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1.0 Introduction

The Lushan earthquake occurred at 8:02 am local time, April 20, 2013. This earthquake is the result rupture on a nearby / adjacent fault segment from the great M 8.0 Wenchuan earthquake of May 12, 2008. The ruptured fault segment in 2013 was located south of the southern end of the rupture in the 2008 event. The distance between the Lushan EQ epicenter is about 83 km SSW of the Wenchuan EQ epicenter.

While the USGS lists the earthquake as moment magnitude 6.6, various other Japanese and Chinese agencies list the earthquake as surface wave magnitudes between 6.9 to 7.0.

The following highlights the findings from the ASCE TCLEE EIC team (J. Eidinger, A. Tang, C. Davis) that visited the epicentral areas on May 27, 28 and 31, 2013 as well as interviewing local individuals who had been to the area. This report places a special emphasis on the "lessons learned and implemented" since the 2008 earthquake.

This report primarily covers the Lushan City area. Lushan City has a population about 25,000 people, as well as some towns and villages within 50 km of Lushan City.

Within Lushan City, the estimated ground motions were generally between PGA = 0.25g to 0.35g, soils generally being firm. Within Lushan City, there were some localized liquefaction effects, and there were no landslides within the main city area. Outside of Lushan City, ground motions were locally higher (closer to the epicenter), and there were many landslides and rockfalls in steep canyon areas.

1.1 Key Findings

This earthquake can be considered a subsequent earthquake of the 2008 M 8.0 earthquake. In other words, the 2008 event placed additional stress on nearby faults, and accelerated the time to which the nearby faults break. Given that the five year interval of time between the two events (2008 to 2013) was long enough to implement some mitigation measures, the purposes for the ASCE team investigation were three-fold:

- First, document the damage (or non-damage) to lifelines.
- Second, describe the "lessons learned" in this area of China with respect to the difference in earthquake hazard mitigation in the five intervening years. This covers both emergency response, as well as seismic design and construction practices.
- Third, describe the implications of the good and bad lifeline performance in the Lushan earthquake, and how these might be considered in US practice.

The following highlights the key findings.

Comparison of the 2008 and 2013 Earthquakes

Table 1-1 lists some parameters that compare the 2008 and 2013 earthquakes.

	2008	2013
Magnitude, M	8.0 Ms	6.6 Mw (USGS)
Epicenter	31.0367N 103.3329E	30.277N 102.937E
Fault Type	Reverse Thrust	Reverse Thrust
Depth, km	19	14 (12.9)
Rupture Area, km^2	330x25	20x25
Azimuth		218° (223.5°)
Dip		39° (80°)
Maximum MMI Intensity	XI	IX
Affected area	Large	Small
Fatalities	87,000	196
Economic Loss	Large	Small

Table 1-1. Comparison of the Two Earthquakes. Values in () are from non-Chinese sources

Damage to Lifelines

There was widespread damage to critical lifelines. We observed no seismic design practices for buried lifelines built pre-2008 or during the 2008-2013 time period; they suffered substantial damage, resulting in widespread and locally lengthy service outages. We observed no seismic provisions for high voltage electrical equipment; there was extensive damage at the Jinhua 110 kV substation.

Lessons Learned

The emergency response was generally good in the 2013 Lushan event. Rapid mobilization by nearly 10,000 emergency responders helped reduce the impacts of the earthquake. The response was faster and more comprehensive than in the 2008 earthquake, reflecting both lessons learned, as well as the relatively smaller affected areas in the 2013 event.

The seismic code for this part of China was increased from "zone VI (pre-2008)" to "zone VII (post-2008)". The implications are that at zone VI, there are essentially no seismic design provisions for lateral loads; but for zone VII, the design of regular building stock is for PGA = 0.1g. Given the high seismic activity and hazard for this region of China, and following US practice, the minimum upgrade could have been for PGA = 0.3g (or higher), but this was not implemented by China, reflecting that "China is a developing country" and "cannot afford" high seismic design practices.

New building construction in Lushan, post 2008, had some measure of seismic design. This included one base isolated hospital which was designed by third parties outside of mainland China, and performed generally very well; and one water treatment plant, also designed by third parties outside of mainland China: water retention basins performed well, buildings and chemical equipment performed poorly. Several governmental multi-story buildings were built to the "updated" seismic code; some were "red-tagged" (no occupancy a month after the earthquake). Overall, post-2008 buildings in Lushan that had been designed to the latest Chinese code (PGA = 0.1g) sustained significant damage.

Implications for US Practice

Buried water pipelines. The Lushan water system uses buried cast iron and PVC pipes (no seismic design). The water distribution system performed poorly, with sufficient damage to basically shutdown almost the entire distribution system. There was not a lot of liquefaction or landslide movements in Lushan, so the damage to the buried pipes is assumed to be attributed largely to the effects of strong ground shaking. Implications for US practice: similar performance can be expected by all US water systems that have not implemented latest seismic design practices for buried pipes; especially smaller systems that lack a great deal of redundancy or work forces able to make rapid repairs. ALA (2005) provides recommended seismic design practices for buried water pipelines.

High voltage substations. The high voltage substations in Lushan experienced heavy damage. Installation practices at these substations is similar to those in the US pre-1975. The Chinese do not follow modern seismic design practices (such as IEEE 693 and IEEE 1527); had they done so, the bulk of the damage would likely have been avoided. The implications for US practice are that it is recommended to implement IEEE 693 and IEEE 1527 and ASCE substation seismic design guidelines.

In one corner of one substation, with low voltage equipment, there was permanent movement of the underlying embankment; this imposed corresponding movements on the equipment, resulting in damage due to inadequate slack in the bus to accommodate such movement. The implication for US practice is to ensure that embankments have no / little movement in the design earthquake; and allow for extra slack in these areas (similar recommendation for liquefaction zones).

Seismic Codes. Following the 2008 earthquake, the Chinese "increased" the seismic zone for Lushan area from Zone VI (de-facto no seismic design) to Zone VII (PGA = 0.1g). A similar code-upgrade effort was implemented in Christchurch New Zealand after the 2010 and 20011 earthquakes (PGA = 0.22g before 2010, = 0.30g post-2012). In both cases, the underlying natural hazard phenomena would suggest that should future near-field earthquakes occur, actual PGA levels might commonly be 0.40g to 0.6g or so (locally higher). For the USA, the implications are that the seismic design standards for relatively lower seismic hazard areas (like Memphis, Charleston, Boston, Montreal) have been either non-existent or very low in the past (less than PGA = 0.10g), and that modern (IBC 2012) practices require much higher design levels (PGA= 0.25g to 0.35g typically). Even so, the bulk of the built inventory remains with little seismic design, and widespread damage must be expected for such inventory when they are exposed to near-field earthquakes. The implication of US codes that "design to high levels of PGA like 0.4g to 0.6g, is not cost effective" implies that society accepts a huge seismic risk in these cities, and for similar situations. Politicians and the general population are likely to be displeased and find the outcomes unacceptable when earthquakes occur in these lower seismic hazard zones of the USA and Canada. As our knowledge of return periods for "eastern seismicity" is sparse, over-reliance on "probabilistic" ground motions in current codes implies that heavy damage in places such as Montreal, Memphis, Charleston and Boston is a near certainty.

Lifeline operators in the US and Canada (especially those in the Eastern US / Canada) should seriously consider adopting a minimum seismic design requirement for new construction, such as PGA = 0.3g plus concurrent geotechnical implications, given the importance of the lifelines to society's well-being. With regards to existing lifeline infrastructure that lacks any seismic design, it is recommended that lifeline operators consider large-scale replacement over a 50-year time frame, (with priority given to key buried utilities that traverse zones subject to liquefaction or landslide, as well as all critical non-redundant above ground facilities) as these older assets age and need functional replacement.

Base Isolation. The one base isolated buildings in the epicentral area (Lushan Hospital) performed well. The "second mode" effects due to the impact of the foundation with the adjacent ground appeared negligible. The design of utilities across the base isolation boundary was not very good for the actual Lushan hospital, and many essential services were broken. Components and function of the building remained serviceable as soon as external lifelines were restored (water, power, etc.). Overall, the performance of the base isolated Lushan hospital was very good, and confirms the effectiveness of this design approach. This suggests that base isolation should be considered a viable design alternative for low to midrise buildings at suitable sites in the US.

1.2 Investigation Team

The Post Earthquake Investigation Committee of the Technical Council on Lifeline Earthquake Engineering (TCLEE), a technical council of the American Society of Civil Engineers (ASCE) organized a reconnaissance team to perform reconnaissance of the lifelines in the earthquake area. This group is referred to herein as the investigation team. The investigation team started the reconnaissance effort on May 26, 2013 and completed on May 31, 2013.

The investigation team consisted of the following ASCE members:

Mr. John Eidinger (team leader), G&E Engineering Systems, Inc., eidinger@earthlink.net

Mr. Alex Tang, L&T Engineering, alexktang@mac.com

Dr. Craig Davis, Los Angeles Department of Water and Power, craig.davis@water.ladwp.com

1.3 Acknowledgements

The investigation team was supported by many people. Their support made this investigation possible. Surnames for Chinese names are capitalized.

Dr. Tao LAI (AIR Worldwide) supported the field effort for one day.

Mr. Marshall LEW (AMEC) supported the field effort for one day.

Dr. Endi ZHAI (Klenifelder, aka Dr. EZ) supported the field effort for one day.

Professor Jianlin MA, of the Southwest Jiaotong University provided information of sites to visit and support of our logistics. Mr. YANG Yanxing, Professor Ma's geotechnical engineering graduate student, supported the field trips.

Dr. Jiping YAN and Dr. Jianping HU of the Los Angeles Department of Water and Power assisted with interpretation of Chinese to English documents and preparation of ground motions presented in Chapter 2.

Dr. LIU Aiwen, of the Institute of Geophysics China Earthquake Authority (CEA) provided information from his own field investigations.

Dr. DAI Junwu, Director, Division of Science and Technology, China Earthquake Administration.

Director CUI Junwei, and Ms. Susan WANG of the Sichuan Association for Science and Technology

1.4 Limitations

This report was prepared by John Eidinger, Alex Tang and Craig Davis of the ASCE TCLEE Earthquake Investigation Committee. The findings in this report do not necessarily reflect ASCE.

As in any earthquake investigation, not all information can be reported, and further investigations may reveal additional data that might change the findings in this report. We apologize for any inaccuracies that this report may contain.

Neither ASCE nor the authors of this report are responsible for use of information in this report by any party, for any purpose. Any use of this information in this report is entirely at the user's own responsibility.

1.5 Interpretation of Strong Ground Motions

In this report, we assign PGA values (usually in ranges, for example 0.35g to 0.45g, horizontal, mean of two horizontal directions) to locations where specific damage (or non-damage) was observed. When we assigned these values, we assume a corresponding response spectra for a firm soil site, with corresponding energy at all frequencies based on a presumed median spectra tied to the assigned PGA value. We assigned these PGA values based on the performance of the items being observed, as well as the performance of buildings and/or structures / equipment in the immediate vicinity (within 100 meters or so), as well as the styles of construction of these items.

For crustal earthquakes like the Lushan event, the standard error on the ground motions will typically mean that about 2/3 of all actual ground motions will be within ±50% of the median motion. Thus, if we estimated PGA = 0.40g, the reader should interpret this to really mean that the nearby motions were most likely between PGA = 0.20g and 0.60g.

In this report, we also report instrumental ground motion readings at various locations, from strong motion instruments. Within 50 km or so from the epicenter, instrumented ground motions (20 records) vary from as low as PGA = 0.15g to as high as 1.02g, averaging

The reader is cautioned that the observed estimated PGA readings do not necessarily correspond to the PGA value from the nearest instrument(s).

It is well recognized that strong ground motions can vary rapidly over short distances, especially for higher frequency components. Therefore, the reader should understand that the estimated strong ground motions are thought to be indicative of corresponding spectra at the dominant frequency of the item being observed.

1.6 Chapter Authors

The primary chapter authors are as follows:

Chapters 1, 3, 4, 5, 6, 9, 10, 11, 12: John Eidinger

Chapters 2, 7: Craig Davis

Chapter 8: Alex Tang

Due to the nature of post-earthquake investigations, it is quite possible that even though every attempt was made to verify the accuracy of the information in this report, this report could still contain inaccuracies and/or incomplete data. The authors apologize in advance to all those people who will point out new, updated or corrected findings and observations.

1.7 Abbreviations

ASCE	American Society of Civil Engineers
EIC	Earthquake Investigation Committee
g	acceleration of gravity = 32.17 feet / sec^2 = 981 cm / sec^2 = 981 gal
HDPE	High Density PolyEhtylene
km	kilometer
kV	kilo Volts
MMI	Modified Mercalli Intensity
M	Magnitude (moment magnitude unless otherwise mentioned)
PGA	Peak Ground Acceleration (g)
PLA	People's Liberation Army
PVC	PolyVinyl Chloride
TCLEE	Technical Council on Lifeline Earthquake Engineering

URM	UnReinforced Masonry
WTP	Water Treatment Plant

2.0 Seismic, Geologic and Geotechnical Issues

Figure 2-1 shows the general location of Lushan, Ya'an (at "A" marker") and the major city of Chengdu. The red ovals indicate the zones of highest ground shaking and damage from the 2008 and 2013 earthquakes (the ovals are not meant to be precisely located).

Lushan has a population of about 25,000 people (perhaps 50,000 people including nearby villages); Ya'an about 1.8 million and Chendgu about 10 million.

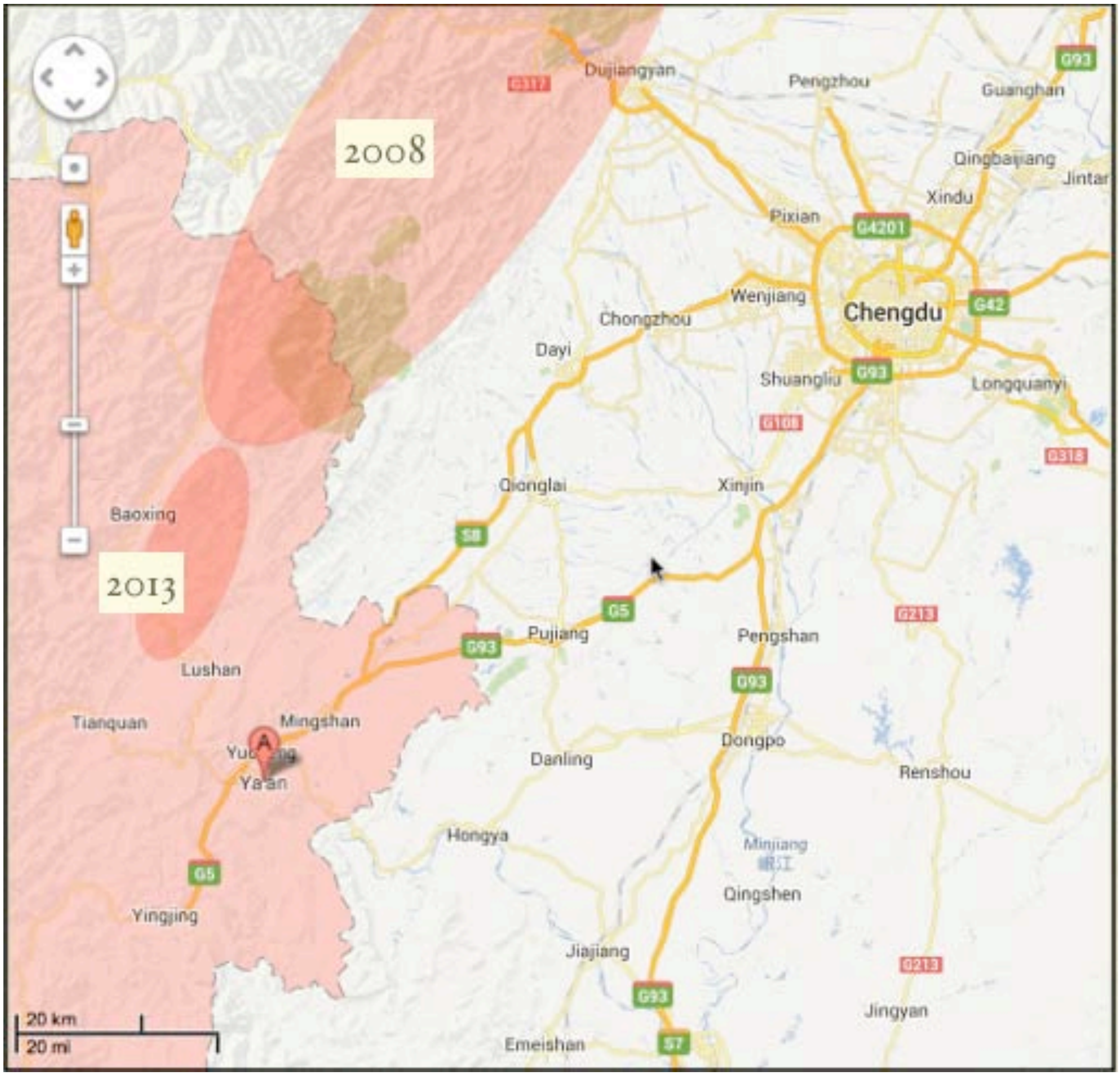

Figure 2-1. Regional Map (Base map copyright by Google)

Figure 2-2 shows five strong ground motion instruments that recorded the 2013 earthquake in the vicinity of Lushan. In Figure 2-2, the "1" point is in the southern part of Lushan. The epicenter of the earthquake was about 15 km north of point 1.

