Wenchuan Earthquake Impact to Power Systems

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ABSTRACT

The Wenchuan M 7.9 earthquake of May 12, 2008 had its epicenter in Yingxiu, about 100 km northwest of Chengdu. The epicenter was 31.0 degrees latitude, 103.4 degrees longitude. The earthquake occurred at 2:28 pm local time.

The earthquake caused widespread and extensive damage to the high voltage power transmission network as well as local distribution systems. If China adopts modern seismic design guidelines for its power system, likely more than 90% to 95% of all such damage will be avoided in future earthquakes in China.

HIGHLIGHTS

Primary contributing effects to the damage were as follows. First, essentially no seismic design was observed. Modern seismic design in the area subjected to this earthquake called for a base shear design of V = 0.03W, which is inadequate. As the proscribed seismic forces are so low, reliance on friction (ie., no anchorage) was prevalent. Fragile 110 kV and 220 kV live tank circuit breakers were prevalent. Swinging of cable-supported wave traps induced damage to adjacent components. Transmission towers were located within landslide zones, or were impacted by boulders rolling down the hillsides.

Quality of construction, per se, was not observed to be a contributing factor to the widespread destruction. In other words, given the seismic design, the performance of the power systems was just about as expected – very poor.

SEISMIC SETTING

Figure 1 shows the location of the May 12, 2008 event (epicenter large red dot), and nine other M 7 or greater earthquakes (pink dots) in the region since 1917. Table 1 lists recorded strong ground motions (location of instrument listed where known).

IMPACT TO POWER SYSTEM

The Sichuan Province State Grid is the primary operator of the high voltage transmission and low voltage distribution electric systems serving some 46,000,000 people in Sichuan province. Power generation includes thermal (nuclear, coal) and hydroelectric power, with the owners of the generation facilities including other companies and agencies.

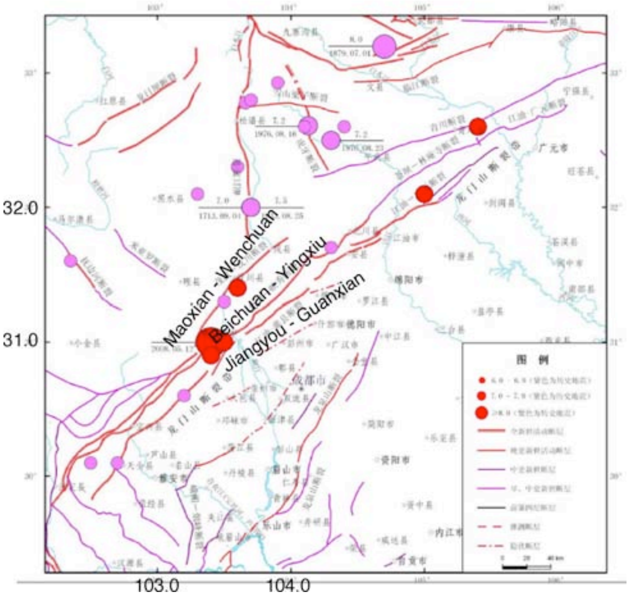

Figure 1. Regional Historical Earthquakes

Instrument Number	Station / Location	PGA EW gal	PGA NS gal	PGA Vert gal	Lat (N)	Long (E)
051HSL	Shuangliusuo Stn in Heishui	108	143	109	33.45	105.00
051GYZ	Zengjia Stn in Guangyuan	424	410	183	32.65	106.20
051JYD	Jiangyou Stn	511	459	198		
051JYH	Hanzeng Stn in Jiangyou	519	350	444	31.75	104.62
051JYC	Chonghua Stn in Jiangyou	297	279	180	31.90	105.20
051JZG	Guoyuan Stn in Jiuzhia	170	241	109		
051LXM	Muka Stn in Li County	321	284	358		
051LXS	Chaba Stn in Li County	221	262	211		
051LXT	Taoping Stn in Li County	340	342	380	31.50	103.50
051MXT	Maoxian Earthquake Office	307	302	267	31.65	103.83
051MXD	Diexi Stn in Maoxian	246	206	144	32.10	105.80
051MXN	Nanxin Stn in Maoxian	421	349	352		
051PWM	Muzuo Stn in Pingwu	274	287	177		
051SFB	Bejiao Stn in Shifang	556	532	633	31.20	104.00
051WCW	Wolong Stn in Wenchuan	653	958	948	31.00	103.20
062WUD	Wudu Stn	185	164	109		
051MZQ	Qingping Stn in Mianzhu	824	803	623	31.52	104.09
051DYB	Maima Stn in Deyang	126	136	89		
051HYQ	Qingxi Stn in Hanyuan	142	125	54		
051YAM	Mingsham Stn	171	175	47		

