Tunnels

Possible Site Effects

Soft soil amplification

The team visited Hanwang (population about 50,000), which experienced heavy damage to its buildings. It is located at where the Mianyuan River exits the Longmen Mountain range onto the Chengdu Basin, see Figure 104. It appears to be on an alluvial fan at the foot of the mountain range. Ground shaking maps indicate seismic intensity VIII to IX shaking, (Figure 29).

The team observed some difference in the degree of damage of building structures, depending on whether they are on the flood plain or on the higher ground. This may have been due to site effects of soft soil amplification.

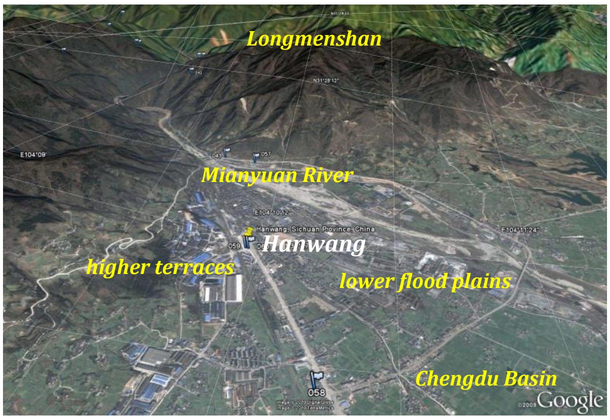

Figure 104: ***Hanwang on alluvial fan of Mianyuan River.***

Basin edge effects

Like Hanwang, the City of Dujiangyan (population about 600,000) experienced heavy damage to its buildings. It is located at the edge of the Longmen mountain, where the Min River exits the mountains, see Figure 9**.**

Ground shaking maps indicate IX to X shaking intensity in the city (Figure 29). Both Dujiangyan and Hanwang are located at the edge of the Chengdu Basin and ground motions at both places may have been amplified due to basin edge effects.

Fault Rupture Damage

Buildings located across fault rupture zones were heavily damaged or collapsed, as seen in the collapse of the teaching blocks in Bailu, see Figure 24. The buildings that did not straddle the fault, survived.

The effect of fault rupture on transportation routes was significant. Bridges collapsed where they crossed surface fault ruptures, see Figure 105**.** Road embankments were also severely damaged, for example see Figure 15 for fault damage to road in Yingxiu.

Figure 105: Bridge collapse due to fault rupture.

Liquefaction and Lateral Spreading

The reconnaissance team saw no evidence of liquefaction, which is not surprising given that the visit was some 6 months after the event.

Given that the epicentral area is mountainous, it is likely that the coarse sediments (gravels and boulders) would have been resistant to liquefaction. Liquefaction is more likely to have occurred in the flat alluvial plains associated with the Chengdu Basin and close to the foothills where the intensity of shaking would have been large enough for liquefaction.

There were confirmed reports of liquefaction. Longwei *et al* (2009) provide the results of a survey that confirms liquefaction on the Chengdu plains along the foothills of the Longmen Mountain range. There were also some pockets of liquefaction well away from the epicentral area, see Figure 106, for example, at Leshan City located more than 200 km from the epicentre. Their report suggests that liquefaction was largely in areas with earthquake seismic intensity of VIII, but were also observed in seismic intensities of VI to IX.

They report water ejection associated with liquefaction, generally to heights of 1 m to 3 m, but to much greater heights in some cases, including one instance of 15 m. The height of ejection of water and sand gives an appreciation of the groundwater pressures generated. One possibility is that at some locations there were groundwater aquifers with artesian pressures confined by aquicludes and the additional pressure generated from liquefaction was sufficient to break out of the aquiclude resulting in ejection of sand and water to the surface.

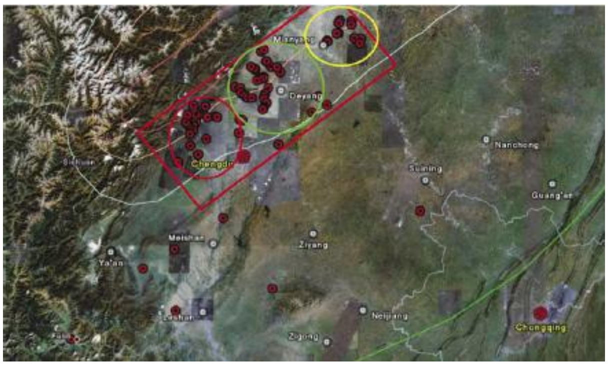

Figure 106: Locations of liquefaction (red circles)- Wenchuan Earthquake (after Longwei et al, 2009).

Longwei *et al.* have also reported particle sizes of materials ejected. Although it was silty sand and fine sand in 50% to 60% of the cases, medium and coarse sand and gravelly sand was also ejected. This includes the case of a 3 m deep well in Baihutou village of Mianzhu City being filled by ejected materials, including gravels of several centimetres to tens of centimetres size, (Figure 107).

