

GEOTECHNICAL LESSONS FROM AN EXTREME GEO-DISASTER: VISIT TO THE MAY 2008 WENCHUAN EARTHQUAKE ZONE, CHINA

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ABSTRACT

This paper summarises key geotechnical findings arising from studies by others and from a visit to the Wenchuan earthquake zone in China. The magnitude and scale of the May 2008 Wenchuan earthquake classifies this event as an extreme geo-disaster. Such events do not often attract the technical attention of the geotechnical profession due to their low probability-high magnitude nature which is outside the normal design codes and construction standards for engineering structures. However, study of these extreme events can provide valuable insight to the performance of natural and engineered systems under severe loading which can lead to improvements in geotechnical models and engineering design under normal loads.

The geology of the Wenchuan earthquake is described including the surface rupture and ground shaking features. Seismic damage to structures including buildings, dams and tunnels is discussed, highlighting the role of design codes and construction standards on damage control. Coseismal geohazards such as landslides, debris flows and landslide dams are summarised including mechanisms and impacts on life and property. Overall, the primary controls on the extensive devastation suffered include the high magnitude, shallow depth and long duration nature of the seismic event, the strong vertical component of movement due to the imbricated thrust tectonic control on movement and the fact that deformation was not constrained to the main rupture plane but also occurred along secondary structures between bounding faults within a structural zone some 50-70 km wide and 500 km long.

1 INTRODUCTION

On 12 May 2008 an earthquake measuring magnitude 8.0 on the Richter scale occurred in Wenchuan County within the Sichuan Province of southwest China. The earthquake and associated secondary geohazards caused catastrophic devastation to major parts of Sichuan province with a total of 69,225 people killed, a further 374,643 injured and 17,923 classified as missing presumed dead (Huang *et al* 2009). More than 45.5 million people in 417 counties and 16 provinces were affected covering an area of more than 440,000 km². At least 15 million people were evacuated from their homes and more than 5 million were left homeless. An estimated 5.36 million buildings collapsed and more than 21 million buildings were damaged in Sichuan and neighbouring provinces. Direct economic losses were totalled at US\$120-170 billion by the World Bank.

A site visit was undertaken to the Wenchuan earthquake zone during the 7th Asian Regional Conference of IAEG held in Chengdu, China during September 2009. This paper summarises work by others presented at the conference (Huang *et al* 2009a) and published elsewhere by mostly Chinese geoscientists. The paper outlines key findings from these studies and from observations made during the visit and discusses examples of the destruction and damage to engineering structures viewed. Lessons from extreme events such as the Wenchuan earthquake can provide valuable information for disaster planning and seismic design elsewhere including Australia.

2 THE CONCEPT OF EXTREME GEO-DISASTERS

A keynote address by Wang Sijing at the conference proposed the concept of Extreme Geo-Disaster and Risk from which the following discussion is based (Wang 2009a). Extreme geo-disasters are massive scale geohazards of the highest risk which take place beyond the ordinary design life of engineering structures. They are characterised by very low probability and long return periods in the order of 1000 to 10,000 years. Such disasters may not have occurred in some regions or have not been recorded and can not be recalled by local people. Examples include the 2004 Sumatra earthquake of Ms 9.0 and associated Indian Ocean tsunami, which killed over 227,898 and the Wenchuan earthquake of 2008.

The size and time scale of extreme geo-disasters are such that they are often do not attract the attention of engineering geologists and geotechnical engineers. Planning and design codes take account of higher probability, shorter return period events but typically do not consider the extreme risks. History shows that extreme disasters can happen at any time regardless of the long return period but the time of occurrence is beyond prediction and forecasting. As the last extreme event probably occurred before or at the early stage of human civilisation there

is little prospect for any recorded information to allow relevant size and occurrence period parameters to be specified in codes and standards. However, with awareness of the possibility of an extreme geo-event, planning can be put in place to manage the potential disaster and mitigate the risk. Obviously measures relevant to extreme geo-disasters would be different from regular engineering protection.

Factors controlling the occurrence of an extreme geo-disaster are:

- Presence of a “fragile” geological structure such as fault zones and volcanoes and
- A very large triggering force.

Earthquakes are an obvious trigger and highly destructive effects normally occur for magnitude M_s 7.0 and over.

Extreme disasters are characterised by the large area that is impacted and evaluating the limits of the affected area is a key component of the risk assessment. For earthquakes the impact area is related to magnitude as studied by Keefer (1984) in relation to landslides (Figure 1). In the case of the Wenchuan earthquake the disaster area covered 440,000 km^2 which is larger than the maximum area of historical events. Factors other than magnitude must also contribute such as susceptibility of geological structures, topography, population density and location of engineering structures.

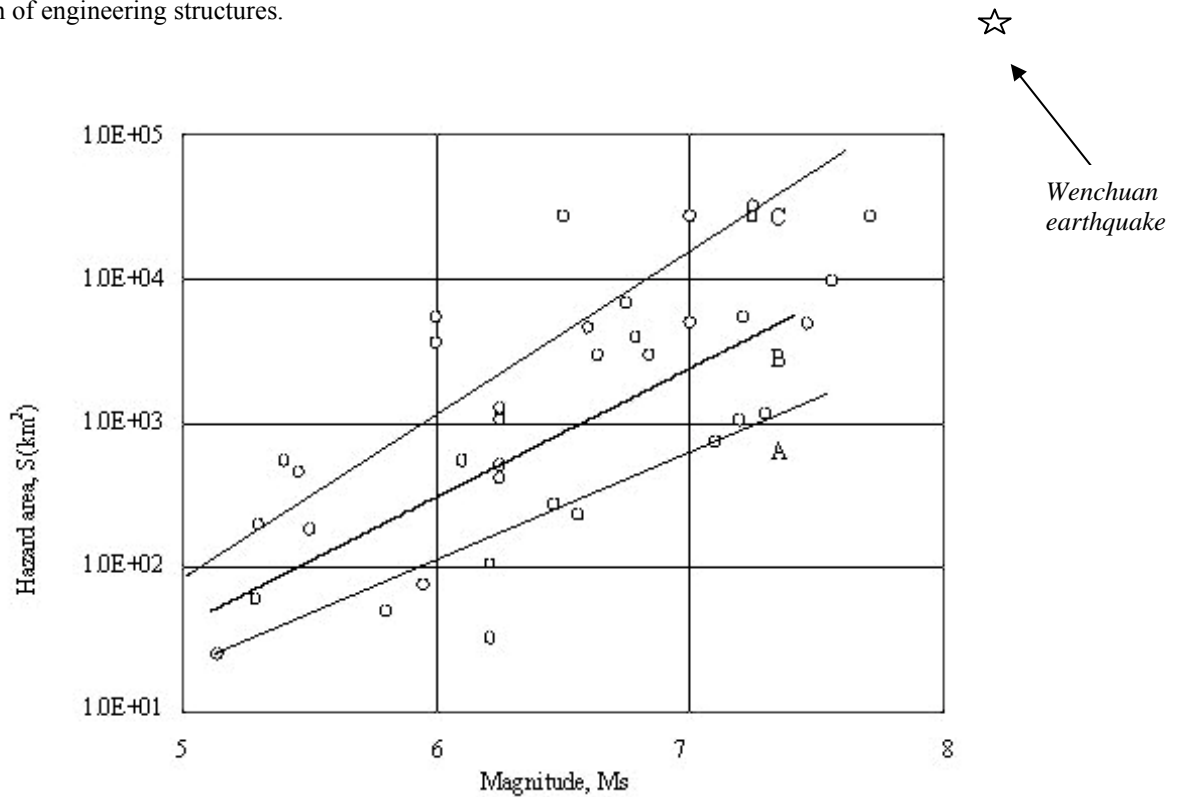


Figure 1: Seismic hazard area versus earthquake magnitude (Keefer 1984 as presented in Wang *et al* 2009).
A – lower band, B-mean band, C-upper band.

Key to the mitigation of extreme geo-disasters is the need for flexibility in the counter measures. Wang (2009a) lists the following strategies.

1. Land use planning should be revised to reflect the risk; for example, reducing the number of the most important buildings in the highest hazard zones.
2. Construction of emergency services such as hospitals and police stations in appropriate sites.
3. Establishment of monitoring systems to detect precursor events for early warning, where possible.
4. Establish evacuation and rescue plans.
5. Improve social awareness with education programs.

3 DESCRIPTION OF WENCHUAN EARTHQUAKE

3.1 SEISMICITY OF CHINA

The seismicity of central and eastern Asia is a result of northward convergence of the India plate against the Eurasia plate with a velocity of about 50 mm/year. The convergence of the two plates is broadly accommodated

by uplift of the Asian and Himalaya highlands and by the motion of crustal material to the east away from the uplifted Tibetan Plateau (USGS website, July 2010).

Mainland China has recorded 15 earthquakes with a magnitude greater than 7 over the last century or so. At least 750,000 people have died during these events and 62% of all deaths associated with natural disasters in China are related to the effect of earthquakes (Wang 2009b). Accordingly seismicity is an important factor in the engineering planning and design of projects in China.

