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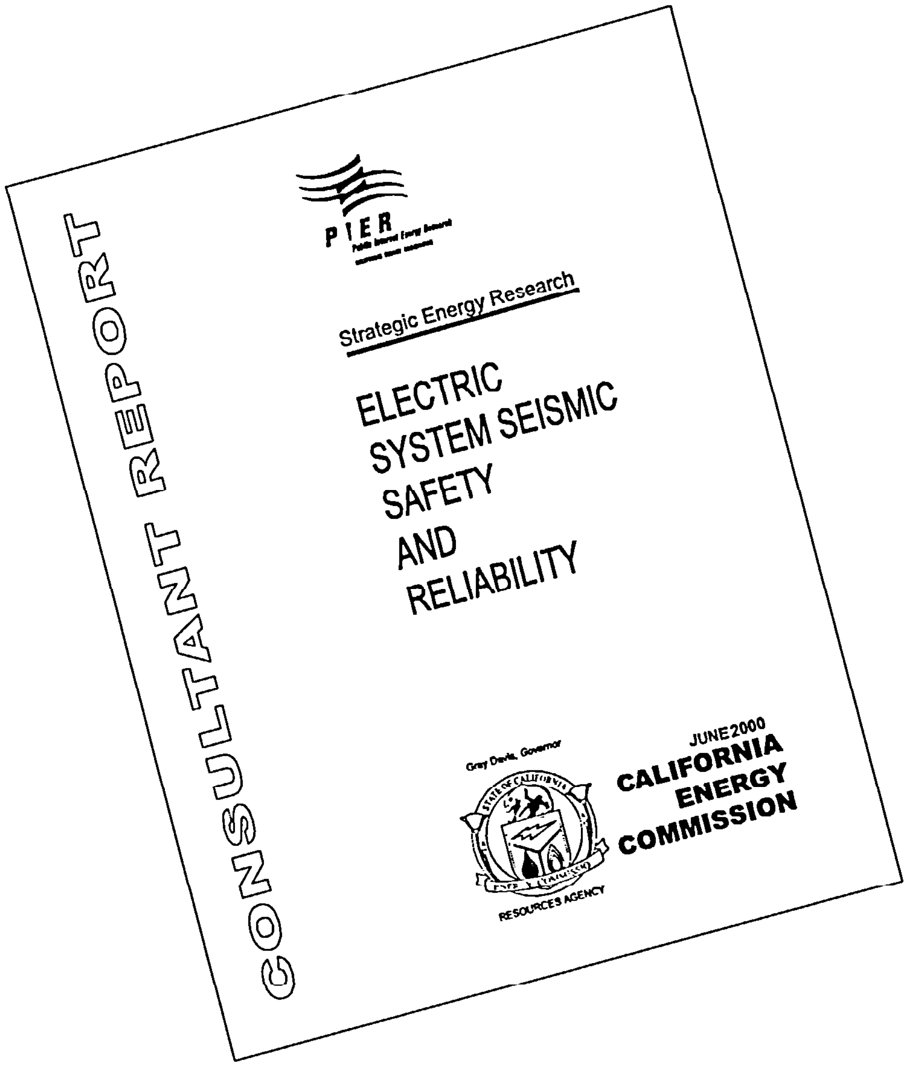

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million through the Year 2001 to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research.

In 1998, the Commission awarded approximately $17 million to 39 separate transition RD&D projects covering the five PIER subject areas. These projects were selected to preserve the benefits of the most promising ongoing public interest RD&D efforts conducted by investor-owned utilities prior to the onset of electricity restructuring.

What follows is the final report for the Electric System Seismic Safety and Reliability project, one of nine projects conducted by the Pacific Gas and Electric Company. This project contributes to the Strategic Energy Research program.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

Executive Summary

The safety and reliability of electric power is given high priority by almost all sectors of society in California. Electricity is the fundamental fuel for the economic engine of technology, manufacturing, and commerce. Even brief power outages can be costly and disruptive to the current fast pace of business and everyday life. The earthquakes in California in 1989 and 1994 are a warning of the potential of even larger and more severe earthquakes to affect the state. Thus, evaluating and improving the post-earthquake functioning of electric power service is an important priority both for providers of that service and for their customers. This report describes the results of applied research being conducted under the direction of Pacific Gas and Electric Company (PG&E) through support of the California Energy Commission (Commission), with the objective of systematically reducing earthquake risks to electric power in California.

Background

In 1996, PG&E initiated a rate-payer funded, utility-directed research program to develop new and improved data sets, models, and methods that could be rapidly incorporated into the company's Earthquake Risk Management Program. This program had been initiated in 1987 and was expanded and accelerated with the experience and lessons of the 1989 Loma Prieta and 1994 Northridge earthquakes. The goal of the applied research program was to allow the utility to better understand the earthquake performance of gas and electric systems, and to develop ways and means, beyond those already known and applied, to improve the systems' safety and reliability, thereby significantly reducing earthquake risks.

A partnership was established with the Pacific Engineering Research Center (PEER), based at the University of California, Berkeley (UC Berkeley), to conduct the research. This collaboration quickly became effective, producing practical results that built on the involvement of talented researchers and excellent facilities in the PEER consortium of universities.

Objective

The objective of this project is to provide data, models, and methods needed to reduce the earthquake vulnerability and to improve the system reliability and safety of electric transmission and distribution systems. Once implemented, these research results would enable faster post-earthquake restoration of customer service by reducing the amount of damage and disruption of electric transmission and distribution service caused by earthquakes, and by providing more accurate and rapidly available post-earthquake information about the state of damage produced by earthquakes. The research results could also be used, as appropriate, by businesses, industry, regulatory agencies, and the general public to reduce earthquake vulnerabilities and respond more effectively to earthquake affects in California and elsewhere.

Topics

PG&E scientists, engineers, and operations specialists identified seven topics of needed research based on the current state of knowledge about earthquake hazards and vulnerabilities of the electric transmission and distribution systems. These topics, incorporating the results of previous research conducted by PG&E and PEER, are described below.