Figure 107: Gravel ejected into well in Baihutou village of Mianzhu City (after Longwei et al, 2009).

Longwei *et al*. also report damage to factories, roads, bridges and farmlands from liquefaction. This included Zhongxing Middle School in Dujiangyan City (Figure 108) and Jianyou Railway Station.

Subsidence of the ground and cracking is also reported alongside the Min River (Lin and Chai, 2008), and is likely to be associated with liquefaction and related lateral spreading.

Figure 108: Liquefaction at Zhongxing Middle School in Dujianyan City (after Longwei et al, 2009).

Impact of slope failures

The mechanism, extent and modes of failures of the natural slopes in the earthquake affected area, is covered in Section 4 of this report. This sub-section reports on the impact of the slope failures on the built environment, observed by the team.

Based on survey conducted by CDUT, presented to the team while they were in Chengdu, there were in excess of 8,600 geological hazards made up by: over 3,600 landslides, almost 2,400 slope collapses, 840 debris flows, 1,700 unstable slopes and 90 locations of hidden hazards. The team was able to see many examples of these in the field. There were at least 5 landslides with volume of material in each landslide in excess of 10 millions m^3, with thousands of immediate casualties.

Slope failures had the most devastating effect on development. Large boulders from rock falls destroyed many buildings, see Figure 109.

Landslides also destroyed many buildings and other infrastructure. The massive landslides that destroyed Beichuan are reminders of the destructive power of landslides, see Figure 46.

Debris flows from slopes destabilised in the earthquake, also caused devastating damage to buildings, such as in the Beichuan area, see Figure 110.

Figure 109: ***Buildings damaged by large rock boulders.***

Figure 110: ***School building partially buried by debris flow in Beichuan.***

Retaining Walls

The performance of retaining walls during the Wenchuan earthquake was variable. At the time of the site reconnaissance, a majority of the failed retaining walls appeared to have been removed, given the local reports of extensive failures. However, the team did see some walls that had failed and were being rebuilt, and also walls that appear to have performed well even close to the surface fault rupture.

Figure 111 shows a section of gravity retaining wall that had collapsed. Such walls are commonly used to support highways and river banks in the earthquake affected area the team visited. Figure 112 shows a cracked concrete retaining wall.

Figure 111: ***Collapsed section of gravity retaining wall.***

Figure 112: ***Cracked concrete retaining wall.***

Figure 113: ***Cracked bridge abutment wall.***

Figure 113 shows a cracked bridge abutment wall. Reconstruction of a retaining wall that had failed is shown in Figure 114.

A number of retaining walls were observed to have displaced, causing cracking of the adjacent road, but survived, maintaining emergency access. Figure 115 shows sections of a wall that has collapsed and another section that has only displaced by some 200 mm, both adjacent to rupture of the fault near Qing Ping.

The team saw a limited number of anchored walls, but a report by the Sichuan Highway Design Institute indicates that they generally performed well, (Figure 116).

Figure 114: ***Reconstruction of gravity retaining wall to replace walls that had collapsed.***

Figure 115: ***Section of retaining wall that has displaced up to ~200 mm, and section that collapsed adjacent to fault rupture near Qing Ping.***

Figure 116: ***Anchored wall generally performed well.***

Tunnels

The Wenchuan earthquake affected a mountainous area, where a number of road and rail tunnels have been constructed. There was little opportunity to explore tunnels during the site reconnaissance. The portals of tunnels are considered to be more vulnerable to damage and loss of access from earthquakes and a couple of portals were inspected (e.g. near Yingxiu where rock falls were observed).

Reports of damage to tunnels during the earthquake, include rock slides affecting the portals, see Figure 117. Aydan *et al*. (2009) have visited five tunnels, three of which were under construction, and report on their performance.

Damage observed was in the form of rupture of the unreinforced concrete lining at the crown and shoulders of the tunnel, buckling and uplift, and in some cases pushing up of the whole invert, see Figure 118. They consider the damage to be due to earthquake ground shaking, as well as permanent ground deformation associated with fault displacement.

Figure 117: ***Tunnel portal blocked by rock slides.***

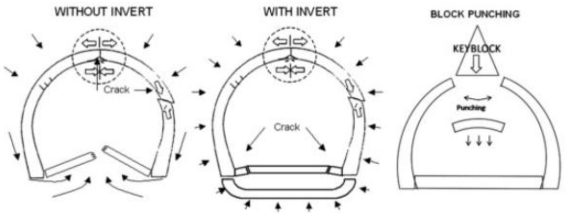

Figure 118: ***Types of damage observed in tunnels (after Aydan et al. 2009).***

Principal observations affecting geotechnical issues include:

- Soft soil amplification and basin edge effects may have led to amplified ground shaking in some earthquake affected areas.
- Buildings and bridges straddling active faults did not perform well, invariably being partially or totally destroyed by surface fault rupture.
- There were thousands of slope failures, the scale of some of these are massive, resulting in catastrophic damage and large immediate casualties when they affect buildings structures. They also often bury infrastructure, including roading, railways, bridge abutments and tunnel portals.