The distribution of most recorded earthquakes in China is shown in Figure 2 up to the year 2000. Most extreme events with M_s 7 and over are associated with major active fault zones.

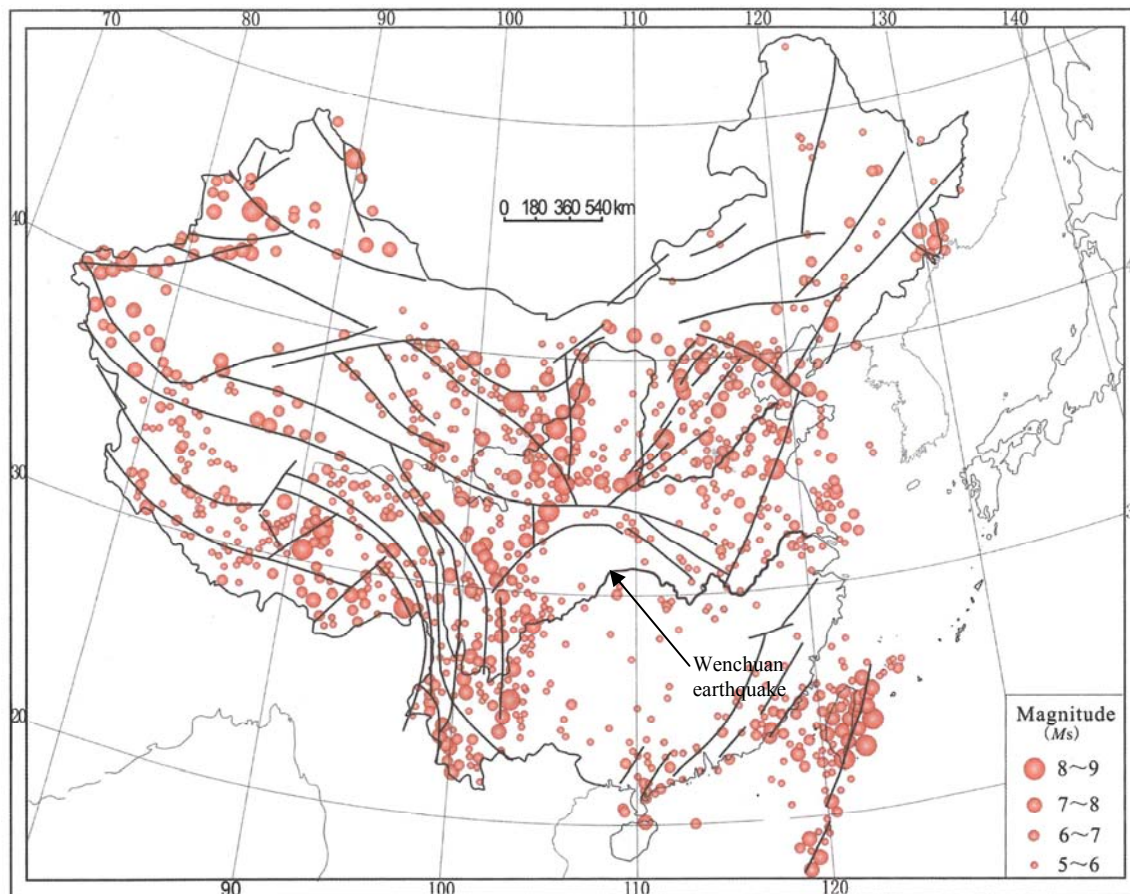


Figure 2: Earthquake epicentre distribution in China from 2300BC to 2000AD for Richter scale ≥ 5 (Wang *et al* 2009).

3.2 REGIONAL SETTING

The Wenchuan earthquake occurred as the result of motion on a northeast striking reverse fault or thrust fault on the northwestern margin of the Sichuan Basin. The earthquake reflects tectonic stresses resulting from the convergence of crustal material moving from the high Tibetan Plateau to the west against strong crust underlying the Sichuan Basin and southeastern China (Figure 3).

The epicenter and focal-mechanism indicate the earthquake occurred as the result of movement on the Longmen Shan fault zone (Figure 3) which marks the tectonic contact between the Sichuan Basin to the East and the mountains of western Sichuan and the eastern Tibetan plateau to the West (Burchfiel *et al.*, 1995). The low elevation and topographically flat Sichuan Basin appears to be a deeply-rooted, mechanically strong unit underlain by craton-like lithosphere that has resisted Mesozoic and Cenozoic deformations that affected the surrounding regions. West of the Longmen Shan fault zone the mechanical strength is much lower than beneath the Sichuan Basin (Royden *et al.*, 2008) and earthquakes reflect tectonic stresses resulting from the relative motion between these tectonic units. Geological structures along the Longmen Shan fault zone suggest total displacement of tens of kilometers since the Late Cenozoic (Burchfiel *et al.*, 1995) and GPS measurements constrain active rates at 1-3 mm/yr (Meade, 2007; Royden *et al.*, 2008). While this rate of slip is relatively low, this region has the potential to generate large magnitude events due to accumulation of movement over long periods of time (Tsang 2008).

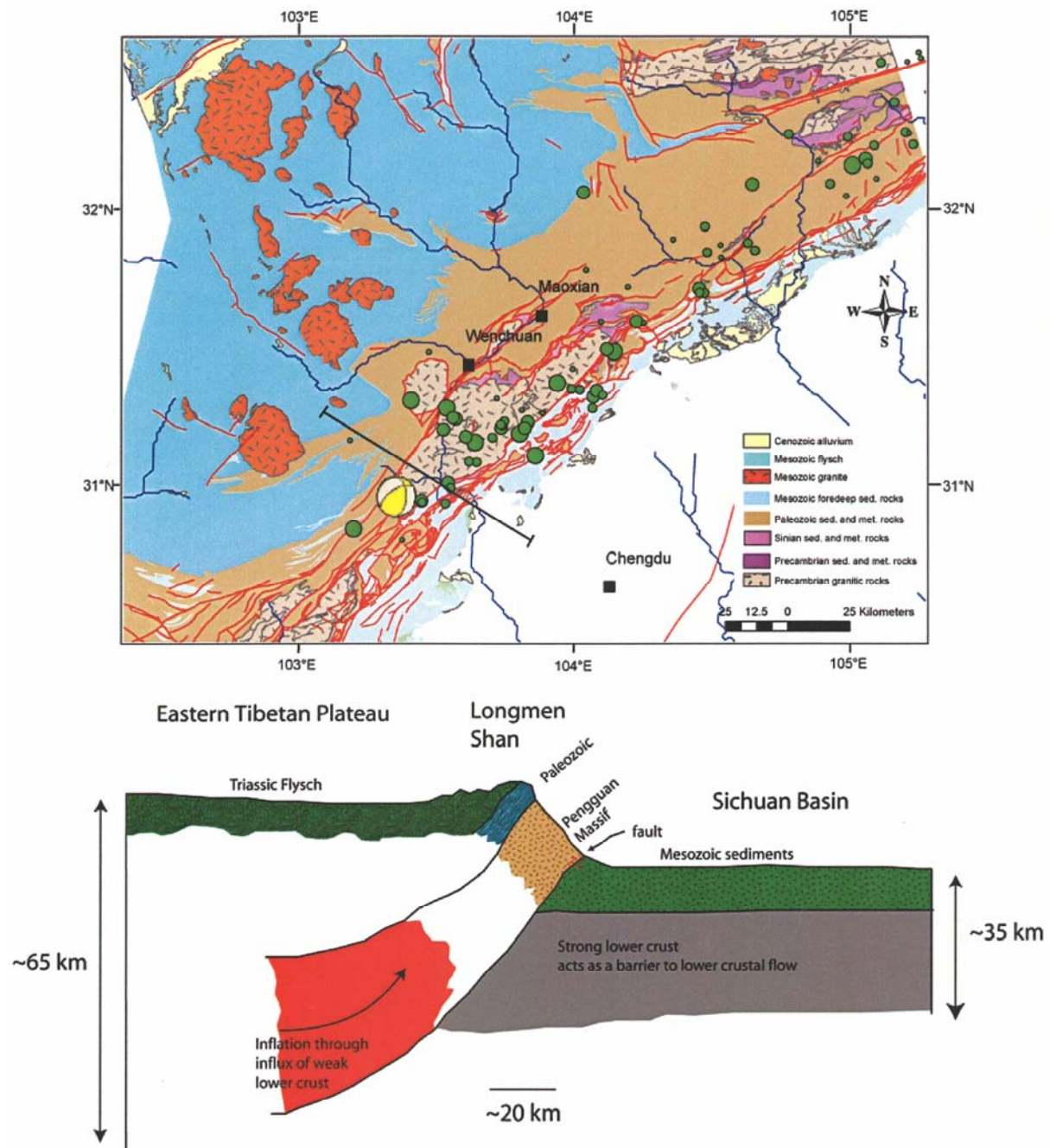


Figure 3: Geological map and section of the Longmen Shan fault zone (<http://quake.mit.edu/~changli/wenchuan.html>).