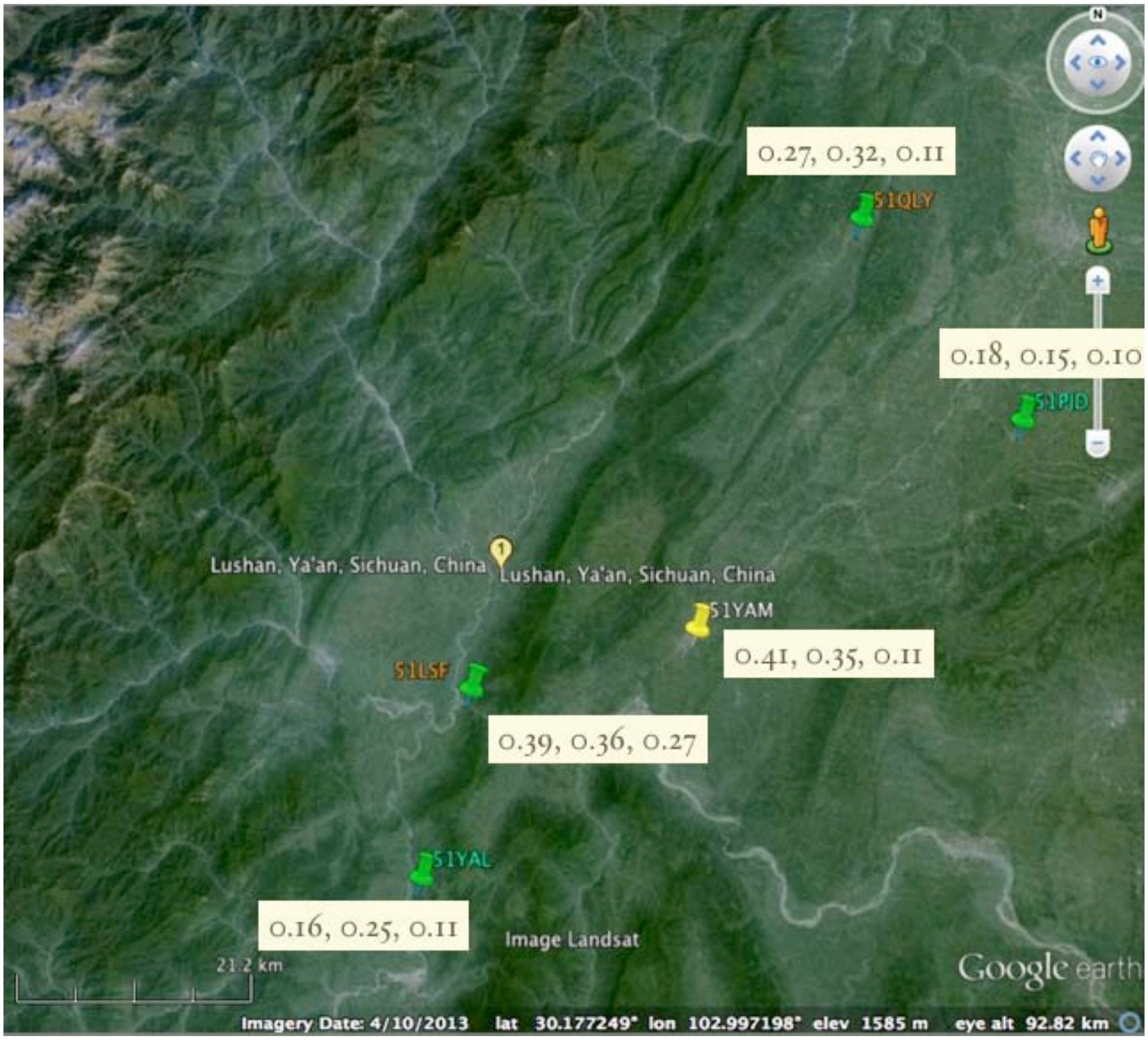

Figure 2-2. Recorded PGA Values (units in g, NS, EW, Vertical) (Base map copyright by Google)

About 123 strong ground motion instruments were triggered by this event. Table 2-1 lists the data for 16 strong ground motion instruments. The coordinate values have been rounded to the nearest 0.1 degrees per the request of Chinese authorities; the locations in Figure 2-2 are more precisely located for instruments YAM, LSF, QLY, YAL, PJD.

Station	Longitude °E	Latitude °N	Distance to Lushan Hospital (km)	Epicentral Distance (km)	Site conditions	PGA (g) EW	PGA (g) NS	PGA (g) Vertical
51BXD	102.8	30.4		19.4	Rock	-1.02	0.84	0.49
51BXZ	102.9	30.5		21.5	Rock	0.59	0.32	0.39
51BXY	102.9	30.5		26.5	Soil	0.44	0.30	0.25
51YAM	103.1	30.1	20	27.7	Soil	-0.41	0.35	0.11
51QLY	103.3	30.4	46	28.2	Soil	0.27	0.32	0.11
51BXN	102.7	30.4		30	Soil	-0.39	0.20	0.13
51LSF	102.9	30.0	15	32.6	Soil	0.39	0.36	-0.27
51YAD	103.0	30.0		35	Soil	-0.53	0.41	0.20
51PJD	103.4	30.2	50	40.8	Soil	0.15	-0.18	-0.10
51YAL	102.8	29.9	31	50.4	Soil	-0.16	0.25	0.11
51DXY	103.5	30.6		59.4	Unknown	0.003	0.008	-0.006
51TQL	102.4	29.9		73	Soil	0.28	0.29	0.15
51KDZ	102.2	30.1		81.8	Rock	-0.024	-0.027	0.020
51LDS	102.2	29.0		85.4	Unknown	-0.006	-0.007	-0.010
51DJZ	103.6	31.0		98.3	Soil	-0.075	0.080	0.031
51PXZ	103.8	30.9		99.3	Rock	0.013	0.012	-0.010

Table 2-1. Strong Motion Instruments Recordings[1]

The instruments BXD, BXN, BXZ, BXY all recorded strong motions, and are all located north and west of the epicenter, and are likely atop the hanging wall of the rupture. Instruments QLY and PJD appear to be on (or very near) the foot wall, and have lower motions.

[1] China Strong Motion Networks Center (2013a), Sichuan Ya'an Lushan M_w 7.0 Earthquake 3rd Report, published on April 21, http://www.csmnc.net/selnewxjx1.asp?id=795,
accessed June 27, 2013. Unnumbered instruments have estimated epicentral distances.

The absolute values of the maximum of the NS, EW and Vertical PGA motions are plotted in Figure 2-3, as a function of epicentral distance (perhaps a better parameter would be as a function of distance to the fault rupture plane, and this should be investigated in future work).

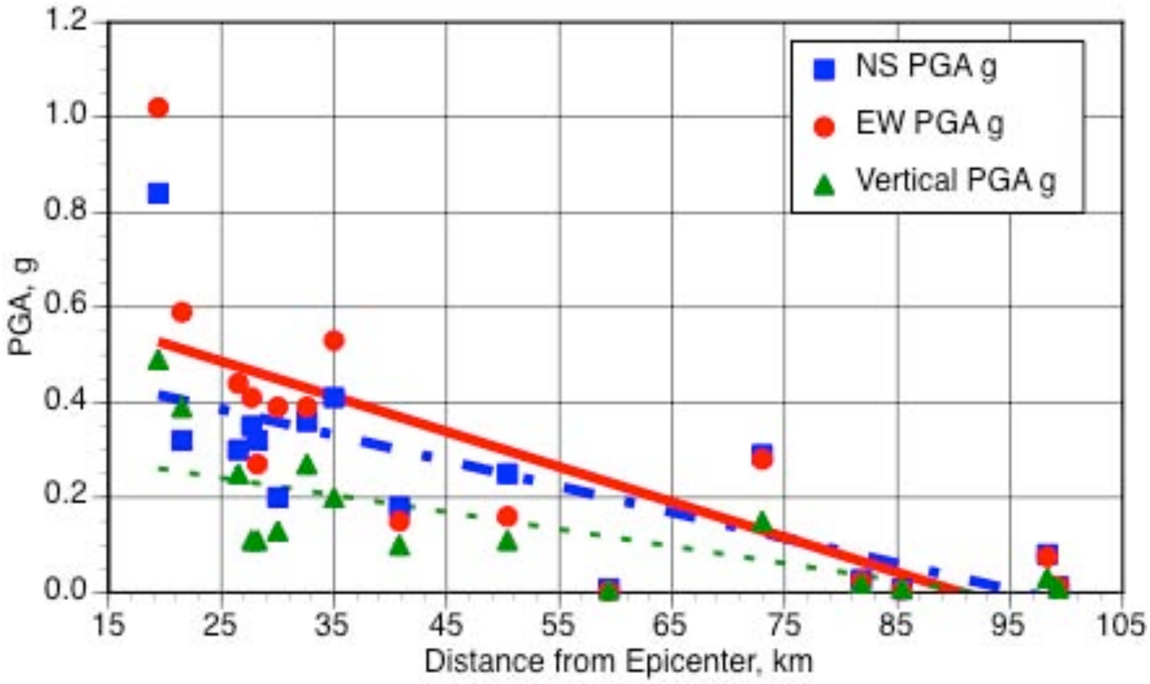

Figure 2-3. PGA as a Function of Epicentral Distance

The three straight lines are least square regressions through each data set. For epicentral distances between about 25 and 40 km, the NS average is about 0.35g; EW is about 0.41g, Vertical is about 0.23g.

Figures 2-4 through 2-14 provides selected recorded acceleration time histories. Points are uncorrected, 18,000 points per record, recording interval 0.005 seconds. The recordings generally show about 7 to 12 seconds (12 to 16 seconds in some cases) of strong ground motions (from the time PGA > 0.1g to the time PGA < 0.1g).