Table 1. Recorded PGA Values (981 gal = 1g)

The damage to the State Grid electric system in Sichuan province is listed in Table 2. The information reflects the damage and repair efforts through October 22 2008. The column "repaired as of 10/22/2008" reflects the replacement and repair of equipment at existing substations / circuits; most of these repairs covered replacement of damaged circuit breakers, replacement of bushings, etc. the column "repair in place beyond 10/22/08" reflects relatively modest repair effort remaining to be done, but where local conditions have prevented the work to be completed. The column "reconstruct entirely beyond 10/22/08" indicates substations which had almost complete damage or which were impacted by landslide or which serve communities essentially destroyed / depopulated; these are considered beyond repair by the State Grid, and will need outright replacement. The rows "10 kV Circuits and Substations" primarily indicate where landslides or surface faulting pulled down major lengths of low voltage distribution, with "substation" indicating pole mounted equipment (like transformers).

Voltage (kV)	Type	Total	Damaged	Repaired as of 10/22/2008	Repair in Place (beyond 10/22/08)	Reconstruct Entirely (beyond 10/22/08)
500	Substation	18	1	0	0	1
500	Transmission Line	41	4	2	2	2
220	Substation	94	13	9	1	4
220	Transmission Line	337	46	24	3	19
110	Substation	351	66	61	0	5
110	Transmission Line	796	118	117	0	1
35	Substation	351	91	84	0	7
35	Transmission Line	603	106	106	0	0
10	Substation	5473	795	749	0	46
10	Circuits	5876	1700	1606	0	94

Table 2. Damage to State Grid Electric System, Sichuan Province

Table 2 does not include damage to privately-owned or non-state-grid substations, such as those at aluminum manufacturers. Also, Table 2 does not reflect the geographic distribution of the substations; for example, there were no 500 kV substations within 15 km of the primary co-seismic fault ruptures; instead, most experienced ground shaking under PGA = 0.10g, so the relatively low damage rate for 500 kV substations should *not* be interpreted that the 500 kV equipment was well-designed for seismic loading. Based on field observations, 100% of 110 kV and 220 kV substations that experienced ground motions over PGA = 0.3g experienced functional damage to at least 15% of the equipment at the substation (sometimes nearly 100%).

Of the 171 substations (35 kV to 500 kV) that had at least some damage, 17 substations were "completely damaged", and are listed to be entirely rebuilt beyond October 22, 2008.

The Sichuan Electric State Grid has estimated that the cost to make all repairs and replacements to the electric system will be 31.3 Billion RMB ($4.6 Billion USD). They also estimate an additional 10.65 Billion RMB ($1.56 Billion USD) as an economic impact.

Table 3 summarizes the damage to equipment owned by Sichuan Electric State Grid (excludes equipment owned by others). Voltage level is provided where we know the data; for circuit breakers, most of the damage would be in 220 kV (2/3) or 110 kV (1/3), with these ratios approximate.

Voltage (kV)	Type	Number Damaged
500	Power Transformers / Reactors	7
220	Power Transformers	25
110	Power Transformers / Reactors	84
110	Current Transformers	115
220	Potential transformers	16
500	Potential transformer	1
	Circuit Breakers	91
	Disconnect Switches	Many

Table 3. Damage to Electric System Components

Of the 116 damaged power transformers, 76 had damage to radiators (pipe connections thereto) leading to oil spills, and 33 had sliding away from their original positions. Other damage observed to power transformers included failed bushings and pulled underground cables. It is speculated that there were likely damage to lightning arrestors, oil conservators, internal cores.

