

The Characteristics of the 2008 Wenchuan Earthquake Disaster with a Special Emphasis on Rock Slope Failures, Quake Lakes and Damage to Tunnels

Ömer AYDAN^{*1}, Yoshimi OHTA^{*2}, Masanori HAMADA^{*3},
Jun ITOH^{*4} and Katsumi OHKUBO^{*5}

Abstract

The 2008 Great Wenchuan Earthquake occurred in Wenchuan County and caused extensive damage to buildings, infrastructures and it induced the failure of natural slopes as well as cut-slopes. More than 85000 people lost their lives besides the heavy structural damage. The characteristics of the Wenchuan earthquake are presented and the causes of failures of natural and cut-slopes and quake lakes are explained. Furthermore, possible mitigation measures against slope failures are presented. Many tunnels in the epicentral area were damaged by the strong motions as well as by permanent ground deformation induced due to faulting. The failure of non-reinforced concrete linings caused by this earthquake is of great concern to tunneling community and it presented an important issue to be dealt with in the earthquake-resistant design of underground structures. Some suggestions for possible earthquake-resistant measures for tunnels lined with non-reinforced concrete linings are proposed in this article.

Keywords: Wenchuan, earthquake, quake lake, slope failure, tunnel, damage

1. INTRODUCTION

An earthquake with an estimated magnitude of 7.9 (Ms 8.0) struck Wenchuan County at 14:28 local time (06:28 UTC) on May 12, 2008. The confirmed casualties are more than 70000 and it is expected to exceed 85000. The earthquake caused widespread damage to buildings, transportation facilities, industrial plants and large-scale slope failures in the earthquake-affected area.

The earthquake occurred at the well-known and well-studied Longmenshan Fault Zone by thrust faulting with a dextral component. Preliminary analyses indicated that the rupture process activated a 300km long fault section. The strong motion records are not available to

the scientific world yet. However, the preliminary estimations indicate that the ground motions are high in epicentral area. The maximum ground acceleration and velocity are were about 1G and 100 kine. A huge number of reinforced concrete buildings collapsed in the epicentral area. The preliminary reports indicate that 5 million people are homeless. The collapse of structures was mainly associated with high ground motions together with their low earthquake resistance. Furthermore, permanent ground deformation induced by landslides as well as relative motion of the earthquake fault also played a major role in the widespread damage.

This article presents an overview of the characteristics of the Wenchuan earthquake and explains the causes of failures of natural and cut-slopes, quake lakes

2009年3月30日受理

*1 東海大学海洋学部海洋建設工学科 (Department of Marine Civil Engineering, Tokai University, Shizuoka, Japan)

*2 東海大学大学院総合理工学研究科総合総合理工学専攻海洋理工学コース (Tokai University, Graduate School of Science and Technology, Shizuoka, Japan)

*3 早稲田大学理工学術院社会環境工学科 (Department of Civil Engineering, Waseda University, Tokyo, Japan)

*4 早稲田大学セーバース株式会社 (SAVEARTH, Waseda University, Tokyo, Japan)

*5 中日本高速道路株式会社 八王子支社 (Naka-Nihon Expressway Co., NEXCO, Tokyo, Japan)

and possible mitigation measures against slope failures. Furthermore, many tunnels in the epicentral area were damaged by the strong motions as well as permanent ground deformation induced by faulting. Particularly, the failure of non-reinforced concrete linings caused by this earthquake is of great interest to tunneling community and this was considered to be an important issue to be dealt with in the earthquake-resistant design of underground structures. Possible earthquake-resistant measures for tunnels lined with non-reinforced concrete linings are proposed in this article.

2. CHARACTERISTICS OF THE 2008 WENCHUAN EARTHQUAKE

2.1 Geography and Investigation Routes

The earthquake occurred in Wenchuan County at the boundary of Tibetan plateau and Sichuan basin. Chengdu with a population of 10 million is the largest city and it is the provincial capital of Sichuan. The epicenter of the earthquake is in Wenchuan County, which is about 90km away from Chengdu. The area affected is mountainous and the elevation of mountains reaches the height of 5000m. The earthquake caused wide-spread structural damage as well as geotechnical damage in Wenchuan, Yingxiu, Maowen, Beichuan,

Shifang, Hanwang, Mianyang, Dujiangyan, Deyang, Mianzhu. The number of the missing people is 18440 and the number of the injured people is 374,177. Figure 1 shows the counties and cities together with the number of casualties and routes used for investigations. The number of casualties is shown in parenthesis. As noted from the figure, the highest casualties occurred in Yingxiu, Dujiangyan, Wenchuan, Beichuan, Mianzhu, Shifang and Qingchuan. These counties and cities are situated on a 270 km long and 70km wide earthquake fault zone. About 5 million people have become homeless.

2.2 Tectonics and Seismicity

The geology of the Longmenshan region, which is the epicentral area, is divided into four distinct tectonostratigraphic packages (i.e. Şengör *et al.* 1993; Burchfiel *et al.* 1995). From oldest to youngest, these include (1) crystalline basement rocks of the Yangtze craton, (2) Neoproterozoic-Permian passive margin sediments, (3) Triassic flysch of the Songpan-Garze terrane, and (4) Mesozoic-Cenozoic terrestrial sediments in the Sichuan Basin. These packages are juxtaposed across a series of structures, collectively termed the Longmenshan Thrust Belt.

There are many quaternary and Holocene-aged strike-slip faults in the Longmenshan region, the bound-