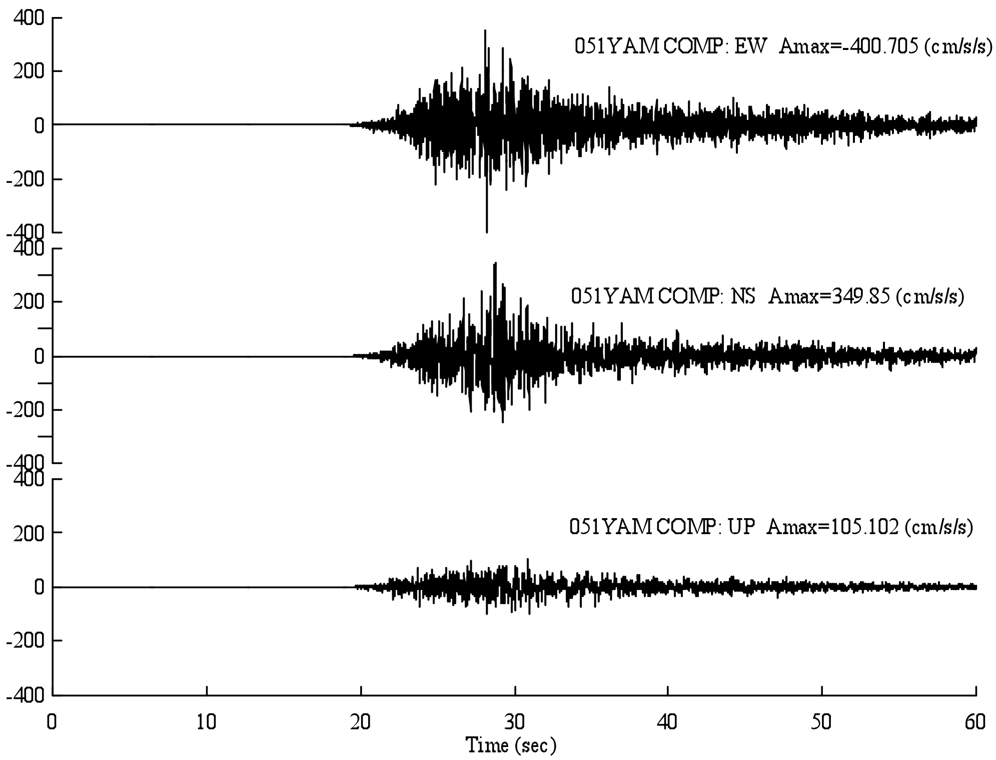

Figure 2-4. Time Histories, Instrument 51YAM

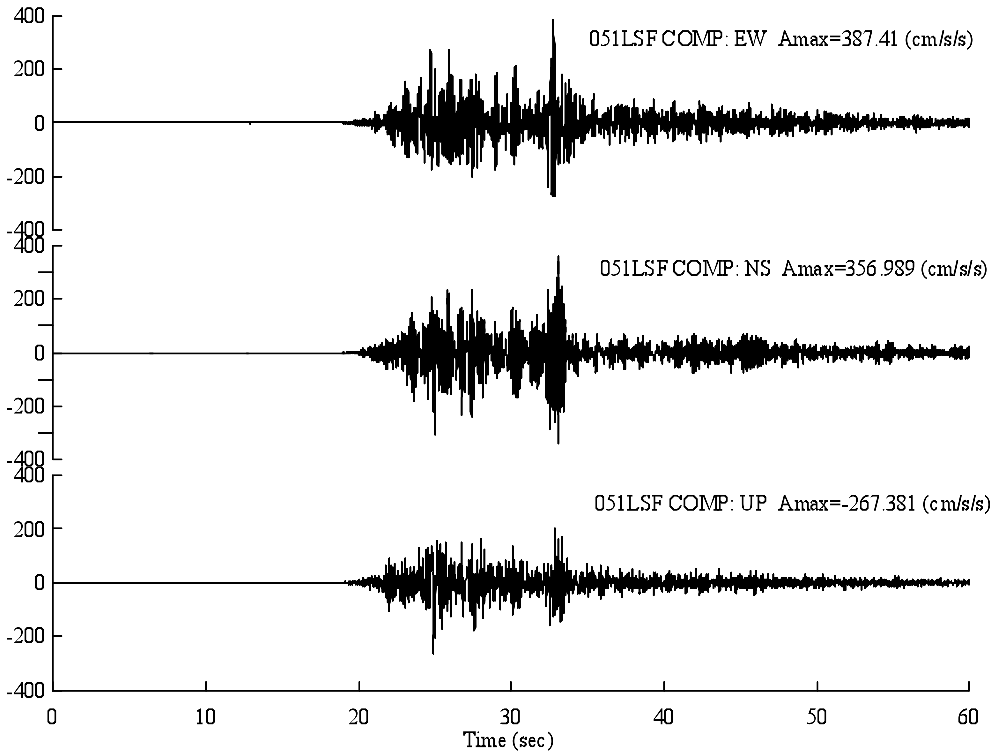

Figure 2-5. Time Histories, Instrument 51LSF

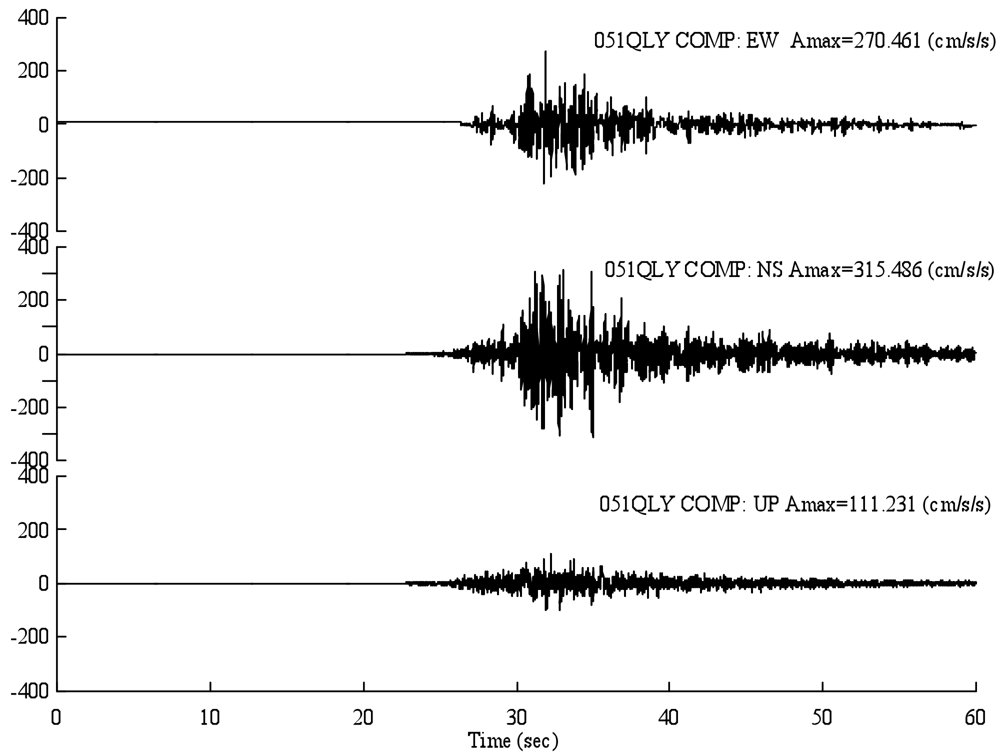

Figure 2-6. Time Histories, Instrument 51QLY

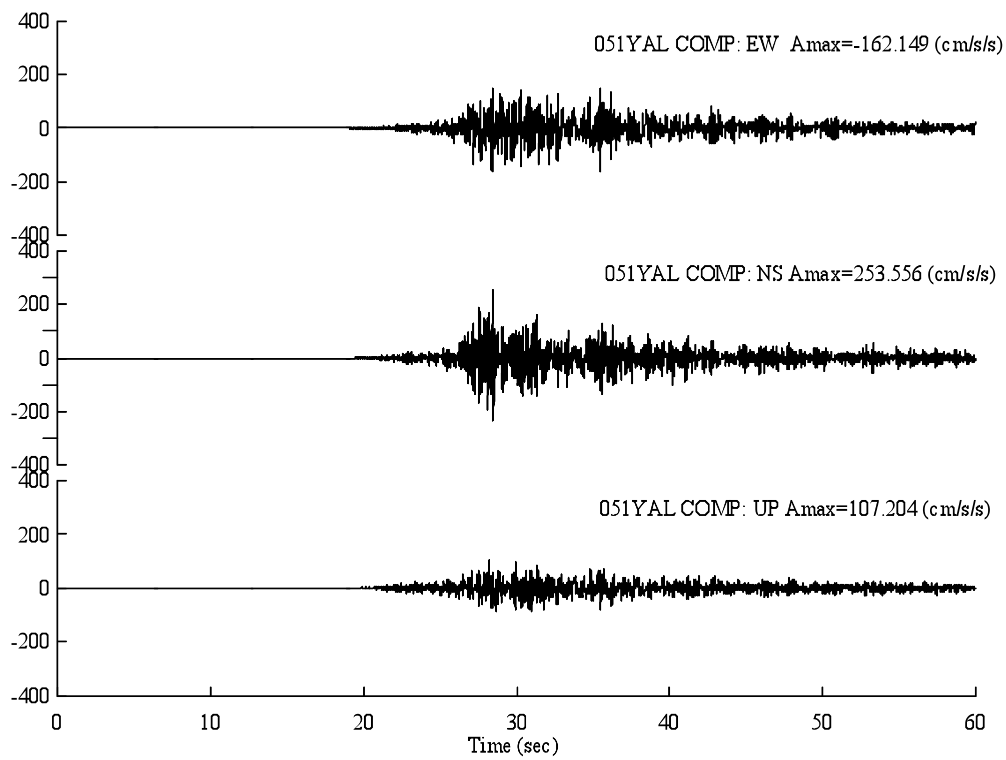

Figure 2-7. Time Histories, Instrument 51YAL

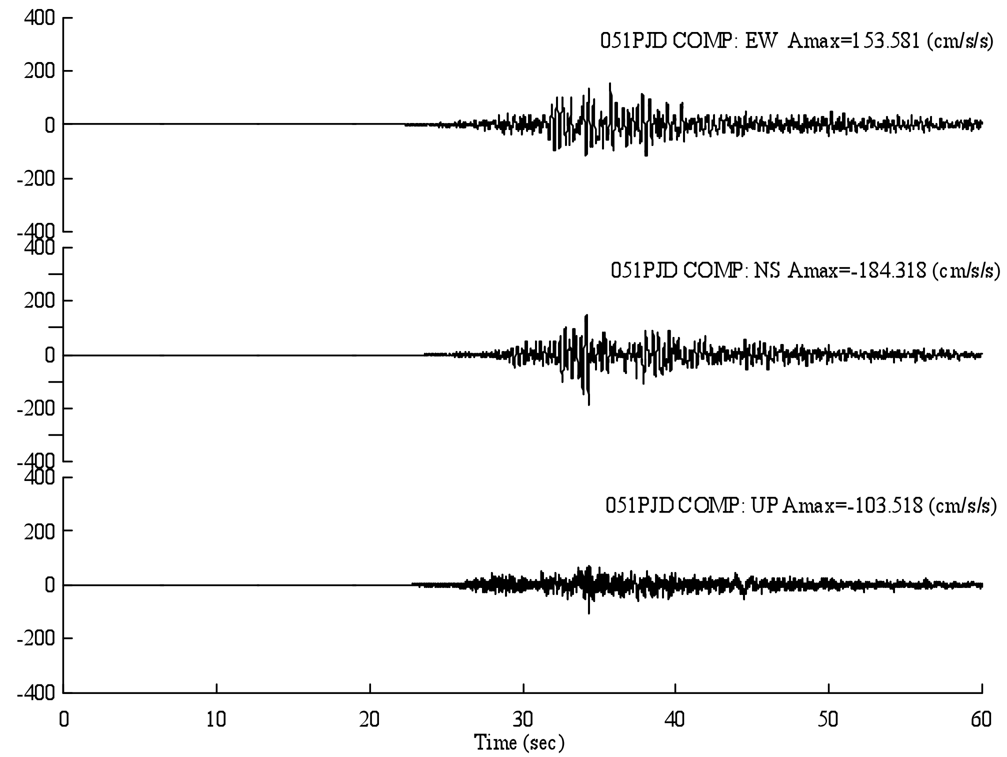

Figure 2-8. Time Histories, Instrument 51PJD

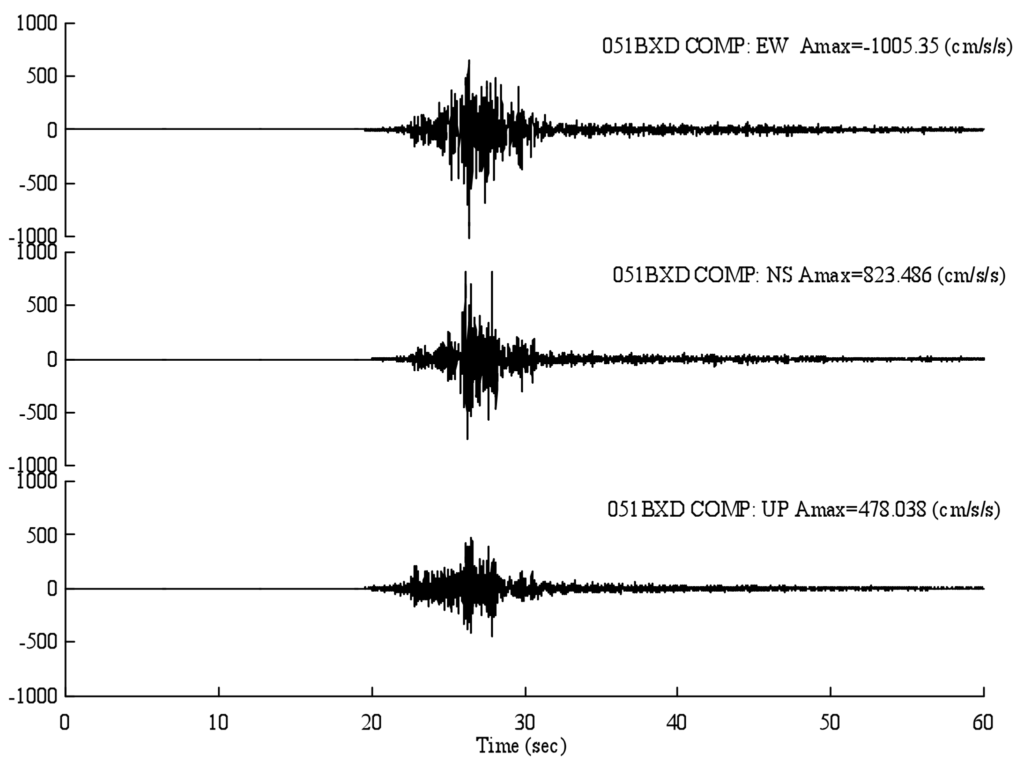

Figure 2-9. Time Histories, Instrument 51BXD

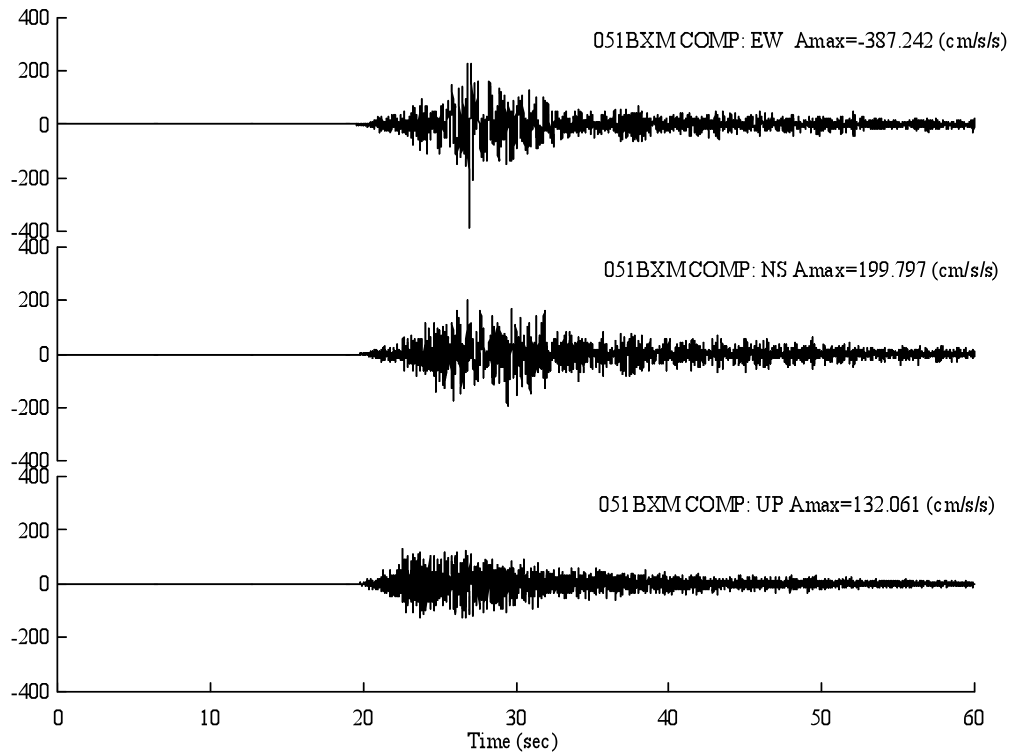

Figure 2-10. Time Histories, Instrument 51BXM

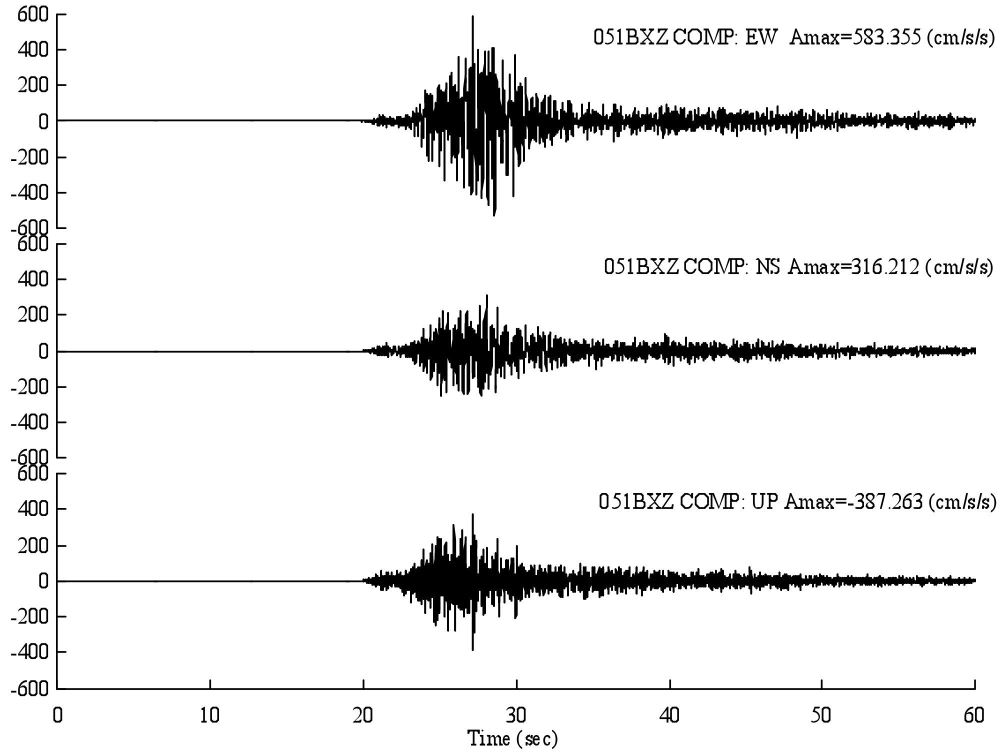

Figure 2-11. Time Histories, Instrument 51BXZ

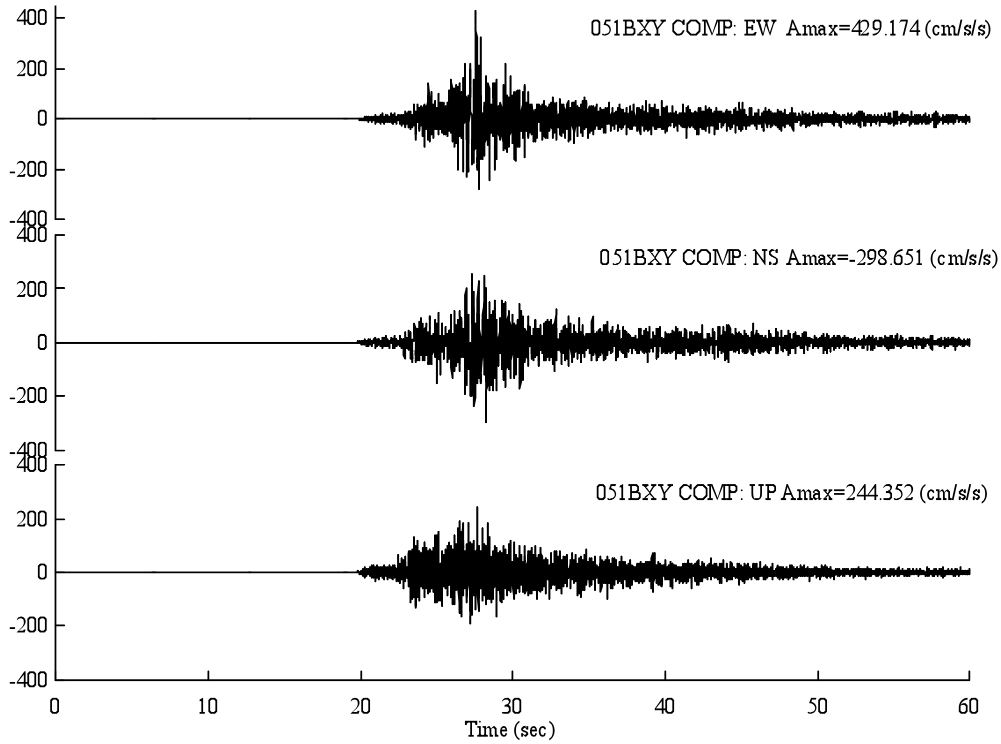

Figure 2-12. Time Histories, Instrument 51BXY

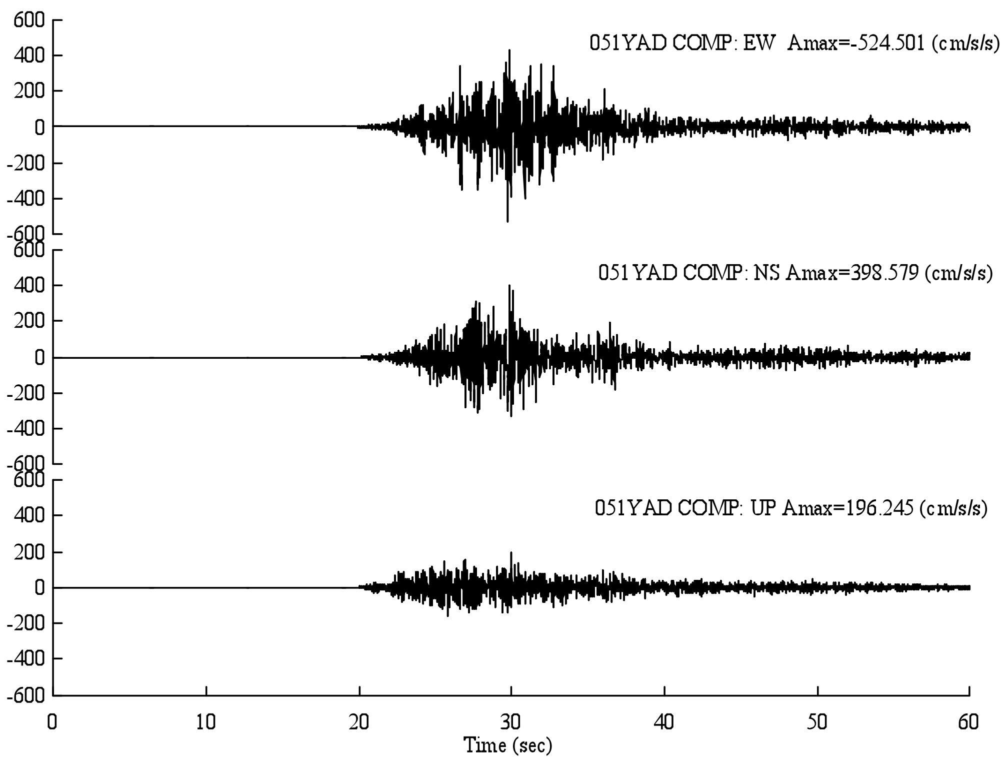

Figure 2-13. Time Histories, Instrument 51YAD

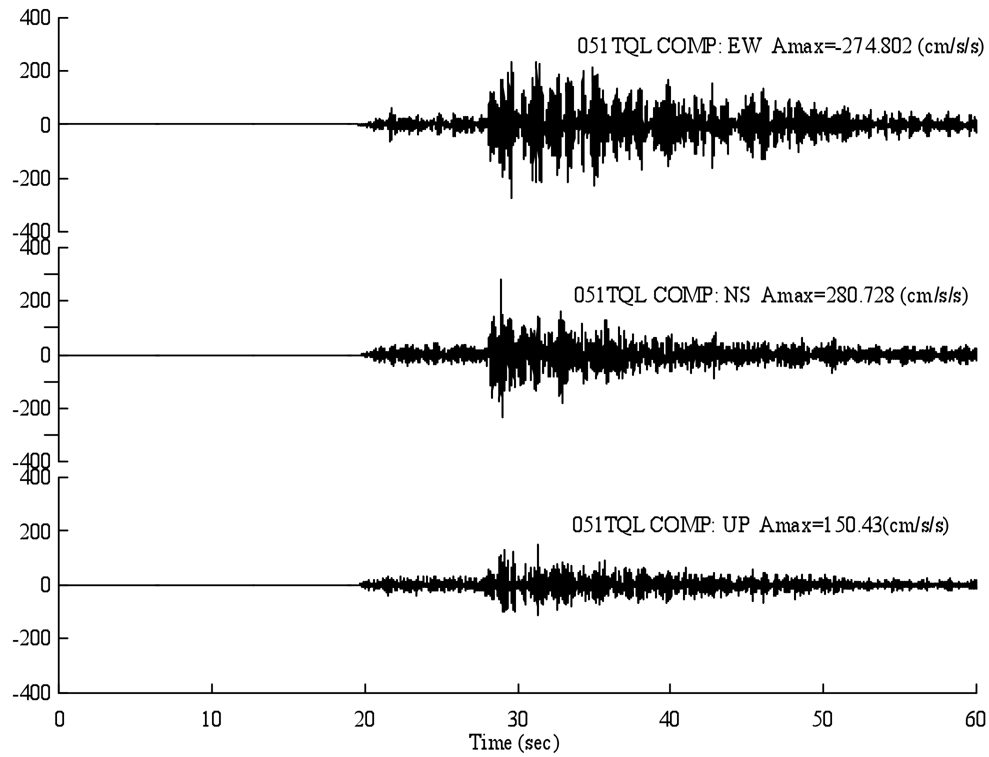

Figure 2-14. Time Histories, Instrument 51TQL

Figure 2-15 shows a map of observed MMI values. The star represents the epicenter. Red dots are MMI 8 to 9. Orange dots are MMI 7.5 to 8. The largest cluster of orange dots, just south of the cluster of red dots, represents the older parts of Lushan City. The red dots represent relatively low populated areas, including a village and narrow valley northeast of Lushan City, heading towards the epicenter. Figure 2-16 takes the raw data from Figure 2-15 and creates a simplified MMI map.

The ASCE team visited several of the sites in the MMI VIII and IX zones, and concurs with the general description of the MMI values. As with all MMI values, the range of performance of adjacent buildings can vary widely, so the reader is cautioned that there is more variance in local performance of structures than might otherwise by indicated by these maps.

Based on our observations of performance of unreinforced masonry buildings, and slippage (or non-slippage) of unanchored items, we estimate the general level of shaking in Lushan City at about PGA = 0.25g to 0.35g (locally higher or lower), with possibly not much long period energy (based on lack of high water slosh levels in reservoirs).

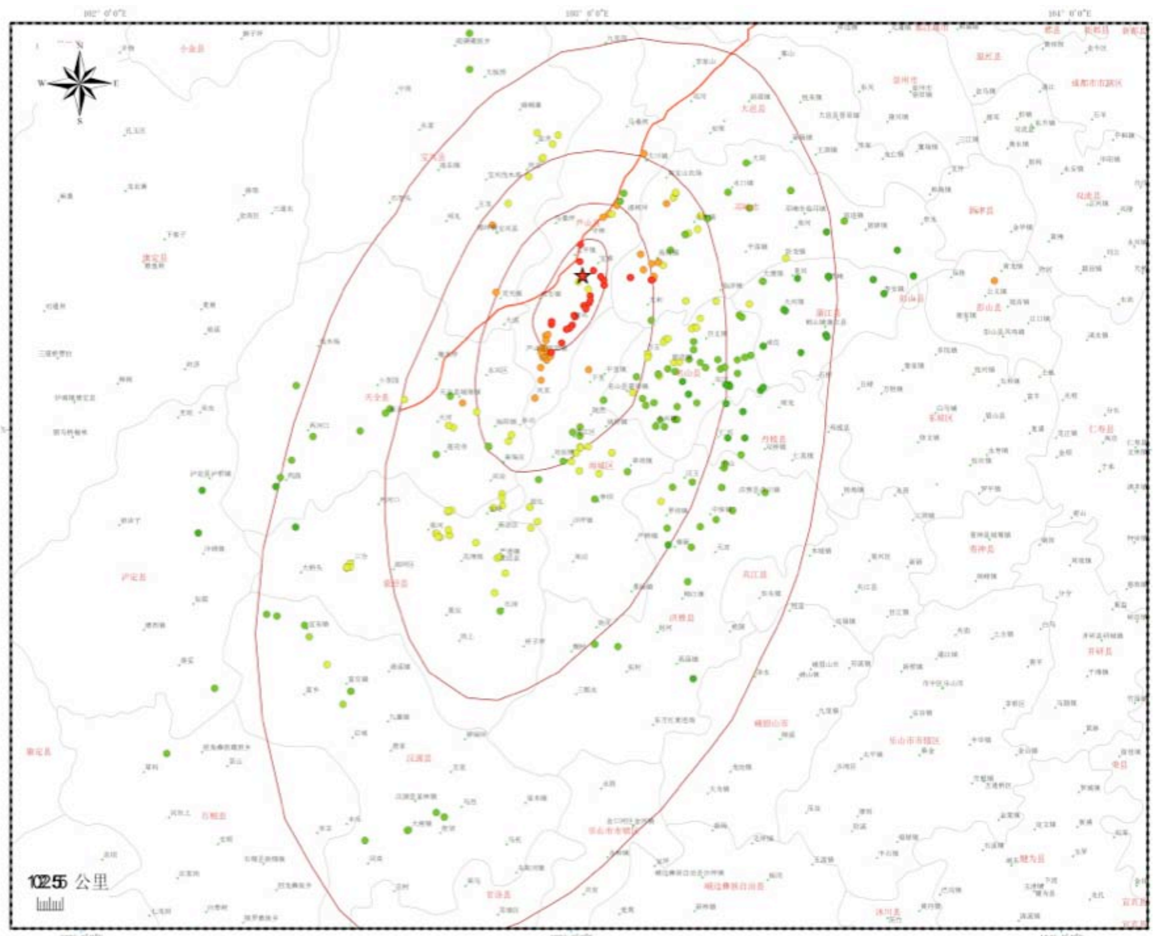

Figure 2-15. Observed MMI Intensities

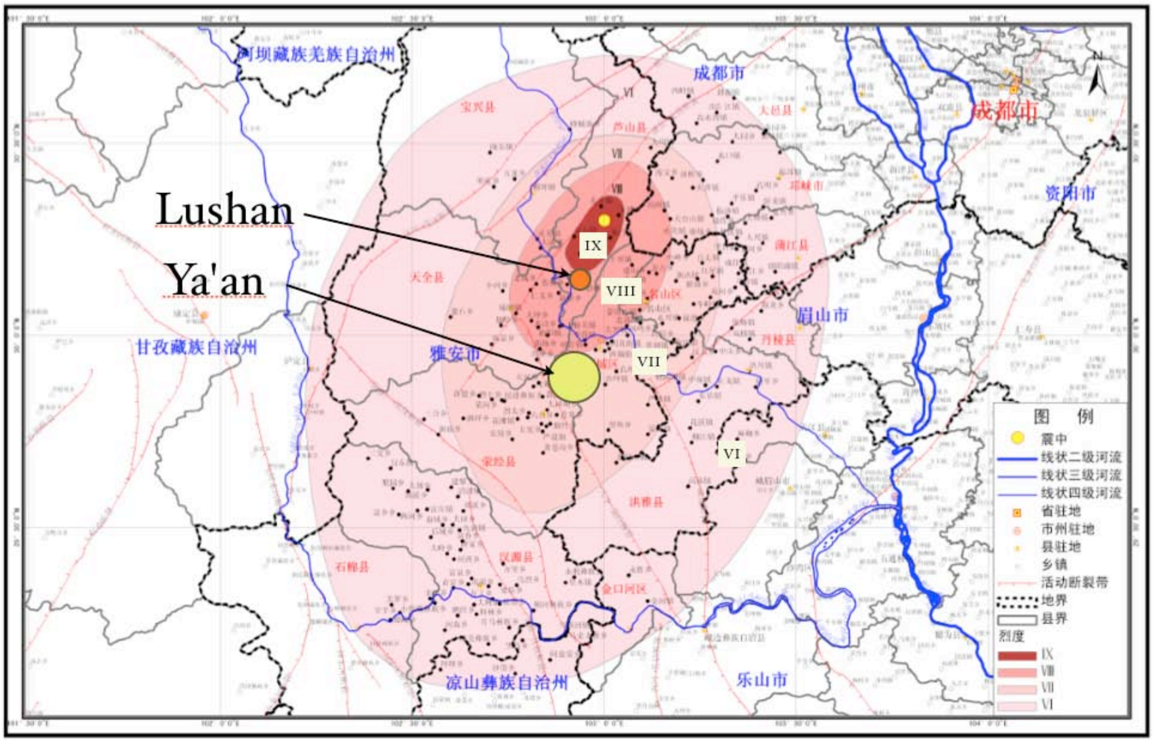

Figure 2-16. Interpreted MMI Map

Interpreting the ground motion recordings radially from the epicenter, one may expect shaking levels in Lushan to be larger than the values reported in Table 2-1 for 51LSF and 51YAM south of the epicenter due to Lushan's closer proximity to the epicenter and fault rupture plane. As seen in Table 2-1, uncorrected near-field recordings reached 1.0g. Station 51YAD (NS PGA = 0.53g) is at Ya'an City and stations 51YAM (NS PGA = 0.41g) and 51LSF (NS PGA = 0.39g) are just northeast and northwest of Ya'an City, respectively.

Note that Ya'an City is large, and the dot location for Ya'an City is not representative of its areal boundary. In the northern part of Ya'an City that was visited by the ASCE team, we observed little or no damage, even for unreinforced masonry structures, indicate of motions commonly in the range of PGA < 0.15g; this corresponds well with the MMI VI to VII range for Ya'an City in Figure 2-16.