Retaining walls that included anchors performed well, and always better than walls with surface treatment only.

Discussions

The Wenchuan Earthquake occurred in an area with steep terrain, not dissimilar to that in New Zealand.

Key lessons from this earthquake for New Zealand are:

1. Site effects such as soft soil amplification, basin edge effects and topographical amplification can significantly exacerbate damage. While the New Zealand Standard, NZS 1170.5 does consider the potential for amplification from soft soils through site classes, effects such as basin edge and topographical effects are still being researched and is not being applied in our practice as yet. This is important given our similar terrain.
2. Earthquake induced slope failures can cause significant damage to New Zealand’s residential and commercial development as well as infrastructure. The scale of damage observed reinforces the message that these cannot often be designed for and need to be taken into consideration in siting development and infrastructure.
3. The geotechnical performance of slopes, particularly steep rock slopes, in earthquakes is less understood. The Wenchuan earthquake has indicated that topographical amplification is a key factor in earthquake induced slope failures, with earthquake induced landslides originating at the upper part of the slopes. Also the team observed that major rock defects do control failures in rock during earthquakes. These need to be taken into consideration in the development of our practice so that hazards can be better assessed and where possible mitigated at a site scale.
4. Geotechnical hazards such as earthquake induced landslides at a regional scale are recognised and in some cases have been mapped at a regional scale. However, these could be better used in land use planning, building and resource consent processes and in planning infrastructure. A concerted effort is required if we are to avoid continuing to build-in vulnerability by developing in hazardous areas, particularly on or adjacent to steep slopes.
5. The Wenchuan Earthquake amply demonstrated that geotechnical hazards have a large destructive influence of the performance and survival of our communities. It is important that we consider the effects of these hazards when we identify earthquake prone communities and buildings and consider how the risk to these communities can be mitigated.

8. LIFELINES

The Wenchuan earthquake resulted in extensive damage to lifeline facilities such as transportation networks, power, telecommunications and water supply. While the damage to other utilities services is consistent with that observed in other large earthquakes, the damage and disruption to transportation networks in the mountainous areas, was particularly devastating and led to very long periods of disruption.

At the time that the reconnaissance team visited the earthquake zone, some 6 months after the earthquake, the basic utilities have been restored. The team therefore focussed on the damage and disruption to transportation networks which were still able to be observed and supplemented by discussions held with the Sichuan Highway Design Institute. The immediate disruption to utilities due to the earthquake, were therefore based on reports, (e.g. IEM/CEA Report, 2008).

Electricity

Severe damage to the power grid was reported after the earthquake, with some 171 substations damaged and 17 of those destroyed by the event, see Figure 119 for example.

Figure 119: Destruction of substation in earthquake.

Transmission lines were severely disrupted, with many transmission towers damaged by landslides, see Figure 120.

Figure 120: Transmission tower destroyed by landslide.

Power supplies to many of the cities was interrupted by the earthquake, but with the provincial capital Chengdu surviving without major power outages. Power supplies to the cities were reported to have been restored in 10 to 20 days. The remote areas experienced the longest outages due to difficulty of access to repair the damage because the highways and roads were closed by landslides and collapse of bridges.

It was reported that electric power generation plants were damaged and remained out of service for some 60 days.

Recovery of the power network was apparently affected by the collapse of workshops, the production capacity for components being affected and employees not being available, as they were affected by the earthquake.

Similar issues are likely to be faced in New Zealand in restoring power supplies.

Telecommunications

The telecommunications reportedly faced severe outages due to damage to equipment and distribution systems, as well as the loss of power supplies. This once again highlights the interdependency between lifeline networks.

The cell phone networks were down for a few days, and it was reported that even where the networks were restored, people could not use their cell phones because the cell phones were out of charge and they could not be charged due to lack of power supplies to the people. Reportedly community charging facilities were set up over time.

Water Supply

Two types of water supplies existed in Sichuan – major cities being supplied by typically government owned and independently operated water works and water sources in the countryside being from wells and springs. The collection from wells and springs were operated by village or town local authorities or groups of homeowners. Water supplies in rural townships and villages were severely damaged, while water facilities experienced some damage at many locations in Chengdu Metropolitan area.

Pumping station buildings were damaged by the earthquake. At least some of the elevated concrete tanks performed well and remained functional, while some water towers (presumably unreinforced masonry) sustained heavy damage or collapsed. The headquarters of Chengdu Waterworks sustained some damage and the control room had to be temporarily relocated to the ground floor from the fifth floor.

Some 690,000 people in the earthquake affected area apparently faced water shortages.

Figure 121: Damage and repair to water supply pipeline.

Of 30,000 km of water supply pipelines, some 22,000 km was reported to be operational by 20 days after the earthquake. Figure 121 shows restoration of pipelines.

