ASCE Manuals and Reports on Engineering Practice No. 96

Guide to Improved Earthquake Performance of Electric Power Systems

ASCE

AMERICAN SOCIETY OF CIVIL ENGINEERS

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Guide to Improved Earthquake Performance of Electric Power Systems

Prepared by
Electric Power and Communications Committee
Technical Council on Lifeline Earthquake Engineering

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Abstract: The Manual documents methods to improve the earthquake response of electric power systems. A review of the Manual should raise the awareness and understanding of the vulnerabilities of power system facilities and equipment. The emphasis is on power system elements that have been damaged by earthquakes, primarily high-voltage substation equipment. Power-generating stations, transmission and distribution lines, substations, system communications and control, and ancillary facilities and functions are also discussed. A detailed review of earthquake damage to power facilities and suggestions to improve their performance are presented. The Manual suggests an overall approach to an earthquake mitigation program. Postearthquake emergency response procedures to reduce the disruption from damaged facilities are also discussed. The Manual demonstrates that improved installation practices and other mitigation measures, particularly for new construction and during refurbishment, that are cost-effective in any region with a history of significant earthquakes can be implemented to improve earthquake performance.

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PREFACE

The development of this document began with a grant from the National Science Foundation with subsequent support from the Electric Power Research Institute and the National Institute of Standards and Technology. The technical content of the document has evolved as additional information has been gathered following damaging earthquakes. The lessons learned from the Northridge earthquake were particularly useful.

Unlike the more frequent disasters that impact power systems, such as severe winds and ice storms, damaging earthquakes may not impact a utility in less seismically active areas during the entire working careers of its personnel. Further, many utilities in seismically vulnerable areas have not been subjected to a damaging earthquake since the introduction of modern power systems. Thus, there is little opportunity for a meaningful learning curve to develop within an organization. Executive Order 12699 mandates that all federal organizations or organizations receiving federal funds must consider seismic vulnerability in the design and construction of their buildings. Under Executive Order 12941, such organizations must review the seismic vulnerability of existing buildings. This guide has been written to address the need for practical guidance for improving earthquake performance of power facilities.

A special effort has been made to have broad representation in the review of this document. Active participants in the review process included representatives from the most seismically aggressive utilities; investor-owned, municipal, and federal power organizations; West Coast and Eastern utilities; and engineer-architects and consultants who design power facilities. Members of the committee and organizations not represented on the committee were asked and participated in the review of the document. All individuals were asked to accept, accept with reservations, or reject the document on a mailed ballot, and all accepted without reservations.

Anshel J. Schiff

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EXECUTIVE SUMMARY

Recent moderate and strong California earthquakes have demonstrated that parts of electric power systems are very vulnerable to damage. Most damage has been due to the failure of porcelain elements in high-voltage substation equipment. However, performance is strongly influenced by specific equipment designs and installation practices. There has also been damage to substation buildings, conductor support structures, cast-aluminum hardware used on both low- and high-voltage equipment, equipment support structures, equipment anchorage, and parts of power-generating stations. The performance of some communication and control systems has been impaired after earthquakes.

Direct cost for repair and replacement of earthquake damage to power system facilities from the 1971 San Fernando (Moment Magnitude, M_w = 6.6), the 1987 North Palm Springs (M_w = 6.1), the 1989 Loma Prieta (M_w = 6.9), and the 1994 Northridge (M_w = 6.7) earthquakes was $45 million, $9 million, $100 million, $183 million, respectively. In spite of extensive equipment damage, system performance after these earthquakes has been good in terms of customer disruption because of the high degree of redundancy incorporated into power systems. However, no major or great earthquake has struck a large metropolitan area. Past earthquake damage to equipment suggests that larger earthquakes, earthquakes that impact larger areas, or earthquakes that occur in regions where less stringent seismic design practices and more vulnerable equipment are used will have more extensive earthquake damage that could overwhelm system redundancies. As a result, unacceptably large direct losses, lengthy disruption of service to the community, and indirect losses borne by customers are likely. Improved installation practices and other mitigation measures, particularly for new construction and during refurbishment, that are cost-effective in any region with a history of significant earthquakes can be implemented to improve earthquake performance.