In some towns visited, the electric power outage was up to 10 days. By June 10, 2008 (29 days after earthquake), 155 of 171 35 kV or higher power stations were repaired and restored to service; and 2,607 out of 2,769 transmission and distribution lines (10 kV to 500 kV) were restored to service. Of the 17 completely damaged substations, 220 kV Anxian, 220 kV Dakang, 110 kV Xiaoba, 100 kV Yuanmenba and 35 kV Jujiaya were planned to be rebuilt by August 31, 2008. As of October 18, 2008, two substations in Yingxou (220 kV and 110 kV) remained in their immediate post-earthquake damaged condition.

SUBSTATIONS

Figure 2 shows typical damage to a live tank circuit breaker. In this case, the initial damage is concentrated at the base of the porcelain, where it is connected to a flange with only a shallow embedment. The primary weaknesses of this type of equipment is either excessive bending moments on the porcelain, or weak porcelain-to-flange fittings.

Figure 3 shows a transformer on wheels that jumped its tracks. This type of damage has been observed in almost every corner of the world when ground motions much exceed PGA = 0.25g or so.

Figure 4 shows a slid 110 kV transformer. The sliding amounts to well over 1-foot, for a steel-on-concrete installation. The staining of the concrete reflects that there was a large oil leak here.

Figure 5 shows the sliding of a 110 kV transformer at Beichuan substation (PGA > 0.3g). It leaked oil. While the two radiators are braced to each other, there appears to be no lateral support for the radiator other then the pipe connections; the State Grid reported many oil leaks due to pipe failures of radiators.

Figure 6 show the damage to a bushing on a 500 kV transformer. The bushing had total failure of its porcelain. This appears to be a grouted bushing. The adjacent surge arrestors, provided with good slack, appear unharmed.

Figure 7 shows a 110 kV substation located near Yingxhou. Damage to nearby structures would suggest PGA ~ 0.5g at the substation. Repair work had not begun as of 160 days after the earthquake, and there were weeds growing in many areas reflecting the lack of maintenance at the yard over 5+ months. It is speculated that the reason for non repair is that the local industrial factories within a mile or so of the yard were heavily damaged, with no repair efforts ongoing, resulting in loss of load.

At this substation, there was gross failure of at least 13 of 21 live tank circuit breakers (it is possible that all were damaged, but access into the yard was limited to verify each individual breaker).

In Figure 8, all three bus drop from hanging wave traps to the potential transformers below are broken, surmised due to large movements of the hanging wave traps that impacted the drop; or (less likely) due to cable dynamics.

Figure 9 shows an aerial view of the destruction of 220 kV Ertaishan substation (PGA about 0.5g). The primary cause of the damage is inertially-induced destruction of concrete line-drop / dead end structures, likely coupled with inertially-caused damage to some otherwise undamaged substation equipment.

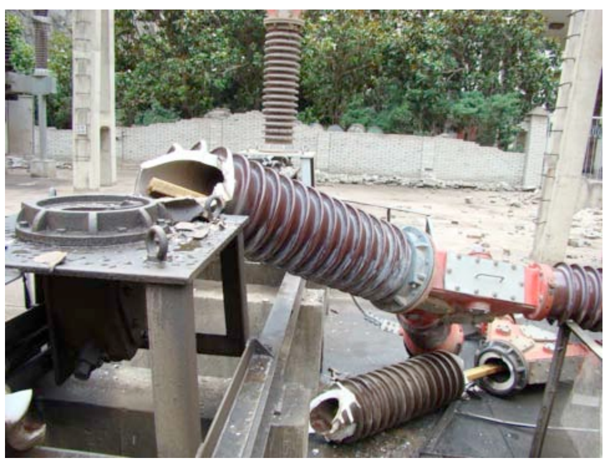

Figure 2. Damaged Live Tank Circuit Breaker (110 kV)