- **Topic 1**: Ground Motion and Site Response -- The site-specific assessments of near-fault ground shaking, and of ground motions at soil sites, need to be improved for more accurate performance assessments of facilities exposed to large earthquakes.
- **Topic 2**: Ground Motion Estimates for Emergency Response -- Accurate and quickly available post-earthquake information about the location of potentially damaging strong ground motions is needed to improve emergency response by utilities for more rapid restoration of utility service.
- **Topic 3**: Ground Deformation Database -- The empirical basis for estimating potential earthquake-related ground deformation needs to be more reliable and accurate for the design of substations and other critical components in the transmission and distribution system.
- **Topic 4**: Electrical Substation Equipment Performance -- Experimental studies and related analyses of different designs and retrofits of high-voltage transformer and interconnected equipment are needed to assure the adequate performance of the electric transmission grid in earthquakes.
- **Topic 5**: Earthquake Fire Safety Associated with Gas and Electric Systems -- A basis is needed for choosing optimal ways to reduce the threat of post-earthquake fires due to natural gas and electric power.
- **Topic 6**: Building Vulnerability -- The protection of utility employees and the general public, and the ability to rapidly restore utility services, are both dependent on assuring the appropriate level of earthquake performance of utility office building, warehouses, service centers, and control buildings. The ability to make accurate assessments of building performance when exposed to various levels of earthquake shaking needs to be improved.
- **Topic 7**: Seismic Vulnerability of Underground Cables -- Because underground high-voltage and low-voltage electric cables are potentially exposed to damaging permanent ground deformation in earthquakes, the vulnerability of existing cables needs to be quantitatively assessed.

The research topics listed above are broad, and it was not immediately obvious what specific research steps were optimal to address the identified needs. PG&E and PEER developed an innovative and effective means to develop specific research projects that would involve the most knowledgeable academic personnel and would provide practical results at the end of each project. PG&E and PEER formed a Joint Management Committee (JMC) composed of five or six representatives from each organization. The JMC provided a forum for identifying the scopes of work of well-focused research projects, selecting highly qualified investigators to conduct the projects, and monitoring the work so that utility user needs would be met. The JMC made coordination with other research activities outside of the Commission-funded project more effective. A representative of the California Department of Transportation joined the JMC during the course of the program to provide input and coordination with their ongoing research.

The JMC approved a detailed Request for Proposals to address the seven topics. Based on the responses received, the JMC decided to eliminate Topics 6 and 7 and to concentrate on the first five topics in this program, deferring research on the other two topics to the future. This program funded a total of 18 research projects. The following discussions, organized around the five topics, summarize the results of these research projects.

Topic 1: Ground Motion and Site Response

Objective

In this topic, eight interrelated projects were carried out to improve and verify the data, models, and methods used to predict earthquake ground motions at utility structures and equipment sites, thus improving inputs to earthquake performance assessments of those facilities. Accurately estimating the ground-shaking effects of future earthquakes is complex and depends on (1) accurate observations of ground motions and the sites on which they are located, and (2) unbiased models and methods for predicting ground motions at any location. The projects described below comprehensively address these needs.

While the strong shaking expected near faults in large (magnitude 7 or greater) earthquakes is very important for facility design and performance evaluation, to date there is only one very well recorded earthquake—the Chi-Chi, Taiwan event of September 21, 1999. In the absence of a robust statistical database, numerical procedures for the reliable simulation of near-fault ground motions are needed for engineering purposes.

Outcomes

In three parallel projects, the ability for three widely used simulation methods to predict the near-fault (within 15 km) recorded ground motions from five pre-1999 earthquakes was evaluated. The evaluation showed that all three methods were successful in replicating the main effects of rupture directivity on ground motions greater than one second in period. With this level of confidence, the models will next be tested against the 1999 data from Taiwan and Turkey. When those data are correctly replicated, the numerical procedures can be used to develop simple parametric models for near-fault ground motions for use in seismic hazard analysis.

In the interim, before the simulation methods can be fully tested, two additional projects exercised the best available techniques to provide estimated ground motions to be used by other projects in this program in cases in which no recorded ground motions were available. The simulated motions were used in the ground response and ground deformation database projects.

The collaborative project called Resolution of Site Response Issues for the Northridge Earthquake (ROSRINE) has been of great value in improving engineering models for estimating site response, and has collected data for more than 40 sites. This PG&E-PEER project supported the collection of site characterization data using boreholes and surface measurements for six additional sites. As shown in the next project summary, the aggregate site characterization database enables the development of improved analysis tools for ground motion response for design and performance assessments.

It is widely observed that ground motions on soil are different from, and typically more severe than, those observed on nearby rock outcrops. In two companion projects, the existing data base of ground motions was analyzed to determine site response factors that quantify the differences in ground motions for difference types of soil, and the benefit of using such site response factors was quantitatively assessed. The site response analysis using surface geology classifications was calibrated using the high-quality site soil characteristics determined in the ROSRINE project. The study showed the site-specific analysis provides significantly improved accuracy in estimating the response of an individual site compared to using generic soil models. Uncertainties in site response estimation are relatively high for soft clay sites, but can be estimated from broad site categories for stiffer sites. These results are immediately useful in utility ground motion evaluations, both probabilistic and deterministic.

Summary

The results of the projects under this topic have immediate application to refined ground motion assessments at sites of both utility and customer facilities. These more accurate assessments can be used for design of new facilities to resist earthquake effects, as well as for the identification of facilities whose future performance in earthquakes is not adequate and needs improvement. In both cases, the implementation of these results leads to greater service reliability and improved safety for utility customers.

Topic 2: Ground Motion Estimates for Emergency Response

Objective

The objective of the project carried out for this topic was to make significant progress in improving the immediate post-earthquake location of areas of strong earthquake shaking, and thus of potential building damage, to enable utility and other emergency responses to be more accurately deployed. In some portions of Southern California there are now sufficient closely spaced strong-motion instruments to enable such information to be compiled into what is called a ShakeMap. However, in other parts of the state, more widely distributed instrumentation exists, including both strong motion and broadband instruments.

Outcomes

This project focused on developing a procedure to rapidly analyze broadband seismic data to estimate the pattern of strong ground motions following a potentially damaging earthquake. The method has been calibrated using the records from the 1992 Landers and 1994 Northridge earthquakes and can provide results in about 20 minutes for any area in the state.