The purpose of this Manual is to document methods to improve the earthquake response of electric power systems. The major goals include:

- reviewing how earthquakes affect power system facilities and equipment;
- raising the awareness and understanding of the vulnerabilities of power system facilities and equipment by reviewing their earthquake performance;
- suggesting an overall approach to an earthquake mitigation program;
- suggesting earthquake preparedness techniques to improve postearthquake response;
- reviewing design details that contributed to both good performance and failures during earthquakes;
- providing insight into facility performance, so facilities can be evaluated to determine their earthquake vulnerability;
- suggesting hardware changes that can reduce earthquake damage to existing facilities;
- suggesting approaches for new construction that have been shown to reduce earthquake damage; and
- suggesting earthquake emergency response procedures to reduce the disruption from damaged facilities.

This document deals with major power system elements—power-generating stations, transmission and distribution lines, substations, system communications and control, and ancillary facilities and functions. The emphasis given to the various elements is strongly related to their earthquake performance. Thus, a large portion of the document is devoted to high-voltage substations, as this is where most power system damage has been concentrated. In facilities where existing practices have performed well, such as transmission lines and power-generating stations, recommendations will be limited to those areas where damage has been observed.

Key findings of the document are the following.

- It is vital to start an earthquake mitigation program.
- Cost-effective methods are available to improve the earthquake performance of power systems.
- Earthquake mitigation practices should be institutionalized by incorporating them into the utility's manual of practice.
- Most seismic upgrading of a utility will occur during normal refurbishment and new construction and may require a few decades to be fully implemented.

In most earthquakes, it has been possible to bypass damaged equipment and continue to get power through or to route power around the damaged

substation. There have been cases where an entire switchyard has been bypassed. Fortunately, when transformers have been damaged, there has been adequate capacity in alternate routes to maintain service. However, it is easy to envision damage, particularly to transformers, that could cause lengthy disruptions. The relatively short time to restore service in the face of extensive damage can be attributed to the high level of redundancy designed into power systems and the resourcefulness and dedication of utility maintenance personnel.

Looking at a utility's response to moderate and strong earthquakes helps to put the recovery effort into perspective. In the 1986 North Palm Springs earthquake, where a single substation was damaged, about 250 people worked 18-hour days for three days to clear damaged equipment from the site. About 180 people continued to work for about an additional 6.5 days to restore service to a critical line. This reconstruction was carried out by several crews working in parallel at all locations where possible, to reduce the disruption time. This damage occurred to a facility that used the then-current and most stringent earthquake mitigation practices instituted after the 1971 San Fernando earthquake. After the Loma Prieta and Northridge earthquakes, it took months to repair and replace damaged equipment, even though service was restored quickly.

In light of the recent experience, many California utilities are reevaluating the vulnerability of their systems and adopting measures to improve their system's response. While some of these measures would be difficult to justify in regions of lower risk, many things, particularly for new construction, can be done that are cost-effective in any region that has a history of significant earthquakes. It would be unfortunate if cost-effective measures were not implemented and that utilities and the communities they serve were exposed to avoidable risks.

Chapter 1
INTRODUCTION

1.1 BACKGROUND

Recent moderate and strong California earthquakes have demonstrated that parts of power systems are very vulnerable to damage. While system performance has been good as measured by customer disruption, the damage pattern suggests that system performance will not be acceptable for larger earthquakes, for earthquakes that impact larger areas, or for earthquakes in regions of the country that use less stringent earthquake practices. Starting with the 1971 San Fernando earthquake, there have been ten California earthquakes that have damaged power system facilities. Most of these small to moderate earthquakes have shaken relatively small areas, so that damage has been concentrated and limited primarily to one or two facilities. The 1989 Loma Prieta, California, earthquake affected a large area; three substations were severely damaged, and the network in the region was disrupted. The 1994 Northridge, California, earthquake also affected a large area, and eleven power facilities were damaged; several experienced peak ground accelerations above 0.75g. Earthquakes in Chile and Japan have also provided lessons that can be applied to facilities in the United States.

Most damage has been due to the failure of porcelain elements in high-voltage substation equipment. However, performance is strongly influenced by specific equipment designs and installation practices. There has also been damage to substation buildings, conductor support structures, cast aluminum hardware used on both low- and high-voltage equipment, equipment support structures, equipment anchorage, and parts of power generating stations. The performance of some communication and control systems has also been impaired after earthquakes.