Figure 3. Wheel-Mounted Transformer

Figure 4. Skid-Mounted Transformer

Figure 5. Skid-Mounted Transformer

Figure 6. Bushing, 500 kV Transformer

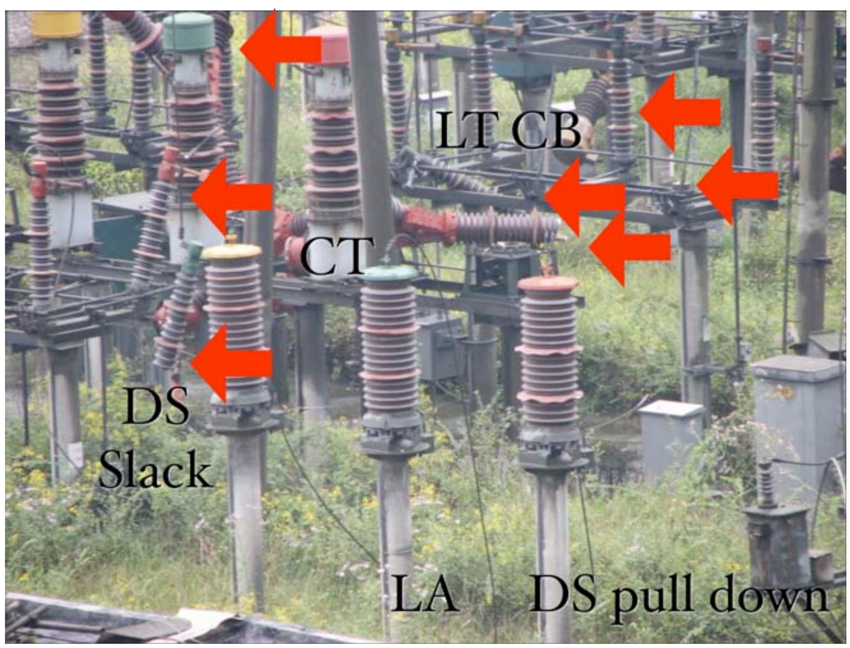

Figure 7. Examples of damage to Yard Equipment, Yingxhou 110 kV Substation

Figure 8. Hanging Wave Traps and Damage to Bus Connections to PTs

Figure 9. Destruction to Ertaishan Substation, 220 kV, Yingxhou

TRANSMISSION TOWERS

There were many partially or completely damaged high voltage (110 kV and higher) transmission towers in this earthquake. The predominant causes for tower failure were landslides that moved the tower foundations many 10s of feet (in some cases 100s of feet); or localized damage due to rock fall impacts. In one case, a tower collapsed apparently due to inertial loading, which is considered very uncommon. Where there were tower collapses, there was the potential of pull down of adjacent towers. The author did not observe tower failures due to large debris flows, but that is not to say that they did not occur.

Landslides occurred frequently in the mountainous areas of Yingxiu, Anxian, Beichuan and Jiangyou Counties. In these areas, PGA values commonly were over PGA = 0.3g (sometimes as high as PGA = 0.9g). Over the course of perhaps 200 km of roadway observations, we estimate that perhaps 1 in 100 towers were impacted by landslides in these areas. However, as the common tower spacing is about 1,000 to 2,000 feet, and distances between substations about 10 miles, then perhaps there are commonly 50 towers per circuit (110 kV), or 100 towers per 220 kV circuit, so it is likely that perhaps a third to three quarters of all circuits had at least one tower failure.

Figure 10. Collapsed Tower

Figure 11. Rockfall-Impacted Tower, #123, Hongxue Line of Yingxiu Town

DISTRIBUTION

Overhead distribution (4 kV – 34.5 kV) is common in cities and towns. The most common style of pole is a concrete tube. These concrete tubes appeared to have no shear steel, (Figure 12) and high bending / shear induced failures occurred where there were pull down forces. Many dead-end frames at substations also use this kind of construction, albeit oriented into a A-frame assembly; at 220 kV substations with PGA > 0.4g, perhaps 25% to 50% of these collapsed due to a combination of inertial loading coupled with cable line dynamic loading (not landslide), leading to gross damage to yard equipment below.