The two highest recorded PGA motions, BXD and BXZ, are both on the hanging wall side of the rupture, well north of Lushan City. For more then a decade, it has been recognized that thrust events produce higher motions on the hanging wall side than on the foot wall side, and this effect appears to also have occurred in this event. More study of the ground motions is contemplated for the future.

The sense of the faulting was reverse thrust, up to the northeast. The fault slip is suggested in Figure 2-17, with dark red = 1.4-1.6 meters, red = 1-1.4 meters, orange = 0.8-1.0 meters, yellow = 0.6-0.8 meters, light yellow = 0.4-0.6 meters, green = 0.2-0.4 meters, white = 0-0.2 meters.

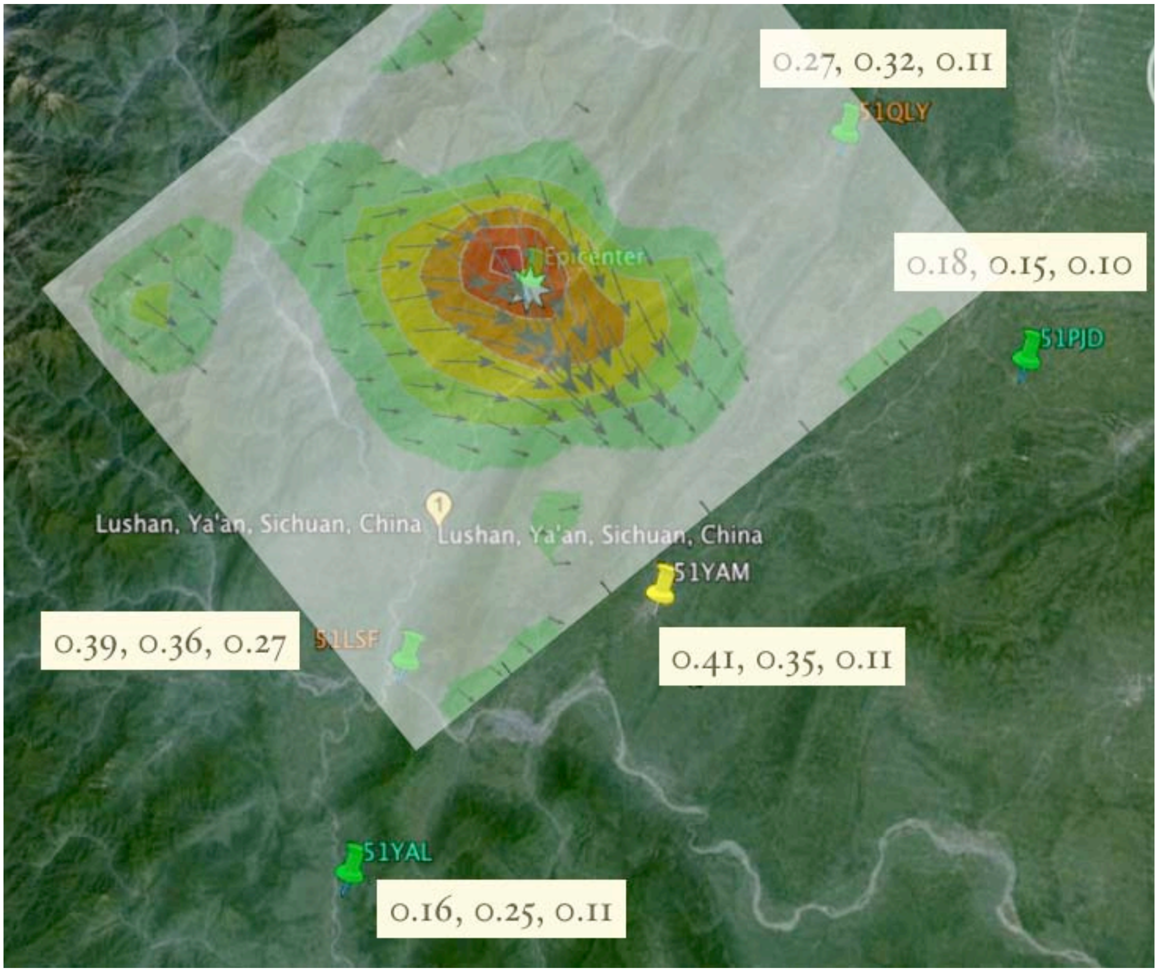

Figure 2-17. Fault Slip on the Rupture Plane (base map by Google)

The City of Lushan is on terraced deposits. In the US, those would typically be classified as either "C" (thin firm soil over rock) or "D" (firm soil). There was sporadic evidence of liquefaction (floating of sewer manholes, buckling of sidewalks).

There was little evidence of landslides within Lushan, although we did observe many slumps due to failure of retaining walls.

Outside of Lushan, there were many landslides, with more than 700 mapped (so far). Roadways in steep canyons were impacted. We estimate that where PGA > 0.3g, about 20% of steep slopes (40° or steeper) failed. Unlike the 2008 Wenchuan earthquake, the slope failures did not generally impact human dwellings… but many small farms were impacted by rockfall and deep seated slides.

Figures 2-18 and 2-19 show typical landslides (PGA values are estimated based on observations of nearby structures). In most cases, the buildings for human occupation were located well set back from the base of the steep slopes, and there were few cases of landslide impacts to people. We suspect that this de-factor "zoning" was derived from a long history of intense-rainfall-caused landslides, resulting that only low occupancy activities (like farming) were allowed at the base of steep hills.

Figure 2-18. Landslide (Bare rock area of mountain)

Figure 2-19. Landslide (Bare rock area of mountain)

Figure 2-20. Rockfall into road and damage of power poles

We did not observe surface fault rupture. As of May 31, 2013, no surface fault rupture had been located, indicating this may have been a blind thrust event. Restrictions by the local police and PLA restricted the ASCE team from fully exploring the entire vicinity above the fault rupture (generally mountainous with just a few small villages, population under 2,000), but in the areas that we did visit, there was collapse of about 30% of the regular building stock.

We did observe some evidence of liquefaction in Lushan, and this will be discussed in the chapters on water and wastewater systems.

Chapter 2 Acknowledgements

Dr. Aiwen Liu of the Institute of Geophysics China Earthquake Authority is acknowledged for generously providing investigation data from the April 20, 2013 Lushan Earthquake, including Figures 2-15, 2-16, and 2-17 fault slip. Dr. Jianping Hu of the Los Angeles Department of Water and Power assisted in obtaining and preparing ground motion recordings in Figures 2-4 to 2-14. Remaining photos are by Craig Davis, Alex Tang, John Eidinger.