Cenozoic deformation in the Longmen Shan fault zone is difficult to constrain, but there is evidence for right-lateral strike-slip, thrusting and normal faulting on several different structures. The fault that appears to have broken in the earthquake is at or very near the boundary between the western Sichuan mountains and the eastern Sichuan Basin. The fault has a history of mostly right-lateral strike-slip and a smaller amount of thrust motion (Densmore *et al.*, 2007).

Rock present in the earthquake area is Precambrian granite, Cambrian sandstones and argillaceous limestones, Silurian slates and phyllites and limestones of Devonian and Carboniferous age.

3.3 EARTHQUAKE GEOLOGY, SURFACE RUPTURE AND GROUND SHAKING

The earthquake occurred at 2:28pm local time on 12 May 2008. The epicentre was located at 30.986°N, 103.364°E (USGS website, July 2010) near the town of Yingxiu and about 90 km west-northwest of Chengdu, at a relatively shallow depth of 19 km. There were 200 aftershocks with magnitude 4.0 or greater and 8 aftershocks greater than magnitude 6.0. Maximum intensity XI was assigned in the Wenchuan area with felt intensity VIII at

the cities of Deyang and Mianyang and VII at Chengdu (Figure 5). The earthquake was felt in much of central, eastern and southern China and also in parts of Bangladesh, Pakistan, Taiwan, Hong Kong, Thailand and Vietnam. The papers are unclear if the Modified Mercalli Intensity scale is used or a local Chinese scale.

The Longmen Shan fault zone comprises three sub-parallel structures (Figure 4):

- The Guanxian-Anxian and Jiangyou-Guangyuan structures in the east forming the front range faults,
- The Yingxiu-Beichuan and Beichuan-Qingchuan structures forming the central faults, and
- The Wenchuan-Maoxian and Pingwu-Qingchuan structures as the back range faults.

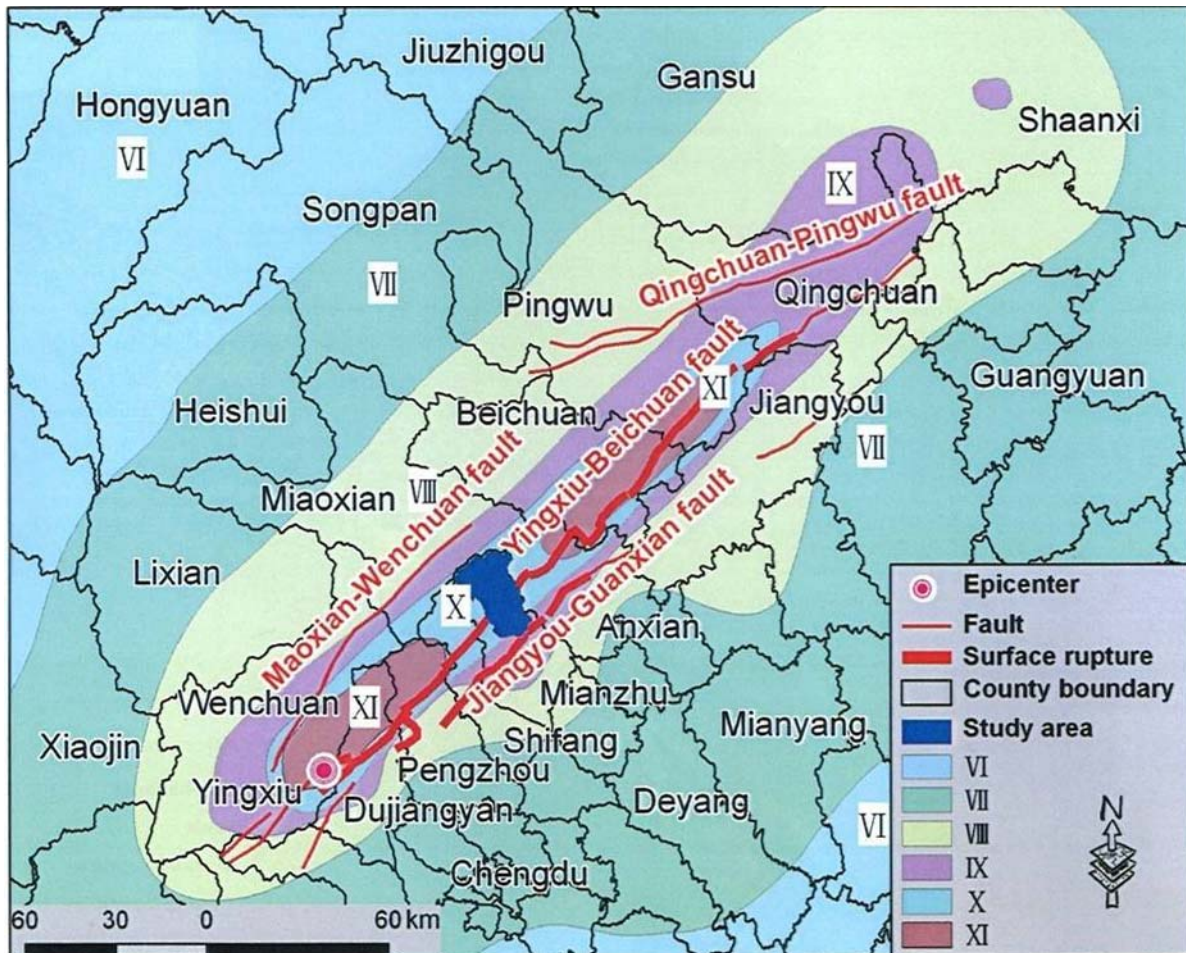


Figure 4: Wenchuan earthquake intensity map and location of front, central and back faults (Li *et al* 2009).

The primary geological structure of the earthquake was the Yingxiu-Beichuan fault which ruptured for a length of some 220 to 300 km over a duration of 120 seconds. The rupture plane was assessed as striking 229° (USGS website, July 2010) with rupture propagation in a single direction towards the northeast (Figure 5). Vertical offsets ranged from 1.6 m to 10.3 m, averaging 3.4 m while horizontal offsets varied from 0.2 m to 6.8 m, averaging 2.9 m (Li *et al.*, 2009). Hence the ratio between thrust and dextral strike-slip movement was approximately 1:1 with the relatively strong vertical component of movement controlled by the imbricated thrust tectonics. Some key findings on the primary rupture by Li *et al.*, 2009 include:

- The largest offset did not occur at the epicentre,
- Surface rupture was smaller than the largest underground displacement by around 60-70%,
- However, the largest surface rupture was approximately coincident with maxima displacement underground and
- Rupture during this earthquake occurred in areas with historical displacements suggesting they are likely to be the location of rupture during future events.

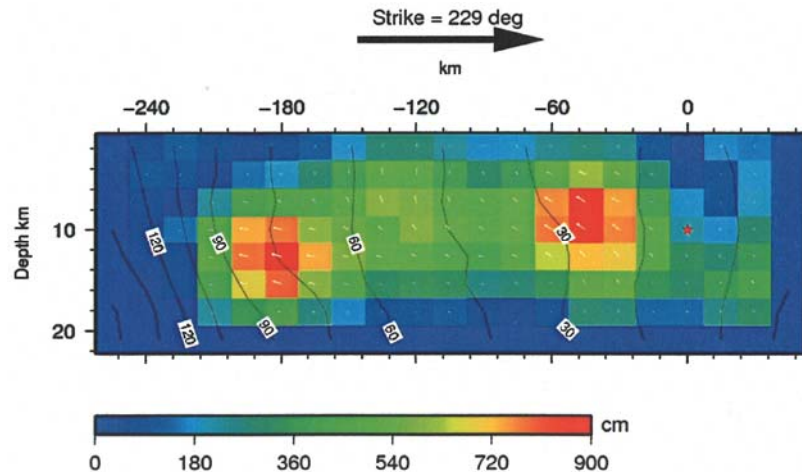


Figure 5: Cross section of slip distribution; hypocentre location is indicated by red star, slip amplitude is shown in colour, motion direction of the hanging wall relative to the footwall is shown by the white arrows and the contours show the rupture initiation time in seconds (http://earthquake.usgs.gov/earthquakes/eqinthenews/2008/us2008ryan/finite_fault.php).

Strong aftershocks were distributed widely over the Longmen Shan fault zone covering an area 50-70 km wide and 500 km long. As well as the primary structure, rupture also occurred along the front range faults and less so on the back range faults. Hence deformation and movement was not constrained to the main rupture plane but also occurred along secondary structures bound between the front and back range faults. This was a key reason for the widespread distribution of damage and associated geohazards.

The front range structures ruptured over a distance of 40-70 km with vertical offsets of 0.4-2.7 m (1.6 m average) and horizontal offsets of 0.2-0.7 m (0.6 m average), Li *et al.* (2009). On the back range faults only 2 km of rupture occurred with 0.2 m thrust displacement (Wang *et al.*, 2009). Overall, displacement was significantly less than the primary structure and thrust movement was dominant over the dextral strike-slip component.

