from the flexibility of tall structures and apparatus, with those heights largely dictated by electrical clearance requirements.

The conductors used to connect the equipment also cause dynamic interaction effects particularly if insufficient slack or flexibility is provided. Recent research has also concluded that conductor interaction effects may be significant even if slack is provided that is sufficient to prevent the conductor from becoming taut during the earthquake. Excessive slack is unfeasible as conductors may violate electrical clearance requirements, become unstable or displace excessively under transverse wind loading.

Buried electric transmission and distribution cables may be vulnerable to permanent ground deformation (PGD) resulting from liquefaction or landslide depending on the details of construction. Overhead transmission in contrast is generally very rugged. However, failures have been observed due to foundation failure such as landslide, or very high amplification of motions such as at the tops of ridges.

Design issues are often key contributors to failure or poor performance. Poorly detailed, improperly restrained, or unanchored equipment have been damaged in earthquakes. Structures may have been designed to be too flexible, anchorages too weak or configured such that non-ductile behavior occurs. Legacy equipment and supporting structures continue to make up significant portions of utility inventories due to life cycle and high cost of replacement with more modern and seismically robust equipment and structures. Old design codes usually specified low lateral force coefficients based on building codes which took advantage of energy dissipation from ductile inelastic behavior that is generally unavailable to high voltage equipment/components.

3 EQUIPMENT PERFORMANCE IN PAST AND RECENT EARTHQUAKES

The performance of electric substation equipment in recent large earthquakes around the world has been somewhat mixed. Generally speaking, seismically qualified equipment (or well-designed equipment that may not have been fully qualified) has performed acceptably in many cases. Restoration time frames for electric transmission systems have generally been good—a few days or less in most cases. However, there have been lengthy delays to restoring service to customers due to widespread damage of the distribution system or if critical lines or stations are lost.

Assessments of substation equipment performance from post-earthquake reconnaissance observations need to consider equipment vintage and basis for seismic design, estimated input motion at the site, conductor loading/interaction issues, as well as site-specific characteristics that might have influenced the performance. Qualified equipment in the field may not have been name-plated, and the generally unknown design bases of the equipment make it difficult to reach conclusions about the adequacy of design without a detailed investigation which is rarely conducted. This presents a complex mix of issues and there is often a lack of key information, which introduces uncertainty and makes it difficult to draw definitive conclusions.

The following subsections provide a brief summary of the performance of electric system equipment and components in recent large earthquakes. This summary is mainly drawn from reconnaissance reports, discussions with utility and other knowledgeable personnel, and observations of the authors.

3.1 Tohoku 2011

The 2011 Tohoku Earthquake (March 11, 2011) resulted in significant damage to electric system infrastructure. However, a significant portion of the damage is attributed to tsunami. Eidinger 2012 [1] reports that recovery of the electric power grid was accomplished rather quickly (90% within 6 days). Substation equipment was damaged due to high levels of shaking from the earthquake (0.55g median PGA near the coast at about 48km distance, and 0.3g PGA at 100km; several instruments reported extremely high levels of shaking, up to 2.9g PGA [1]).

The two hardest hit large utilities, Tohoku Electric Power Co. and Tokyo Electric Power Co. suffered damage to high voltage transformers and their bushings, live tank circuit breakers, air disconnects, instrument transformers, surge arresters, cable terminations and buried transmission cables. Failures likely attributable to conductor interaction effects were also observed.

The Japanese seismic qualification standard in force at the time of the earthquake required high voltage equipment (>170kV) to be subjected to shaking table tests with a three-sine wave input motion (3m/sec) at the resonant frequencies of the equipment. Standard developers reportedly have decided to maintain this set of requirements for the present, although they are considering the adoption of alternative qualification requirements.

3.2 New Zealand 2010-2011

The Christchurch, New Zealand area was struck by a sequence of three significant (M_w 7.1, 6.3, and 6.0) earthquakes between September, 2010 and June, 2011. These earthquakes were particularly noteworthy because of damage to lifeline systems resulting from widespread liquefaction. During these earthquakes, above ground electric equipment and systems performed quite well.

In the M_w 7.1 event, the transmission system suffered minor damage including failed porcelain surge arresters mounted on the transformer radiators, and non-structural substation building damage. Electric substations commonly experienced ground motions in the 0.2g PGA range. Spare parts and materials were also damaged due to inadequate restraint and the failure of warehouse storage racks. Restoration of the transmission system occurred within 4 hours [2]. Damage to buried distribution systems was more significant largely due to liquefaction-induced ground displacement. At the hardest-hit electric distribution provider, 85% of peak capacity was restored to 95% of customers within 48 hours, with full restoration requiring about a month [2].

The M_w 6.3 event of February, 2011 was centered much closer (10km vs. 40km) to the Christchurch central business district and shallower compared to the M_w 7.1 event of September, 2010. As a result, much more damage occurred in the city itself, and to the lifeline systems serving it. Transmission and distribution substations experienced ground motions of 0.5g PGA and more [3, 4].

The transmission system performed well, and was able to deliver service within 5 hours. Substation damage was relatively minor, including a 220kV CCVT, 66kV transformer

transformers slid, dropped, even overturned during the earthquake. This failure mode lead to complete failure of the equipment due to internal damage or damage to components including cores/coils, bushings, radiators, conservators and other accessories. In many cases, damage to transformer internals caused faults sometime after the earthquake leading to fires and complete loss of the transformer. The large displacements of the transformers from tippling or sliding lead to ruptures of rigid and flexible connectors attaching other equipment to the transformer components.