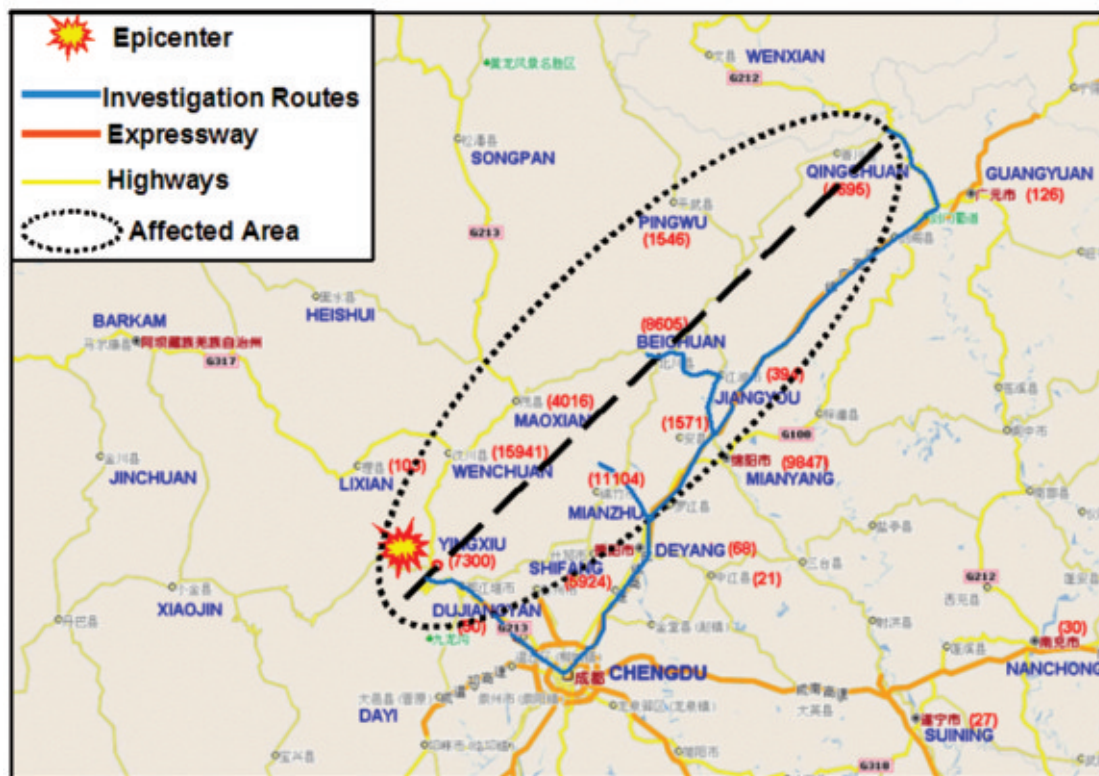


Figure 1. Routes of investigation and major cities along the routes

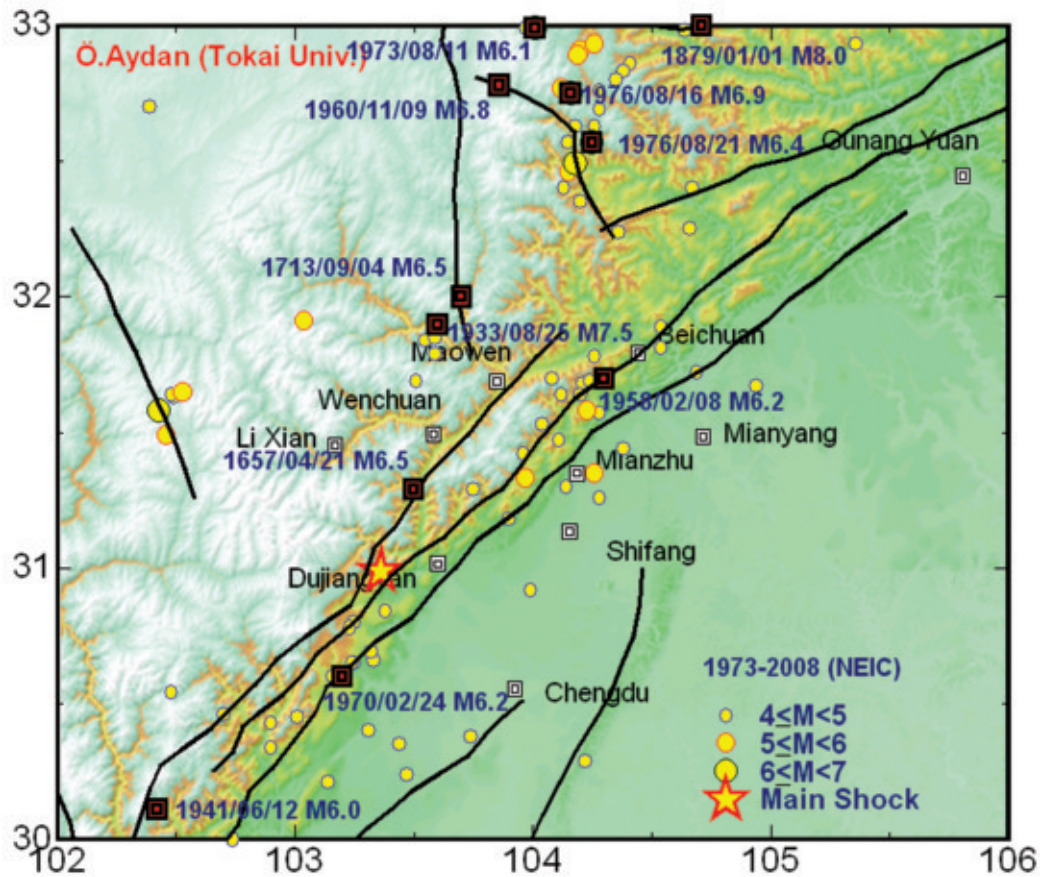


Figure 2. Historical and modern seismicity of the earthquake affected region and major faults

ary between the eastern Tibetan plateau and the Sichuan basin (Figure 2). Active faults within the mountainous region include the N to NNE-trending Min Jiang and Huya faults and the ENE-trending Maowen-Wenchuan, Beichuan and Pengguan faults (Densmore *et al.* 2007). The latter are exposed for hundreds of kilometers within the Longmenshan proper. Less well known but probably equally significant is the NNE-trending Dayi fault, which lies at and partly defines the edge of the Chengdu basin, the western sub-basin of the Sichuan Basin. The Huya Valley fault marks the eastern boundary of the N-S trending Min Shan, and is generally mapped as a west-dipping thrust. Observations and inspection of aerial photographs over a distance of ~ 30 km reveals a prominent N to NNW trending fault that offsets a channel sinistrally by ~ 100 m. The Beichuan fault, near Beichuan, comprises three distinct ENE-trending en echelon segments. Channel and ridge offsets show clear evidence for sinistral displacement. The fault is well expressed across the youngest terrace ~ 4 m above the modern river and likely of Holocene age. A minor thrust component is visible along part of the fault, but the overall expression is predomi-

nantly strike-slip.

Figure 2 also shows the seismicity of the region using the USGS database together with major historical events reported. The historical seismicity data is compiled from various sources (Lu *et al.* 2004; Yang *et al.* 2005; China Earthquake Administration 2008). As noted from Figure 2, the seismicity between 1973 and 2008 before the main shock occurred along the well-known faults in the domain bounded by Latitudes 30–33 and Longitudes 102–106. However, there is no earthquake with magnitude greater than 7 within the Longmenshan fault zone. The focal plane solutions of the earthquakes in Longmenshan fault zone indicate that earthquakes are due to either thrust faulting with dextral component or pure dextral slip.

2.3 Faulting Mechanism and Its Parameters

The fundamental parameters of the May 12, 2008 earthquake estimated by various institutes worldwide and they are listed in Table 1. Although there are some differences among the parameters of the earthquake estimated by various institutes, the all solutions indicate thrust faulting with a slight lateral component. As two

Table 1: Parameters of the earthquake estimated by different institutes

Institute	Latitude	Longitude	Depth (Km)	Magnitude	Strike	Dip	Rake
HARVARD	31.49	104.11	12	M _w =7.9	NP1 229° NP2 352°	33° 70°	141° 63°
USGS	31.969	103.186	16	M _w =7.9	NP1 239° NP2 2°	59° 47°	128° 45°
IGP-CEA	31.021	103.367	10	M _s =8.0 M _w =8.3	NP1 229° NP2 7°	43° 55°	123° 63°
Nishimura-Yagi	–	–	10	M _w =7.9	NP1 229°	33°	146°
Yamanaka-NGY	–	–	11	M _w =7.8	NP1 230°	30°	120°

fault planes are obtained from these solutions, the causative fault should be inferred from additional observations and seismic data. In view of the regional tectonics, after-shock activity, the fault plane dipping to NW should be the causative fault. If NW dipping fault is taken as the causative fault, then lateral strike-slip component of the faulting implies a dextral motion.

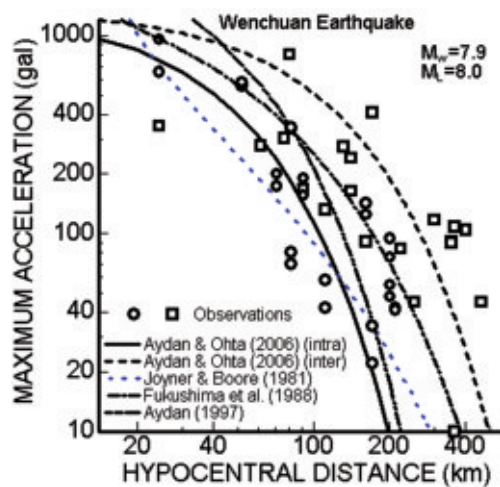
Nishimura-Yagi (2008) and Yamanaka (2008) pointed out that a 120km fault ruptured with a dominant thrust mode first, and it was followed by almost strike-slip faulting by a 10 second delay. Although the overall rupture length seems to be about 300km long, the earthquake is a result of two fault segments rupturing successively. Furthermore, it was pointed out that there is a 50–100km long gap between two ruptured fault segments.