The water works companies and the military provided water to central locations and temporary housing areas. Apparently Chengdu water works had installed some 6,500 metres of temporary piping by June 14 to distribute water to temporary housing areas.

There was a contamination scare that also affected the water supply for a short time, as people were scared to use the water supplies that had been restored.

Airport

Chengdu airport was only closed for a few hours due to damage to equipment in the control tower that had apparently not been restrained.

Railway

Many landslides, bridge collapses and other damage affected railway lines, see Figures 122-124.

Figure 122: Damaged railway line.

Figure 123: Railway line destroyed by landslide.

On the day of the earthquake, many trains were stranded on railway lines linking Chengdu with the rest of the country. Some 34 stations of the Baoji – Chengdu railway line lost power. Some lines were restored by midnight that day, whereas other lines were closed for months.

Figure 124: Railway bridge collapse due to landslide.

Highways and Roads

Highways and roads, particularly in the mountainous areas, were heavily damaged in the earthquake. Some 30,000 km of highways and 18,000 km of roads were reported to be damaged. Some 3,000 bridges, 100 tunnels and many kilometres of retaining walls along the highways and roads were affected.

Much of the severely damaged road network was located in the mountainous area affected by the earthquake. There was some slight damage in the Sichuan Basin, which experienced shaking intensity VIII or less.

Road Construction

The roads which have been formed by sidling fills supported by retaining walls or fill embankments cracked or failed as a result of the earthquake shaking, closing the roads, see Figure 125. Where the hillsides had been stabilised with rock anchors, these were reported to have performed well in the earthquake. Rock anchor supported cuttings and hillsides were observed on roads adjacent to the Zipingpu dam.

Figure 125: Loss of road platform due to underslips.

Retaining walls supporting road

The performance of these retaining walls is covered in Section 7 of this report.

Landslides

Landslides caused severe damage to the road network, cutting off many roads and highways for many months, see Figure 126. This has had an enormous impact on recovery and reconstruction.

Figure 126: Highway completely removed by landslides.

Tunnel Access

Tunnel access were severely affected by the earthquake, with portals buried and access roads leading to tunnels blocked, see Figure 127 and Figure 117.

Figure 127: Tunnel access road removed and blocked by landslide.

Loss of Access from Bridge Collapse

Bridge collapses led to loss of access across rivers, see Figure 128. A number of bridge spans collapsed due to fault rupture. An example is shown on Figure 105. Many bridges were partially destroyed by landslides, see Figure 129 and 130.

Figure 128: Loss of access from collapse of river bridge.

Figure 129: Landslide destroying bridge access across river.

Figure 130: Viaduct bridge destroyed by landslide.

Section 5 of this report describes the collapse of the Baihua Bridge, a major bridge link on Highway Route 213.

The team observed a bridge that had been displaced off its piers near Yingxiu, due to a large rock slide at one end of the bridge, refer Figure 29 and Figure 43.

Effects on Access

Temporary access immediately after the earthquake was provided by:

- Helicopters providing relief to people cut-off.
- Military personnel carrying food over rugged slopes, see Figure 131.
- People moving across landslides at great risk, where the landslides had cut-off access for long sections of the road.

Figure 131: Soldiers transporting food on foot.

Restoration of Access

Reinstatement of access is a difficult process. As an example temporary access to Yingxiu was cleared from Dujiangyan (32 km) was made by May 16, four days after the earthquake. However, full reinstatement was taking much longer and was still in progress at the time of the team's visit. Access along some of the highways beyond Yingxiu was still being reinstated at the time of the team's visit some six months after the earthquake.

The remaining spans of the partially collapsed Baihua bridge, in a precarious state, had to be blasted using explosives to make access into Yingxiu along the banks of the reservoir, see Figure 132.

Figure 132: Partially collapsed Baihua bridge blasted down with explosives to make access along Highway 213.

Where fault rupture had displaced road embankments, often with some metres of level difference between either side, temporary access was quickly provided by ramping up with fill, see Figure 133.

Figure 133: Ramping up road across fault rupture, near Qingping.

Damaged spans of bridges were propped and weakened bridge sections were spanned to provide temporary access using Bailey bridge type truss structures, see Figure 134, or steel pipes and frames.

Figure 134: Reinstating temporary access across damaged bridges using truss structures.

Entire river crossings were also restored using Bailey type truss bridges, see Figure 135. Note use of steel framed cages filled with rock to form abutments.

Figure 135: ***Reinstating temporary access across rivers using truss bridges.***

Temporary access across rivers was also observed to have been provided using culverts and fords to create access across rivers, see Figures 136 and 137.

Figure 136: ***Reinstating temporary access across rivers using culverts and fords.***

Figure 137: ***Fords with culverts and sandbags.***

Reopening access through areas affected by landslides is a very slow process. Figure 138 shows a road cut off completely by landslide and also ongoing rock slides in the background (6 June 2008), hampering restoration of access.