3.0 Seismic Building Code

Since the Wenchuan 2008 earthquake, the Lushan area had been "up-rated" from seismic zone VI to seismic zone VII, per Chinese code. Zone VII translates to design of new buildings for PGA = 0.10g (regular building stock with I = 1.0). The code also allows an increase or decrease of seismic forces for ordinary buildings (I = 0.6) or important buildings (I = 1.25 to 1.5). Like US codes, the Chinese code includes factors to account for spectral amplification and ductility. For the case of I = 1.0 and a ductile high frequency structure (about 5 hertz), the equivalent US base shear would be about V = 0.03W (for PGA = 0.10g zone).

In other words, the newly-up-rated Chinese code only requires about one-fifth of the seismic base shear as was required by the California building code through about 1988 (V = 0.14W) or current (V = 0.18W) in moderately high seismic regions of California. Chinese officials state that the low level of seismic design (PGA = 0.10g) in this area of China reflects that "China is a developing country" and the relatively lower wealth of this part of China. From a US perspective, the introduction of economic variables into setting of prescriptive seismic design levels implies that society is seeking a "cost effective" solution, balancing initial construction costs against annual probability of earthquakes and their resulting impacts on society (killed and injured people; loss of economic assets and economic function). Therefore, applying the earthquake code for California (high economic activity, high value of life) to China might not be directly applicable, owing to different economic factors and values of life. Even so, given the occurrence of an actual earthquake, with ground motions well in excess of the design target, the natural result will be fatalities (197 killed people reported in this earthquake), injuries (11,826 injured people reported in this earthquake, of which more than 968 people seriously injured), damaged buildings (thousands in this earthquake), and loss of regional economic activity.

There is no national code for lifelines in China. Many universities in China are involved in testing and research works on IEEE 693 standards for electric power substation transformers. They were also involved in IEC standards (including seismic provisions) for telecommunication systems.

4.0 Electric Power System

Overview

The power system for Lushan is operated by the State Grid, the same company that operates the high voltage power network for all of Sichuan province; and that had suffered major damage in the 2008 earthquake.

The City of Lushan is supplied with power from two 110 kV substations. One of these substations suffered widespread and serious damage; the other had less damage. North of Lushan, there are a number of penstocks and small hydro electric power plants in the mountainous areas; several were heavily damaged.

The speedy recovery of damaged substations was a result of the order from Premier Li (李克强总理) that prioritizes the need of functioning lifelines.

Substations

The following observations are at two substation locations in Lushan City with PGA > 0.25g.

The equipment and buildings at the two high voltage substations (110 kV is the highest voltage at substations in the epicentral area) showed no lessons learned from the 2008 earthquake.

Unanchored power transformers (110 kV) were used at both 110 kV substations. It appears that every 110 kV transformer that was in the epicentral area (PGA > 0.25g) had functional failures due to damage of bushings or radiators; sliding of the transformers up to 30 cm was observed.

Substation 1. Lushan, Jinhau (金花)110KV Substation .

The site is located on a gently sloping hillside, with the yard formed using cut-and fill methods. We estimate PGA = 0.30 to 0.40g at the site.

The site is surrounded by an unreinforced masonry wall. About a third of the wall was damaged due to inertial shaking, Figure 4-1. Also seen in Figure 4-1 in the control building (it had major x-cracks, see Figure 4-3) and dead end structure for low voltage feeder circuits (two of the disconnect switches were damaged). Unlike the gross failure of dead end structures at Ertishan substation (2008 earthquake), we did not see failure of the precast concrete – steel lattice dead-end structures in the 2013 earthquake; this "improvement" is likely because there were no 230 kV substations impacted buy the 2013 event, and the Ertishan substation was subjected to higher shaking (PGA ~ 0.60g).

Figure 4-1. Damage to URM Wall, Cut Side. Some low voltage circuits were still not in service as of May 27 2013.

Figure 4-2 shows the damage to the exterior masonry wall at the corner of the substation on a gravity retaining wall. The damaged free-standing wall here was due to a combination of inertial loads, coupled movement of the gravity wall. The gravity wall movement resulted in about 2 to 4 inches of settlement and up to 6 inches of lateral movement at this corner of the yard. This corner of the yard included low voltage equipment only.

Figure 4-2. Damage to URM Wall, Fill Side

Figure 4-3 shows major x-cracks through a primary shear wall of the control building. The control building is normally occupied by several people, and remained in use a month after the earthquake.

Figure 4-3. Damage to URM Control Building (Also houses low voltage feeder equipment)

Figure 4-4 shows one of the two three-phase 110 kV transformer banks in the yard. This transformer slide 25 to 30 cm in the earthquake, and broke all 3 of its 110 kV-side bushings. Figure 4-5 shows the sliding of the transformer. A crew of some 110 high voltage linemen repaired the yard within 3 days of the earthquake, and restored one transformer 28 hours post-earthquake. When asked if the oil for the transformer was treated, site staff replied that it was not…. Suggesting the urgency to restore power to Lushan, and also suggesting that there may be future reliability issues for the transformers.

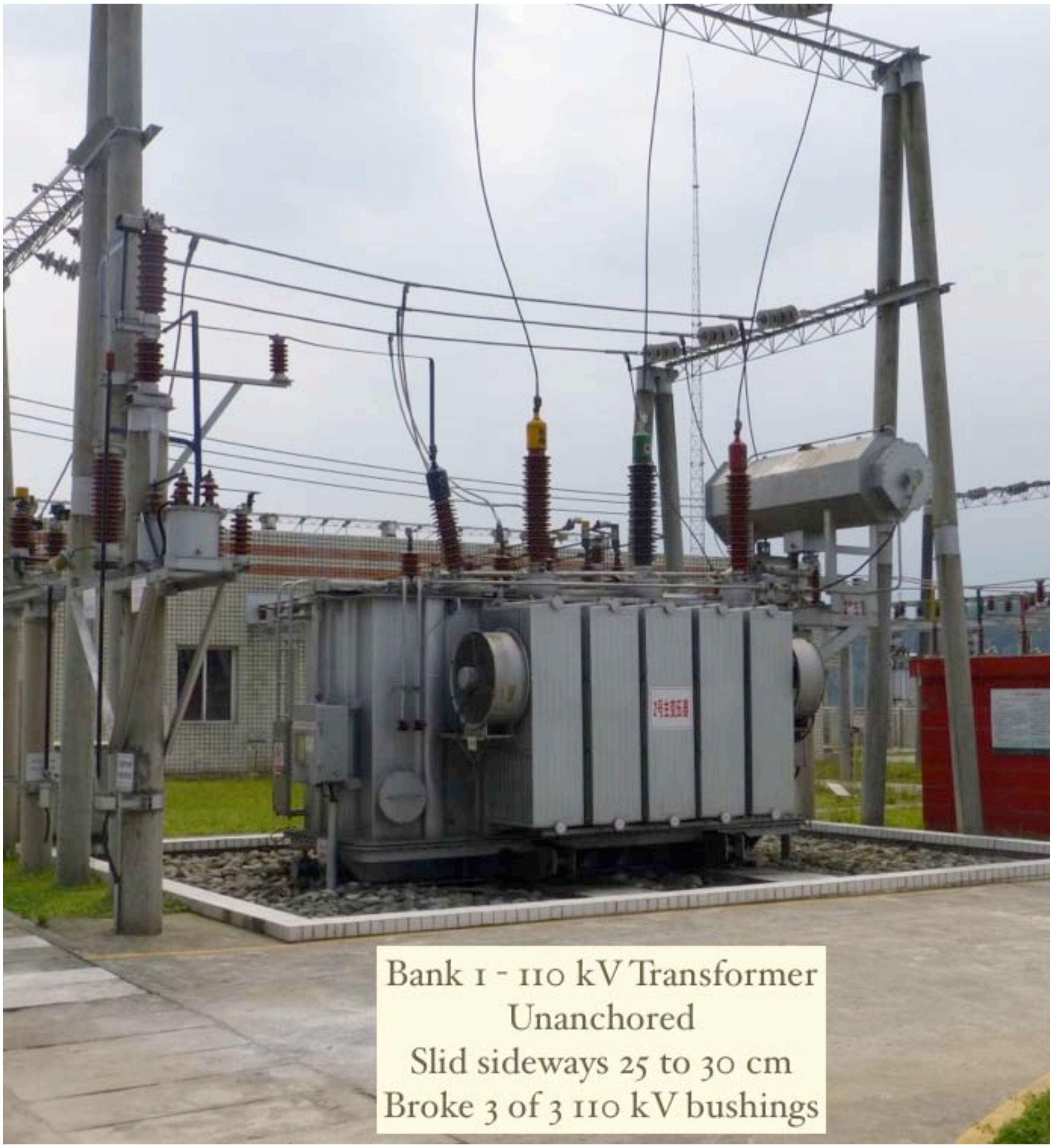

Figure 4-4. Bank 1 Transformer

Figure 4-5. Bank 1 Transformer – Evidence of sliding (broken tiles over concrete foundation) and leakage of oil. The transformer was pushed back to its original position.

The Bank 2 transformer (similar design) had leaks from its oil conservator and damage to 1 of 3 bushings.

When asked, the power company staff informed us that the "we do not believe that anchoring transformers is an good seismic practice". This is in direct opposite direction to what most US power companies adopt, as well as IEEE and Japanese seismic design practices for high voltage equipment. It seems clear that lack of anchorage leads to rocking and sliding, leading to damage to equipment due to cable slack issues.

About 40 percent of all equipment in the 110 kV yard was damaged. Figure 4-6 shows the 110 kV yard, after it has been repaired. The 40% failure rate of the 110 kV yard is much higher than what would normally be expected at a seismically designed 110 kV yard in the US. The question is: why did this yard have so much damage?

Figure 4-6. 110 kV Yard (after repair)

Twelve of the 110 kV current transformers were broken, Figure 4-7. When inspected, one damage mode was due to high tension forces applied to the terminations, leading to fracture of the porcelain, Figure 4-8. These high forces were likely due to inadequate cable slack between the current transformers and adjacent switches / circuit breakers, aggravated in large part by swinging wave traps.

Figure 4-7. 110 kV Broken Current Transformers

Figure 4-8. 110 kV Broken Current Transformers

Figure 4-9 shows a portion of the 110 kV yard. Circled components are replacements for those damaged in the earthquake. The cable slack, after replacement, remains inadequate in many positions. One solution would be to increase the cable slack, or use stiffer components (steel beams, etc.) and increase the frequency of the components, to lessen the displacement demand. It appears that the original cables were used for the replaced equipment; there was no evidence of replaced cables. Damaged components in this photo include candlestick-type circuit breakers, horizontal-break disconnect switches, and current transformers.

Figure 4-9. 110 kV Yard – After Repair

Figure 4-10 shows one end of the 110 kV yard, with the red circle highlighting two hanging wave traps. When the wave traps swing in the earthquake, they impose large displacements on the flexible bus, leading to high tension forces in the bus when the displacements exceed the available slack. These high forces are the primary reason for damage to the equipment in the yard. This problem can be readily mitigated in several ways: removal of the wave traps; support of the wave traps using posts; adding suitable cable slack; etc.

Figure 4-10. 110 kV Yard – After Repair – Wave Traps Highlighted in Red Circle

Figure 4-11 shows damaged air core reactors in the low voltage side of the yard. This failure mode occurred at three locations in the yard; two of the damaged reactors are seen in Figure 4-12.

Figure 4-11. Damaged Air Core Reactors

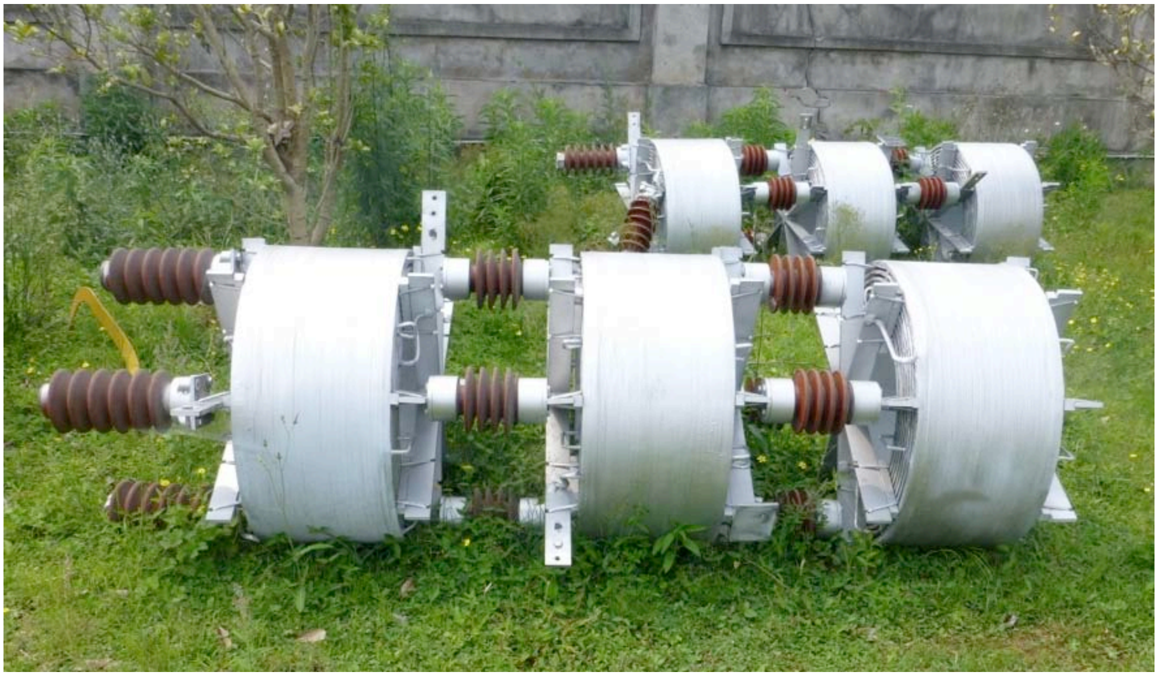

Figure 4-12. Damaged Air Core Reactors

Normally, in the US one would not expect to see this type of damage to low voltage equipment, even at very high levels of ground shaking. For this yard, the cause of the damage appears to be that the adjacent equipment (either capacitors or station service transformers) rocked (all were unanchored), leading to high forces transferred to the air core reactors via the attached rigid bus (see Figure 4-11).

Within the control room, unanchored batteries slid, but did not topple, Figure 4-13. After sliding, the batteries continued to function. Even so, unanchored batteries are not considered to be an acceptable design practice; had the level of shaking been higher at this substation, the battery cabinets may have toppled.

Figure 4-13. Sliding Batteries within Cabinets (uneven spaces between batteries due to sliding)

The following discussion pertains to the corner of the yard subjected to settlements and lateral spreads due to the failure of the gravity wall seen in Figure 4-2.

The area inside the substation just behind the damaged wall shown in Figure 4-2 sustained permanent ground displacement of about 6 inches horizontal and 2 to 4 inches vertical (cumulative). This deformation resulted from displacement of the gravity wall supporting fill in this corner of the substation. Figure 4-14 shows damaged concrete and open cracks near the low voltage equipment that was damaged. There was some evidence of pre-existing cracks overgrown with weeds, which widened during the earthquake; indicating that the fill placed behind the wall was probably settling over time and cracking the concrete slab.

Based on our field observations, the damage in the low voltage part of the yard affected by these ground movements was caused by inadequate slack of the bus between adjacent pieces of equipment, coupled with completely unanchored pieces of equipment that allowed rocking (and hence increased demand on the slack of cables between the equipment). It appeared that the ground movements exacerbated the damage.

Figure 4-14. Cracks in the concrete pavement / cable trench due to the permanent ground movement

Substation 2, Miaoxi (苗溪) 110 KV Substation

Figure 4-14 shows the 110 kV yard at Substation 2 in Lushan City, located within 8 km from Substation 1. Substation 2 experienced ground motions perhaps somewhat lower than at Substation 1. The control building showed several x-type cracks, and exterior masonry walls had minor cracking, and there were partial collapses to conventional buildings just outside the substation. The estimated ground motion at Substation 2 was PGA ~ 0.25g.

This substation uses the same type of 110 kV equipment as at the Jinhua Substation. However, the yard had little damage. Why? Based on initial observations, this substation does not use any hanging wave traps, as seen in Figure 4-14.

Figure 4-14. Undamaged 110 kV Yard at Substation 2

Even though Substation 2 had little 110 kV yard damage, it appears that the two 110 kV transformers had radiator failures. Figure 4-15 shows two radiators on wood skids, with replaced radiators on the transformers.

Figure 4-15. 110 kV Transformers and Radiators at Substation 2

Substation 3, Dayanqiang (大 岩 腔) 35kV substation

This substation is located within 100 meters from the Dayanqiang (大 岩 腔) hydro power plant. The 10KV feed line comes from the power plant as shown in Figure 4-16. There is one 35 kV transformer at this substation, Figure 4-17. This feeds the Jinda Line (金大线), exiting the far end of the substation.

There are four low voltage lines leaving this substation, they are all 10 kV. Only two of them are energized; they are Dashuang Road (大双路) and Daren Road (大仁路) lines.

The only damage informed by the staff was one of the V-break disconnect switch that fell off its mount, Figure 4-18.

The other damage observed was the URM wall and the gate to the yard, Figure 4-19.

Figure 4-16 Dayanqiang (大岩腔) 35kV substation with the power feed from the left.

