Fig. 4.62. Collapsed 110 kV tower

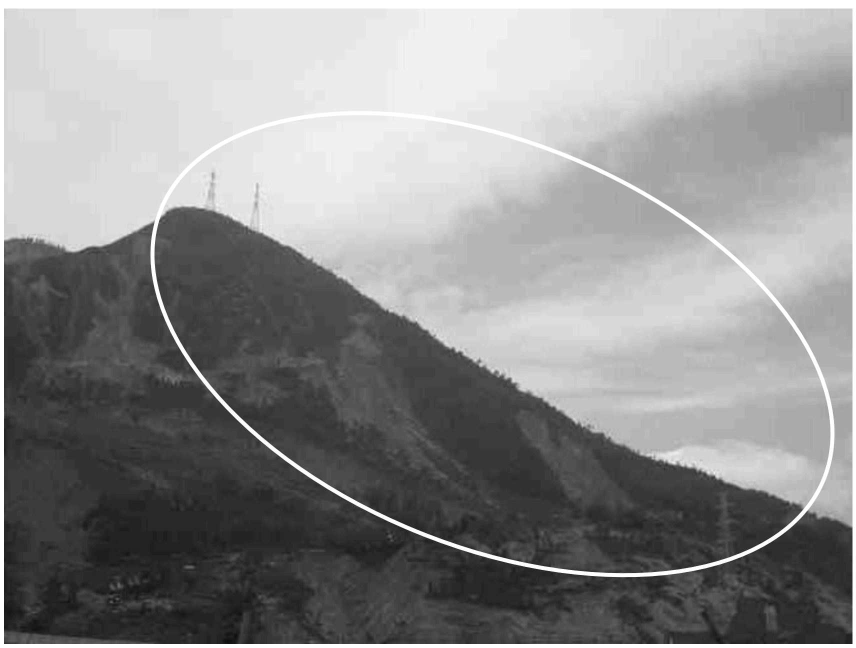
Fig. 4.63. Collapsed 10 kV line

Fig. 4.64. Collapsed tower

Fig. 4.65. Collapsed tower, #123, 500 Maotan line

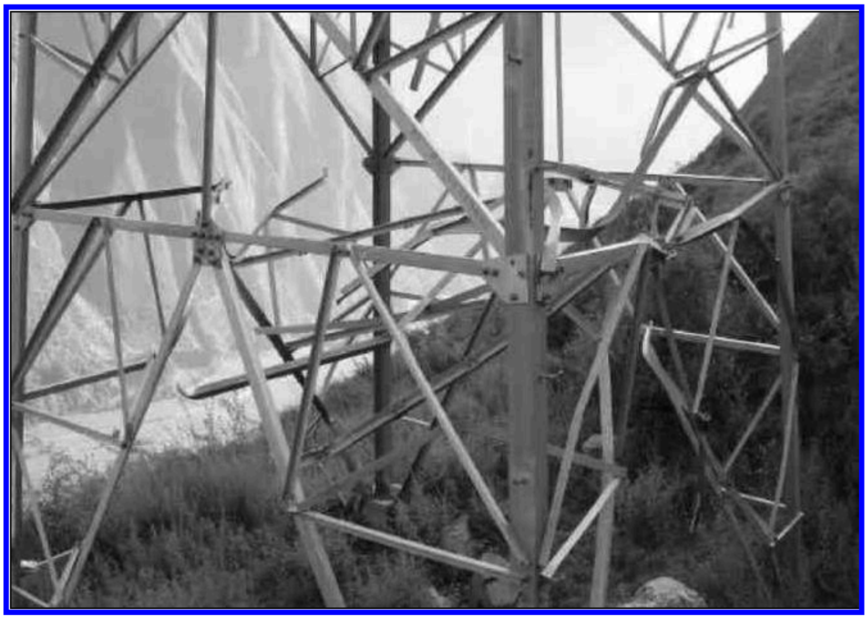

Fig. 4.66. Rack fall-impacted tower, #123, Hongxue line of Yingxiu Town

Fig. 4.67. Rock fall-impacted tower, #79, Zhouman line

Fig. 4.68. Collapsed Tower, #13, Jiangsang line

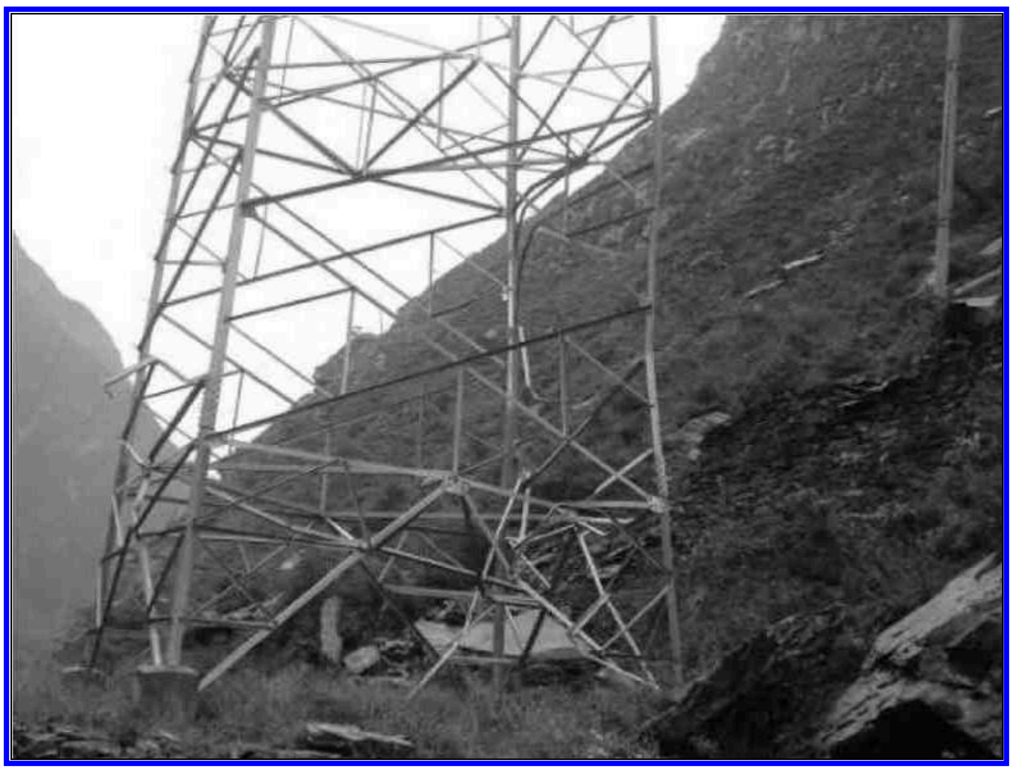

Fig. 4.69. Rockfall impacted tower, #14, Tianjin line, Jinlong Lake area, Wenchuan

Fig. 4.70. Collapsed tower, #11, Tianjin line, Jinlong Lake Area, Wenchuan

4.4 Distribution System

Overhead distribution (4 kV – 34.5 kV) is common in cities and towns in China. The most common pole style is a concrete tube. These concrete tubes appeared to have no shear steel (Fig. 4.71), and high bending/shear induced failures occurred where there were pulldown forces. Many dead-end frames at substations also use this construction, albeit oriented into an A-frame assembly. Several of these collapsed at a number of 110 kV and 220 kV substations with PGA > 0.4 g, (Fig. 4.30, 4.36, 4.48) due to a combination of inertial loading coupled with cable line dynamic loading (not landslide), leading to gross damage to yard equipment below.

Landslides and rock falls caused loss of poles in many areas (Fig. 4.72).

At Shenxigou village, we observed rockfalls that were likely triggered by the first rupture, followed by surface faulting of more than 3 m thrust upwards and 4 m lateral (some of this might have been induced landslide) that toppled power poles and caused power lines to come to rest atop the rock fall debris.

Platform-mounted transformers were observed. Figures 4.74 and 4.75 show two such examples. 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 similar retrofits be adopted in China as a high priority in all high-seismic regions of the country.