Direct costs of earthquakes for repair and replacement of damaged facilities have not been overwhelming in terms of utility assets, but are nonetheless significant. There were direct losses of about $45 million in the 1971 San

Fernando earthquake (Moment Magnitude, M_w = 6.6), $9 million in the 1986 North Palm Springs earthquake (M_w = 6.1), $100 million in the 1989 Loma Prieta earthquake (M_w = 6.9), and $183 million in the 1994 Northridge earthquake (M_w = 6.7). Some smaller, less costly earthquakes have been very disruptive. In the 1988 Tejon Ranch earthquake, the California Aqueduct, which supplies water to the Los Angeles area, was shut down for four days; there is typically only a 15-day supply of water stored downstream of the point that was damaged. In the 1984 Morgan Hill earthquake, one of the three Pacific Interties (major power circuits connecting the Northwest and the Southwest) was down for three days.

In most earthquakes, it has been possible to bypass damaged equipment and continue to receive power through or to route power around the damaged substation. There have been cases where an entire switchyard has been bypassed. Fortunately, when transformers have been damaged, there has been adequate capacity in alternate routes to maintain service. The relatively short time to restore service in the face of extensive damage can be attributed to the high level of redundancy designed into power systems and the resourcefulness and dedication of utility maintenance personnel. However, it is easy to envision damage, particularly to transformers, that could cause lengthy disruptions.

Looking at a utility's response to moderate earthquakes helps put the recovery effort into perspective. In the 1986 North Palm Springs earthquake, about 250 people worked 18-hour days for three days to clear damaged equipment from the site. About 180 people continued to work for about an additional 6½-days to restore equipment and service to a critical line. This reconstruction was carried out by several crews working in parallel at all locations where possible in order to reduce the disruption time. This damage occurred to a facility that used the then-current and most stringent earthquake mitigation practices. After the Loma Prieta and Northridge earthquakes, it took months to repair and replace damaged equipment, even though service was restored quickly.

This experience suggests that larger earthquakes, earthquakes that impact larger areas, or earthquakes that occur in regions where less stringent seismic design practices and more vulnerable equipment are used will have more extensive earthquake damage that could overwhelm system redundancies. As a result, unacceptably large direct losses, indirect losses borne by customers, and lengthy disruption of service to the community are likely. In light of the recent experience, large California utilities are reevaluating the vulnerability of their systems and are adopting measures to improve their system responses. While many of these measures would be difficult to justify in regions of lower risk, some things—particularly for new construction—can be done that are cost-effective in any region that has a history of significant earthquakes. It would be unfortunate if cost-effective

measures were not implemented, and utilities and the communities they serve were exposed to avoidable risks.

Much of the information on earthquake damage to power systems has been gathered by the Earthquake Investigation Committee of the Technical Council on Lifeline Earthquake Engineering. Members of the committee investigated eleven U.S. and five foreign earthquakes that have damaged power system facilities, including the 1985 Chile; 1978 Sendai, Japan; 1988 Soviet Armenia; 1990 Philippines; and 1995 Kobe, Japan earthquakes.

1.2 PURPOSE

The purpose of this Manual is to improve the earthquake response of electric power systems. This is to be achieved by doing the following:

- review how earthquakes affect power system facilities and equipment;
- raise the awareness and understanding of the vulnerabilities of power system facilities and equipment by reviewing their earthquake performance;
- suggest an overall approach to an earthquake mitigation program;
- suggest earthquake preparedness techniques to improve postearthquake response;
- review design details that contributed to failures or that performed well in earthquakes;
- provide insight into facility performance so that facilities could be evaluated to determine their earthquake vulnerability;
- suggest hardware changes that could reduce earthquake damage;
- suggest approaches for new construction that have been shown to reduce earthquake damage; and
- suggest earthquake response procedures to reduce the disruption from damaged facilities.

1.3 BASIS FOR RECOMMENDATIONS

The recommendations in this Manual are based primarily on experience in California earthquakes and a few foreign earthquakes. Many of the recommendations have been drawn from innovations initiated by California utilities, and their contributions are acknowledged. Because practices and equipment used in different parts of the United States vary, the effectiveness of some practices and equipment is unknown. Also, there may be differences in earthquakes and their effects in other parts of the country. For example, there are indications from records of small, Eastern earthquakes that ground