Figure 138: ***Highway completely removed by landslides.***

In Sichuan, heavy machinery from both public and private organisations were working from different directions to open access, see Figure 139. Heavy machinery was transported at times by helicopter, see Figure 140.

Figure 139: ***Reinstating access along roads closed by landslides.***

Figure 140: ***Transport of heavy plant by helicopter.***

Discussion

There are many pertinent lessons for New Zealand from the performance of lifelines and the recovery.

Power and Telecommunications

Our substations and key nodes may function better due to improved seismic design and retrofit measures being implemented.

Our transmission lines and networks are likely to be equally vulnerable in earthquake events, particularly where they cross steep terrain prone to slope failures or areas subject to liquefaction. It would be prudent to consider the vulnerability of such networks, and provide for appropriate redundancy or improved siting of transmission towers, taking into consideration the geohazards.

Recovery of lifelines after a large earthquake of this size will be hampered by lack of materials and people resources. China faced such issues despite its large economy and people resources. In New Zealand, such issues are likely to be more critical.

Interdependencies were again highlighted in this earthquake. Power supplies affecting telecommunications and railway systems, and lack access affecting the recovery of these other lifelines are themes we are also likely to face in New Zealand.

There has been focus on providing back up batteries etc., but it is worth noting that cell phones were affected by the cell phone handsets running out of charge and this will affect people’s ability to use a restored network and needs to be given consideration when planning for response after earthquakes.

Water Supply

Our water reservoirs may function better, where these are located on high ground and their vulnerability having been addressed through seismic risk assessment and mitigation work in progress in a number of areas, compared to the water towers predominant in China. We need to check whether these are in areas prone to landslides. Water towers may be at risk depending on their construction.

Pipelines leading to and from these reservoirs, often over steep terrain, are likely to be vulnerable, making our water systems also vulnerable. We need to consider these and improve the resilience of water pipelines or have temporary pipes that can be quickly installed.

The scare regarding water contamination is a key lesson that needs to be considered. In such an earthquake event, and given the lack of information, such scares could happen. Regardless of whether real or not, such rumours would affect the public’s confidence in using the scarce water necessary for communities.

Transportation

A number of bridges collapsed in the earthquake, providing valuable lessons for our programme for seismic assessment and retrofit of bridges around New Zealand.

One of the key lessons is the impact of the natural environment on the bridges and the potential severe damage or collapse that was caused by landslides in areas on steep terrain. It is important that we take these lessons on board, not only in assessing the vulnerability of our bridges, but also in siting new bridges and viaducts.

An appropriate form of crossing of faults is another key lesson for us in New Zealand. Roads that crossed faults on embankments and were damaged were able to be quickly restored for access, whereas bridges that crossed faults were out of action for many months and possibly for years. While we often have no option, but to cross active faults, we should endeavour to as far as possible cross active faults on forms of road construction that can be quickly restored after fault rupture.

Many of our key lifeline roads in our steep mountainous or hilly terrain are also likely to be prone to large landslides and are likely to be cut off for many months. It is important that we understand these effects and take these into consideration in the planning of new routes, as such landslides are often difficult to mitigate.

The response after the Wenchuan earthquake was quick and China was able to marshal a lot of resources including military personnel. Military helicopters were able to transport men, plant and equipment to allow restoration of lifelines and access. In New Zealand, we are likely to be severely constrained by the availability of plant and human resources after an earthquake of such magnitude. These resources are important to restore our lifelines for the recovery of our communities. For example, while there are some Bailey Bridges available at two centres, one each in the North and South Islands, the adequacy of these resources is questionable.

Prior planning of response measures will enable us to recover our lifelines more quickly.

9. EMERGENCY RESPONSE & RECOVERY

The reconnaissance team visited affected families living in tents and mobile houses in the epicentral area to collect information of their experience in the earthquake and their living status. The team was also able to meet with Dr Xie Hong, the Vice Chairman of the Wenchuan Earthquake Re-construction Committee of Sichuan Province, to understand the Chinese Government's approach to Emergency Management and Recovery.

The response from the Chinese government to the massive earthquake was quick and decisive. Only a few days after the earthquake, Premier Wen Jiabao arrived in Dujiangyan, a devastated city about 10 km from the epicentre, and set up an earthquake relief headquarters there with the priorities of restoring the livelihoods of the 51 affected counties and its 20 millions affected residents.

The Chinese government had organised response to this natural disaster in two levels:

First Response

The central government rapidly mobilised and deployed over 130,000 People's Liberation Army (PLA) to provide search and rescue, restore access and maintain order.

Many of the initial search and rescue efforts were undertaken by family members, friends, neighbours and local rescue groups before outside help arrived. In towns like Yingxiu, at the epicentre, landslides were making the roads impassable, so local resident had to carry out the bulk of rescue efforts before government troops arrived.

Non government organisations such as the Chinese and International Red Cross were involved very early on to assist with the distribution of food, water and medical supplies.

Figure 141: 130,000 Military Personnel were deployed in the First Response.