Figure 4-17 35kV transformer at Dayanqiang (大岩腔) 35kV substation

Figure 4-18 V-shape disconnect switch.

Figure 4-19 Entrance to the Dayanqiang (大 岩 腔) ***35kV substation yard. Note the broken railing and part of the wall.***

Penstocks – Hydro Power Plants

We visited four small (2 MW to 20 MW) hydroelectric power plants. Three of the four plants were shut down as of 6 weeks post-earthquake; the fourth was operable. All experienced motions from PGA = 025g to 0.45g. The damage at these power plants included:

- Loss of water supply to the penstocks due to upstream landslides that damaged canals.
- Damage of a penstock, leading to flooding within the turbine – generator hall.
- Damage to step-up transformers, as they were unanchored. Sporadic damage in substation yards.
- Damage to the control / turbine generator buildings (generally modest, the buildings are reinforced concrete frame with URM in fill walls).
- Gross failure of suspended ceilings.
- Sliding of control cabinets on raised computer floors.

Figure 4-20 shows the generator hall in one of the power plants. Note the failure of the suspended ceiling. The traveling crane did not detail (it had no seismic restraints). Estimated level of ground shaking at this site was PGA = 0.35g. A few reinforced concrete columns at the window levels showed significant damage. The plant was not operational, owing to loss of the upstream water supply (flume and canal damage due to landslides).

Figure 4-20. Generator Hall, Hydro Power Plant

Distribution

We observed many damaged power poles, either due to adjacent building collapse, or due to rockfall / landslide impacts, Figure 4-21.

Figure 4-21. Damaged Power Pole

Fallen platform-mounted transformers occurred sporadically, Figure 4-22. This type of poor seismic installation was observed in California earthquakes of 1952 through 1971, but this failure mode has since been eliminated by use of proper anchorage.

Figure 4-22. Damaged Platform-Mounted Transformer

Dams

We visited one run-of-the-river concrete gravity dam, Figure 4-23, located immediately upstream of "bridge 1" (Figure 7-6). The operator of the dam reported that upon cessation of shaking, he immediately opened all radial and slide gates; all gates opened upon demand (no sticking). The dam included an emergency generator; we observed that the generator had an unanchored battery (Figure 4-24), and the dam operator confirmed that the generator failed to start on demand; but was quickly repaired.

Figure 4-23. Undamaged Dam (PGA ~0.35g)

Figure 4-24. Emergency Generator with Unrestrained Startup Batteries

The reinforced concrete flume-bridge seen in Figure 4-25 seems to have had no damage. Still, there was no water flowing in the flume, due to upstream landslide-induced damage to the canals.

Figure 4-25. Undamaged Water Flume over River (PGA ~0.35g)

Transmission Towers

We know of one transmission tower that collapsed (landslide suspected). Hundreds of transmission towers (110 kV to 230 kV) were located on mountain ridge tops throughout the epicentral area, and would have been exposed to PGA from 0.25g to 0.70g or more.

Recommendations

For China, it is clear that some type of seismic design standard should be implemented for high voltage substations. The ongoing Chinese practice of using unanchored transformers in high seismic hazard areas is inconsistent with practice in the rest of the developed world. Chinese substation design (for all parts of China in Chinese Zones VII, VIII and IX) would be greatly enhanced by adopting the seismic design requirements outlined in IEEE 693.

For the US, the damage observed in China shows that providing adequate cable slack (or stiffening components to higher frequency, and thus lower displacement demands) remains a practice that needs to be implemented.

5.0 Water System for Lushan

The potable water system for Lushan is much the same as used in similar sized cities in the USA. It consists of a raw water pump station, taking water from a river up a hill to a water treatment plant; conventional water treatment (settling, flocculation, filters, disinfection); and then gravity flow to the customers via buried pipe.

The Lushan City managers reported that they focused on improving the water treatment plant for seismic performance after the 2008 Wenchuan earthquake; this was reflected in the new (2011 vintage) facility, that will be described below. Even so, the overall performance of the water system was very poor. As of five weeks post-earthquake, essentially none of the city of Lushan was being served potable water via the distribution system. This is relatively remarkable (unexpected per US terms), as there was little liquefaction or landslide to speak of in the City, and thus the water system was exposed primarily to strong ground shaking.

The distribution pipe system was severely damaged, with (apparently) many leaks / pipe breaks. As of late May 2013, no attempt had yet been made to make buried pipe repairs, even after 6 weeks after the earthquake. The ASCE team observed no upgrades from "lessons learned" for installation of buried pipes or design of control buildings, etc.

The investigation team observed no above ground water distribution tanks of the type commonly used in the US (50,000 gallon to 5,000,000 gallons+).

Water Treatment Plant

A new (2011 vintage) water treatment plant had just been competed prior to the 2013 earthquake, using funding from the World Bank. Figure 5-1 shows the entrance, using a URM wall (the wall was damaged, but this did not impact the plant's performance).

Figure 5-1. Entrance to Water Treatment Plant

Raw water enters two sets of settling basins, flocculation basins and tube settlers, all in one rectangular reinforced concrete structure, Figure 5-2. We saw no evidence of damage to any part of this structure. Launders over the filters were steel, anchored to the reinforced concrete walls; the launders were undamaged.

Figure 5-2. Settling and Filter Basin Structures

Water leaves the filters and enters two rectangular reinforced concrete clearwells, Figure 5-3. The clearwells appeared to be undamaged.

Figure 5-3. Two Partially Buried Clearwells

It appears that all the water-retention structures of this 2011-vintage-designed plant worked well. Whether this good performance is due to minimum requirements for water leak-tightness; or if these facilities were designed per modern seismic codes (or both), is unknown.

Several other facilities at the WTP were damaged. The control building is URM, and suffered large cracks (but did not collapse), Figure 5-4.

Figure 5-4. Damaged Control Building

The chemical tanks rocked, Figure 5-5, leading to damage of attached PVC pipes, Figure 5-6. The small plastic stops (4 of them) did restrain the tank from sliding, but not rocking. The rocking led to damage of the attached restrained PVC pipe.

Figure 5-5. Plastic Tank for Chlorine Dioxide Disinfectant

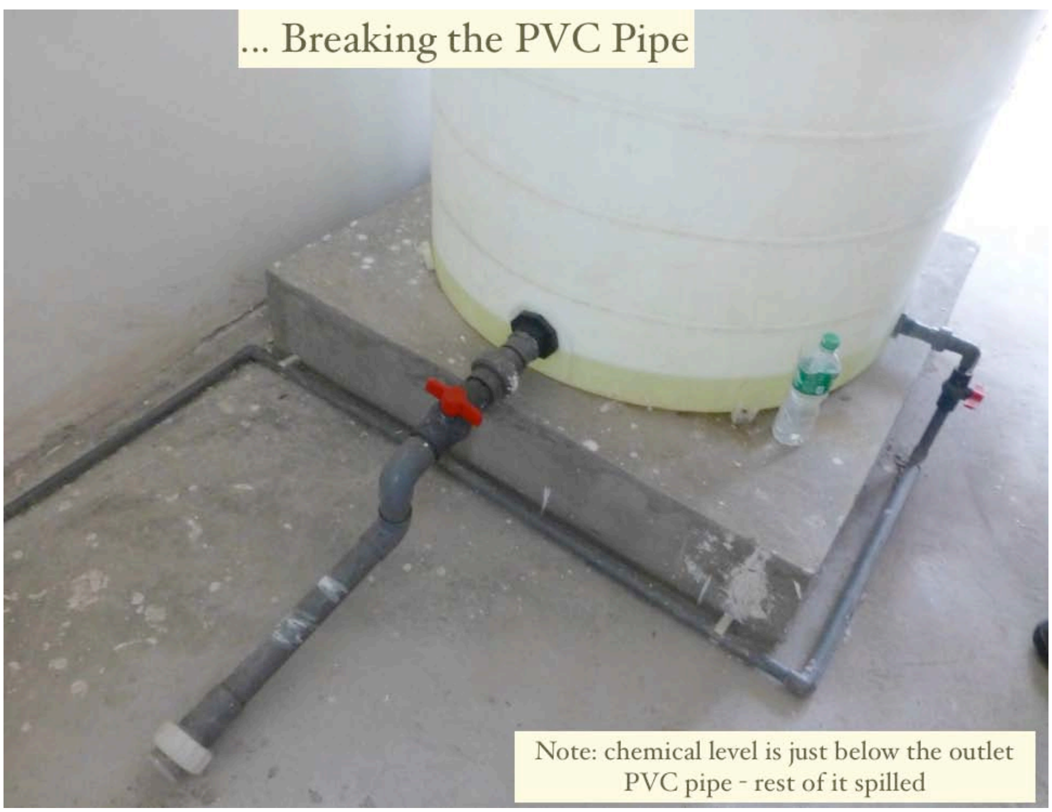

Figure 5-6. Broken PVC Pipe (the motor and pump also broke and have been removed)

Water Distribution Pipes

Lushan city has about 300 km of water distribution pipes. Most are cast iron (dating back 50+ years) and newer pipes are PVC. Most distribution pipes are 100 mm diameter; 500 mm diameter is the largest pipe in the system. Figure 5-7 shows a TCLEE team member with a fire hydrant. Note the temporary office buildings in the background: dozens of such buildings were placed on main city streets in Lushan, providing needed services: life insurance, telecom, banking, etc.

There were zero reported fire ignitions in Lushan. Within Lushan, it is common to use propane for cooking, and some buildings have natural gas supply. The lack of fire ignitions suggests a few possible changes to US practice: perhaps the lack of ignitions was due to the widespread power outages (lasting at least 28 hours in Lushan City), and that perhaps the HAZUS fire ignition model should be updated.

Figure 5-7. Fire Hydrant in Lushan City (John Eidinger)

As of six weeks post-earthquake, no attempt had yet been made by the local public works (water) department to locate the damage to buried water pipes. We inquired to the city officials why this might be so: they replied that "there was no money" and that they were waiting the "the government to take care of this".

City officials also noted that they have a temporary water system that functions and all resources have been devoted to aiding local with needed housing since many/most housing units were damaged or destroyed. Therefore, one reason for this lack of effort to repair the buried pipe is related to the PLA installation of the above-ground water pipe network for most of the city immediately post-earthquake, Figure 5-8. It took the PLA 1 week to place the temporary water lines for the majority of the city and an additional week to complete the temporary network; the outskirts of the city have fewer people but took longer to place the system.

Figure 5-8. Above Ground Temporary Water Pipe

In this manner, nearly every resident is able to gather water from the hose bibs off these pipes, for gray-water / sanitary purposes. Traditionally, the Lushan and nearby Ya'an residents boil all water from the water pipeline system, so water from the above ground system could therefore also be used for potable purposes.

Emergency response also included use of bottled water delivery for drinking water.

Immediately after the earthquake the people could not purify water due to loss of power. There was a public health concern until power was restored. However, there was no reported outbreak of water borne disease after the earthquake.

6.0 Wastewater

In Lushan, there is a wastewater collection system and one wastewater treatment plant. The collection system has several lift stations. Sewage collection was unable to be performed immediately after the earthquake, at least in some areas, due to power loss and inability to lift the sewage. The sewage treatment plant was not able to be investigated, but the Lushan City managers reported that it is a new plant built within the last year and was not significantly damaged.

Several manholes that were raised ("floated") up to a few cm above the sidewalk level, in the eastern part of the city (so-called "New Town" area), Figure 6-1. At one location, a set of portable pumps and hole was being used to pump sewage between manholes, presumably due to a blockage.

Figure 6-1. Floated Manhole

There were dozens of portable toilets in use, six weeks after the earthquake, Figure 6-2.

Figure 6-2. Portable Toilets

City staff reported there were no sewage backups to the street level.

7.0 Roads and Bridges

The Lushan earthquake damaged many roads. The damaged roads resulted in severe traffic congestion in some areas. The loss of critical roadways combined with traffic congestion on the few usable roads severely impacted emergency response capabilities in the damage region.

The area affected by the Lushan earthquake has steep mountainous terrain in narrow river canyons and valleys. Many roadways are cut into the steep slopes. The steep slopes are also highly susceptible to landsliding and rock falls when subjected to strong ground motions. As a result, the roads are highly susceptible to landslide damage. The two-lane paved road in Figure 7-1 was closed by landslide / rockfall, and the road was repaired to one lane gravel status a month after the earthquake; even so, local officials were prohibiting access to such roads, even a month after the earthquake, should there be rain, for fear of continued landslides.

Figure 7-1. Typical terrain for roads in the mountainous areas near Lushan (photo late May 2013)

Figure 7-2 shows a map of important transportation routes in the Lushan earthquake affected area. Preliminary reports identified four Highways (G5, S8, S9, and G4201), two National and Provincial main lines (G318, S210) and six County Roads (X073, X074, Z001-Y004, XT26, XT27, XT06) that were damaged by either subgrade collapse, subsidence, landslides, or rock falls.

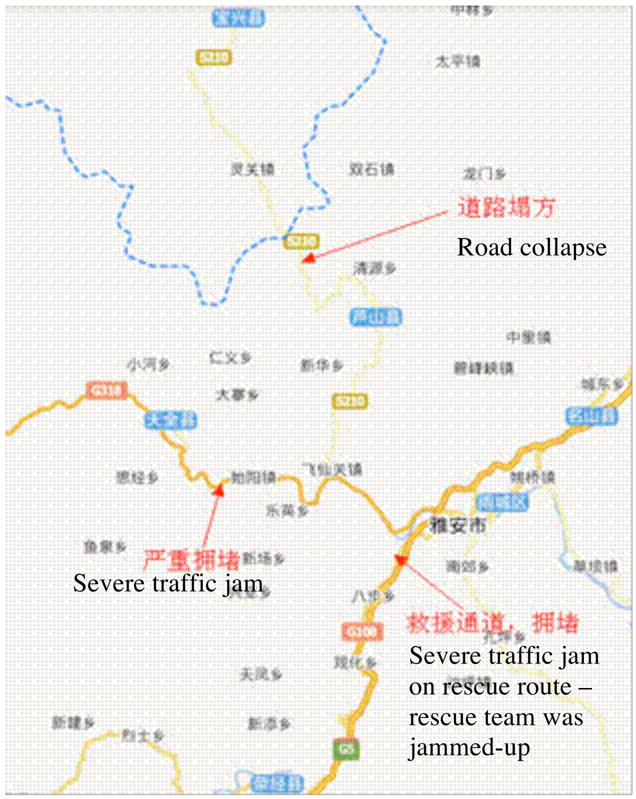

Figure 7-2. Map of roads and highways in Lushan earthquake damage area, some areas of severe problems noted for G318, G108, and S210

In addition, there were numerous damaged bridges, including serious damage to an arch bridge. Figure 7-3 shows damage to S210 Feixianguan (飞仙关) Road from large boulders.

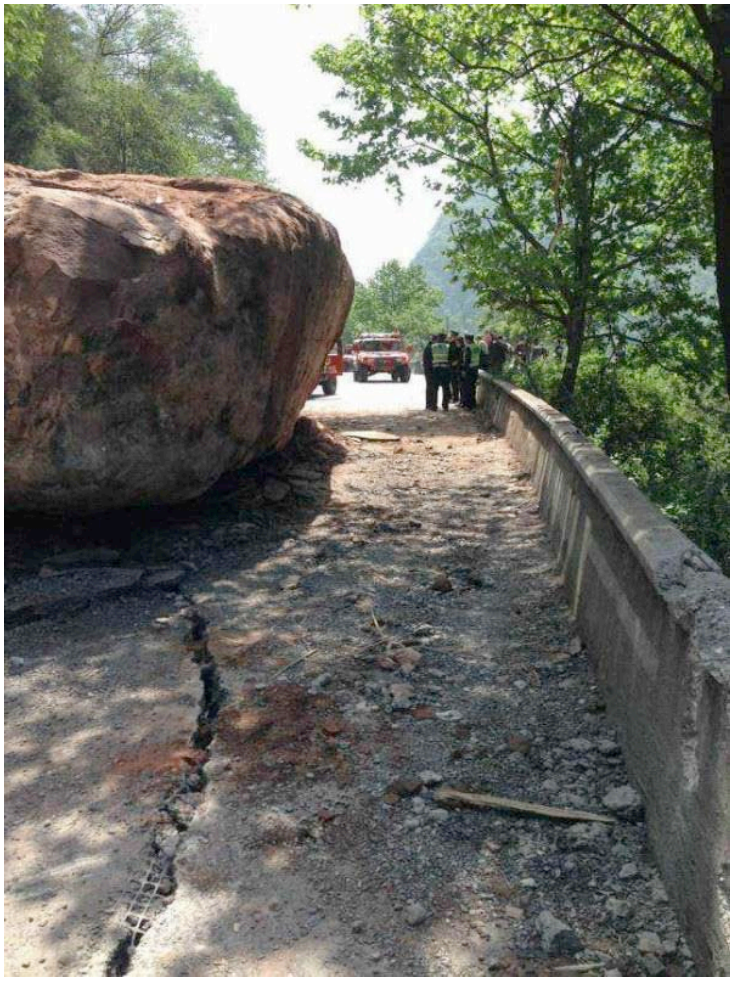

Figure 7-3. S210 damage on Feixianguan (飞仙关) Road by large boulders

Figure 7-4 shows damage to S210 Ling Guan（灵关) Road from landslide debris sliding onto the roadway.