Along the Yingxiu-Beichuan segment, rupture structures included road arching, mole tracks, push ridges and tensional fractures, which indicate eastward

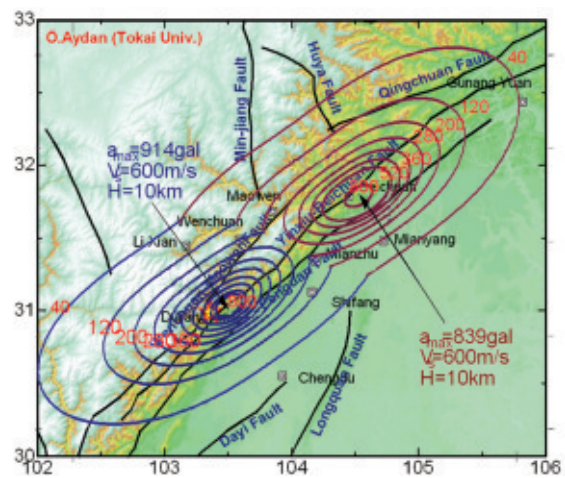
thrusting of the Yingxiu-Beichuan fault with vertical displacements of 2.5–3m, accompanied by a dextral strike-slip component. The co-seismic vertical displacements measured at Yingxiu Township and the Beichuan County showed the same order of amplitude at several locations indicating that the upward movement of the fault ranges between 2.5 and 3 m.

2.4 Strong Motions

There is a strong motion network operated by China Earthquake Administration. However, the digital data from strong motion networks are not available to the international earthquake engineering community yet. There are acceleration contour maps published by China Earthquake Data Center⁷⁾ using the available strong motion records. Nevertheless, some of digital data were lost due to the collapse of housing buildings or mal-functioning of instruments. For example, there was no strong motion record in Qushan town of Beichuan County and Yingxiu town, where the most severest



(a) Attenuation of maximum ground acceleration



(b) Estimated maximum acceleration contours

Figure 3. Attenuation and contours of maximum ground acceleration

damage occurred. The maximum ground acceleration was 958 gals at Wolong Station in the close vicinity of earthquake epicenter. Qingping station, which is 88km away from epicenter and 3km from Yingxiu-Beichuan fault, recorded the maximum ground acceleration of 839gals. As noted from Figure 3(a), the empirical attenuation relations for intraplate earthquakes are far below the reported measurements. The estimations by the attenuation relation proposed by Aydan and Ohta (2006) for interplate earthquakes somewhat closer to the reported measurements. Figure 3(b) shows the contours of maximum ground acceleration using twin earthquake hypocenter model by considering the 10s delay between two segments and the relations proposed by Aydan and Ohta (2006) for intraplate earthquakes. The estimations by this double hypocenter model are quite similar to measured results.

3. SLOPE FAILURES

One of the most distinct characteristics of 2008 Wenchuan earthquake is the widespread slope failures all over the epicentral area. The term of slope failure is preferred herein and the landslide is considered to be a special form of slope failures involving slippage on a curved or planar failure surface. Slope failures, which are fundamentally similar to those observed during 2005 Kashmir earthquake, may be classified into three categories as follows (Figure 4):

- a) Soil slope failures
- b) Surficial slides of weathered rock slopes

c) Rock slope failures

- * Curved or combined sliding and shearing failure
- * Planar Sliding (active and passive)
- * Wedge sliding failure
- * Flexural or Block Toppling (active and passive)

In addition to the failures shown in Figure 4, some passive forms of sliding and toppling failures were observed. Figure 5 shows some pictures of model tests on jointed rock mass with a thoroughgoing discontinuity set carried out during 1984–1986 at Nagoya University by the first author and his colleagues (i.e. Shimizu *et al.* 1988, Aydan *et al.* 1989, 2006a, 2006b). To initiate passive modes of sliding and toppling failures, it should be noted that very high ground accelerations are necessary. The passive mode is defined when the vertical component of the movement of the unstable body of the slope is upward. The relative displacement of the block on the sliding plane at the toe of the slope should be greater than its half-length for the collapse of the slope in passive sliding mode. When such relative movements take place, the initial sliding movement changes its character to the rotational mode. As a result, the unstable part of the slope rolls down the slope. As for the passive toppling mode, the blocks in the upper part of the slope rotates and rolls down. So many rock falls observed during this earthquake are related to these two phenomena.

3.1 Weathered Rock Slope Failures

Rock units in the epicentral area are phyllite or

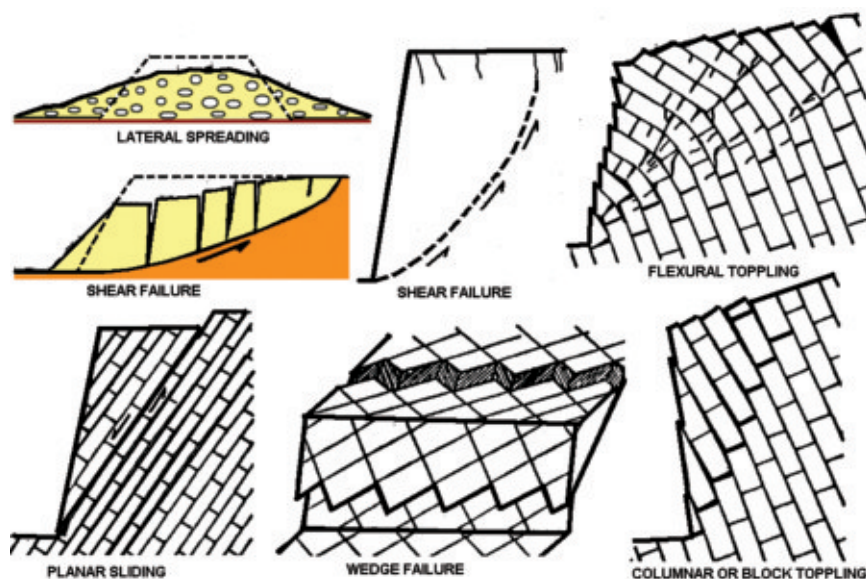


Figure 4. An illustration of slope failures (from Aydan and Hamada, 2006)



$a_{max}=590$ gals

$a_{max}=670$ gals



$a_{max}=770$ gals

$a_{max}=780$ gals

(a) Passive sliding and subsequent rotation of unstable part of the slope



$a_{max}=710$ gals

$a_{max}=400$ gals

(b) Passive toppling of blocks of unstable part of the slope

Figure 5. Several views of model tests on jointed rock slopes with a thoroughgoing discontinuity set during 1984–1986 at Kawamoto Laboratory of Nagoya University (Shimizu *et al.*, 1998; Aydan *et al.* 1989, 2006a, 2006b)



Figure 6. Spectacular surficial rock slope failures

slate, sandstone, mudstone, shale and limestone. Particularly reddish mudstone and brackish shale are very prone to weathering. Furthermore, the rocks at higher elevations are also subjected to thawing and freezing as well as other atmospheric conditions. Most of these rock units contain joints, bedding or schistosity planes as well as fracture zones due to intense tectonism associated with Longmenshan fault zone. In addition, the limestone is very prone to solution by percolating ground water along fractures and they contain many solution cavities. Figure 6 shows several surficial slope failures in limestone unit in the vicinity of the Weizhou and the Zipingpu dam site. The surficial slope failures in limestone unit was spectacular and continued for several kilometers as they are clearly noticed in satellite images.

3.2 Rock Slope Failures and Rockfalls

As said above, rock units are phyllite or slate, sandstone, mudstone, shale and limestone. Geologically, granitic unit exist in the epicentral area. However, the authors did not have chance to see such sites. Except granite, all rock unit has at least one throughgoing discontinuity set, namely, bedding plane or schistosity plane. Since rock units had been folded, they also include joint sets and fracture planes as a result of tectonic movements. Furthermore, the measurements on faults in limestone outcrops in the vicinity of Miaoziqing bridge indicated three dominant faults, which divide the limestone unit into large blocks. Granite generally has at least three discontinuity sets. In regard with rock slope failures classified in Figures 4 and 5, the rock slope failures are mainly planar sliding, flexural or block toppling failure (Figure 7). In addition, passive sliding and toppling failures were observed in intercalated sandstone and shale units. Active planar sliding failures were probably much larger in scale as compared with other slope failures. Several large scale slope failures will be presented and discussed in next sub-section. Rockfalls in the epicentral area are generally result of the toppling of rock blocks due to excitation of the earthquake. Numerous rockfalls were observed for a great length of roadways. Rockfalls were common in sandstone and limestone slopes, which caused a huge number of vehicle crushing events resulting in heavy casualties.