Summary

Future plans for this method are to improve it to better handle earthquakes with large fault ruptures, and to integrate it into the rapid earthquake analysis systems being operated by United States Geological Survey (USGS), California Institute of Technology (Caltech), and UC Berkeley. When these results are implemented, PG&E’s emergency response personnel and customers and other Californians in earthquake-affected areas can benefit by emergency response that is more rapidly and more accurately directed to the areas with severe building damage and utility and transportation system disruption. This improved emergency response will save lives and promote faster restoration of utility services and recovery of normal living conditions following the earthquake.

Topic 3: Ground Deformation Database

Objective

The objective of the project carried out under this topic was to improve the existing database of ground deformations observed in past earthquakes.

Outcomes

Extensive data on amounts of ground deformation due to liquefaction from the 1995 Kobe, Japan earthquake were quality checked and incorporated into the existing statistical database. Pre-1995 data in the database were systematically reviewed and checked using original sources. Particular attention was paid to smaller deformations, in the range of 0.1 to 2 meters, which are significant for underground utilities, but have received little attention from the research community.

Summary

The database produced by this project will be the basis for developing a simplified model for preparing probabilistic maps of potential ground deformation following earthquakes. With the application of these products, electric power customers will benefit from reduced outages due to new facilities being better designed to avoid or resist earthquake-related ground deformation. As a byproduct of these results, other critical utilities, such as water and natural gas distribution and wastewater collection, can take advantage of the improved knowledge of ground deformation hazards to reduce future earthquake losses and improve the reliability of post-earthquake functionality.

Topic 4: Electrical Substation Equipment Performance

Objectives

The vulnerability of high-voltage substation equipment, particularly transformers, has been the primary reason that power grids have failed in past earthquakes. The objectives of the seven projects carried out under this topic were to improve the understanding of the vulnerability of transformers and interconnected substation equipment, and to identify specific actions that can be taken to reduce significant vulnerabilities.

Outcomes

Two projects focused on the porcelain insulators used in power transformers to insulate the conductors that pass through the body of the transformer to connect to the internal windings. Shaking-table tests were performed on several different transformer insulators, called bushings, in two voltage classes, 196,000 volts (196 kV) and 550 kV. Testing was done in accordance with the shaking levels used in the industry qualification standard for substation equipment, Institute of Electrical and Electronics Engineers (IEEE) Std 693-1997. Data collected during the tests identified factors that lead to improved bushing ruggedness, including higher clamping forces holding the bushing on the transformer, and using a modified retrofitted retaining ring at the base of the bushing. Important modifications needed in the IEEE Std 693-1997 testing and analysis procedures were also identified.

In a related study, experimental data on the vibratory response of large transformers were collected to measure the effect that the transformer body has on the level of shaking transmitted to the bushing in an earthquake. These tests revealed that the sources of flexibility of a transformer need to be better understood, since there was a significant reduction in the vibration frequency of bushings mounted on a transformer versus the same bushing tested on a shaking table support. The tests also indicated that the simple model used in IEEE Std 693-1997 is not adequate to account for the complex behavior of the bushing and support system of a large transformer.

Conductors that are used to electrically interconnect substation components can also damage those components if the relative motions of the components exceed the conductor slack. Shaking table testing and analytical modeling of flexible strap and cable connectors of configurations currently in use by PG&E and other utilities were carried out in two projects. The analytical studies developed a simple concept of Response Ratios that relates the unconnected performance of the equipment to its performance when connected. A method was also developed to estimate the conductor slack required to prevent the effects of interaction during strong shaking. A coordinated set of shaking table tests on bus connectors produced a good test data set that confirmed the analytical studies and demonstrated that significant energy dissipation occurs when shaken equipment is connected.

In past earthquakes, rocking and toppling of substation equipment, particularly transformers, has been observed. Analytical studies were extended to investigate such factors as the influence of anchorage strength, the role of vertical seismic motions, and the impact loading associated with rocking. The results showed that conventional engineering methods using static coefficient analysis provide a safe design in most cases. Although vertical motions were found to be insignificant, there are certain frequencies of rocking that have a heightened potential for overturning. These results can be readily formed into practical engineering design guidelines.

A special project was instituted late in the research program to help deploy a post-earthquake investigation team from PG&E and the Commission to assess the impacts of the Kocaeli, Turkey earthquake of August 17, 1999 on the Turkish electric transmission and distribution system. The team found that the types of damage that occurred were typical of past earthquakes, but that the designed redundancy of the transmission system coupled with an aggressive emergency response effort enabled power to be restored within less than one day to all but the most heavily damaged cities. The lessons from this earthquake affirmed the scope and purpose of the PG&E-PEER-Commission research program.

Summary

These results provided both immediately useable performance information about currently installed equipment, and guidance for additional studies to specify practical mitigations of significant earthquake vulnerabilities in substation equipment. The application of these results could lead to improved designs and procedures for substation equipment purchase and installation, directly providing reduced outage times for the electric grid following earthquakes, both benefiting customers and optimizing equipment expenditures by the utility.

Topic 5: Earthquake Fire Safety Associated with Gas and Electric Systems

Objectives

The ignition and fueling of fires following earthquakes has long been a concern in earthquake-prone regions. This study focused on life-safety issues. It used a logical methodology to examine the factors affecting sources of fuel and ignition, and the potential for structural damage that could trap occupants.

Outcomes

In this project, the scenarios that have led to fire ignitions in past earthquakes were derived from review of post-earthquake fire data for the 20th century. The primary factor involved in fire ignitions is structural and non-structural building damage. Alternate means to reduce fire risks were analyzed for residential structures. The study resulted in identifying older, seismically vulnerable multi-family residential buildings (R-1 occupancies) as presenting the most likely setting for people to be trapped inside and exposed to life-safety threats from fire.

Summary

Improvement of structural performance would significantly improve fire safety in these structures; however, the installation of appropriate gas flow interruption devices could provide some protection to the occupants in the absence of structural improvements. One- or two-family residences (R-3 occupancies) typically have multiple means of egress and pose a significantly lower life-safety threat. For R-3 structures, the primary fire-safety improvements are to anchor water heaters and other appliances, and install flexible connectors to reduce the potential for gas leaks. This study provided information and analyses that are useful contributions towards the process of improving earthquake-related fire safety and promotes the wider distribution of accurate information on alternative safety improvement actions.