Figure 7-4. S210 Ling Guan Road damaged and blocked from landslide debris

Figure 7-5 shows Lushan County roads blocked by falling rock debris.

Figure 7-5. Lushan County roads damaged and blocked by falling rock debris

Figure 7-6 shows a masonry arch bridge. The PGA level indicated is based on the ASCE teams review of nearby structures. This is "Bridge 1", one of three nearly identical masonry arch bridges located on the road northeast of Lushan heading to Longxingxiang. The unreinforced masonry railing on this bridge (both lanes) fell, and was readily seen below the water in the river below; by the time this photo was taken (May 31 2013), the railing was replaced with a metal railing. Other than the damage to the railing, we could see no material damage due to inertial shaking to Bridge 1 (or Bridges 2 and 3 that are discussed later in this chapter). We could not discern whether or not these bridges were unreinforced or reinforced.

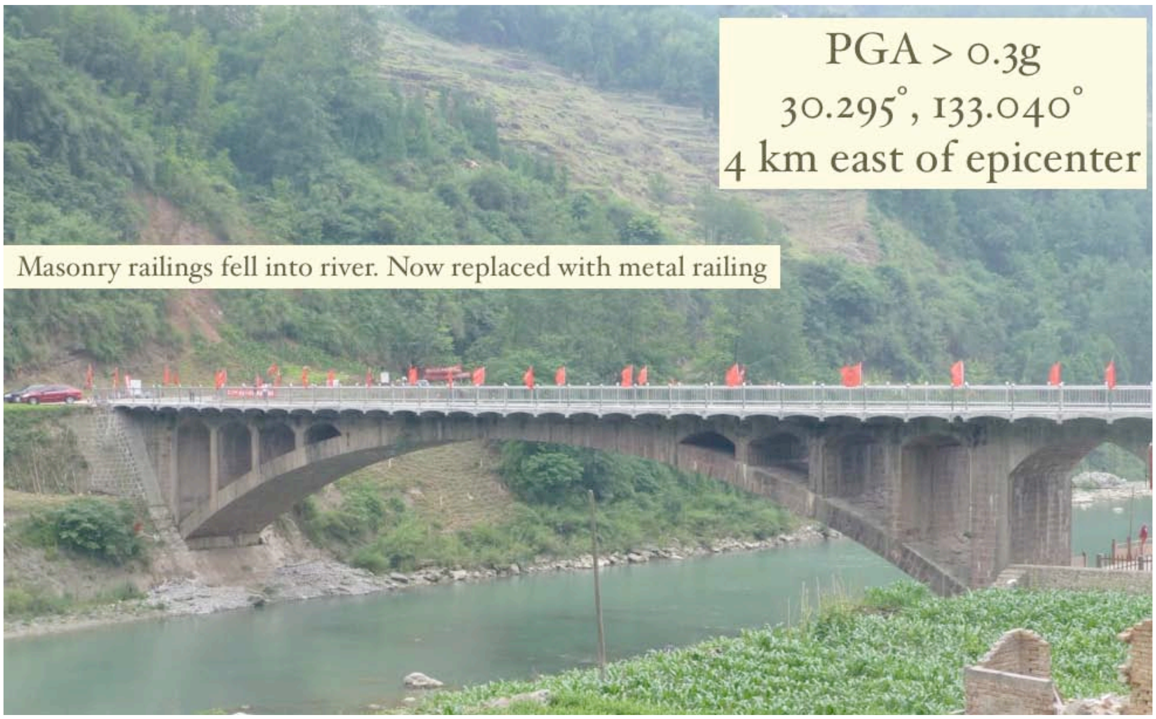

Figure 7-6. Damage to stone arch Bridge 1 in Lushan County (photo date May 31 2013)

Figure 7-7 shows Bridges 2 and 3, both of essentially identical design as Bridge 1. Bridges 2 and 3 are located a few km northeast of Bridge 1. As with Bridge 1, we observed no damage to Bridges 2 and 3 due to inertial loading. However, the rockfall seen in Figure 7-7 substantially impacted Bridge 3, and struck just a glancing blow to Bridge 2.

Figure 7-7. Source Rockfall zone that Impacted Bridges 2 and 3 (photo date May 31, 2013)

Figure 7-8 shows the status of Bridge 3 within a day after the earthquake. As can be seen, a portion of the URM railing was toppled over the bridge, and a large boulder came to rest on Bridge 3. This boulder was finally removed by blasting it, Figure 7-9.

Figure 7-8. Damage to stone arch Bridge 3 in Lushan County, Blossom Sector Road from large boulders. Left Image: Large boulder rolls onto bridge, destroys masonry rails. Right image: excavator attempts to remove large boulder.

Figure 7-9. Blasting of large boulder to remove it from stone arch bridge

Figure 7-10 shows the steel reinforcement placed in two spans of Bridge 3 (spans under the excavator in Figure 7-8).

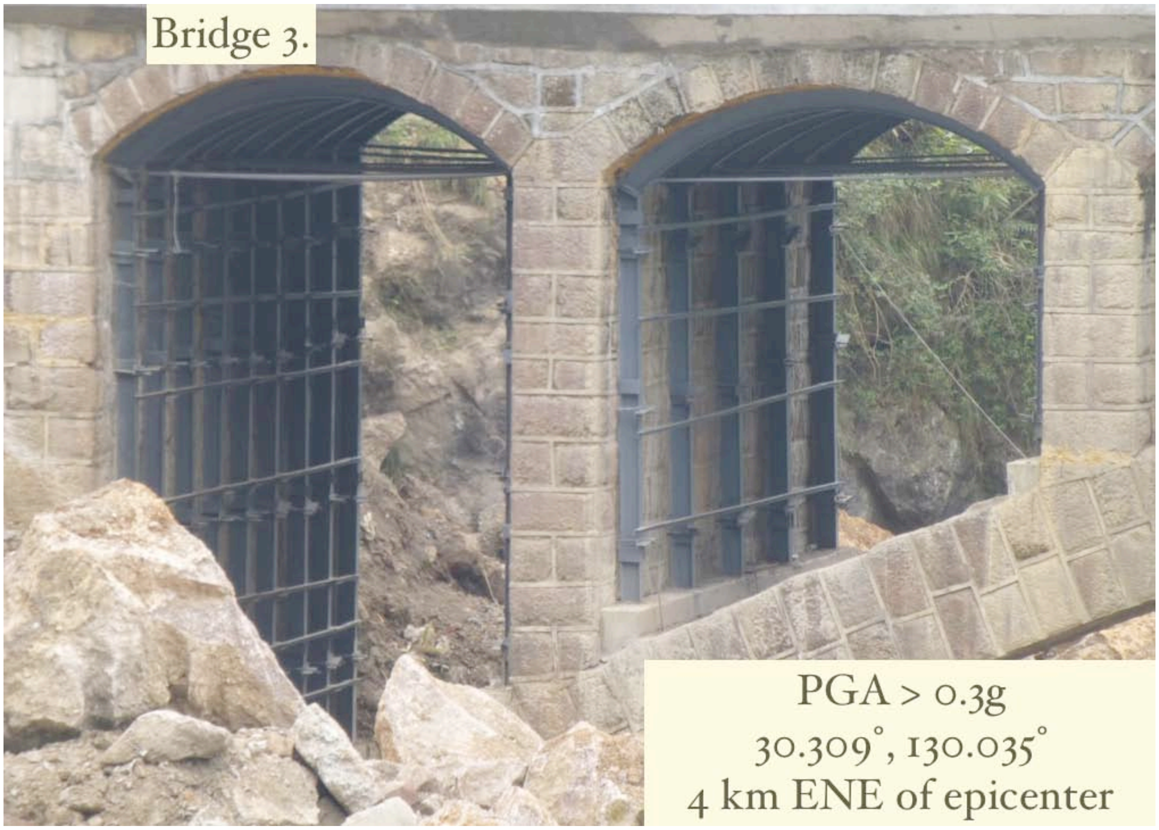

Figure 7-10. Steel Reinforcement Placed in Bridge 3 (May 31, 2013)

Figure 7-11 shows the headwall for a highway tunnel in Lushan (PGA ~ 0.30g). While the headwall shows damage (inertial loading only, evidence of racking), we observed no significant damage to the liner within the tunnel. This tunnel is the only major road tunnel observed in the epicentral area.

Figure 7-11. Highway Tunnel in Lushan

The damaged roads had a severe impact on emergency response and general transportation capabilities. Figure 7-12 shows the road map of Figure 7-2 overlain with preliminary seismic intensity contours and identifies road closures. As indicated in the Figure 7-2 map and photographs in Figures 7-3 to 7-6, critical roads were blocked forcing all in-bound and out-bound traffic onto a few narrow roads, most of which also suffered damages of some kind. The Chinese quickly mobilized a large rescue team, but transportation into the area to perform rescue and recovery activities was inhibited by damages to the transportation network. Figure 7-2 identifies a large traffic jam created by the rescue team during mobilization on Highway G108.

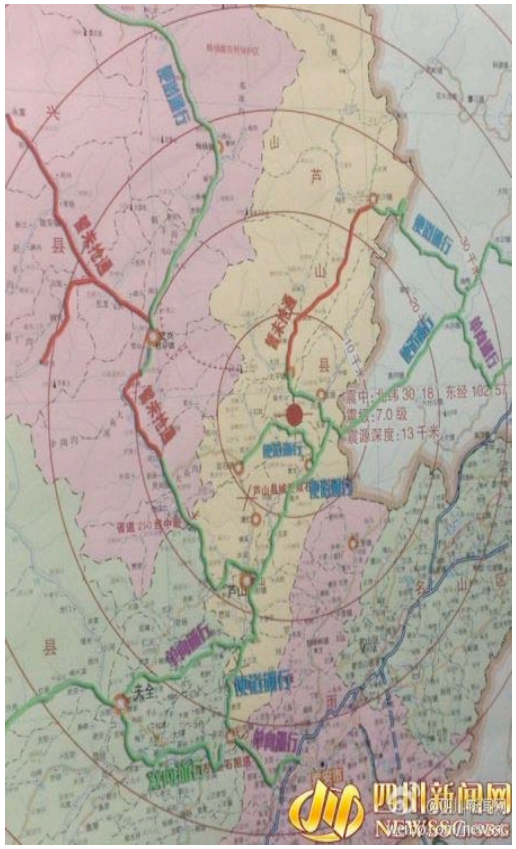

Figure 7-12. Road map overlain with seismic intensity contours, showing road closures

The traffic control map in Figure 7-13 shows a regional emergency traffic control map covering most of the earthquake damaged area. This map shows the emergency response traffic controls used to coordinate the logistics of emergency response and recovery. The arrows in Figure 7-13 show the allowable directions for traffic flow. Most roads only allowed one-way traffic. For example S210 was allowed one-way traffic into Lushan from the south and one-way out of Lushan to the north.

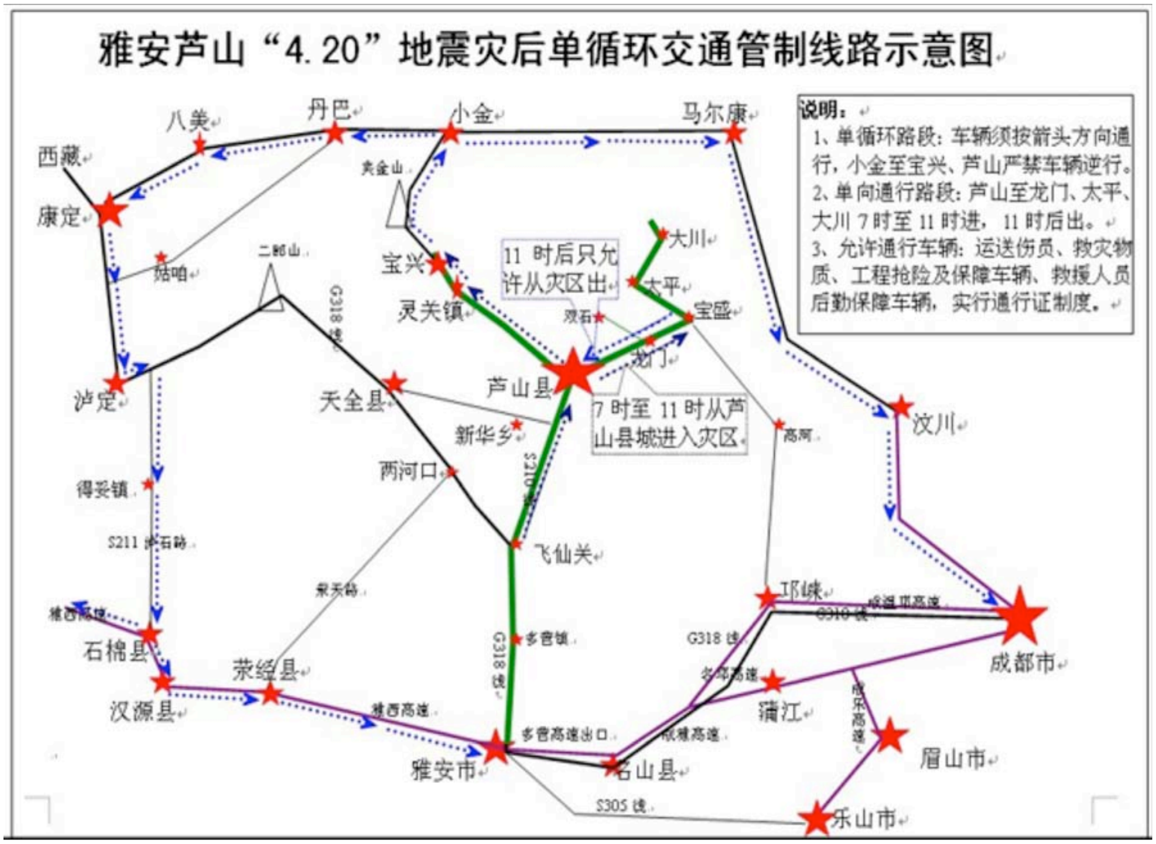

Figure 7-13. Emergency response traffic control map. Stars identifies city and town locations.

The Longmen, Baoshen, Taiping, Dachuan, and Shuanshi townships and surrounding areas northeast of Lushan and closest to the epicenter could only be accessed by a single roadway. This road allowed traffic toward these townships from Lushan from 7 am to 11 am daily and away from them toward Lushan after 11am. These areas were the most severely damaged from this earthquake and as a result traffic control to these townships was critical. For example, Figure 11-5 shows severe damage in Shuangshi located about 5 km south of the epicenter.

During the emergency operations the only vehicles that could pass were ambulances, emergency material supplies, damage repair and rescue teams. All required a government authorized vehicle pass to enter.

By May 31, 2013, the main road S210 from Ya'an to Lushan (large star in center of Figure 7-13) was open to two-way traffic, but police continued to maintain checkpoints to allow only "authorized local residents" into the area (foreigners such as the ASCE team were required to have special permissions).

Chapter 7 Acknowledgements

Dr. Aiwen Liu of the Institute of Geophysics China Earthquake Authority is acknowledged for generously providing investigation data from the April 20, 2013 Lushan Earthquake, including Figures 7-2, 7-3, 7-4, 7-5, 7-8, 7-9, 7-12. Remaining photos are by Craig Davis, Alex Tang, and John Eidinger.

8.0 Telecommunications

The earthquake-impacted communities are served by the three major telecommunication service providers – China Telecom (offers both landline and wireless), China Mobile and China Unicom (the later two provide wireless). All of them sustained various degrees of damage; however, the service disruption was about the same.

China Mobile has the largest market share in wireless service (also called cellular phone). Due to damage of their office building, temporary shelters were set up on sidewalks within one block of the Lushan city government office building, in order to provide service to their customers, Figure 8-1. Temporary landlines were routed to the temporary offices.

Figure 8-1. China Mobile temporary office to serve the customers in Lushan

In and near Lushan, the mobile phone service was interrupted a few minutes after the earthquake. About 15 to 20 minutes later, the mobile service was back on but operation was sporadic, according to the people interviewed by the ASCE team.

The hospital employees at Lushan (卢山) Hospital said that the landline was not working right after the earthquake, but the mobile phone service was fine. However, everyone indicated that the week after the earthquake hit, the mobile phone services were sporadic. After the first week everything seemed normal. Some said that the mobile service was normal after about 28 hours after the earthquake.

While the ASCE team was in the Lushan area about five weeks after the earthquake, the mobile signal in the area was quite strong. However, along major roads in mountainous areas outside of Lushan, the signal in some areas was either too weak or there was no signal indicating no service. That showed the cellular phone coverage in some areas was not available yet, and it was suspected by the ASCE team that some cell sites in the mountainous areas had not yet been repaired (due to landslide).

As discussed elsewhere in this report, there were widespread power outages in the Lushan area for the first few days after the earthquake. As a result of these power outages, many cell sites were "lost"; therefore, the three wireless service providers deployed COWs (Cell On Wheels) around Lushan (卢山) city to provide service and coverage for the residents, Figure 8-2. These COWs have their own power generator, but refueling is required.

Figure 8-2. China Mobile COW parked just outside the front door of the Lushan City Office Building

Temporary optical fiber cables were routed along sidewalks, wrapped around poles or trees to provide both landline services and Internet services, Figure 8-3.

Figure 8-3. This fiber optic cable provided temporary connection to the hospital. All three telecommunication service providers placed their cabinets close to the power termination box (the small cabinet to the right).