3.3 Large Scale Slope Failures - Landslides

The satellite images and in-situ investigations indicated that there were very large scale slope failures

along the earthquake fault zone. These large scale events took place in Xuankou (Yingxiu) (SW tip), Beichuan (central part, three large scale slope failures including the Tangjiashan landslide) and Donhekou village (NE tip). All these large scale slope failures were visited by the authors. The characteristics of these large scale slope failures are briefly explained in this subsection.

(a) Xuankou (Yingxiu) Landslide

The Yingxiu landslide (Figure 8) involved mainly limestone, which dips to the valley side with an inclination of 20–25°. Furthermore, there is a fault dipping parallel to the failure surface within the rock mass. The angles of the lower and upper parts of the failed slope are 60° and 30°, respectively. In addition to this new landslide, one can easily notice the existence of a paleo-landslide in the fore-ground. The failure plane of this slope failure or landslide is bi-planar and it involved the fault and bedding plane. The fault plane probably assisted the separation of the failed body from the rest of the mountain. The in-situ tilting tests on the limestone joint surfaces yielded the friction angle as 38–42°. If the resistance is purely frictional the expected lateral horizontal seismic coefficient should be greater than 0.36g. Since Yingxiu town was heavily damaged by this earthquake, it is more likely that such a high ground acceleration did act on this slope.

(b) Beichuan Landslides

There are several large landslides in Beichuan town and its close vicinity including the Tangjiashan landslide (Figure 9). UNOSAT (2008) recently released a topographic map of the area (unfortunately such topographic maps are generally inaccessible in China) and a part of this topographic map is shown in Figure 10. In association with the sliding motion of the earthquake fault, NW and SE facing slopes failed during this earthquake. There were two large scale slope failures (landslides) in Beichuan county, which destroyed numerous buildings and facilities. The NW facing landslide (Jingjiashan) involved mainly limestone while the SE facing landslide (Wangjiaya) involved phyllite (it is mudstone and sandstone according to some) rock unit, which is folded with the anticline axis plunging NE (Figure 11). Limestone layers dips towards the valley side with an inclination of about 30°. Furthermore, there are several faults dipping parallel to the failure surface within the rock mass. The angles of the lower and upper parts of



Figure 7. Some examples of rock slope failures and rock falls



Figure 8. A view of the Xuankou (Yingxiu) landslide

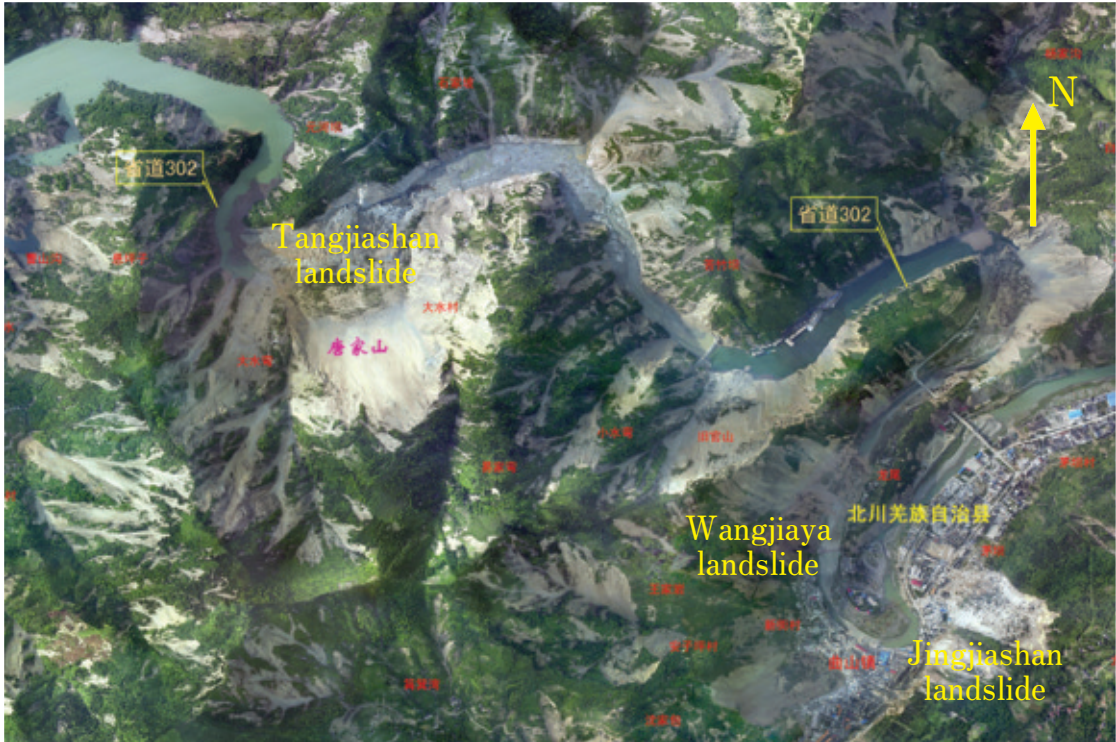


Figure 9. A satellite view of Beichuan and its close vicinity (modified from CGSI)

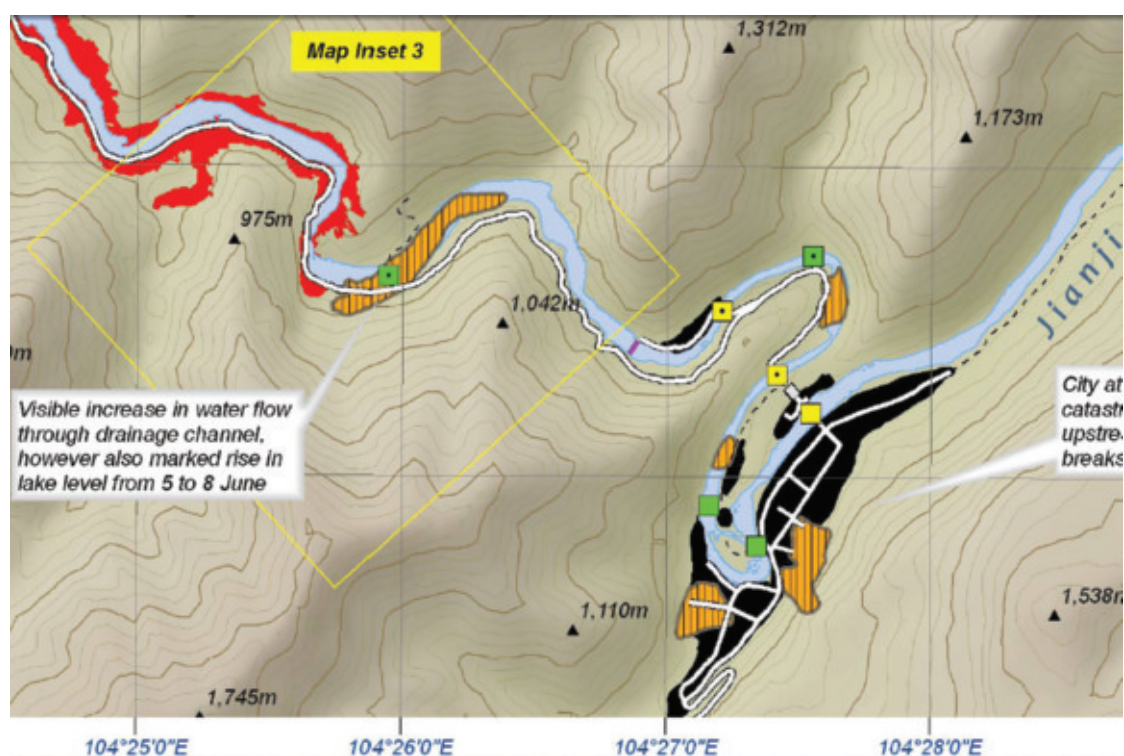


Figure 10. A topographic map of landslides in Beichuan and close vicinity (modified from UNOSAT, 2008)



Figure 11. Views of landslides in Beichuan

the failed slope are 60° and $30-35^\circ$, respectively. The existence of several faults dipping parallel to the slope with an inclination of about $60-65^\circ$ creates a stepped failure surface. If the resistance is assumed to be purely frictional the expected lateral horizontal seismic coefficient should be greater than 0.18g.