Conclusions and Recommendations

Conclusions

The goal of this applied research program was to improve the earthquake safety and reliability of electric power transmission and distribution in California. The research program was organized by the JMC to assure that the research results would directly address electric utility needs in preparing for future earthquake occurrences, and that the results could be quickly implemented by utility personnel or their consultants.

As described in the previous sections of this report, the 18 projects have provided useful results that meet utility needs in the five topic areas. However, it is important to also note the integration of the projects to meet the goal of the program, namely to improve utility earthquake performance. The following bullets summarize, in narrative form, the cumulative connections between the topics that address the goal.

- **Topic 1** results (improved ground motion and site response models and methods) are used as input to **Topic 2** (rapid estimation of ground shaking for emergency response)
- Topic 1 results are used as input to **Topic 3** (ground motion database) to improve the assessment of locations and amounts of post-earthquake permanent ground deformation caused by ground shaking.
- Topic 1 results, along with Topic 3 results, are used as input to **Topic 4** (assessing the vulnerability of pieces of substation equipment and the vulnerability of interconnected equipment). Severe ground shaking and ground failure are the direct causes of substation damage that can disrupt power transmission to customers.

- Topic 1 and 3 results improve the assessment of building damage (damaged buildings are the structures within which most earthquake-caused fires start), and thus underlie and are input to **Topic 5** (earthquake fire safety associated with gas and electric systems). Levels of ground shaking can be used to control utility service shutoff valves and to quickly identify likely locations of damaged buildings where fires could start and people could be trapped.

Although the connections among the individual projects are multi-faceted, a broad picture can be seen of the research results linking up to enable utility personnel (and their regulatory counterparts) to have significantly improved information for taking actions regarding earthquake risks. These actions often include retrofitting a vulnerable building that houses office workers, upgrading equipment and improving anchorages in substation yards, and modifying emergency response procedures to take advantage of new information. The customer benefits from these actions following an earthquake in terms of greater electric power reliability, and faster and less expensive recovery of the overall functioning of society. Of course, there will always be some utility system damage due to random failures of components or facilities. However, the redundant electric system design and the operation skill of utility personnel can make the extent and duration of outages no worse than those of a winter storm.

Benefits to California

The measure of the success of this user-driven, applied research program is the extent to which the results are being put to use to directly benefit the California electric power ratepayers and others in the state. Even before the reports were prepared, some of the results, such as the substation equipment seismic performance data and analyses, were being implemented in managing the equipment inventory at several utilities and in preparing to modify the national seismic qualification procedures for substation equipment. Significant progress has been made in the ultimate goal of the project, to improve electric system safety and reliability in earthquakes. Clear directions for further applied research were also identified, and provide the basis for planning the next phase of work.

When the results have been implemented in the utility system, then the ratepayers (who have funded this research) and other members of society will benefit from the research by (1) receiving more rapid restoration of service following an earthquake due to less utility damage and improved emergency response capability, (2) avoiding possible utility rate increases because there is less direct damage to equipment and facilities, and (3) experiencing more rapid overall recovery of societal functioning following the earthquake due to rapid power restoration and use of the research results by other organizations to recover their functionality more quickly.

This research program provides several additional benefits to utilities and to the State of California. Although they are secondary to the goal of this program, these benefits have substantial long-term value.

- Enhanced academic expertise: This research program has created an expanded group of university faculty who have gained extensive knowledge about electric utility systems and who have demonstrated interest and talent in addressing utility research needs and problems. In the future, they will have opportunities to continue research in these areas, and to guide their students into graduate work involving utility systems and earthquakes. This reservoir of academic experience will provide ongoing benefits to the utility industry and the State.

- The establishment of the PG&E-PEER-Commission research program has attracted great interest nationally. Other organizations, both public and private at the local to national level, have observed the success of the program, and are influenced by its research goals and project topics. Thus, by providing strong technical leadership, well-defined research project scopes, and results that have clear value and applicability, the PG&E-PEER-Commission program is helping to shape the direction and topics of other research activities. Over the next several years, there will be more coordination of research among the funding agencies, if not among the individual researchers. This coordination will significantly leverage the results of the studies reported herein.

- The PG&E-PEER-Commission program has also attracted highly motivated research partners who are willing to co-fund this program's future work or to perform separately funded but closely coordinated studies that fit together nearly seamlessly. The California Department of Transportation (Caltrans) is the first such partner. It is likely that in the next several years a number of others will join.

Recommendations

Although the results of the individual research projects reported herein have successfully met their objectives, it is clear that there are additional research activities whose results would provide further improvements in the earthquake performance of utility systems. Many of these opportunities for further study and implementation have been identified in previous sections. They include the following major research areas:

- Ground Motion and Site Response: More accurate ground-motion assessments for utility sites are critical to evaluate the seismic hazard at those sites and to make good risk management decisions. Data and models to reduce uncertainties in ground motions are needed, particularly for locations near large-magnitude seismic events. Because current databases and models for predicting site response have limitations and uncertainties, improved and reliable methods for assessing site response are needed for assessing site-specific ground motions.
- Ground Deformation Database: Expanded empirical databases and new analysis tools need to be developed to better model the probability of permanent ground deformation as a function of geologic and geotechnical data and level of strong ground shaking, so that potential extensive damage to underground as well as above-ground utility structures can be reduced or avoided.
- Electrical Substation Equipment Performance: Further efforts are needed to accurately understand the seismic performance of existing high-voltage equipment to be able to either use elsewhere or replace equipment that is unacceptably vulnerable in its current locations. Seismic performance data obtained from shaking table tests and analytical models of substation equipment, their interconnections, and their system functionality under various earthquake scenarios would be important products of this research.

- Ground Motion Estimates for Emergency Response: Advanced instrumentation capabilities and methods for using them are needed so that strong-motion data and other data can be used to make rapid estimates of damage and functionality prior to getting input from experienced field operations personnel.
- Building Vulnerability: Additional data and models are needed to better assess expected earthquake performance of older substation buildings and service buildings to enable better decision-making by utilities regarding seismic retrofits or other mitigation measures for these buildings.
- Seismic Risk Analysis: A flexible and powerful capability to evaluate the likely functionality of customer services following earthquakes is needed. This capability could be used to evaluate alternative earthquake mitigation actions, and to evaluate the current state of earthquake preparedness of the utility system from the perspective of the utility, customer and regulator.