In small towns outside of Lushan, such as Longmanxiang (龙门乡), there were no COWs to be seen. However, the cell site buildings showed signs of stress from strong shaking, Figures 8-4a,b and 8-5.

Figure 8-4a. The white building with the tower on top, showed large cracks on the wall. See Figure 8-4b for cable management issue.

Figure 8-4b. Note that cable management is poor, the cables were dropped from the edge of roof to the head of the pole, site in Fig 8-4a.

Figure 8-5. The cell tower at this site in Longmenxiang showed no damage, but the building showed large cracks on the side and front walls. Estimated PGA = 0.35g

There were many cell sites on hill tops that did not have landslide or rock fall hazards were not damaged. Figure 8-6 shows one of these cell sites (with no damage) that was located on the hill next to the Lushan city water treatment plant. Ground motions at this site were likely around PGA = 0.25g to 0.35g.

Figure 8-6. This cell cite did not show any sign of failure to the tower and to the building.

China Mobile and China Telecom management was willing to provide the ASCE team with information relating to the performance of the cellular networks. The manager at China Unicom office in Lushan (卢山) was reluctant to talk to the ASCE team about their network performance. However, one person who worked at the temporary customer service tent gave us some details about what happened to the network.

Cellular service of China Mobile and China Telecom was out of service mainly due to power outage for the first 2 days in different areas. Some areas were out for only half a day, while in the rural areas it was out up to two days. The main issue was coverage was not continuous, that is calls were cut out in areas without cell site coverage. There were damaged towers in the mountainous areas due to rock falls and landslides. The ASCE team tried to gain access to the damaged cell sites in the mountainous areas, but access to these areas was blocked by PLA, we did not have a chance to observe the actual damage.

The other problems experienced by the cell sites were power outages and on site generators that failed to start. Both companies indicated that full service was back in 2 weeks for the whole region.

For landlines, China Telecom indicated that many aerial fiber optic cables were damaged due to collapsed poles along the main highway leading to Lushan (芦山) and Baoxing (宝兴). Temporary cables were routed along the same right of way to provide both voice and IT services. In Lushan, the ASCE team observed many fiber optic cables lying on the sidewalk or wrapped around light poles to provide connections to the network, Figure 8-7.

Figure 8-7. This temporary fiber optic cable was left here unattended after the network was restored.

China Unicom had about 47 cell sites in the earthquake-impacted area. About 6 to 7 had collapsed tower due to landslides and rock falls. Many cell sites were on power generators for as long as 20 days after the earthquake. China Unicom was able to deploy power generator sets to cell sites within 3 hours after the event. The system was "normal" after 3 days. Normal means having dial tone and able to receive and send calls or text messages. It seems that in China, people don’t talk on the cell phone as much as texting messages – a growing phenomena.

COWs were deployed in Lushan by all three service providers. Some of the COWs were running on power provided by the power termination cabinets.

Cell towers in Taipingzhen (太平镇), which is within 10 km east of the epicenter were not damaged, Figure 8-8. The road leading to Shuangshizhen (双石镇), which is a town close (about 5 km south of epicenter) to the epicenter was an area where the wireless signal to be weak and missing, even as of May 26-31, 2013. In this mountainous region, damaged telecommunication cable poles (due to landslide and rock fall) were everywhere, as for example Figure 8-9. In these areas, we observed temporary repairs being made by laying new fiber optic directly on the ground (no poles), as for example see in Figure 8-10.

Figure 8-8. Cell site in Taipingzhen was not damaged.

Figure 8-9. This road leading Taipingzhen (太平镇) had many sections of rock fall that destroyed the poles carrying the fiber optic cables.

Figure 8-10. On the right side of the road, a bunch of fiber optic cables were placed on the ground without any protection. It is a temporary fix to provide connection to the network.

In Tianquan (天全) town, which is southwest of Lushan (卢山) one landline cross connect cabinet was destroyed by rock fall, Figure 8-11.

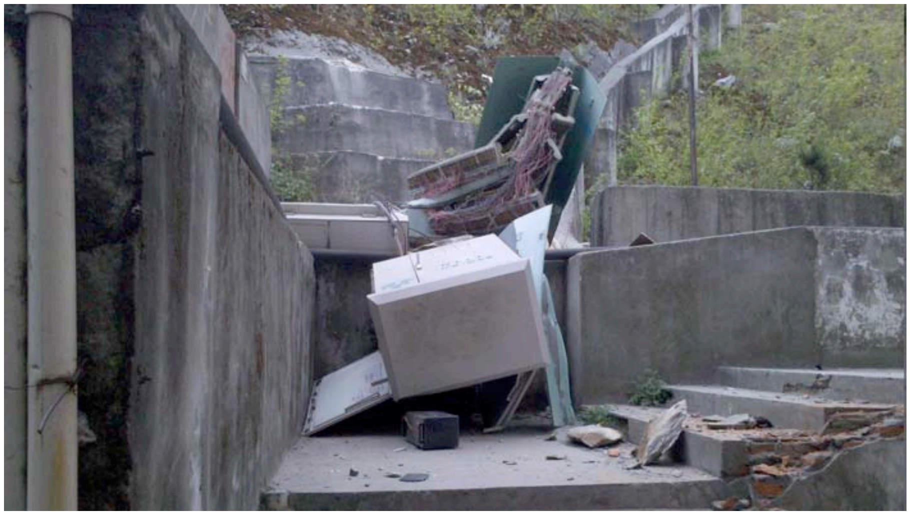

Figure 8-11. This cross connect cabinet in Tianquan (天全) town was destroyed by the rocks from above.

Discussion and Recommendations

Electric power outages continue to be a major problem area for post-earthquake performance of the telecommunication cellular network. The approach to mitigate this is either to have a much more reliable offsite power source, or to have much longer battery backups and many more emergency generators available for the cell sites. Given the great number of cell sites, it would appear that the more cost effective solution would be to have a more reliable offsite power source, with outage times mostly less than the backup battery capability. In remote areas, where it might not be cost effective to have a highly reliable offsite power source, the strategy needs to be a combination of rapid access to those locations to install (and re-fuel) emergency generators, or to accept that there will be lengthy cell phone outages in those area.

Cell sites that are deployed or to be deployed in the mountainous regions shall be protected again both landslide and rock fall. This means that more geologic and geotechnical support is needed in the initial cell site selection process, so that suitable advice and mitigation is taken initially to reduce these hazards. For existing cell phone sites in such areas, suitable geologic hazard investigations should be done to identify the vulnerabilities, and then suitable steps taken to mitigate them.

Upgrading cell site buildings that are URMs to improve survivability should be part of the network improvement effort. There are many proven methods to enhance the structural integrity of URM buildings. As evidenced in this report, we saw many URM buildings being used for cell phone sites and tower supports.

With perhaps one known exception, the 700+ landslides in this earthquake missed all major high voltage transmission towers. While this is relatively good news, it is suspected that this rather good outcome was more "lucky" than otherwise; and that future earthquakes might yet result in landslides and rockfalls impacting many high voltage transmission towers.

If geologic studies are taken to ensure that high voltage transmission towers are indeed located outside of rockfall / landslide sites, then in some cases, the fiber optic cable routing may consider using these towers to feed the cables to the towns or villages in the mountainous regions. This may involve obtaining right of way permission or leasing the facility to attach the cable, and would have to consider that high voltage tower spans are commonly 1,000 feet or more, while fiber optic spans are often a few hundred feet or less.

Poor cable management in routing aerial landlines is evident everywhere, Figure 8-12. Loops of excess cable length were hung on the poles, most of the time next to the splice case. It is a good practice to mine (remove) cables that are no longer used in order to reduce weight and that will help reduce time in restoration process.

Figure 8-12. Example of poor cable management in Lushan

9.0 Emergency Response

From what the ASCE team observed, the emergency response was much improved since 2008. The People's Liberation Army (PLA) responded quickly with about 8,000 soldiers, along with about 1,200 local rescue workers, to provide victim extraction and other services. They also installed emergency generators, constructed an above ground temporary water system, installed temporary housing, and provided many tents.

By May 1, 2013, the following square footage of temporary buildings had been put into place (total inhabitable space was about 213,846 square meters):

- Temporary Shelters for Schools: 98,886 square meters
- Temporary Shelters for Hospitals: 28,160 square meters
- Temporary Shelters for Housing: 86,800 square meters
- Temporary Shelters Being Built: 14,408 square meters (as of May 1, 2013)

The temporary shelters generally consisted of single story metal buildings (like those in Figures 5-7, 8-1) as well as tents (like those in Figures 9-1, 10-2, 11-1, 11-2, 11-3).

Figure 9-1 shows an example of people queued to receive emergency relief supplies (photo taken May 31, 2013). This included water, food and building supplies.

Figure 9-1. Example of Distribution of Relief Supplies

An official reported that local fire fighters were trained to perform earthquake emergency response by the PLA after the 2008 Wenchuan earthquake, and this helped the speedier response. There were no fire ignitions.

10.0 Essential Building Stock

Two older (pre-2008) hospital buildings in Lushan were heavily damaged and "red-tagged", having sustained major structural (Figures 10-1, 10-2) and non-structural damage (see Chapter 12). All patients were evacuated from these conventional-designed buildings. These two damaged hospital buildings provided more than half the emergency care facilities for the region. While these buildings did not collapse out-right, they might have collapsed had the earthquake been higher magnitude or the hospital located a little closer to the epicenter. The style of construction was reinforced concrete frame with infill unreinforced masonry tiles. Close-up inspection of these buildings show major yielding in columns where they are connected to heavy horizontal reinforced concrete spandrel beams, and localized failure of infill walls.

Figure 10-1. Conventional Hospital in Lushan (PGA ~ 0.30g to 0.40g)

Figure 10-2. Conventional Hospital in Lushan (PGA ~ 0.30g to 0.40g)

Six weeks post-earthquake, these two conventional-designed hospital buildings remained red-tagged (no entrance). Unlike the practice adopted in Christchurch, New Zealand, local officials did not "red-tag" out the potential adjacent "drop zones" from these two damaged buildings.

Immediately adjacent to the two older hospital buildings was a third new (post-2008) hospital building, Figure 10-3. This newer building was base-isolated using high-friction rubber bearings. The building was designed (and paid for?) by the generosity of the people of Macau, partially as an outcome of the 2008 earthquake. As seen in Figure 10-3, repairs are being made all around the base isolated building, as nearly all water / sewer / storm drain pipes broke at the interface from the isolated building to the non-isolated surrounding area.

Figure 10-3. Base Isolated Hospital Building (on Right) with Walkway to Conventional Building (on Left)

This building performed well, with the isolators displacing sideways about 10 inches or so. As the isolators moved sideways, the concrete floor slab of the isolated building bumped into the adjacent storm drains at many locations.

Figure 10-4 shows the dispensary within the base isolated building. We asked the nurses at the hospital whether any of the items in the shelves fell over in the earthquake: they replied "no". Note the fire sprinkler pipes in the suspended ceiling: they did not break.

Figure 10-4. Dispensary in the Base Isolated Hospital Building

The original emergency generator for this hospital complex did not function post-earthquake, taking a few hours to repair. A newer emergency generator (as part of the base isolated building) was not yet fully installed at the time of the earthquake.

Fire sprinkler pipes (Figure 10-5) that crossed from the base isolated building (background) to the conventional non-isolated building (foreground) had damaged pipe supports, owing to the differential displacements imposed. Had the pipe supports been at "10-foot intervals" and made even "stronger" (as nominally required by IBC 2012), the pipe itself would likely have been broken. If instead of lateral supports, the sprinklers had used lower-cost rod hanger supports, then the damaged would have likely been avoided.

Figure 10-5. Damaged Sprinkler Pipe Support

Most new (post-2008) "essential" multi-story buildings (government offices, etc.), built to the Chinese code (intensity VII), were functional "failures" after this earthquake. Examples are seen in Figures 10-6 and 10-7.

Figure 10-6. Post-2008-Constructed Building in Lushan (Red Tagged)

Figure 10-7. Post-2008-Constructed Building in Lushan (Dropped Exterior Panels)

Figure 10-8 shows a building that was under construction at the time of the earthquake, in Lushan City. Note the continued use of unreinforced masonry infill walls. The infill walls were damaged when the building mass and stiffness irregularities placing high in-place shear forces on these walls.

Figure 10-8. Post-2008-Constructed Building in Lushan (Failed Masonry Walls)

In US terms, the buildings were either "yellow tagged" or "red tagged" due to a combination of structural damage (large cracks in in-fill URM walls and some damage to reinforced concrete frames); and widespread damage to suspended ceilings and other non-structural components. Many of the new (post-2008) buildings remained unoccupied as of 6 weeks post-earthquake. While, we did not observe outright collapses of these engineered buildings in Lushan, several of the new government buildings may need to be torn down and re-built.

The city government offices were severely damaged and had to be essentially abandoned and relocated into temporary buildings. Figure 10-9 shows damage to city government offices. Figure 10-10 shows the temporary city buildings used to help provide services to city residents.

Figure 10-9. Damaged Lushan City Government Building

Figure 10-10. Temporary Lushan City Government Buildings

11.0 Regular Building Stock

Lushan (卢山) is a major community center within 30 km of the epicenter of this earthquake. There is a mix of old, new, half completed, and completed engineered structures within the city core. There were some building collapses in Lushan. There were some buildings that sustained extensive damage, and most of the building stock suffered minor to moderate levels of damage.

The "regular" building stock consists of concrete frame structures with infill unreinforced masonry, generally 1 and 2 stories in height; along major roads, the first floor is dominated by open facades facing the roads for shops, leading to "soft story" weaknesses.

We observed no significant (if any) seismic mitigation of the regular building stock (no seismically retrofitted buildings). The buildings appeared to have more-or-less the same style of construction as would have been the case in the 1970s to 1990s when most of these buildings were constructed.

We did observe hundreds of collapses as well as complete tear-downs of otherwise seriously damaged regular (pre-2008) building stock.

For many still standing buildings, a tent was set up, as many occupants no longer wanted to stay within their URM buildings, even if there was only slight damage, as for example, Figures 11-1 and 11-2. We observed hundreds of similar tent installations.

Figure 11-1. Example of Tent in front of Slightly Damaged Building (PGA ~ 0.35g)

Figure 11-2. Example of Tents Adjacent to Damaged Building (PGA ~ 0.35g)

Figure 11-3 shows a typical situation in a small village north of Lushan: a few collapsed (or pulled down) structures with debris accumulation; tents in front of remaining slightly-to-moderately damaged buildings. The style of construction observed in this figure is common throughout Lushan and surrounding small farming communities.

Figure 11-3. Debris, Tents and Remaining Damaged Buildings (PGA ~ 0.35g)

Figure 11-4 shows a common style of construction, using a combination of masonry (brick) load bearing walls, reinforced concrete columns and beams (with poor stirrup placement), lumber post and beams, infill clay tile bricks, roof using wood lathes with clay tiles (tiles having been removed in this photo), and soft story (store fronts). The structure in the foreground was seriously damaged and subsequently pulled down for debris removal; the structure in the background was considered good enough to remain in service.

Along the highway there were an increasing number of debris piles along the road, similar to that shown in Figures 11-2 and 11-3 as Lushan was approached from Ya'an.

Figure 11-4. Construction Style of Common Buildings (PGA ~ 0.35g)

Figure 11-5. Severe Damage in Shuangshi Township (PGA ~ 0.5g).

12.0 Non Structural Components

We observed many collapsed suspended ceilings at hospitals (Figure 12-1) as well as at power plants (Figure 4-20) and essential building stock. Mostly, these were wire hung, with no evidence of any seismic design features. There were no reported fatalities due to these failures.

Figure 12-1. Suspended Ceiling at Lushan Hospital (PGA ~0.25g to 0.35g) (Non-base-isolated)

Figure 12-2. Suspended Ceiling at Lushan Hospital (PGA ~0.25g to 0.35g) (Non-base-isolated). About 60% of the area of the suspended ceilings were heavily damaged, with those over larger rooms being relatively in worse condition

At the Lushan hospital, the oxygen tank (Figure 12-3) rocked, leading to failure of the attached oxygen pipe, and release of all the oxygen. Fortunately, it did not catch fire.

Figure 12-3. Unanchored Liquid Oxygen tank rocked at the hospital in Lushan. The rocking resulted in failure of the attached pipe. All liquid oxygen evaporated.

The emergency generator at the hospital failed to start, but was repaired within an hour and then started.

Unrestrained batteries at two substations and one power plant slid, but were not damaged and remained functional.

Unbraced rod-hung sprinklers swayed, but did not break. Some sprinkler heads pushed through weak suspended ceilings, Figure 12-4.

Figure 12-4. Sprinkler head moved sideways and impacted the suspended ceiling.

Water slosh heights at a fish-pond-farm (Figure 12-5, with more than 20 basins) were reportedly "under 30 cm high, and did not overtop the basin walls" per the local official who observed the sloshing (basin sizes typically 20 to 50 feet in plan dimension). It is hard to say if this observation was correct (the official might not have observed higher waves in the first few minutes post-earthquake), or if this indicates a lack of energy in the long-period portion of the spectral content of the ground motions.

Figure 12-5. Water Basins at Fish Farm (PGA = 0.25g to 0.35g)

A raised computer floor at a power house (Figure 12-6) suffered some damage (panels popped off), and adjacent floor-supported (non-anchored) control cabinets "walked" towards the "holes" in the floor, but did not topple in.

Figure 12-6. Raised Floor at Power Plant