The SE facing slope (Wangjiaya landslide) may involve a slippage along the steeply dipping discontinuity plane (fault plane?) and shearing through the folded rock mass. In other words, it may be classified as a combined sliding and shearing failure (Aydan *et al.* 1994). The angles of the lower and upper parts of the failed slope are $40-45^\circ$ and $30-35^\circ$, respectively. The layers dip at angle of 40° towards the valley and shearing plane is inclined at an angle of 20° . Since material properties and conditions of rock mass are not well-known for this site yet, no estimation for possible ground acceleration has been done. Nevertheless, it is more likely that such a high ground acceleration did act on this slope since Beichuan town was heavily damaged by this earthquake.

Tangjiashan landslide, which obstructed Jian River, is located about 2km NW of Beichuan (Qushan) town (Figure 12). The landslide faces NW. The rock units involved in this landslide is limestone (top part), and intercalated sandstone and shale (lower part). Rock

layers dip towards the valley at an inclination of $40-50^\circ$. Although the upper part of the mountain has a slope angle of $40-45^\circ$, the lower part is more steeply inclined up to 70° due to the toe erosion by Jian River. The earthquake induced almost a planar sliding of 600m wide and 450m long body of rock mass. This landslide blocked Jian River for a length of 800m and created a landslide dam with a maximum height of 124m.

(c) Donghekou Landslide

This landslide occurred at Donghekou village of Hongguang Township, Qingchuan County and it is located at the NE tip of the earthquake fault. The upper part of the mountain covered by limestone, below which phyllite exist. This phyllite formation is considerably thick and it is inclined at an angle of $30-45^\circ$ to NE and it is slightly discordant with upper limestone formation. A paleo landslide exist to the east of the new landslide source area. The in-situ tilting tests on the phyllite schistosity (bedding) plane surfaces yielded the friction angle as $22-24^\circ$, which is considerably small. In other words, slopes facing NE can not be stable even under static conditions if the resistance is only frictional. The initial movement of the unstable part of the mountain should have been in NE direction and then its direction of motion rotated towards SW (Figure 13). Further investigations and laboratory tests on samples from this



Figure 12. A view of Tangjiashan landslide (arranged from the image by Xinhuanet)



Figure 13. A view of Donghekou landslide in Qingchuan County

site should provide essential parameters for investigating the conditions for the failure of the slope at this site.

3.4 Mitigation Measures

The mitigation measures against huge slope failures and rockfalls must be based upon the knowledge and know-how of modern rock slope engineering. Most of roadways were obstructed by the slope failures in the epicentral area. The debris of failed slopes should be cleared from top to bottom. Following the clearance of the failed part, an utmost care should be taken against the stabilization or clearance of the loose part. If possible, rockbolts, rockanchors with wire meshes and shotcrete could be utilized (Figure 14). However, it should be noted the shotcrete has no structural support effect except preventing the small scale falls and erosion. Furthermore, the slope failures were analyzed together with some computational results from previous studies by the first author. The results are shown in Figure 15 and this figure was prepared as a guideline for local engineers how to select the slope-cutting angle in actual restoration of the failed slopes.

4. QUAKE LAKES (LANDSLIDE DAMS)

The 2008 Wenchuan earthquake caused the formation of 34 quake lakes. Figure 16 shows the location of

major quake-lakes and Figure 17 shows pictures of some of quake-lakes before breaching.

Among 34 quake-lakes, three quake-lakes formed in Anxian, Qingchuan and Beichuan counties, were of great scale and were caused by mainly the planar sliding failure of mountains. Among all, the biggest quake-lake was the Tangjiashan “quake lake”, which was formed by the collapse of a section of Tangjiashan Mountain. Tangjiashan quake-lake was formed 2 km from Beichuan and at its peak was 803m long by 612m wide and 70-124m high. The estimated volume of water of the Tangjiashan quakelake was 250M m³. Initially several spillways were constructed. However, the drainage through constructed spillways was not successful and several leakages occurred. At the final stage, explosives were used to create channels. However, these measures were not sufficient and missiles were used to control the drainage and erosion of the flow path (Figure 18, pictures by Xinhuanet (2008)). This dangerous operation resulted in a successful drainage of the Tangjiashan quake-lake almost one-month elapsed after the earthquake and a peak discharge of 980 m³/s was observed at 11:50 on June 10. Some 250,000 people downstream had already been evacuated during the drainage on June 10, 2008. Figure 19 shows the water level rise between May 12 and June 10 and drainage flow rate on June 10.

In Anxian county, the second largest quake lake



Figure 14. Proposed quick recovery and permanent measures for the restoration of failed slopes (Hamada and Aydan, 2008)

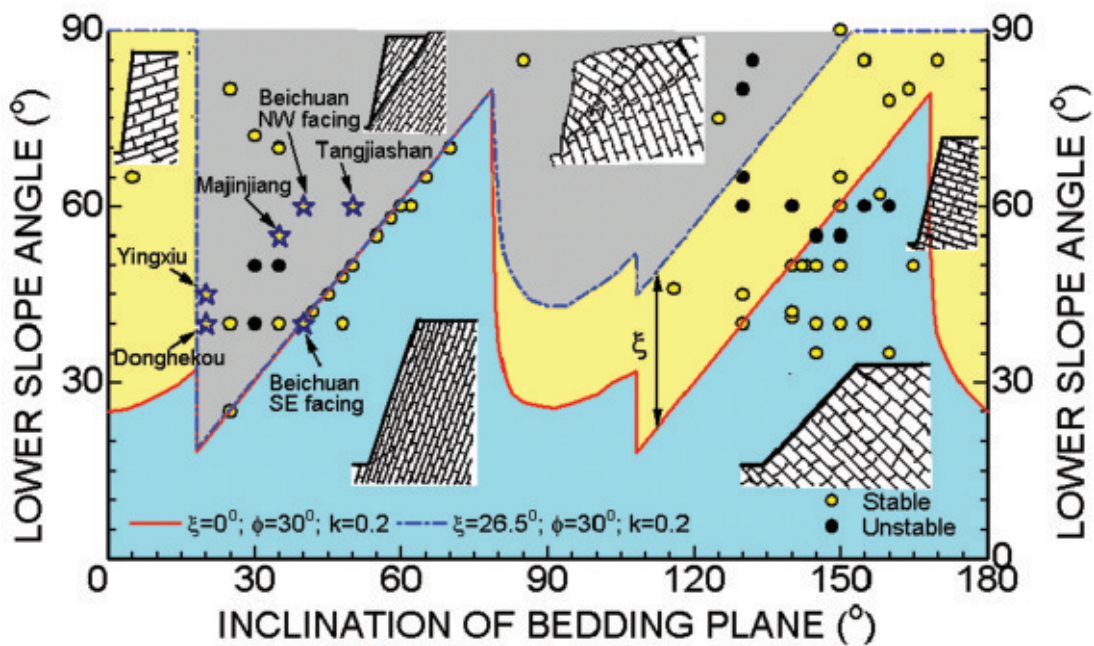


Figure 15. Proposed guideline for slope-cutting angle in relation to the bedding plane angle for the restoration of the failed slopes (ξ : intermittency angle; k : horizontal seismic coefficient; ϕ : friction angle).