It is recommended that this successful earthquake research program be continued to address these and other topics.

The scope of further research projects needs to be viewed from a broad and integrated perspective to ensure that other related opportunities are not being missed. It is recommended that the continuation of this program should incorporate a comprehensive planning effort by the JMC.

It is also recommended that the next phase of the program be structured to provide for and to optimize the involvement of multiple co-funding organizations, particularly Caltrans. The JMC member organizations (PG&E, PEER, and Commission) should identify prospective additional partners and enlist their participation. Such efforts will enable significant leveraging of the available funding and make possible rapid gains in knowledge and applications to profoundly reduce earthquake risk in California.

Abstract

Pacific Gas and Electric Company (PG&E) under California Energy Commission contract number 500-97-010 has conducted a one-year user-driven applied research program in partnership with the Pacific Earthquake Engineering Research Center (PEER) based at the University of California, Berkeley. The goal of the program was to collect data, prepare models, and develop methods that could be rapidly and systematically applied to reduce earthquake vulnerability and improve earthquake safety and reliability of electric power for the benefit of utility customers and others in California. Once implemented, these research results would enable faster post-earthquake restoration of customer service through reducing the amount of damage and disruption of electric transmission and distribution service caused by earthquakes, and through providing more accurate and rapidly available post-earthquake information about the state of damage produced by earthquakes.

Five topics involving 18 research projects were addressed based on utility-identified needs for improving knowledge about earthquake hazards and vulnerabilities of electric transmission and distribution systems. PEER management and PG&E technical specialists monitored the projects, individually and collectively, to assure that practical, useful results were obtained.

1. Ground Motion and Site Response: Three numerical procedures for estimating near-fault ground motions were tested against data from recent earthquakes. After further calibration, these methods can be used for predicting ground motions near large-magnitude earthquakes. As part of the collaborative Resolution of Site Response Issues for the Northridge Earthquake (ROSRINE) project, six additional sites where strong ground motions were recorded in the Northridge earthquake were characterized using boreholes and geophysical measurements. These data will be used in future site response studies. Additional studies quantified site response effects, using the ROSRINE data for calibration of soil conditions.

2. Ground Motion Estimates for Emergency Response: A method was developed to estimate rapidly the distribution of strong ground motions from a large earthquake in California using a small number of broadband recordings of the event. This method supplements the use of strong-motion recordings in urban areas and provides maps of shaking severity anywhere in the State, for utilities and emergency response agencies.

3. Ground Deformation Database: Improvements were made in the accuracy and completeness of compiled observations of past earthquake-caused permanent ground deformation, particularly involving liquefaction and lateral spreading. This database will lead to improved probabilistic models for ground deformation, which can be used by utilities to design for or avoid areas of potentially damaging ground failure when installing facilities.

4. Electric Substation Equipment Performance: Shaking table testing and related analysis of high-voltage transformers and bushings led to improved fragility models for these critical substation components, and identified areas for improved design or retrofit practices. The potential for overturning of massive equipment and the effect of interconnection of pieces of equipment were also analyzed. The results are leading to

changes in industry practices and design of new equipment that will provide increased power reliability after a major earthquake.

5. Earthquake Fire Safety Associated with Gas and Electric Systems: Fire-safety factors were identified and logically modeled through assessment of past earthquake-caused fires,. Fires occur in proportion to building damage. Older, seismically vulnerable multi-family residential buildings are a particular concern for life safety. Alternate means of improving fire safety were reviewed, including building strengthening, water heater anchorage, gas shutoff devices, and coordination of power restoration where significant building damage occurs.

1.0 Introduction

1.1 Purpose of Research

The greatest single natural-hazard threat to the reliability of the electric power system in California is the likely occurrence of a major urban earthquake. The 1989 Loma Prieta and 1994 Northridge earthquakes, although deadly and destructive events, were only a portent of potential future earthquake affects. They serve as a warning to all sectors of society to increase the state of earthquake readiness. Emergency responders and society in general view post-earthquake functioning of utility systems, in particular electric power service, as absolutely vital for rapid response and recovery from a major urban earthquake.

In typical academic-based research, there is a time interval of as long as 10 to 20 years between the start of the research and the results being in a form useable for engineering applications. Preparing for earthquakes in California is too urgent to wait for a decade or more for implementation of research findings. The results are needed in the short term, not in the long term. The goal of this user-driven research program was to shorten the time between initiating research and practical application to less than two or three years.

Because of this accelerated schedule for getting the research into use, a framework has been developed to organize the types of research. We developed three classifications for the research conducted under this program: data, models, and methods.

- Research projects classified as **data** produce the scientific or engineering data sets that are necessary for subsequent studies. The data can be either empirical observations or data generated as part of numerical or experimental studies. In general, data are not the useable result, but rather are the input for the development of models or methods as discussed below. An example of a data project is the development of a database of ground deformations and the associated site information.
- Research projects classified as **models** produce simplified descriptions of data. Models can be either parametric descriptions of data (such as equations) or maps. An example of a model project is deriving an algorithm for the amount of amplification of the ground motion expected for a given site condition.
- Research projects classified as **methods** develop new procedures or evaluate existing ones for using models or data to compute a desired parameter. An example of a method project is the evaluation of the relative accuracy of different procedures for predicting site response.

The purpose of this research program was to provide data, models, and methods needed to reduce the earthquake vulnerability and improve the system reliability and safety of electric transmission and distribution systems. Once implemented, these research results will enable faster post-earthquake restoration of customer service by reducing the amount of damage and disruption of electric transmission and distribution service caused by earthquakes, and by providing more accurate and rapidly available post-earthquake information about the state of damage produced by earthquakes. The research results can also be used, as appropriate, by businesses, industry, regulatory agencies, and the general public to reduce earthquake vulnerabilities and respond more effectively to earthquake effects in California and elsewhere.