The earthquake resulted in the discovery of two new faults, the Xiaoyudong and Leigu faults. The Xiaoyudong fault strikes approximately north-northwest, is about 15 km long and appears to be a transform structure linking the front range and central faults. Average vertical offset was 1.0 m and horizontal offset 2.3 m with the southwest hanging wall moving over the northeast footwall with increasing thrust displacement to the north. The Leigu fault is a 3-5 km long north-south transform structure between two parallel splays in the Yingxiu-Beichuan central fault. Displacement averaged 1.8 m vertically and 1.4 m horizontally (Li *et al.*, 2009). The highest sub-surface displacements along the primary Yingxiu-Beichuan fault occurred in two zones coincident with the intersection of the Xiaoyudong and Leigu transform faults.

In general the width of surface rupture was less than 20 m with most disturbance taking place on the hanging wall block of the thrust faults and little deformation on the footwall block. Focal mechanism solutions suggest the early movement was thrusting in the first 60 seconds and then gradually shifted to strike slip movement in the last 60-120 seconds (Chen *et al.*, 2008).

Ground motion has led to catastrophic damage to structures. The combination of high magnitude, shallow depth and relatively long duration resulted in intense damage and triggered many geohazards. The complex mountainous terrain contributed to the strong ground motion with a recorded peak ground acceleration of 1.5-2.0 g in some areas. Of particular note, the vertical peak acceleration was only slightly less than or equal to the horizontal acceleration at most recording sites (Huang *et al.*, 2009). The intensity XI zone located on the Yingxiu-Beichuan fault hanging wall covered an area of 680 km² in which structures almost completely collapsed particularly in the towns of Yingxiu and Beichuan (Li *et al.*, 2009). Intensity X covered an area of 2520 km² where most structures collapsed.

4 SEISMIC DAMAGE TO STRUCTURES

4.1 BUILDING DAMAGE

The earthquake resulted in significant damage and a large number of collapses with huge loss of life and property. A paper by Ye *et al.* (2008) reported seismic damage data gathered from the major disaster area, although the exact location of the surveyed areas is not specified. Building damage was classified into 4 categories:

Operational – whole building was undamaged or only some non-structural elements were slightly damaged.

Out of service before retrofitting – load bearing structure is damaged; without retrofitting the damage may become more severe and threaten injury or economic loss.

Not repairable – damage is too severe for repairs but structure is not likely to collapse.

Immediate demolition – structure is near collapse and dangerous. It is assumed buildings that collapsed during the earthquake are included in this category although the paper does not explicitly state this.

The level of damage was assessed by building type as presented in Figure 6 with the following conclusions (Ye *et al* 2008).

- *Masonry (brick, stone blocks) structures* – widely used in single storey commercial, industrial, school and residential buildings in rural areas due to cheap materials; timber roof structures are usually old and lack maintenance with strength of walls and columns not likely to meet current building codes. Around 42% of these buildings collapsed or were beyond repair and only 21% remained operational. These buildings were vulnerable due to factors such as lack of concrete structural columns and ring beams and poor connections of pre-cast slabs.
- *Hybrid RC frame and masonry structures* – there are many hybrid layouts with the load-bearing system in most being disordered resulting in inconsistent deformation between different parts of the building. Vertical and horizontal stiffness of these structures is typically also poorly distributed. While 48% of these types of structures remained operational, 31% collapsed or were beyond repair with the most common damage being collapse of upper storey masonry structures or collapse of weak lower floors which were sandwiched by upper storeys.
- *RC frame* – these structures performed the best with 63% remaining operational. Most damage occurred in the enclosed structures and filler walls which threatens safety and are costly to repair. Some RC frame buildings did collapse (17% collapsed or were non-repairable) reportedly due to poor construction or badly designed structural systems.

Overall, apart from structural differences in building types, building quality has been cited as an important issue. Masonry structures are favoured in the rural areas where construction is not under the national supervision system and buildings are constructed without designs and/or by unqualified builders.

The time period during which the building was constructed had a major bearing on seismic performance during the earthquake. Over 50% of buildings constructed prior to 1979 collapsed or became permanently inoperable whereas 52% of buildings constructed post-2001 remained in operation. The older buildings were dominantly the masonry type with lower safety margins. Buildings constructed during the 1980's and 1990's saw a significant improvement in seismic performance such that the proportion of buildings six years old or less that collapsed or became unrepairable reduced to 16%. The proportion of buildings requiring retrofitting decreased slightly from older (39%) to younger buildings (31%) as noted by Ye *et al.* (2008). However, 31% for the most recently constructed buildings remains a relatively high rate of damage. While the more recent design codes have reduced the amount of damage there is an argument for further improvement. In response to this experience the Chinese government has recently modified the seismic building codes as discussed in section 4.3.

Assessing damage by building function reveals an interesting trend (Figure 6). The worst performing buildings were schools where 57% collapsed or were deemed unrepairable. This contrasts with government buildings where only 13% were in the worst category. A large number of school buildings comprised masonry structures with large window openings in the load bearing walls and Ye *et al.* (2008) state some of these buildings were constructed without any seismic design and construction measures. Government buildings, on the other hand, are typically RC frame structures which performed relatively better. About half residential buildings remained operational, a quarter required retrofitting and quarter were unrepairable or collapsed.

Several other factors are discussed in papers reporting on building damage during the earthquake (Paterson *et al* 2008).

- *Effects of long duration of ground motion* – with ground shaking lasting 120 seconds, and in some cases lasting as long as a few hundred seconds, the continuous impact accumulated the damaging effects and compounded the development of fractures within structures. Building codes reflect the typical situation where earthquakes have a higher horizontal movement component compared with vertical. In the Chinese design code the maximum vertical component is specified to be less than two-thirds of the horizontal component. However, the Wenchuan earthquake generated a larger component of vertical movement, adding to the gravity loading and exacerbating the damage caused by unusually high horizontal loading.

- *Poor building configuration (soft storey mechanisms)* – when the ground floor is cleared of walls to make space for commercial areas (such as shops) or car parking, the stiffness provided by walls in the upper levels is removed and the remaining columns and beams experience severe concentration of loading. Failure of these structural members at the joints is a common cause of collapse.

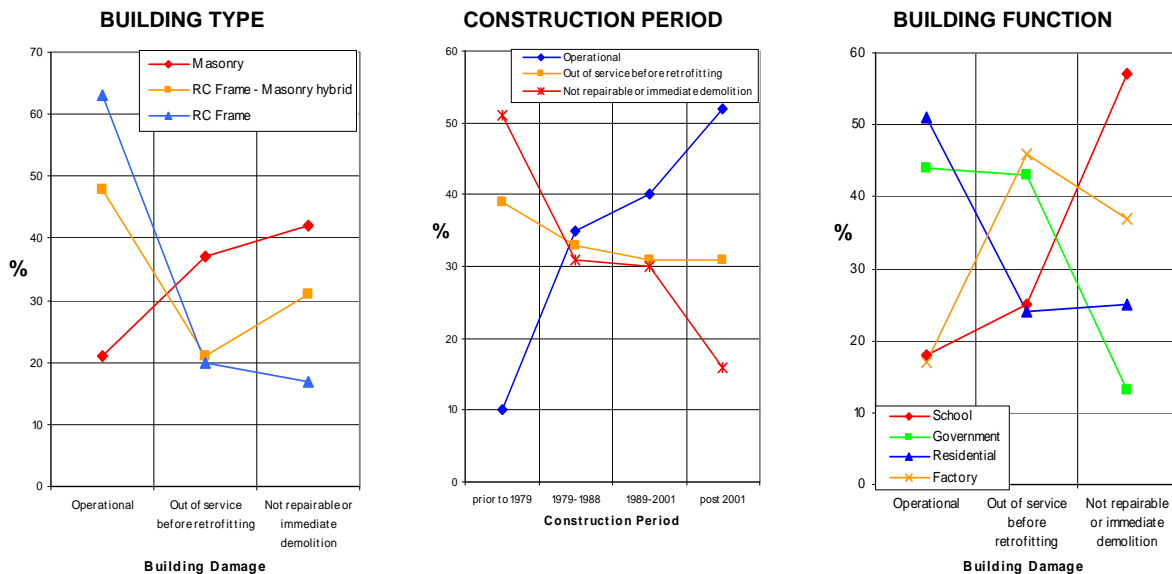


Figure 6: Results of building seismic damage survey (Ye et al 2008).

4.2 COLLAPSE OF SCHOOL BUILDINGS AND DESIGN CODES

The extensive collapse of school buildings attracted major attention in the media with an estimated 10,000 school children killed. A large part of the blame was attributed to local officials and builders who were accused of alleged poor construction quality of school buildings. However, there is a national standard in China that differentiates between importance of buildings as listed in Table 1. Low rise (6 levels or less) schools buildings were re-categorised from Standard Protection (SP) to Emphasised Protection (EP) buildings in 2004 which means the structural design should be enhanced to withstand one seismic intensity higher. Some authors suggest not all school buildings are of class EP even if they were built after 2004.

The seismic design procedure in China comprises two phases (Tsang 2008):

1. Section design of the structural elements (strength) and a deformation check by elastic analysis based on the Minor Earthquake Design Level. This is basically a check on yield strength with checks on stiffness based on the 50 year return period earthquake.
2. Structural deformation (collapse) check by elasto-plastic analysis based on the Major Earthquake Design Level.