Figure 16. Locations of major quake-lakes



Figure 17. Views of some of quake lakes before breaching (partly from Xinhuanet)



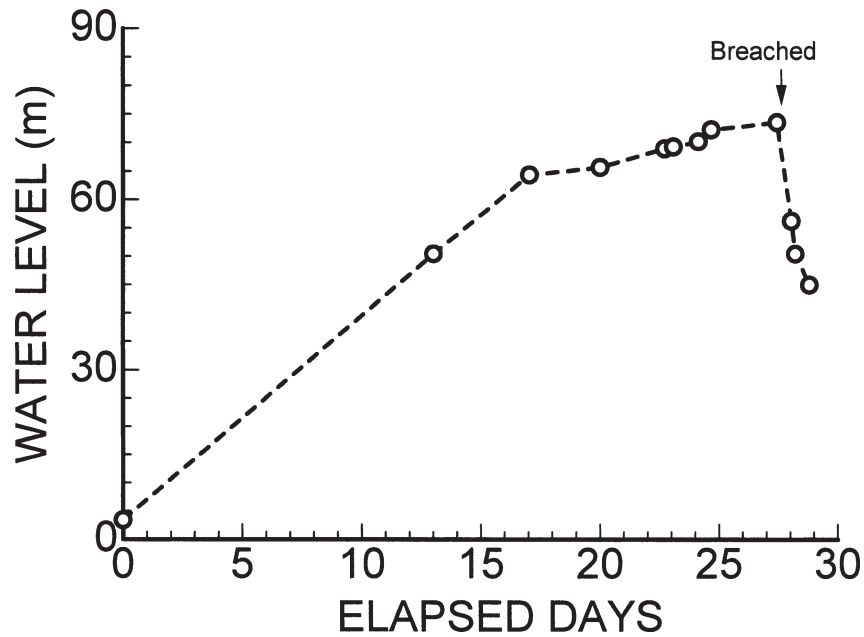
Figure 18. Views of several stages of Tangjiashan quake-lake (from Xinhuanet)

was caused by a landslide blocking Chaping River (Chapinghe) and it is named as Majingjiang. This quake-lake submerged Shuangdian village. Majingjiang (Chapinhe) quake-lake was estimated to be 40m deep and water was rising at a rate of 2.5m per day. The troops used construction machinery to create spillways of 2m wide to drain the quake-lake. This operation was successfully completed on June 6. However, the quake lake burst the remaining bank and drained through the constructed spillway (sluice). The operator of the machinery was lucky to save his life during the breaching of the remaining banks of the landslide dam. The huge landslide, which buried the village of Donghekou and two other small villages, blocked Qingzhu River in

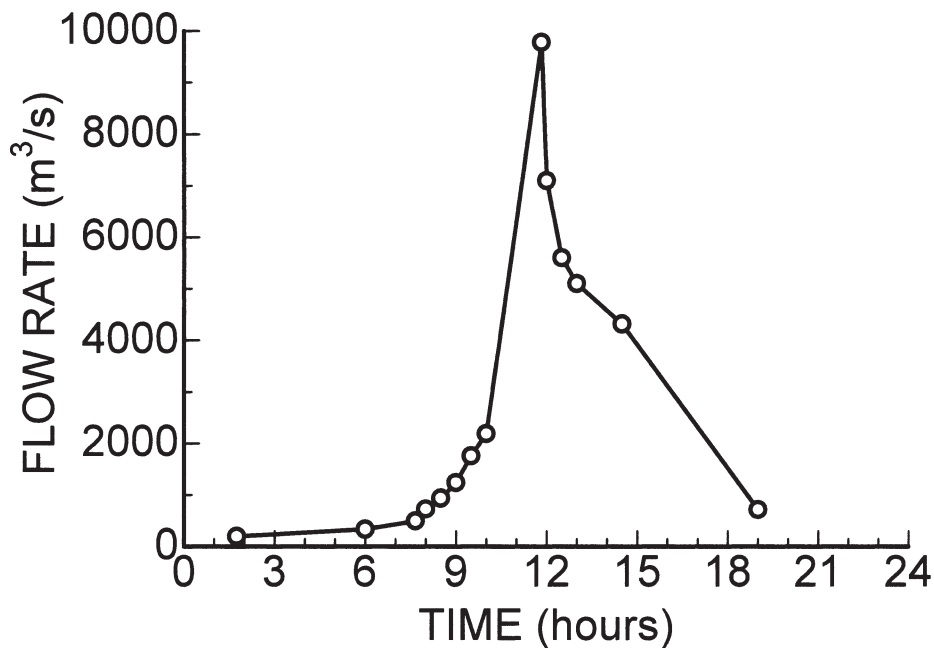
Qingchuan County. This landslide also resulted in two quake lakes. However, these quake lakes were successfully breached using construction machinery as well as blasting technique (Figure 20). The lower quake lake is not fully breached and one can still see the top of electricity utility poles.

5. DAMAGE TO TUNNELS

There are many roadway and railway tunnels in the epicentral area. Some of them are under construction. It is well known that the underground structures are earthquake-resistant compared to surface structures when



(a) Water level rise versus elapsed day



(b) Discharge rate in June 10 during which the landslide dam was breached

Figure 19. The water level rise between May 12 and June 10 and drainage flow rate on June 10 (data from China Water Resources)

ground shaking is concerned. The damage to tunnels is generally limited to portals, which are mainly caused by slope failures and rockfalls. Several examples of portal damage are shown in Figure 21. Similar damage to portals of railway tunnels was also observed. Nevertheless, such damage is light in scale and did not cause any major structural stability problems so far.

The authors had the chance to visit five tunnels,

three of which were under construction and suffered heavy damage during the earthquake. The tunnel nearby Zipingpu dam (N31.04888, E103.56463) is a two-lane tunnel with a length of about 1000m. The lining was damaged at several locations perpendicular to its longitudinal axis, which is aligned NW-SE direction. This tunnel was already repaired at the time of the investigation (June 21, 2008) (Figure 22). The tunnel is about 18.



Figure 20. Views of the drainage of Donghekou quake-lake



Figure 21. Damage to tunnel portals

5km away from the earthquake epicenter and it is very close to the Yingxiu-Beichuan fault. The tunnel floor was stepped at the damaged zones implying the NW side is moved upward. Since this earthquake is of great scale and it is relative slip was presumed to be about 7m, it is very natural to expect a diluted deformation zone as the fault approaches the ground surface due to the reduction of vertical stress. The damaged section of the tunnel rebolted and shotcreted.

Longxi tunnel is a part of Wenchuan-Dujiangang expressway. Two double laned tunnels are excavated with a 3D wide pillar. The maximum overburden is about 480m and the maximum in-situ stress measured is about 26 MPa. The fault named as F8 is 900m from the SE portal and its strike is perpendicular to the longitudinal axis of the tunnel. The engineers informed the authors that they had difficulty of maintaining the stability and controlling the deformation of the tunnel during excavation, indicating that the tunnel experienced squeezing phenomenon.

The tunnel was excavated using the rockbolts and shotcrete as an initial support and then the unreinforced

concrete lining was constructed. The concrete lining was ruptured and the crown concrete was fallen down (Figure 23). However, the overall rupture trace dips NW. The floor of the tunnel was also ruptured and uplifted by buckling. The tunnel collapsed at the location where the overburden is about 70m. The collapse may have created a sinkhole at the ground surface, which should be checked. The similar type of the collapse occurred at the Elmalik section of Bolu Tunnel during the 1999 Duzce-Bolu earthquake (Aydan *et al.* 2000). The ground conditions at both tunnels were remarkably similar to each other. The engineers still did not checked the zone beyond the collapsed section of the tunnel. The fundamental causes of the damage to this tunnel is probably the permanent ground deformations along the fault zones as well as high ground shaking.