1.2 Background

This program continues utility-directed seismic safety and reliability research that Pacific Gas and Electric Company (PG&E) initiated at the end of 1996 using funding provided by the ratepayer-financed investor-owned utility research and development (R&D) program. The applied research needs were identified as vital to optimize PG&E's Seismic Risk Management Program, which was initiated prior to the 1989 Loma Prieta earthquake. The objective of the applied research was to allow the utility to better understand the earthquake performance of gas and electric systems, and to develop ways and means of improving the systems' reliability and safety, thereby significantly reducing earthquake risks.

A partnership was established with the Pacific Earthquake Engineering Research Center (PEER), based at the University of California, Berkeley (UC Berkeley), to involve talented academic engineers and scientists and their students in the research. PEER is a consortium of 18 universities whose mission is to reduce the risk of constructed facilities through research and implementation of performance-based design methodologies. PG&E's investment in PEER as a Founding Partner in the Utility Component of the PEER Business and Industry Partnership helped to secure National Science Foundation funding for PEER. PG&E's support and involvement in PEER helped to focus the research on California utility infrastructure, important because of the life-safety issues and economic consequences that significant seismic events cause to this infrastructure.

To develop and manage this user-directed program, PG&E and PEER established the Joint Management Committee (JMC). Collaborative management through the JMC has become a highly effective approach to identify specific research studies and to assure that they are focused on utility needs and provide results that can be directly used by the utility. In the JMC, a small group of PEER and PG&E representatives agreed upon specific research scopes that would meet PG&E's needs. They selected Principal Investigators (PIs) to carry out the desired studies according to planned schedules and budgets, and guided the PIs to provide results in formats that utility personnel could quickly implement. The JMC was successful in engaging academic PIs from within the PEER member institutions and consulting PIs in private practice, who were enthusiastic about the applied research topics and were diligent about meeting the research commitments. The JMC also provided coordination between the PG&E / PEER research activities and complementary applied research in the earth sciences that PG&E supported at the U. S. Geological Survey (USGS) in Menlo Park, CA, through a Cooperative Research and Development Agreement. A representative of the California Department of Transportation joined the JMC during the course of the program to provide input and coordination with their ongoing research.

The research needs identified by PG&E consisted of a set of topics that addressed the board needs of earthquake hazard assessment and earthquake risk reduction, and that were intended to set the framework for a multiyear, comprehensive, utility-focused applied research program.

A total of 25 individual research projects were carried out in this initial program. Appendix I identifies the specific projects by topic and provides the Principal Investigator, the institution, and a brief description for each project.

PG&E and PEER JMC representatives, technical and administrative personnel in the two organizations, and individual researchers were very satisfied with the results achieved by the initial projects. The experience provided some suggestions for improving the administrative process, but the quality of the research effort and the value of the result were both quite high.

1.3 Transition Funding for Strategic Energy Research

As part of the implementation of Legislative Act AB 1890, the California Energy Commission (Commission) established a Public Interest Energy Research (PIER) program, which coincided with the termination of most investor-owned utility ratepayer funded R&D. To preserve the benefits of promising public interest R&D projects, such as the PG&E utility-directed seismic safety and reliability research, the Commission funded the continuation of the earthquake studies under the PIER Transition Research Program.

During the first four months of 1998, the JMC selected topics for possible research, prepared a request for proposals (RFP) on the topics, and selected the projects to be carried out.

1.3.1 Research Topics

The topics from the initial PG&E / PEER research were reviewed and the following were chosen as a focus for the preparation of the RFP. The following list gives a brief description of the needed studies for each topic.

- Topic 1. Ground Motion and Site Response
  - A number of studies under this topic are needed to improve the site-specific assessments of near-fault ground shaking and ground motions at soil sites.
- Topic 2. Ground Motion Estimates for Emergency Response
  - Emergency response by utilities requires rapid information about the location of potentially damaging strong ground motions.
- Topic 3. Ground Deformation Database
  - Further work beyond the initial PG&E / PEER study is needed to improve the quality of the empirical ground-deformation database.
- Topic 4. Electrical Substation Equipment Performance
  - Shaking-table studies of different designs and retrofits of high-voltage transformer bushings are needed to extend the results of the initial PG&E / PEER studies.
- Topic 5. Earthquake Fire Safety Associated with Gas and Electric Systems
  - The previous study of the role of natural gas in post-earthquake fires is extended by incorporating consideration of the role of electric power.
- Topic 6. Building Vulnerability
  - Improved techniques to analyze building performance in earthquakes are needed to extend the initial PG&E / PEER studies.
- Topic 7. Seismic Vulnerability of Underground Cables
  - This new topic addresses the need to investigate the deformation capacity of older underground electric cables.

1.3.2 Project Selection

The JMC prepared and issued a RFP that addressed these topics and described in detail the desired research (Appendix II). The JMC received and reviewed more than 32 proposals. Because the total requested amount was much greater than the available funding, the JMC had to both evaluate and rate the proposals and then prioritize the projects that would be funded. The decision was made to give lower priority to Topics 6 and 7. As other organizations were analyzing the earthquake performance of typical utility buildings, it was judged that the consequences of not funding Topic 6 were relatively small. There was limited response to Topic 7, and it was decided to not fund work in this area until a more refined research need could be prepared and another solicitation issued. This process resulted in the selection of 17 projects and established contracts with the host institutions (Table 1). The actual expenditures for these projects are also listed in the table.

An additional special project was created late in the research period to partially support travel by PG&E and Commission personnel to the site of the August 17, 1999 Kocaeli, Turkey earthquake to investigate the consequences of the event on the Turkish electric power system.

Section 2 of this report summarizes the need, project description, results, and applications of the research program. The goal of this summary is to concisely convey (1) the importance of the applied research in addressing real utility needs in providing safe and reliable services in the face of significant earthquake hazards and significant earthquake vulnerabilities of system components or significant consequences in the event of utility service disruption or damage; and (2) the direct and immediate applicability of the research results to satisfy these needs. Appendix III contains the complete final reports for each project.