The Phase 2 check is only compulsory for:

- Buildings with a low strength storey,
- Building located on “soft soil” sites,
- Buildings in regions with higher intensity,
- Taller buildings, or
- Important buildings (PP and some EP).

Normal or SP buildings would not be subject to Phase 2 design checks.

Table 1: Standard for Classification of Seismic Protection of Building Construction (Zhao *et al.* 2010)

Protection Category	Moderate Protection Buildings (MP)	Standard Protection Buildings (SP)	Emphasized Protection Buildings (EP)	Particular Protection Buildings (PP)
Structural Details	Appropriately lower than the seismic intensity	Equal to the seismic intensity	One level higher than the seismic intensity	One level higher than the seismic intensity
Seismic force	Equal to the seismic intensity	Equal to the seismic intensity	Equal to the seismic intensity	Higher than the seismic intensity or based on the site safety evaluation

The immediate epicentral areas had a design intensity level of VII only, hence buildings that underwent Phase 2 design would be expected to be sufficiently robust to withstand ground shaking up to intensity VIII. However, this area suffered up to intensity XI and therefore it should be no surprise they suffered severe damage. Any chance of survival of the majority of buildings in areas of intense ground motion could only rely on any intrinsic conservatism built in to the design assumptions (Tsang, 2008).

Ye *et al.* (2008) describe the Phase 1 design as the “fundamental strength safety margin” and the Phase 2 check as the “integrated safety margin”. On a lateral resistance to displacement curve (Figure 7), Phase 1 is represented by the curve between points A and B while Phase 2 corresponds to the curve between points B and C. They go on and suggest there should be a third phase which considers the portion between points C and D, the latter being the collapse point. They called this phase the “unexpected safety margin” and would take account of the low probability, high magnitude and high consequence event and is probably equivalent to Tsang’s “intrinsic conservatism”. In other words, the safety margin between points C and D would help prevent building collapse; certainly during the Wenchuan earthquake many buildings were severely damaged with deformations greater than point C but did not collapse which saved lives.

In summary, the Phase 1 fundamental safety margin helps secure the building under predicted, relatively minor earthquakes; however, the Phase 2 integrated and Phase 3 unexpected safety margins are required to resist severe earthquakes.

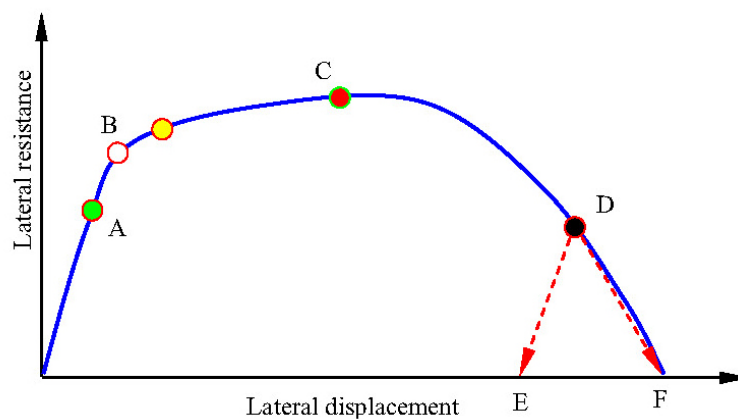


Figure 7: Lateral load resistant behaviour of structures (Ye *et al.*, 2008).

4.3 CODE MODIFICATION POST EARTHQUAKE

Based on findings from studies of the earthquake area the Chinese government has recently updated the following standards and codes:

- Standard for Classification of Seismic Protection of Buildings and
- Code for Seismic Design of Buildings.

The main modifications are summarised as follows (Zhao *et al.*, 2010).

- *Seismic protection categories of buildings* – as discussed in Section 4.2, school buildings have been upgraded from Standard to Emphasised Protection.
- *Seismic zone map* has been modified for the 70 affected counties and cities in Sichuan, Gansu and Shaanxi provinces. This has included increasing design intensities and design peak ground accelerations.
- *Construction* – a building set back distance of 200 m has been specified from an active fault and benched excavations recommended for sloping sites.
- *Structural regularity* – irregular architectural design schemes should be seismically strengthened.
- *Structural robustness* – column strength and beam stiffness requirements have been revised and cast-at-site reinforced concrete slabs recommended in place of pre-cast floor slabs which experienced a higher proportion of failure.
- *Structural staircases* – use of RC constructional columns and ring beams in staircases. Many staircases in masonry structures without constructional columns at the intercrossing walls collapsed during the earthquake.
- *Multi-protection line of structures* – during the earthquake, single-span frames experienced widespread collapse whereas two-span frames stood without complete collapse which helped save lives. The objective of multi-protection line of structures is to reduce the likelihood of progressive collapse due to failure of key members or components similar to seismic codes in USA, Japan and Europe.

While the damage experience and building performance during the Wenchuan earthquake has resulted in changes to codes and standards, these improvements do not take account of the extreme event. In the epicentral area the design intensity has increased from VII to VIII which means for EP buildings, such as new schools, the design would be expected to be sufficiently robust to withstand ground shaking up to intensity IX. If the Phase 3 “unexpected safety margin” step were introduced into the seismic design procedure, this may provide sufficient “intrinsic conservatism” in the design to improve the chances of preventing collapse and reducing deaths under shaking from intensity XI in an extreme event.

4.4 DAMAGE TO OTHER STRUCTURES

4.4.1 Roads, Rail, Bridges and Dams

Substantial damage occurred to the transportation system during the earthquake. Approximately 50,000 km of roads and railways, 3,000 bridges, 100 tunnels, and many kilometres of retaining structures were damaged by the earthquake with total losses exceeding US\$10 billion (EERI 2008). On the day of the earthquake, 31 passenger trains and 149 cargo trains were stranded on lines linking Chengdu with the rest of the country. There were many landslides, bridge collapses, and other damage along rail tracks. The repair effort was swift with road access to all county centers restored within 14 days of the earthquake and to 248 of 254 other towns by 14 June 2008.

A large number of bridges with simply supported spans were unseated and collapsed. Some bridges had damaged shear keys at the abutments and bent caps when the strongest ground motions were in the transverse direction. The Baihua Bridge near Yingxiu had damage to the transverse beams between the piers as well as flexural distress near the base of some of the bent piers (EERI 2008). Many bridges also appeared to suffer due to poor detailing in the concrete construction with inadequate reinforcement and poor bonding between rebar and concrete.

In Sichuan Province there are more than 7,000 dams, most of which (about 70%) were built in the 1950s and 1960s. According to a survey by the Chinese Ministry of Water Resources on 25 May 2008, 2380 dams were placed under emergency conditions due to earthquake induced damage including 69 dams in Sichuan. Of these, 18 dams were reported as “nearly collapsed” and 135 dams “severely damaged” although a vast majority are listed as small with a reservoir volume less than 5 million m³. No damage was reported at the Three Gorges Dam located approximately 600 km east of the epicenter, although it is not clear if this was due to the distance or improved design and construction standards for this major structure.

4.4.2 Tunnels

There are several examples of seismic damage to tunnels in the Asia region in recent earthquakes. During the Kobe earthquake in Japan on 17 January 1995, about 10% of mountain tunnels within the earthquake zone suffered damage. In the Chi-Chi Taiwanese earthquake of 1999, 25% of 44 tunnels within 25km of the epicentre were damaged.

An investigation by Li (2009) on the 11 tunnels along the highway between Dujiangyan and Wenchuan within the epicentral area identified the following basic types of tunnel failure:

- Blockage of portals by landsliding and rockfall,
- Cracking of portal engineering works up to 0.5m wide in the concrete headwall structure,
- Collapse of lining and surrounding rock which mainly occurred in soft rock closer to the epicentre,
- Cracking and dislocation of lining which occurred in 8 of the 11 tunnels comprising longitudinal, traverse and some oblique cracks,
- Ring fractures up to 0.2m wide caused by dislocation of construction joints,
- Uplift and cracking of the invert up to 1.2 m high and
- Deformation and cracking of preliminary lining.

The main factors that appear to control the extent of tunnel damage are listed as follows.

- Epicentre distance - < 30 km serious damage; >30 km slight damage,
- Seismic wave propagation direction – parallel to tunnel axis is the most vulnerable,
- Proximity to faults including secondary structures,
- Nature of the bedrock-overburden interface due to the surface Rayleigh waves,
- Release of *in situ* stress – a horizontal stress of 26 MPa prior to the earthquake was reduced to 15 MPa as measured after the earthquake in one of the tunnels,
- Tunnel depth below ground surface – in hard rock, < 50 m experienced moderate to severe damage; >50 m experienced moderate to slight damage; >100 m in hard rock there was no to slight damage.

4.5 DISCUSSION ON SEISMIC HAZARD

The high death toll and extensive damage to structures has substantially been attributed to the large magnitude of the seismic event. However, there is evidence which suggests the regional seismic hazard in the affected areas has been significantly underestimated and this also offers an explanation to the extensive collapse of buildings (Tsang 2008).