Jiujiaaya Tunnel is a 2282m long double lane tunnel and the coordinate of its south portal is N32.41288 and E105.12046. The tunnel is 226.6km away from the earthquake epicenter and it is about 3-5km away from the earthquake fault of the Wenchuan earthquake. The tunnel face was 983m from the south portal at the time of the earthquake (Figure 24). The concrete lining



Figure 22. Views of repaired damaged section of the tunnel near the Zipingpu dam

follows the tunnel face at a distance of approximately 30m. The tunnel suffers from metan gas problem due to coal seams below the tunnel. The rock consists of phyllite with intercalations of dolomite. The bedding planes has the orientation of NW50/64, which is roughly similar to that of the Longmenshan fault zone. The geological investigation indicated that the tunnel pass through several fracture zones. The engineers informed the authors that 30 workers were working at the tunnel face and one worker was killed by the flying pieces of rockbolts, shotcrete and bearing plates caused by intense deformation of the tunnel face during the earthquake. The concrete lining was ruptured and fallen down at several section (Figure 24). However, the effect

of the unreinforced concrete lining rupturing was quite large and intense in the vicinity of the tunnel face. The rupturing of the concrete lining generally occurred at the crown sections although there was rupturing along the shoulders of the tunnel at several places. Furthermore, the invert was uplifted due to buckling at the middle sections. Sometimes, the whole invert was pushed upward. The authors noticed that the tunnel heading was offset in a dextral sense with an upward movement with respect to the rest of the tunnel. The lateral and vertical offset displacements are approximately 100mm. This sense of deformation is very similar to that of the Longmenshan fault zone, which probably cuts through the tunnel with an acute angle of 50–

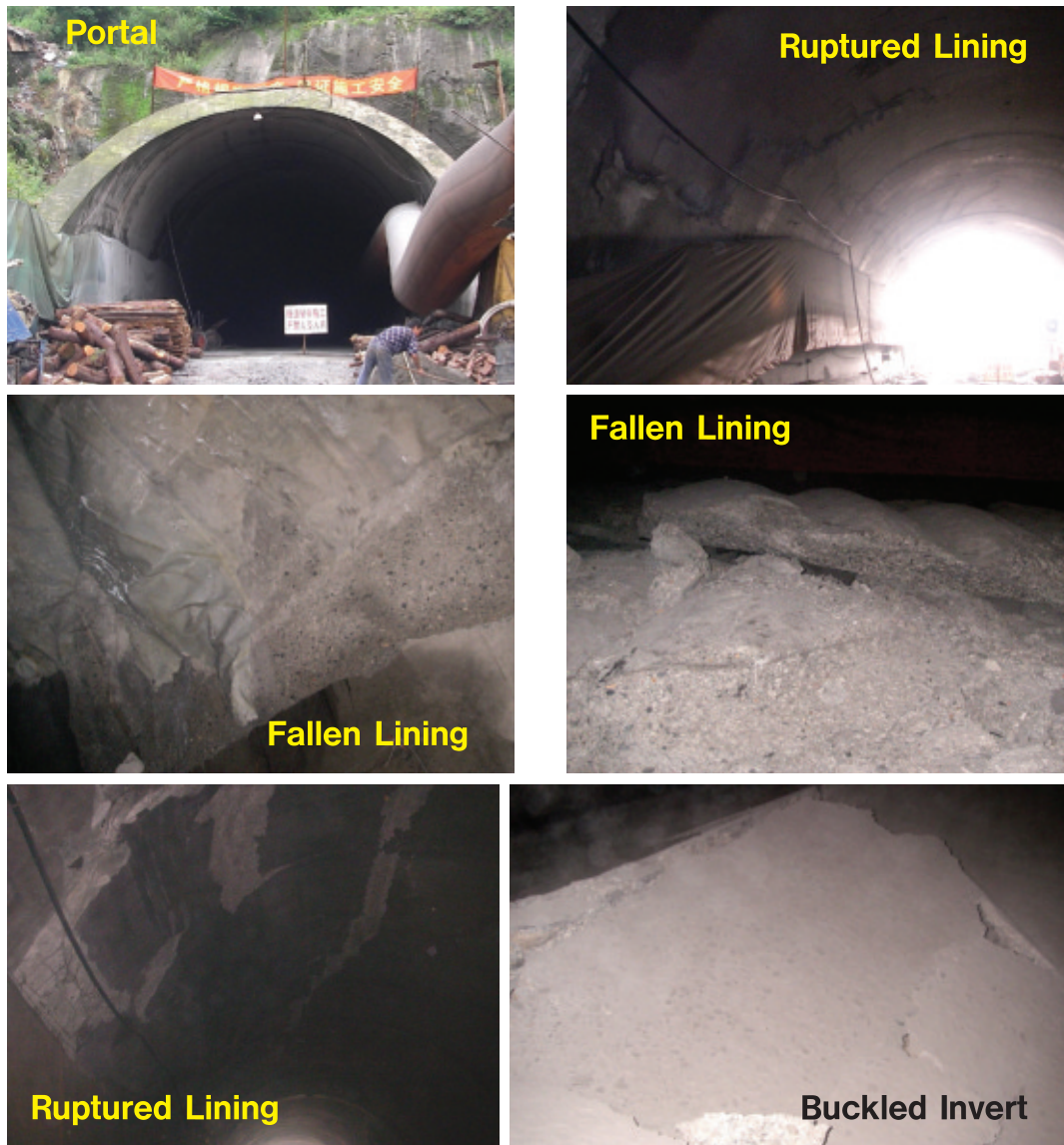


Figure 23. Views of earthquake damage at Longxi (Longqi) Tunnel

60°. Besides the high ground shaking, the permanent ground deformations definitely played an important role on the damage observed in Jiujiaya Tunnel. Figure 25 illustrates a classification of damage to tunnel linings.

The local engineers for Jiujiaya tunnel also pointed out some problems associated methan gas emission from coal layers below. To deal with methan gas emission problem in the tunnel, it was suggested to create an impermeable ground around the tunnel by grouting or to install some drain holes for methan gas emission and introduce a proper ventilation system.

The non-reinforced concrete linings are commonly used for tunnels worldwide except the tunnel portals. As the non-reinforced concrete linings fail in a very brittle

manner, this may result in secondary disasters during their service life. Therefore, some counter-measures are necessary to deal this problem. There may be two possible ways to deal with this issue. The first alternative would be to line the concrete lining with thin steel platens together with rockbolts. The other alternative may be to use fiber reinforced polymers together with rockbolts to line the inner side of the conceret lining. These countermeasures should be introduced not only in China but also other countries.



Figure 24. Views of damage at Jiujiaya Tunnel

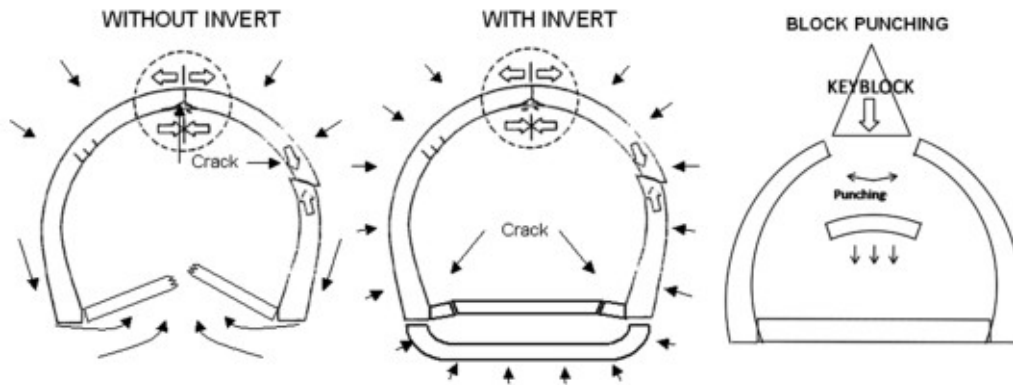


Figure 25. Classification of damage to tunnel linings

4. CONCLUSIONS

The 2008 Great Wenchuan earthquake caused the failure of natural slopes as well as cut-slopes besides the extensive damage to buildings, infrastructures and the loss of lives of more than 85000 people. The scale of slopes failures was tremendous and they indicated the vulnerability of natural slopes against failure during earthquakes, which are stable under non-seismic conditions. This topic probably deserves further studies and it implies the necessity of developing susceptibility maps of natural rock slopes against failure during earthquakes together with the consideration of discontinuous nature of rock mass. In addition, there were numerous rockfalls causing heavy casualties and damage in transportation system as well as buildings. Although it is a difficult topic to be dealt with, it is an urgent issue to be studied and addressed. If it is possible, rockbolts, rock-anchors with wire meshes and shotcrete could be utilized to stabilize the disturbed slopes in the earthquake-affected area. Figure 15 may serve as a guideline for local engineers how to select the slope-cutting angle in actual restoration of the failed slopes. The so-called quake-lakes have a high potential to cause secondary disasters following the earthquakes by breaching or slippage due to piping. When their scales are so large as in the case of Tangjiashan quake-lake, the successful drainage or sustaining their stability by the construction of spillways are not easy issues to be dealt with. Nevertheless, the quake-lakes caused by the 2008 Wenchuan earthquake were successfully drained through the utilization various techniques together with software measures such as evacuation people to higher ground in spite of several unsuccessful hardware attempts. The Wenchuan earthquake also showed that underground struc-

tures, especially tunnels, are vulnerable to sever damage when they are constructed in active fault zones. If the linings could not accommodate the deformation, there may be collapses of non-reinforced concrete linings. In such zones, the linings must be constructed as reinforced. As for existing non-reinforced tunnel linings in active fault zones, some counter-measures must be introduced to retrofit it with steel platens or fiber-reinforced polymers with rockbolts.