Table 1. Funded Research Projects 1998-2000

Project Title and Number*	PI and Institution	Amount
Topic 1: Ground Motion and Site Response		
Evaluation of Numerical Procedures for Simulating Near-fault Long-period Ground Motions Using Graves Method (5A)	P. Somerville, Woodward-Clyde Federal Services	$45,642
Evaluation of Numerical Procedures for Simulating Near-fault Long-period Ground Motions Using Zeng Method (5.A)	Y. Zeng and J. Anderson, University of Nevada, Reno	$49,269
Evaluation of Numerical Procedures for Simulating Near-fault Long-period Ground Motions Using Silva Method (5.A)	W. Silva, Pacific Engineering and Analysis	$33,732
Surface Geology-based Strong-motion Amplification Factors for San Francisco and Los Angeles Areas (5.B)	W. Silva, Pacific Engineering and Analysis	$41,007
Evaluation of Uncertainties in Ground Motion Estimates for Soil Sites (5.B)	J. Stewart, UCLA	$50,000
Ground Motions for Site Response Estimates—1906 Earthquake (5.C)	P. Somerville, Woodward-Clyde Federal Services	$15,000
Ground Motions for Site Response Estimates—Permanent Ground Deformation Models (5.C)	W. Silva, Pacific Engineering and Analysis	$4,000
ROSRINE IV-A (5.C)	T. Henyey, University of Southern California	$99,990
Topic 2: Ground Motion Estimates for Emergency Response		
Rapid Estimation of Ground Shaking for Emergency Response (7)	D. Dreger, UC Berkeley	$50,000
Topic 3: Ground Deformation Database		
Enhanced Ground Deformation Database (4)	J. P. Bardet, UC Santa Barbara	$63,633
Topic 4: Electrical Substation Equipment Performance		
Seismic Evaluation of 550 kV Porcelain Transformer Bushings (2.A)	G. Fenves and A. Whittaker, UC Berkeley	$79,807
Performance of 230 kV and 500 kV Bushings (2.B)	G. Fenves and A. Whittaker, UC Berkeley	$92,051 + $65,000 cofunding
Analytical Studies of Substation Equipment Interaction (2.C)	A. Der Kiureghian, UC Berkeley	$49,614
Experimental Studies of Substation Equipment Interaction (2.C)	A. Filiatrault, UC San Diego	$118,651
Amplification of Ground Motions at the Base of Transformer Bushings (2.D)	R. Villaverde and G. Pardoen, UC Irvine	$50,000
Rocking Response and Overturning of Equipment (2.D)	N. Makris, UC Berkeley	$49,981

Project Title and Number*	PI and Institution	Amount
Field Investigation of Effects of the Kocaeli, Turkey, Earthquake	G. Fenves, UC Berkeley	$7,627 + >$20,000 cofunding
Topic 5: Earthquake Fire Safety Associated with Gas and Electric Systems		
Ignition of Fires Following Earthquakes Associated with Natural Gas and Electric Distribution Systems (6)	R. B. Williamson, UC Berkeley	$47,308
Project Administration	G. Fenves, UC Berkeley	$48,607
TOTAL for 18 Projects and Program Administration by PEER		**$995,919**

*The project numbers shown in parenthesis were used during administration of the research program and are provided only because they are used in the technical reports in Appendix III.

2.0 Research Results

2.1 Topic 1: Ground Motion and Site Response

2.1.1 Objectives

This topic addressed a number of requirements for improving the estimates of earthquake ground motion and response at specific sites. The objectives were to:

- Improve methods to predict near-fault ground motions from large earthquakes.
- Improve accuracy and reduce uncertainties in predicting the effects of soil on site response estimates.
- Provide additional site characterization data for sites that have recorded strong ground motions.

The outcomes of the specific projects that address these objectives are described in Sections 2.1.2 through 2.1.6.

This topic is at the core of addressing earthquake hazards, since the level of shaking at an individual site is the primary earthquake hazard that affects soils, foundations, and structures. The seven projects that addressed the objectives listed above focused on particularly important needs for utility facilities constructed in areas exposed to very strong levels of ground motion. Uncertainties in the input ground motion for design or for performance evaluation can lead to large unnecessary cost if the ground motions are overestimated, or to significant damage if they are underestimated. There is great benefit, then, to utilities as well as owners of other facilities, to use accurate ground motion assessments that fully consider site response.

2.1.2 Evaluation of Three Numerical Procedures for Simulating Near-fault Long-period Ground Motions

Background and User Needs

The ground shaking close to large earthquakes can have special characteristics with very different impacts on structures than typical ground shaking observed in past earthquakes. These near-fault effects on ground motions are strongest at low frequencies (< 1 Hz). To date, there are only a small number of instrumental recordings of ground shaking close to a few large earthquakes (i. e., within about 15 km of the fault rupture). As a result, we are not sure that the available empirical data set of ground motions provides a reliable statistical sample of the characteristics of ground motions close to large earthquakes.

One way to augment the sparse data set of recorded ground motions is to use computer models to artificially generate ground motions close to the fault. There are several computer models that have been developed to simulate earthquake ground motions. However, the calibration of these computer models has not addressed important features of ground motions close to the fault: the dependence on whether the rupture is toward the site or away from the site (directivity effect); and the differences between the ground motion on the two horizontal components oriented parallel and perpendicular to the fault strike (orientation effect). Before engineers should rely on the computer models to predict ground motions close large earthquakes, the models have to be checked for their ability to simulate the key features of observed near fault ground motions from past large earthquakes, including directivity and orientation effects.

Project Approach

This project tested the ability of three widely used ground-motion simulation procedures to simulate the key features of near fault ground motions. In previous work for the PG&E-PEER program, these three simulation methods were applied in a forward prediction of the near-fault ground motion for a specified hypothetical earthquake. They produced very different results. The current evaluation of the three methods was intended to help understand what caused the differences between the three methods and, if possible, to calibrate the methods.

The objective of this project was to evaluate the ability of the three ground motion simulation computer programs to predict the recorded near-fault ground motions from the following five large earthquakes:

- 1979 Imperial Valley M=6.4 29 recordings
- 1989 Loma Prieta M=6.9 34 recordings
- 1992 Landers M=7.2 13 recordings
- 1994 Northridge M=6.7 34 recordings
- 1995 Kobe M=6.9 18 recordings

These earthquakes were selected because they have a relatively large number of near-fault ground motions (the number of strong motion recordings within 30 km for each earthquake is also listed). We evaluated the ability of the model to predict directivity effects on the low frequency ground motion and any systematic differences in the ground motion on the two horizontal components of shaking oriented parallel and perpendicular to the strike of the fault. The evaluation considered all sites within 30 km of the fault, and addressed low frequency ground motions (0.125 to 1.43 Hz).