Second Response

The government was able to establish temporary housing camps around the province quickly, given that it had the authority to redirect land and resources.

The team had seen some impressive housing camps during the trip. The temporary housing units were reportedly constructed in a matter of weeks. The temporary housing camps had hospitals, pharmacies, schools, banks and retail shops to cater to the needs of the residents.

By July 2008, some two months after the earthquake, 1.6 million tents and 600,000 mobile houses had been erected, providing basic shelter for 4.5 million affected families.

It was interesting to note that the temporary housing camps were organised in such a way that essentially the same villagers were housed as neighbours in the same camps. This, we understand is to create a sense of community, for mutual support, within these temporary camps.

The control of spread of diseases was paramount to the government, given that there were tens of thousands of unrecoverable casualties buried by rubble. Disinfectant was reported extensively applied. In addition, the authorities were able to provide help on food preservation and water rations, etc.

Figure 142: Tents erected immediately after the earthquake.

Figure 143: A temporary housing village.

Figure 144: Banking facility in the temporary housing village.

Figure 145: Functional temporary accommodation for primary school at Yingxiu (Epicentre).

Figure 146: Meng Foon with students of Yingxiu Primary School.

Recovery and Reconstruction

The recovery plan is ambitious. The Chinese government had allocated a reconstruction budget of 1.2 trillion RMB (US$ 170 billion), about twice New Zealand's GDP 2007, with a time frame of 3 years to complete reconstruction. As part of this reconstruction effort, the team learnt that each family was given a subsidy to rebuild their home.

The State Council swiftly passed legislation action to establish a multi-governmental framework for the recovery effort. A key element of the post disaster recovery management effort is the pairing up of unaffected with earthquake affected regions, to provide resources and funding for the recovery and reconstruction.

The disaster stricken areas of Sichuan, Gansu and Shaanxi provinces were divided into 24 districts and matched up with 24 localities across China. For example, Guangdong province is paired up with Wenchuan County, Shandong with Beichuan, etc.

The reconstruction plan was in place when the reconnaissance team was there six months after the earthquake. The team was able to see new villages being built, the majority however were in masonry construction, see Figure 147.

Figure 148 shows the masterplan model for the reconstruction of Yingxiu township (epicentre).

Figure 147: Reconstruction of houses, typically in masonry.

Figure 148: Yingxiu Township, reconstruction masterplan model.

10. CONCLUSIONS

This paper presents the observations made by the NZSEE reconnaissance team on the M8.0 Wenchuan earthquake of May 12 2008. This was a devastating earthquake, with massive economic and also human cost to China.

What the team have learnt in the reconnaissance trips include the following:

Observations:

- Fault surface rupture extended 240 km along the Yingxiu Beichuan Fault and 72 km along the Peng-Guang fault, with maximum displacements of 6.2 m and 4.9 m, respectively.
- Maximum seismic ground acceleration was of 957.7 cm/s^2. This was many times larger than expected for the area. The shaking intensity was MM XI, compared to the area designated to be MM VII for the design of structures.
- Earthquake induced landslides had a major and catastrophic impact. In this earthquake, their impacts are massive when there are high levels of population, and the associated development and infrastructure.
- Site selection was demonstrated to be critical. In areas prone to geohazards, as in the Wenchuan Earthquake areas, knowing the nature and location of the hazards for a particular site, is absolutely critical in risk mitigation. This was recognised by the Chinese in the reconstruction effort.
- There was major loss of life from the collapse of non-engineered structures.
- Brittle or non-ductile and irregular buildings performed very poorly especially in a seismic overload situation, often collapsing. Typically these are unreinforced masonry buildings (URM).
- Well engineered structures and dams performed well.
- Lifeline facilities were severely tested and damaged.
- The lack of access due to interruptions to the key transportation routes, especially on highway 213, inhibited rescue and recovery operations
- For such a major disaster, the response by the Chinese government was considered to be well resourced and effective

Key Lessons for New Zealand

Key lessons from the observations made by the reconnaissance team for New Zealand are:

- Hazard recognition is important to planning and development.
- Our earthquake prone buildings need to be managed.
- We need to reaffirm the emergency management plans.

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REFERENCES

Arne, D.C., Worley, B.A., Wilson, C.G.L., Chen, S.F., Foster, D.A., Lou, Z.L., Liu, S., and Dirks, P.H.G.M., (1997). Differential exhumation in response to episodic thrusting along the eastern margin of the Tibet Plateau, *Tectonophysics*, **280**, 239-256, 1997.

Aydan, O., Ohta, Y., Mamada, M., Itoh, J. and Ohkubo, K., (2009). The characteristics on the 2008 Wenchuan Earthquake disaster with special emphasis on rock slopes failures, quake lakes and damage to tunnels. *Journal of the School of Marine Science and Technology, Tokai University*. **7**(2), pp 1-23, 2009.