Prior to the recent update the seismic hazard map places most of the affected area in intensity level VII with a design PGA of 0.10g (it is unclear if this is the Major or Minor earthquake level). Tsang (2008) comments a 500 year PGA of 0.10g for the affected area seems anomalous given 8 earthquakes with magnitudes greater than 7 have occurred in the vicinity over the last 100 years. The understated seismicity could be due to the following causes (Tsang 2008):

- The maximum considered earthquake levels of the regions have been under-estimated and
- The ground motion attenuation models were too simplistic to take account of local geological conditions.

Kato *et al.* (2008) assess the Wenchuan earthquake may have released energy accumulated over 1000 to 3000 years and as such the earthquake has filled a “seismic gap” where previously, the seismicity was considered to be “low to moderate” due to absence of seismic history. This highlights an interesting line of reasoning by Tsang (2008); for regions where earthquake records have limited time coverage, the modelled seismic hazards can be prone to errors with the potential for under-estimation of the rate of occurrence. He recommends a “broad-brush” approach in these areas to avoid a false sense of accuracy with more precise seismic zoning left until a site-specific hazard assessment can be carried out.

This approach is particularly important for low to moderate seismic regions such as Australia where the historical earthquake records cannot necessarily provide an adequate and accurate projection for the occurrence of low probability, high consequence events. Tsang (2008) recommends more attention should be given to neotectonics and paleoseismology rather than relying entirely on modelling. This is particularly relevant to intra-plate, continental settings where the seismic cycle time is longer than the recorded history.

5 COSEISMAL GEOHAZARDS

A large number of coseismal geohazards were generated in association with the earthquake. Huang *et al* (2009) estimate over 50,000 geohazards were triggered with more than 16,000 that directly threatened human safety.

About one third of all casualties resulted from coseismal geohazards with 31 landslides causing the death of 4996 people (Wu *et al.* 2009).

5.1 LANDSLIDES

The China Geological Survey, with a team of about 1000 geologists all sourced from China, surveyed a total of 18,117 landslides triggered by the earthquake across three provinces with over 75% occurring in Sichuan (Wu *et al.* 2009). A majority were classified as rock/debris slides and avalanches (69%) with the remaining being rockfall (26%) and debris flows (5%). At least 18 landslides displaced material greater than 1 million m³. Slope movements occurred during the main earthquake, during aftershocks and as a result of heavy rainfall following the earthquake including a 1 in 20 year rainstorm on 23/24 September 2008.

These events caused heavy losses by destroying roads and vehicles, burying villages and blocking rivers. Landslides were also responsible for major impediments to the rescue effort in the days following the earthquake due to blocked access and ongoing risk of further events.

5.1.1 Shallow Slides and Falls

Shallow slides and falls were the most widely occurring slope failures, characterised by movement of highly fragmented soil and rock material (regolith) less than 3m thick over bedrock on steep slopes. They dominantly occurred along the top of major ridgelines at relatively close spacing, described as a “string of beads along the mountain ridge”, probably due to the topographic amplification of the seismic wave. Failure volumes ranged from a few m³ to thousands of m³. Debris from shallow failures typically accumulates in the base of gullies or hang up and become stored on the slope. In both situations they become source material for subsequent debris flows.

5.1.2 Deep-Seated Landslides

Deep-seated landslides also occur on steep slopes and have a thickness of tens of metres upwards and a volume of 100,000 m³ to 10,000,000 plus m³. These slides are characterised by high travel speed and long runout distances.

The intense seismic response due to the high magnitude, shallow depth and long duration of the earthquake which took place in a steep, high altitude topographic setting resulted in deep-seated landslide characteristics that are different to slope failures under normal gravitational loading (Huang *et al.*, 2009).

- Many failure mechanisms were described as involving “*shattering*”. This appears to be a process of rupture in response to severe shaking and ground motion followed by relaxation and disintegration of the rock mass. Typically a steep sliding surface is generated followed by a rear back scarp due to vertical tension. If there is no controlling sliding plane the shattered and disintegrated rock mass falls as an avalanche.
- Some failures involved a component of “*ejection*” where a portion of rock mass is “thrown out” from the slope as a projectile. This typically occurs on slopes facing the faultline where topographical effects appear to amplify the seismic energy. The process occurs at high speed and can involve long travel distances once the ejected mass lands, disintegrates on impact and degenerates into a rock avalanche.

On this basis Huang *et al.* (2009) divide intense earthquake slope instability mechanisms into 5 main types:

1. Shattering-sliding,
2. Shattering-falling,
3. Ejection,
4. Peeling and
5. Shattering-cracking.

The shattering-sliding mechanism (Figure 8) was the most common slope failure type. Discontinuities seem to play a major role in influencing the propagation behaviour of the seismic waves and can form a stepped sliding surface at the base of the shattered and disintegrated rock mass. Several sub-types are defined based on the role of structure: tension crack, bedding or shearing shattering-sliding and a mixture sub-type. It is probable that non-daylighting but unfavourably oriented bedding and foliation plane shears were a major control on instability with toe breakout through the “shattered” rock mass.

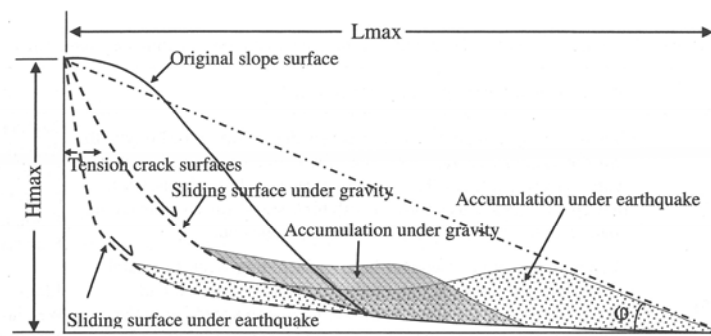


Figure 8: Schematic section showing characteristics of “shattering-sliding” landslide (Huang *et al.*, 2009).

Shattering-sliding failures occur at high speed and result in long travel distances with runout zones ranging between 600 m and 1300 m. In some cases the shape of the debris lobe was said to resemble an “airplane wing” resulting in an aerodynamic effect which was considered to contribute 180-350 m to the runout distance (Yin *et al.*, 2009). The largest example of the shattering-sliding mechanism is the Daguangbao landslide (Figure 9) situated 7 km from the Yingxiu-Beichuan fault. The slide geometry comprises (Huang *et al.*, 2009):

- 4.2 km long in the main slide direction,
- Up to 2.2 km wide,
- An area covering 7.8 km²,
- With an estimated volume of 742 million m³.

This failure formed a landslide dam up to 690 m high, probably the highest landslide barrier dam known in the world.

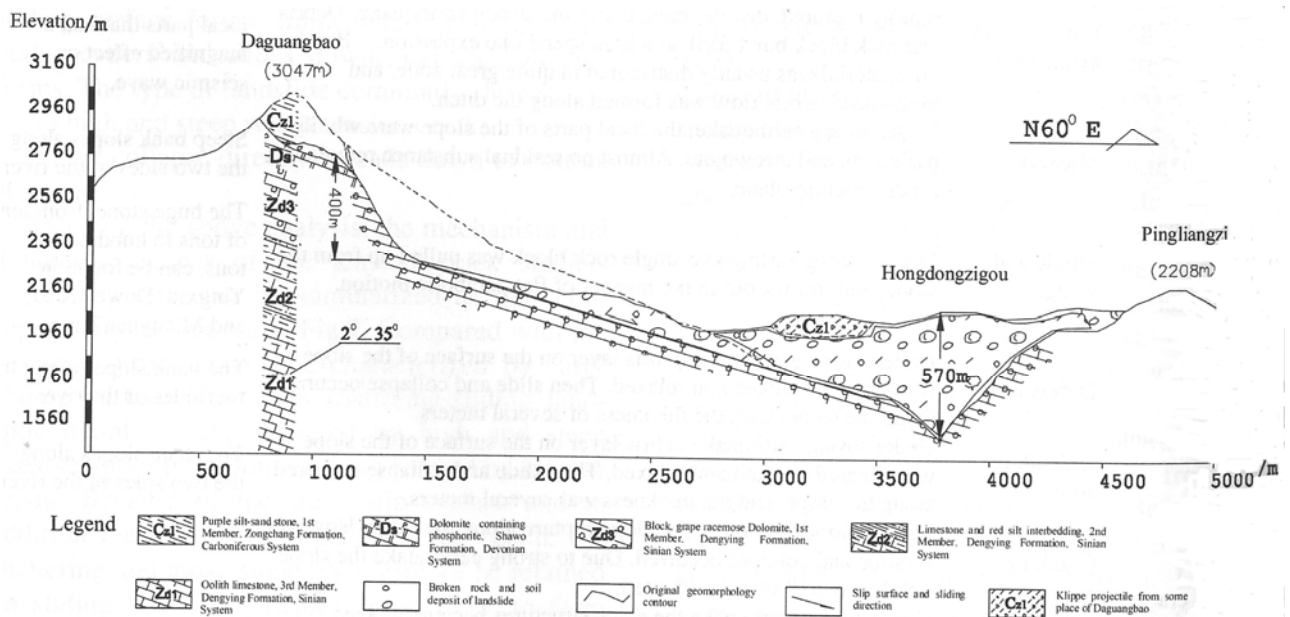


Figure 9: Longitudinal section through the Daguangbao landslide (Huang *et al.*, 2009).