Fig. 4.71. Collapsed 10 kV distribution pole (10-in. diameter, 2.5-in. wall thickness)

Fig. 4.72. Pull down of power and telecom distribution due to landside

Fig. 4.73. Surface faulting uplift of about 3 m and lateral shift of about 4 m with damaged road and tilted distribution poles

Fig. 4.74. Fallen distribution transformer

Fig. 4.75. Distribution system transformer (10 kV) being replaced (Hongkou), July 16 2008

Figure 4.76 shows the failure of a low-voltage (10 kV) power cable crossing a bridge at Dujiangyan. The movement of the bridge embankment by a few inches resulted in the non-ductile failure of the PVC pipe at two locations and one location at the other abutment. It is likely that the power remained in service because it appears that the cables did not break at the PVC failure points and there was no new power line observed.

Figure 4.77 shows a distribution transformer resting on a pile of recently assembled bricks. Its predecessor fell off this pole. PGA at this site was about 0.3 g.

The physical requirements for the generation, transmission, and distribution of electrical power in China result in systems that are similar to those throughout the world. The function of equipment and substation configurations are almost the same. The major differences we observed between China and recently built substations in California were usually associated with equipment installation details and the seismic design of building structures.

4.5 Lessons Learned and Recommendations

The high-voltage switchyard equipment damage to the China State Grid substations is the same type we have seen many times in earthquakes in the United States and around the world.

Fig. 4.76. Damage to low-voltage power conduit at bridge abutments

The damage at high-voltage substations was severe, resulting in significant power disruption. The damage was largely due to the collapse of live tank circuit breakers, failure of high-voltage transformer bushings, movement of unanchored high-voltage transformers, collapse of dead-end towers, collapse of substation control houses, swinging of suspended wave traps with limited to no cable slacks, and to a lesser extent, pulldown of disconnect switches due to failed live tank breakers. It is our understanding that essentially none of the equipment at the substations had been procured with any seismic requirements.

The large number of damaged control buildings was observed in the 2001 India Bhuj earthquake. The damage to building contents as a result of their failure contributed to system disruption and aggravated the overall power restoration effort. The reason these buildings did not conform to reasonably high seismic standard design codes for critical lifeline facilities is unclear, but should be considered a major flaw in seismic design philosophy in China.

It is vital that China institutes good construction and equipment installation practices for new facilities. Good installation practices involve adequate anchorage, which constitutes a very small percentage of total project cost for new construction. Adequate cable (or bus) slacks should be provided for connecting equipment. Improving inspection practices during the transition is also critical, as there is a tendency for simple tasks such as anchorage to be done without referring to construction plans. Construction plans must detail those elements that improve seismic performance. These include anchorage and providing adequate slack in conductors connecting equipment. New equipment (especially at 110 kV and higher voltages) should be procured with seismic requirements as specified in IEEE 693. Additionally, test requirements for pole mounted transformers and their installation designs should be developed to reduce distribution system failures or pole mounted transformers should be eliminated in the distribution system. The rebuilt Yingxiu, Ertaishan Substation showed a promising improvement in installation quality but lacked good seismic design.

Generally, retrofitting is not a cost-effective procedure in areas of moderate seismicity. However, three activities are generally recommended at all locations where the 475-year return period PGA exceeds 0.20 g.

- Station batteries should be restrained to their racks, and the racks should be of adequate design and be adequately 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 4 or more; the PGA value should be at least the 475-year return period value. When the PGA value is not known and the owner suspects the equipment is in a high seismicity region, use PGA = 0.5 g 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 adequately anchored. For areas of the country where the 475-year PGA exceeds 0.30 g, bushings for high-voltage transformers (200 kV and higher) should be seismically qualified (IEEE 396).

- Every dead-end tower in China within substations should be evaluated and, where necessary, rebuilt using materials (either steel or reinforced concrete) that can sustain the worst case loading of wind + ice + line loads or PGA=0.5 g without damage (keep stresses in steel below 0.96 F_y). All such structures that currently use under-reinforced concrete tubes should be replaced in a 5- to 10-year effort. Impact of the dead-end towers by adjacent under-designed items (like light poles) must be avoided; whenever possible relocate these items. The replacement of dead-end structures program should start with the critical nodes (substations) first.