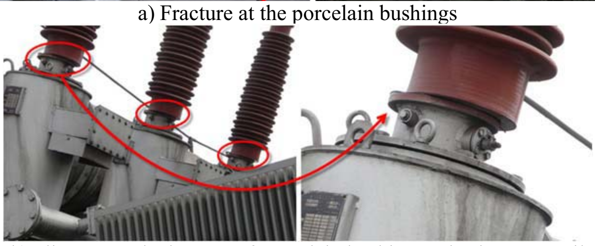
The observed damage modes of transformers were mainly as follows: (a) slippage of an anchored transformer on its foundation, (b) falling off the foundation on the ground if displacement exceeded the foundation dimensions, (c) collapse due falling on the ground, (d) oil leakage of transformer bushing, and (e) damage of accessories caused by the large displacements of transformers. The most common modes of failure were modes (a) through (c) and in many cases they resulted in modes (d) and (e). Because the mass of a transformer is extremely high, a vibration of a transformer during strong earthquake produces a large inertia force that can cause slippage, overturning, or collapse. Figure 1 shows some typical transformer failure modes observed in this earthquake.

a) Overturning of 110kV transformer b) Slippage of a 220kV transformer

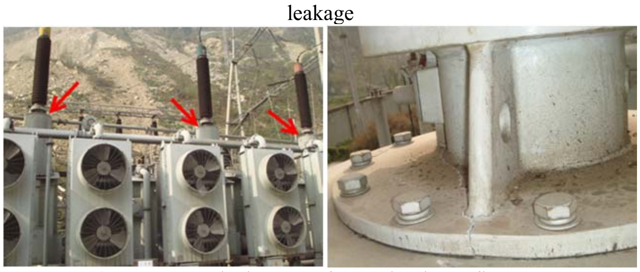
Figure 1. Typical failure modes of transformers in China.

Damage to transformer bushings. Bushings are typically attached by bolting to the top plate of a transformer tank, or to a turret extending from the top of the transformer tank. The bushings are installed in plumbed and inclined configuration. In the latter case, the angle between the longitudinal axis of the bushing and the vertical direction can vary and was about 20 degrees for the bushings investigated after the earthquake. Structurally, bushings represent long and slender members with the majority of them made from porcelain. In many cases the flexibility of the top plate of the transformer caused a significant amplification of the ground motion leading to large bending moment and shear force at the base of the bushing. The results of this amplification combined with poor structural strength and brittleness of the porcelain demonstrated extremely high vulnerability of the bushings to the effects of this strong earthquake. Porcelain bushings may exhibit different failure modes depending on the style of construction. Center-clamped porcelain bushings derive their lateral load-resisting capacity from a post-tensioning force applied through the core of the bushing. Such bushings typically fail by slippage of the bottom porcelain/gasket on the bushing flange resulting in oil leaks or gasket ejection. Bushings may also be constructed with porcelain sections that are grouted or mechanically clamped to the bushing flanges. These bushings may also fail by slippage accompanied by oil leak, or by porcelain fracture. Figure 2 shows the typical failure modes of bushings in Wenchuan Earthquake, which includes (1) fracture at the base of the bushing as shown in Figure 2a, (2) movement of the upper porcelain unit relative to its support flange and extrusion of rubber gasket as presented in Figure 2b, and (3) fractures at the cast-aluminum flange of bushings as shown in Figure 2c.

a) Fracture at the porcelain bushings



b) Slippage at the bottom of porcelain bushing and subsequent oil leakage



c) Fracture at the bottom of cast-aluminum flange

Figure 2. Typical failure modes of transformer bushings in China.

Damage to other substation equipment. Besides the severe damage of transformers, switchgear and instrument transformers, including circuit breakers, voltage and current transformers, disconnect switches and lightning arresters also suffered a wide range of damage. Figure 3a shows the damage of the Ertaishan switchyard, near the epicenter of the earthquake in which all substation equipment and structures were destroyed without any survivors. Catastrophic failure of substation structures is rare in earthquakes. In the case of Ertaishan switchyard, lightly-reinforced concrete pole modules with weak connections likely contributed to the failures. Figure 3b shows the damage to outgoing line equipment, which occurred in a substation, including disconnect switches, circuit breakers, and current transformers, which were interconnected by flexible bus work.

will greatly improve the development of accurate and cost-effective qualification procedures.

- Conductor loading/interaction has long been suspected of contributing to failures in substation equipment. Recent post-earthquake reconnaissance continues to support and strengthen this conclusion. Although significant advances have been made in the development of design procedures for dealing with this problem [14, 15], the complexity of the behavior of conductors and equipment, and the cumbersome nature of existing procedures hinder progress in this area. Additional research is needed to develop a better understanding of these phenomena and improved analysis and design procedures.
- The vulnerability of buried cables to liquefaction-induced ground displacement has been observed in a number of earthquakes. The extensive damage observed in the New Zealand earthquakes near Christchurch should serve as a warning to utilities and electric system operators of the long time frames required for restoration of such systems.

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