The ejection mechanism can involve movement of a single or small group of blocks or ejection of a large portion of slope. Block ejection occurred with rocks up to hundreds of tonnes in size. A 300 ton block at Yingxiu was estimated to have been ejected by a ground acceleration of 1.38 g (Huang *et al.*, 2009). The Donghekou landslide, situated 3 km from the primary Yingxiu-Beichuan fault, is an example of a large-scale slope ejection with an estimated projectile distance of 300 m (Figure 10).

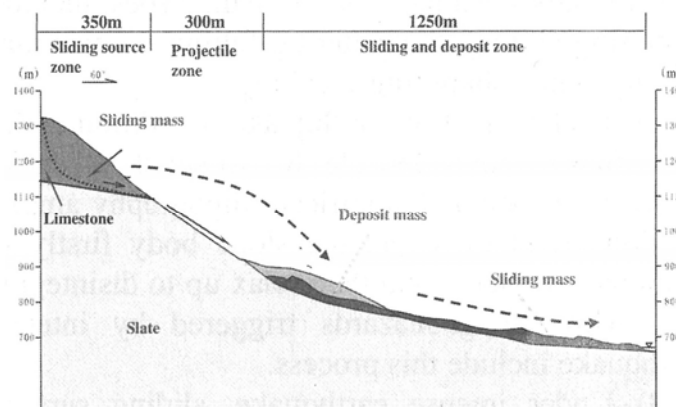


Figure 10: Displacement process of the Donghekou landslide showing the “ejection” mechanism (Huang *et al.*, 2009).

5.1.3 Debris Flows

Debris flows were triggered directly by shaking and ground motion and subsequently by rainfall, mobilising debris generated by earthquake triggered landslides. The strongest impact was in the intensity X and XI zones with some activity in the VIII and IX zones and almost no impact in the VII zone (Yu *et al.*, 2009). Field surveys identified 515 new debris flows during the May-June 2008 rainy season (Cui *et al.*, 2009). It is expected the debris flow hazard will reduce over time as the debris in storage is reduced by ongoing flows and floods, estimated to be over a time span between one and tens of years.

On 24 September 2008, some four months after the primary earthquake, a heavy rainstorm in Beichuan county triggered a number of debris flows killing 42 people, causing serious damage to roads and threatening relocation areas (Tang *et al.*, 2009). High intensity rainstorms on 23 September and the morning of 24 September triggered the flows which mobilised debris generated by the earthquake 4 months earlier. Tang *et al.*, (2009) estimate the threshold rainfall value for triggering debris flows was lowered after the earthquake with the accumulated rainfall threshold reduced by 15-22% while the critical hourly rainfall intensity value was reduced by 25-32%. Debris derived from the Silurian slates and phyllites were particularly prone to this type of movement probably due to the flaky, smooth nature of the fragments and lower resistance to weathering. This contributes to the development of clay minerals and a fine particle size forming the matrix to the debris mixture which is important in a flow mechanism.

5.2 LANDSLIDE SUSCEPTIBILITY AND DISTRIBUTION CONTROLS

Conditional and triggering factors controlling the occurrence of landslides were studied by Tang *et al.* (2009) and Li *et al.* (2009b). Conditional or fundamental causes assessed include slope gradient, elevation, lithology, fault proximity and stream proximity. Triggering causes were rainfall (hourly rainfall intensity and mean annual precipitation) and earthquakes (seismic intensity).

Overall, fault proximity was the main control with slopes within 3 km of a ruptured faultline the most susceptible. Slopes on the hanging wall contained a higher density of landslides compared with the footwall slopes by a factor of 2 within the 3 km zone (Figure 11). This pattern is attributed to the thrust mechanics of the earthquake. The highest density occurred in the 1 km to 2 km range from the fault on the hanging wall side rather than the 0 to 1 km range. This is probably due to the direction of seismic wave propagation and a combination of horizontal versus vertical acceleration against topography, in particular slope direction.

Lithology and stream proximity were also found to be important controls. Phyllite and interbedded sandstone-shale were the most susceptible rock types, most likely due to anisotropy within the foliated and bedded rock mass. The anisotropy most likely renders these lithologies susceptible to the dominant “shattering-sliding” failure mechanism. Slopes within 500 m of streams were the most vulnerable due to undercutting and oversteepening of valley flanks by fluvial erosion.

A majority of the affected area occurs between an elevation of 1000 m to 3000m but most failures (63%) occurred between 1000 m and 2000 m. This is the elevation in the earthquake area where the steepest slopes typically occur within the transition from mountain tops to valley floor. This slope location is where the maximum unloading from erosion has occurred and where the seismic response was the highest. Most failures took place on slopes steeper than 30°, in particular:

- In the transition between shallow and steep slopes,
- Relatively thin ridges and
- Isolated peaks or topographic highs.

Significantly, density of landsliding on the two sides of a major ridgeline was quite different. Slopes opposing the central fault contained a higher density of failures compared with slopes facing the fault with the same pattern for both hanging wall and footwall terrain. Further, slopes orthogonal to the fault direction are more susceptible than slope aspects parallel to the fault. These topographic relationships of landslide distribution are likely to be controlled by the response of different slope configurations to the dominant seismic wave direction and the corresponding amplification effect.

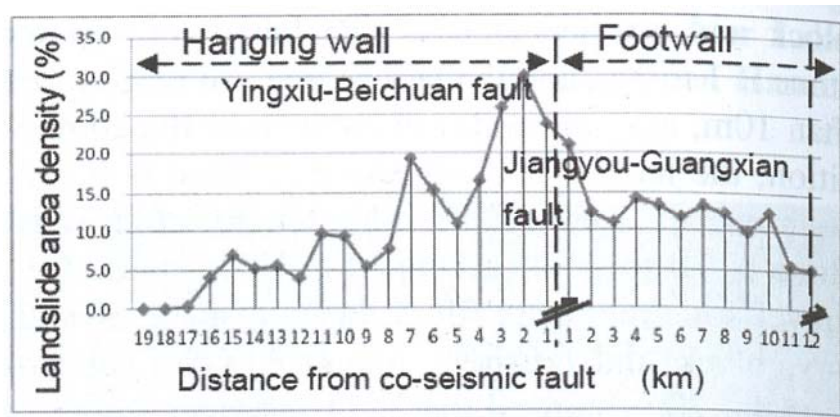


Figure 11: Landslide distribution between hanging wall and footwall of fault (Li *et al.*, 2009b).

5.3 LANDSLIDE INTENSITY

Landslide intensity was assessed by Wu *et al.* (2009) using remote sensing images and statistical methods. The maximum areal density (MAD) was evaluated as a regional measure of landslide intensity which measures the percentage of landslide area over the total affected area. This is preferred over the more traditional parameter of number of landslides in the affected area where the typical event size is relatively large.

The classification of landslide intensity for regional scale studies proposed by Wu *et al.* (2009) is shown in Table 2. Rainfall triggers landslides from about a MAD of 1-3% (low intensity), which is the limit where landslide activity becomes visible. Heavy rainfall is required to trigger landsliding at 5% (moderate intensity) which is the level where sliding becomes very obvious visually. A strong earthquake can generate a MAD of 10% (high intensity).

The highest MAD for the Wenchuan earthquake was 63% in the slopes near Yingxiu on the tributaries of the Minjiang River. This is an extremely high intensity and reported to be the maximum value of landsliding in historic earthquakes. Elsewhere within the earthquake zone, Beichuan county recorded a MAD of 34% which is very high.

Table 2: Classification of landslide intensity at a regional scale (Wu *et al.*, 2009)

Intensity Class	Description	Maximum Areal Density (MAD)	Point Density (per km ²)
0	Extremely low	≤ 1%	≤ 0.1
1	Very low	1 – 3%	0.1 – 1
2	Low	3 – 5%	1 – 3
3	Moderately low	5 -10%	3 – 5
4	Moderately high	10 – 20%	5 - 8
5	High	20 – 30%	
6	Very high	30 – 50%	8 - 10
7	Extremely high	> 50%	> 10

5.4 LANDSLIDE DAMS AND BARRIER LAKES

Barrier or earthquake lakes formed by landslide dams are considered to represent the most dangerous earthquake hazard (Costa and Schuster 1991). The obvious hazard is created by flooding upstream of the dam and dam-break resulting in catastrophic flooding downstream, however, the geohazard model is actually more complex as originally assessed by Korup (2005) and summarised in Figure 12.

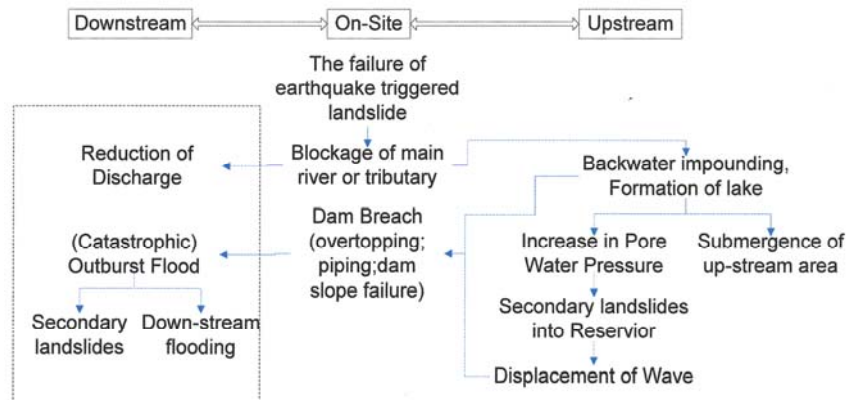


Figure 12: Hazards related to landslide dams (modified by Xu *et al* 2009 from Korup 2005).