Burchfiel, B.C., Royden, L.H., Hilst, R.D. van Der, Hager, B.H., Chen, Z., King, R. W., Li, C., Lü, J. Hao, H. and Kirby, E., (2008). A geological and geophysical context for the Wenchuan earthquake of 12 May 2008, Sichuan, People's Republic of China. *GSA Today*. **18**. p. 11.

Charlewood, R., Babbitt, D. & Wieland, M., (2009) "Wenchuan 5-12-2008 EQ impacts on dams in Sichuan Province, China. Trip report for ICOLD field inspection". *Presentation to United States Society on Dams annual meeting 20 – 24 April 2009, Nashville and World Bank, Washington June 26 2009*.

ChenYuntai, Xu Lisheng, Zhang Yong, Du Hailin, Feng Wanpeng, Liu Chao and Li Chunlai, (2008). Analysis of the source parameters of the great Wenchuan earthquake of May 12, 2008. *Scientific report.* Institute of Geophysics, CEA, *(in Chinese).*

Dave's Landslide Blog. http://daveslandslideblog.blogspot.com

Dellow, G.D., Ali, Q., Ali, S.M., Hussain, S., Khazai, B. & Nisar, A., (2007) "Preliminary reconnaissance report for the Kashmir earthquake of 8 October 2005". *Bulletin of the New Zealand Society for Earthquake Engineering.* **40**(1), 18-24.

EERI & GEER, (2008). The Wenchuan, Sichuan Province, China, Earthquake of May 12, 2008. *EERI Special Earthquake Report*. October 2008. pp1-12.

Guan, Z., (2009) Investigation of the 5.12 Wenchuan Earthquake damages to the Zipingpu Water Control Project and an assessment of its safety state. *Science in China Series E: Technological Serices*. **54**(4). 820-834.

Hancox, G.T., Perrin, N.D., Dellow, G.D., (2002) "Recent studies of historical earthquake-induced landsliding, ground damage, and MM intensity in New Zealand". *Bulletin of the New Zealand Society for Earthquake Engineering*. **35**(2), 59-95.

Hancox, G.T., Cox, S.C., Turnbull, I.M., Crozier, M.J., (2004) "Landslides and other ground damage caused by the M_w 7.2 Fiordland earthquake of 22 August 2003". *Proceedings of the 9th Australia New Zealand Conference on Geomechanics. 8 – 11 February 2004. Auckland.* 747-753. Centre for Continuing Education, University of Auckland.

Institute of Engineering Mechanics & China Earthquake Administration, (2008). General introduction of engineering damage of Wenchuan Ms8.0 Earthquake. *Journal of Earthquake Engineering and Engineering Vibration*, Vol.**28** Supplement, pp1-114.

Jia, J., Xu, Z. & Chen, H., (2008). Strong earthquake on May 12th in China and its impact on dam safety. *Presentation by Chinese National Committee on Large Dams to 67th ICOLD Annual Meeting, Sofia, 2 – 6 June 2008.*

Jing, L., Chen, G, Li Y. & Tang, H., (2009) "Investigation on earthquake-induced damage during the Wenchuan Earthquake". *Journal of Earthquake Engineering and Engineering Vibration*. **29**(1), 14-23.

Kawashima, K., Takahashi, Y., Ge, H., Wu, Z. and Zhang, J., (2009). Damage of bridges in 2008 Wenchuan Earthquake, Investigation report of the May 12th 2008, Wenchuan Earthquake, China. Grant-in-Aid for Special Purposes of 2008, Ministry of Education, Culture, Sport, Science and Technology (MEXT), No.**20900002**, pp111-130.

Lee, George C., (2008). The 512 Wenchuan Earthquake of China – A preliminary report. *Powerpoint presentation, Department of Civil, Structural and Environmental Engineering, MCEER, University of Buffalo*.

Li Xiaojun, Zhou Zhenhua, Yu Huiyin, Wen Ruizhi, Lu Dawei, Huang Moh, Zhou Yongnian and Cu Jianwen, (2008). Strong Motion Observation and recordings from the great Wenchuan Earthquake. *Earthquake Engineering and Engineering vibration.* Institute of Engineering Mechanics (IEM), China Earthquake Administration. **7**, pp235-246.

Li Yong, Huang Runqiu, Zhou Rongjun, Alexander L. Densmore, Michael A. Ellis, Yan Liang, Nicholas Richardson, Dong Shunli, Zhang Yi, He Yulin, Chen Hao, Qiao Baocheng, Ma Bolin (2009). Geological background of Longmen Shan Seismic Bell and surface suptures in Wenchuan Earthquake., *Journal of Engineering Geology* **17**, p3-18, *(in Chinese).*

Li Yong, Zhou Rongjun, A. L. Densmore, M. A. Ellis, Li Yongzhao, P. A. Allen, D. Steffen, Li Bing, Zhang Yi, N. J. Richardson, Wang Fenglin, He Yulin, Xi Xiaohong, Li Xiaogang, Si Guangying and Wang Mou, (2006). Continental Dynamics and Geological responses of the eastern margin of Qinghai-Tibet Plateau. China Press of Geology, p148, *(in Chinese).*

Li Yong, Zhou Rongjun, Dong Shunli, Zhang Yi, He Yulin, Chen Hao, Yan Liang, Qiao Baocheng and Ma Bolin, (2008). Surface rupture, thrusting and strike-slipping in the Wenchuan earthquake of Sichuan, China. *Journal of Chengdu University of Technology*. **35**. p404-413, *(in Chinese).*

Lin and Chai (2008). Reconnaissance report on the China WEnchuan Earthquake, May 12, 2008. *NCREE Newsletter,* **3** (3), September 2008.