Figure 12. Collapsed 10 kV Distribution Pole (10 inch diameter, 2.5-inch wall thickness)

Figure 13. Fallen Distribution Transformer

Platform-mounted transformers were observed, Figure 13. This type of damage was observed in a California earthquake in 1952, and since then, power distribution companies in California have all but eliminated the placement of unanchored transformers on elevated platforms for new installations. We recommend that in China that similar retrofits be adopted as a high priority in all high-seismic regions of the country.

RECOMMENDATIONS AND LESSONS LEARNED

There are several activities that are recommended for power substations in China at all locations of the country where the 475-year return period PGA exceeds 0.20g. Station batteries should be restrained to their racks and the racks should be of adequate design and be anchored. Control cabinets should be anchored or otherwise adequately secured. Power transformers should be anchored, with anchorage forces computed using V = PGA * W (V is base shear, PGA is in g, W is total deadweight of the transformers including all oil and attached equipment), and the anchors designed for the corresponding overturning forces with a minimum factor of safety of 2 or more; the PGA value should be at least the 475-year return period value, but if not knowing this and the owner suspects the equipment is in a high seismicity region, use PGA = 0.5g as a default. Live tank circuit breakers should be replaced for all critical circuits; using either dead tank bulk oil (older style), or dead tank SF6 (newer style); all equipment must be anchored. For areas of the country where the 475-year PGA exceeds 0.30g, bushings for high voltage transformers (200 kV and higher) should be seismically qualified. Every dead-end tower in China within substations should be rebuilt using materials (either steel or reinforced concrete) that can sustain the worst case loading of wind + ice + line loads; or PGA=0.5g without damage (keep stresses in steel below 0.96 Fy); all such structures that currently use under-reinforced concrete tubes should be replaced in a 5 to 10 year effort.

While costly, seismic improvement should be made substation control buildings. Most if not all of the failures of the control buildings could easily have been mitigated had the China rigorously adopted and implemented common standards for building construction for PGA = 0.40g using I=1.25. The upgrading of control buildings would require a long-term mitigation plan, but because of the vulnerability of these buildings and the risks that present to equipment an urgent mitigation program is indicated.

At many Chinese substations there are also residential buildings for local workers. While these buildings do not house substation equipment, their collapse in the earthquake was prevalent, resulting in substantial life safety consequences. As a matter of human decency, these buildings should be upgraded or replaced with suitably-designed buildings for PGA = 475 years (in high seismic hazard areas) or 2/3 of 2,475 years (in low seismic hazard areas) with I=1.0. Unreinforced masonry construction should not be allowed for human occupation where the design level PGA exceeds 0.15g.

If China adopts modern seismic design guidelines for infrastructure, such as those commonly adopted in the high seismic zones of California, likely more than 90% to 95% of all infrastructure damage will be avoided in future earthquakes in China.

China should upgrade its seismic design criteria for at least Intensity IX (Chinese scale) or PGA = 0.30g for all portions of the country that are exposed to M 6+ events more than once every 100 to 200 years. Higher requirements should be established within 10 km either side of active faults. Zonation requirements to avoid construction of substations for locations beneath steep slopes subject to earthquake or intense-rain triggered landslides.

China should implement a seismic retrofit program for all of its high value infrastructure. The retrofit program should include high priority low cost fixes (anchorage of all 115 kV or higher transformers at substations), and selectively upgrade buildings and facilities for the effects of inertial shaking. All new critical infrastructure must be designed for the simultaneous effects of strong ground shaking, landslide, liquefaction and surface fault offset.

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

UNITS AND ABBREVIATIONS

1 g = 981 gal
1 foot = 0.305 meter
ASCE = American Society of Civil Engineers
Fy = Yield stress of steel
I = importance factor (1 for regular buildings)
kV = kiloVolt
M = moment magnitude
PGA = peak ground acceleration (horizontal)
V = design basis earthquake shear force
W = weight of structure or component