REFERENCES

- Aydan, Ö. (2006): Strong motions, ground liquefaction and slope instabilities caused by Kashmir Earthquake of October 8, 2005 and their effects on settlements and buildings. *Bulletin of Engineering Geology*. No. 23(15-34).
- Aydan, Ö. and Hamada M. (2006): Damage to Civil Engineering Structures by Oct. 8, 2005 Kashmir Earthquake and Recommendations for Recovery and Reconstruction . *Journal of Disaster Research*, Vol.1, No.3 pp. 1-9.
- Aydan, Ö., Ohta, Y. (2006). The characteristics of ground motions in the neighbourhood of earthquake faults and their evaluation. *Symposium on the Records and Issues of Recent Great Earthquakes in Japan and Overseas*, EEC-JSCE, Tokyo, 114-120.
- Aydan, Ö., T. Kyoya, Y. Ichikawa, T. Kawamoto and Y. Shimizu (1989). A model study on failure modes and mechanisms of slopes in discontinuous rock mass. *The 24th Annual meetings of Soil Mechanics and Foundation Eng. of Japan*, Miyazaki, 415, 1089-1093.
- Aydan, Ö., Sakoda, S. and Kumsar, H. 2006a. Stability of slopes under dynamic loading and its modelling. *Symposium on Modern Applications of Engineering Geology*, Turkish National Group of Engineering, Denizli, 101-109.
- Aydan, Ö., Daido, M., Ito, T., Tano, H. and Kawamoto, T. (2006b): Prediction of post-failure motions of rock slopes induced by earthquakes. *4th Asian Rock Mechanics Symposium*, Singapore, Paper No. A0356 (on CD).

- Burchfiel, B. C., Z. Chen, Y. Liu, and L. H. Royden (1995): Tectonics of the Longmenshan and adjacent regions, *Int. Geol. Rev.*, **37**, 661– 735.
- China Earthquake Data Center (2008): A quick report on the strong motion data of 5.12 Wenchuan earthquake (in Chinese). <http://www.smsd-iem.net.cn/>
- China Geographical Survey Institute (2008): Tangjiashan quake lake (in Chinese). <http://www.cgisi.cn/>
- China Water Resources (2008): A series of reports on water level variations on Tangjiashan quake-lake (in Chinese). <http://www.cwr.cn/>
- Densmore, A. L., M. A. Ellis, Y. Li, R. Zhou, G. S. Hancock, and N. J. Richardson (2007): Active tectonics of the Beichuan and Pengguan faults at the eastern margin of the Tibetan Plateau, *Tectonics*, **26**, TC4005, doi:10.1029/2006TC001987.
- Hamada, M. and Aydan, Ö. (2008): The 2008 Sichuan Great Earthquake Disaster and Technological Restoration and Recovery Support Activities of Interdisciplinary Liaison Council led by JSCE. WFEO-JFES-JSCE Joint International Symp. On Disaster Risk Management, Sendai, 12–25.
- HARVARD (2008): HARVARD Centroid Moment Tensor, Department of Earth and Planetary Sciences, HARVARD University, Cambridge, MA, USA.
- IGP-CEA (2008): Institute of Geophysics, China Earthquake Administration, M8 Wenchuan Earthquake. <http://www.cea-igp.ac.cn/index.htm>
- Kumsar, H., Aydan, O. and Ulusay, R. (2000): Dynamic and static stability of rock slopes against wedge failures. *Rock Mechanics and Rock Engineering*, Vol.33, No.1, 31–51.
- Lin, C.J. and Chai, J.F. (2008): Reconnaissance report on the China Wenchuan Earthquake May 12, 2008. NCREE Newsletter Vol. 3, No.3, Sep. 2008.
- Lu, Jun., Shunzhang Xue, Fuyue Qian, Yulin Zhao, Huaping Guan, Xianjin Mao, Aiguo Ruan, Surong Yu, Wujun Xiao (2004): Unexpected changes in resistivity monitoring for earthquakes of the Longmenshan in Sichuan, China, with a fixed Schlumberger sounding array. *Physics of the Earth and Planetary Interiors* **145** (2004) 87–97.
- Nishimura and Yagi (2008): Mega earthquake of May 12, 2008 in Sichuan province (in Japanese). http://www.geol.tsukuba.ac.jp/press_HP/yagi/EQ/20080512/
- Şengör, A.M.C. (1984). The Cimmeride Orogenic System and the Tectonics of Eurasia *Geological Society of America Special Paper*, **195**, 1–82.
- Shimizu, Y., Ö. Aydan, Y. Ichikawa, T. Kawamoto (1988). An experimental study on the seismic behaviour of discontinuous rock slopes (in Japanese). *The 42nd Annual Meeting of Japan Society of Civil Engineers*, **III–180**, 386–387.
- USGS: U.S. Geological Survey, National Earthquake Information Center, Golden, CO, USA. <http://earthquake.usgs.gov/>
- Yamanaka, Y. (2008): May 12, 2008 Sichuan Earthquake, No.8 (in Japanese) http://www.seis.nagoya-u.ac.jp/sanchu/Seismo_Note/2008/NGY8.html
- Yang, Z.X., F. Waldhauser, Y.T. Chen and P.G. Richards (2005): Double-difference relocation of earthquakes in central-western China, 1992–1999. *Journal of Seismology* (2005) **9**: 241–264.
- UNOSAT (2008): Overview of Tangjiashan quake lake, Beichuan, China from 3–8 June 2008. EQ-2008-000062-CHN. <http://www.unosat.org/>
- Xinhuanet (2008): Pictures of 5.12 Wenchuan earthquake. <http://www.xinhuanet.com/>

要 旨

岩盤斜面の崩壊、地すべりダムおよびトンネルの損傷に重点をおいて
2008年汶川大地震の特徴とその災害について

アイダン・オメル

東海大学海洋学部海洋建設工学科

太田 良巴

東海大学大学院総合理工学研究科総合総合理工学専攻海洋理工学コース

濱田 政則

早稲田大学理工学術院社会環境工学科

伊東 淳

早稲田大学セーバース株式会社

大窪 克己

中日本高速道路株式会社 八王子支社

汶川地震（中国四川省）は中国時間で2005年5月12日14時28分に発生し、そのマグニチュードは7.9であった。この地震で85000人以上の命が奪われて、350000人以上のケガ人が出た。この地震は、四川盆地の北西端にある走行が北東—南西である逆断層型の龍門山断層（ロンメンシャン断層）の長さ約300kmにわたる破壊に伴って発生した。山岳地帯で数多くの斜面崩壊が発生し、道路、鉄道などに大きな被害をもたらした。また、強い地震動と斜面崩壊によって数多くの建物が全壊あるいは大きな損傷を受けた。本論文で斜面崩壊に関していくつかの対策法を紹介した。この地震で数多くのトンネルにおいて無筋コンクリート・ライニングの破壊が見られ、地震に強いと考えられている地下構造物の耐震性について数多くの課題があることが明らかになった。活断層帯で掘削されるトンネルのコンクリート・ライニングについて建設時の設計の考え方がどうあるべきか、既設構造物に関してどのように対策すべきかを提案した。