In the Wenchuan earthquake area 256 barrier lakes were identified with data available for 32 lakes that posed a threat to people (Xu *et al.*, 2009). The relationship between landslide dam concentration and distance from the Yingxiu-Beichuan fault is presented in Figure 13, which shows a logarithmic decrease in dam numbers away from the primary structure.

The smaller lakes began breaching from 17 May 2008 just 5 days following the primary earthquake once they started overflowing and rapid downcutting commenced. The largest lake formed behind 20 million m³ of debris in a dam 82 m to 124 m high located at Tangjiasham, 3.2 km upstream of Beichuan town. This lake had an estimated water storage volume of 315 million m³ (315 megalitres) and submerged an area over 8.9 km² for a distance of 23 km upstream (Cui *et al.*, 2009). There were a further 7 smaller landslide dams downstream on this river and breach of the Tangjiasham landslide dam would likely induce failure of several other dams threatening 1.3 million lives downstream. A total of 250,000 people were evacuated from the city of Mianyang.

The Chinese army excavated an artificial spillway 12-13 m deep and 475 m long to alleviate the dam-break risk commencing work on 25 May 2008 and taking 7 days. The water level rose to the spillway level just a week after completion and the maximum discharge reached 6,500 m³/sec on 11 June. The artificial breach was successful in reducing the water level from 743.1 mRL to 714.3mRL and the volume of stored water from 247 million m³ to 86 million m³ (Xu *et al.*, 2009). There have been plans discussed to build a hydroelectric power station at the site or develop the lake as a scenic area to help rebuild the Beichuan County which was devastated by the earthquake.

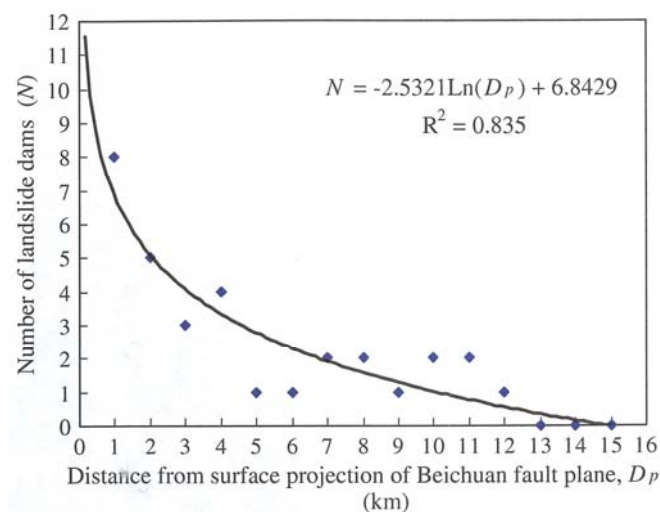


Figure 13: Landslide dam concentration versus distance from the primary fault zone (Xu *et al.*,2009).

6 EXAMPLES OF DESTRUCTION AND DAMAGE

Examples of the destruction and damage observed during the three day field visit will be shown during the symposium presentation. It is difficult to translate the impact the visit had on participants of the field trips in terms of the scale of destruction and loss of life. This was particularly the case at Yingxui and Beichuan where the devastation was virtually beyond comprehension and we were led through areas of collapsed buildings where so many people died and with so many people listed as missing.

The examples come from the following areas and engineering structures.

- Yingxiu Middle School - Yingxiu was the closest town to the epicentre and was virtually completely flattened by the earthquake with an estimated two thirds of its 10,000 inhabitants lost to the quake (Figure 14a). Almost no safe buildings were left and mountain roads into Yingxiu were blocked by dozens of landslides.
- Bailu Town – situated on the front range fault, damage in this town is contrasted to the devastation experienced in towns located on the primary fault.
- Beichuan Town – situated in a narrow valley between high mountain ranges, the primary Yingxiu-Beichuan fault strikes through the middle of the town which was devastated by surface fault ruptures, intense ground shaking, landslides, debris flows and inundated by flooding from landslide dams on the adjacent river. About 15,000 perished in Beichuan, around two thirds of the population. More than 1,000 were killed in Beichuan Middle School from a landslide on one side of the valley (Figure 14b) and 1600 perished under the Wangjiayan landslide on slopes on the opposite side of the valley. The Wangjiayan landslide caused the highest number of fatalities for a single landslide during the earthquake with the air blast from the landslide sufficiently strong to destroy buildings on the edge of the runout zone.
- Zipingpu dam – this is the largest dam in the region which is a 156 m high concrete faced rockfill dam designed for a seismic loading of 0.26 g. The dam is situated 10 km east of the epicenter and experienced a maximum horizontal acceleration of 0.7 g and vertical acceleration of 0.5 g at the crest (Wang 2009b). The following damage was suffered (Figure 15a):
 - Subsidence of the crown in the central part of up to 0.81 m with 0.3 m horizontal movement,
 - Deformation of the lower downstream face over an area of about 1000 m²,
 - Deformation of structural elements through out the face of the dam including widening of construction joints up to 15 cm in the upper face,
 - Landslides throughout the reservoir slopes.



a



b

Figure 14: Examples of earthquake damage and destruction from Yingxiu Middle School; a - classroom building, b – collapsed first storey of dormitory building



Figure 15: Examples of earthquake damage and destruction; a – overview of destruction at Beichuan Town, b – Beichuan Middle School landslide, c – fault rupture in school playground at Bailu Town, d – downstream face of Zipingpu dam, e – collapsed middle span of Xiaoyudong Bridge

The total reservoir volume of the dam is approximately 1.2 billion m³ of water. After the initial survey of damage, the reservoir was discharged through the emergency spillway to lower the water level. However, only a low increase in overall seepage flows (<15 l/s) was recorded and inspection of the grouting gallery indicated no serious damage to the grouting curtain or interior of the dam (Wang, 2009b). Repair works were completed within 3 months and power generation was resumed. One hundred fishermen were reported to have been killed

by 10 m high waves in the reservoir during the earthquake. These seiche waves may have resulted from the combined effects of landslides entering into the reservoir and earthquake shaking.

Xiaoyudong Bridge – the bridge suffered collapse of a middle and side span (Figure 15b). The side span collapse was due to surface rupture of the newly discovered Xiaoyudong Fault, which is a transform structure linking the primary, central fault and front range fault. The fault strikes under the bridge approach and at this location the fault moved approximately 0.5m. The reason for collapse of the middle span is less clear, however, it may have buckled from longitudinal compression. Inspection during the field visit suggests there were no bearings holding the deck onto the support beam. A temporary crossing was initially constructed as the bridge is an important transport link between Pengzhou city and Longmen town. This temporary crossing subsequently became the site for the new bridge, now completed, which happens to also be directly along strike of the Xiaoyudong Fault.

7 CONCLUSIONS

The May 2008 Wenchuan earthquake qualifies as an extreme geo-disaster due to the low probability-high consequence nature. Primary controls on the extensive devastation include the high magnitude, shallow depth and long duration of the seismic event, the strong vertical component of movement due to the imbricated thrust tectonics that controlled movement and the fact that deformation was not constrained to the main rupture plane but also occurred along secondary structures between bounding faults within a structural zone some 50-70 km wide and 500 km long.

Disasters of this size often go beyond the jurisdiction of normal design and construction of engineering structures and do not usually attract the technical attention of the geotechnical profession. However, study of these extreme events can provide valuable insight into the performance of structures and natural slopes under severe loading which can lead to:

- Improving our knowledge of both the regional and local geological conditions, particularly “fragile” geological structures, which is fundamental to the geotechnical models underpinning engineering design,
- Enhancement of our knowledge of the geohazards that are triggered by extreme events,
- In particular, increasing our understanding of controls on instability of natural slopes for both small and large scale failure mechanisms including the impacts on transportation systems, settlements, major engineering systems such as dams and natural systems such as sedimentation and drainage and
- Improving standards and codes for design and construction.

Over time this will assist with improving how risk to life and property is assessed, not only under extreme hazards but also for higher probability-lower magnitude events which control the normal design of engineering structures. While the wider discussion continues as to whether or how extreme events should be accounted for in engineering design, improved knowledge and understanding of extreme natural disasters can be used to progress land use planning to mitigate the risk, at least at the regional to district scale.

For Australian geo-practitioners a particular issue that arises from the Wenchuan experience is the reliance or otherwise on modelling of historic earthquake records in the seismic design codes. Given the intra-plate, continental setting of Australia where the seismic cycle time is longer than the recorded history, perhaps more attention should be given to neo-tectonics and paleoseismology rather than relying entirely on modelling.

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