Liu Shugen, Tian Xiaobin, Li ZHiwu, Sun Wei, Guo Bing and Liu Shun, (2008). Structure features of the central Longmen Mountains and the Wenchuan earthquake in Sichuan, China. *Journal of Chengdu University of Technology*. **35**. p388-397, *(in Chinese).*

Longwei, C., Xiaoming, Y., Zhenzhong, C., Longqing, H., Rui, S., Lin, D., Weiming, W., Fanchao, M. and Hongjuan, C., (2009). Liquefaction macrophenomena in the great Wenchuan earthquake. *Earthquake Engineering & Engineering Vibration*, **8**:219-229.

Luo Zhi-li, Yong Zi-quan, Liu Shu-gen, Sun Wei, Deng Bin, Yang Rong-jun, Zheng Quan-lin and Dai Han-song, (2008). Relationship between C-subduction and the Wenchuan earthquake and suggestions on preventing earthquakes and mitigationg disasters. *Journal of Chengdu University of Technology,* **35,** pp337-347, *(in Chinese).*

Ma Xingyuan *et al.* (1989). *Lithospheric dynamics atlas of China.* China Cartographic Publishing House, *(in Chinese).*

Petley, D., Parker, R., Rosser, N., Densmore, A., Runqiu, H., Kauser, A., Jiun Chuan, L., (2009) “Damage caused by landslides during earthquakes” *Keynote address to XII Chilean Geological Congress, 22-26 November 2009, Santiago*. Daveslandslideblog.com/2009_11_01_archive.html (Thursday 26 November 2009)

Tang, Yongjian, Zhuang Weilin, and Ji Shuiwang, (2008). enchuan Earthquake: Emergency Investigation and Measures for Sichuan Highways in the Earthquake Region, *China Communication Press*, pp1-178.

Wang, E, & Meng, Q. (2009). Mesozoic and Cenozoic tectonic evolution of the Longmenshan fault belt. Science in China Series D: Earth Sciences **52**(5), 579-592.

Wang, F., Cheng, Q., Highland, L., Miyajima, M., Wang, H. & Yan, C., (2009). “Preliminary investigation of some large large landslides triggered by the 2008 Wenchuan earthquake, Sichuan Province, China”. *Landslides*. **6**. 47-54 (doi:10.1007/s10346-009-0141-z).

Wang Xu-ben, Yu ian, Zhu Ying-tang, Xu Quan-hui, Huang Wen-bin and Gao Shu-quan, (2008). Preliminary result of Magnetotelluric sounding in the Longmen thrust bell of West Sichuan, China. *Journal of Chengdu University of Technology*. **35**. pp398-403, *(in Chinese).*

Wu Shan, (2008). The large-scale gliding-type skippe system in Longmen Mountains and neotectonic activitie of the Longmen Orogen. *Journal of Chengdu University of Technology*. **35**. p377-382, *(in Chinese).*

Xu, G., and Kamp, P.J.J., (2000). Tectonics and denudation adjacent to the Xianshuihe Fault, eastern Tibet Plateau: Constraints from fission track thermochronology: *Journal of Geophysical Research,* **105**: 19,231-19251.

Xu Xiwei, Wen Xueze, Yu Shen’e, *et al.*, (2008). Discovery of the Wenchuan M8.0 Earthquake Surface Ruptures and Discussion for its Seismogenic Structure, Seismology and Geology (in press), *(in Chinese).*

Yin, Y., Wang, F. & Sun, P., (2009). Landslide hazards triggered by the 12 May 2008 Wenchuan earthquake, Sichuan, China. *Proceedings of the First World Landslide Forum, Tokyo, 18 – 21 November 2008. International Programme on Landslides, Tokyo*. 1-17 (also Landslides. **6**(2). 139-152).

Zhang Yong, Xu Lisheng and Chen Yuntai, (2009). Spatio-temporal variation of the source mechanism of the 2008 great Wenchuan earthquake. *Chinese Journal of Geophysics*. Chinese Academy of Sciences. **52,** *(in Chinese).*

Zhu Jieshou, Cai Xuelin, Cao Jiamin, Gao Dezhang, Zhao Fengqing, Du Yangsong and Wang Yang, (2005). The three-dimensional structure of lithosphere and its evolution in South China and East China Sea. *China Press of Geology,* p308, *(in Chinese).*