The evaluation was carried out in three parallel efforts under the direction of three PIs and their colleagues who developed and improved the three alternative ground motion simulation computer programs:

- Graves, Pitarka, Collins, and Somerville of Woodward-Clyde Federal Services (referred to as the Graves method)
- Zeng and Anderson of the University of Nevada, Reno (referred to as the Zeng method)
- Silva, Gregor, and Darragh of Pacific Engineering and Analysis (referred to as the Silva method)

Norm Abrahamson was the PG&E Technical Contact.

All three simulations are finite-fault methods in that they break the fault into a subset of small sub-events, propagate the ground motion from each sub-event to the site, and then sum up the ground motions from each sub-event to estimate the total ground motion during the earthquake. These models make different assumptions about the seismic source, wave propagation, and site response that affect the prediction of ground motions. The most important differences in the methods are as follows: (1) the Silva method is the only one that fully treats non-linear site response, while the other models only treat gross soil-versus-rock site categories; and (2) the Graves and Zeng methods generate three components of motion, whereas the Silva method generates an average horizontal component.

Outcomes

Each of the three alternative methods were used to predict the ground motions at locations that recorded the five large earthquakes listed above. To evaluate the ability of a method to predict directivity effects, the differences in the response spectra for the simulated and observed ground motions (residuals) were computed for response spectral periods of 0.125 Hz to 1.4 Hz. If the simulations were properly modeling the directivity effects, then the residuals would be randomly scattered about zero as a function of the rupture direction. On the other hand, if, on average, the residuals are positive for forward rupture and negative for backward rupture, that would indicate that the model is not predicting near-fault rupture directivity effects.

- Graves, Pitarka, Collins, and Somerville. In general, the residuals based on the Graves simulation method do not show a trend as a function of rupture direction, indicting that the simulation is capturing the main effects of directivity on the ground motion. This indicates that the computer simulation is picking up directivity effects that the empirical attenuation relation has not picked up. This indicates some of the potential improvements that can be made in ground motion models by using numerical simulations.
- Zeng and Anderson. In general, the residuals based on the Zeng method also do not show a trend as a function of rupture direction, indicting that the simulation is capturing the main effects of the directivity on the ground motion.
- Silva, Gregor, and Darragh. The Silva method found a trend in the residuals as a function of the rupture direction. It found that inclusion of site response effects significantly affects the predicted ground motions. Since the models of the slip on the fault were determined from previous studies that did not include site response effects, these slip models may incorporate site-response effects into the slip models. This result indicates that the site response needs to be incorporated into the slip model inversions.

The comparison of these three methods identified an important potential shortcoming of the current standard for predicting ground motions. Site effects need to be added to the method that generates the slip model on the fault. If that is not done, then the site-specific site effects cannot be added to simulations since they are to some extent incorporated in the slip model.

Application and implementation

These results are one step in the development of a methodology for generating artificial ground motions close to large earthquakes. This methodology is not complete with the results of this project. With the occurrence of the 1999 Turkey and 1999 Taiwan earthquakes, there has been a tremendous increase in the number of ground-motion recordings that are available close to large earthquakes. These important recordings are included in the planned evaluation of the simulation procedures to be conducted in the next phase of applied research work.

Once this additional evaluation is complete and the models modified, if needed, they can then be used to generate artificial ground motions for a suite of possible future earthquakes on the major faults in northern California. This simulated data set will then be used to develop simplified parametric models of the behavior of near-fault ground motions for use in seismic hazard analyses.

2.1.3 Surface Geology-Based Strong-Motion Amplification Factors for San Francisco and Los Angeles Areas

Background and User Needs

The primary tool used for predicting ground motions for engineering applications have been empirical attenuation relations. Most empirical attenuation relations have used very simple site classifications of soil and rock. It has long been known that local site conditions can have a significant effect on ground motions and that there can be large differences in the site response effects for different types of soils.

Recently, the 1997 Uniform Building Code used the average shear wave velocity in the top 30 m as the site parameter to distinguish between the site response effects for different types of soils. This approach provides a clear definition of the site category; however, for most projects, measurements of the shear-wave velocity are not available.

There is a need for attenuation relations that incorporate the site effects better than just simple soil versus rock categories, yet use readily available site classification information.

Project Approach

Surface geology maps provide a readily available means of classifying sites into sub-categories for different soil conditions. The objective of this project was to develop site response factors that quantify the differences in the ground motions for different site categories based on the surface geology.

Ideally, site response factors could be developed based entirely on observations of strong motion data. But the limited number of strong motion recordings does not provide enough observations on each geology class for a range of earthquakes magnitudes and distances. In particular, the different geologic categories are not well sampled for very high levels of shaking. Because of this limitation of the empirical data, 1-D numerical simulations are used to develop a comprehensive site response data set.

Measurements of the shear-wave velocity at strong motion sites from the ROSRINE and other site characterization studies were grouped according to the surface geology for each borehole site. With this grouping, the median and variability of the velocity profile was estimated for each geologic category. This allows the input soil profile for the analytical models to be tied back to a general surface geology category.

In addition to the velocity profile, non-linear soil properties must also be defined for each geologic category. Again, the ROSRINE database and other site response studies are used to correlate the non-linear soil properties with the surface geology. Separate non-linear properties (G/Gmax and hysteretic damping curves) are used for San Francisco Bay Area and Los Angeles area cohesionless soils to reflect the different degrees of non-linear response of the soil in these two regions.

The amplification factors are then computed relative to rock site geology conditions in the San Francisco Bay area (Franciscan) and Los Angeles area (granite). This allows the standard attenuation relations to be used to develop the reference ground motion. Then the amplification factors can be used to scale the median ground motion from the rock attenuation relations to define the median ground motion on different soil categories.

W. Silva of Pacific Engineering and Analysis, located in Berkeley, CA, carried out this project. S. Li, R. Darragh and N. Gregor assisted him. Norm Abrahamson was the PG&E Technical Contact.

Results

Analytical site response calculations were made for 11 geologic categories (Table 2). In addition to varying the geologic category, the thickness of the soil deposit was also included as a site parameter (soil thickness varied from 30 m to 1500 m). To account for on-linear site response effects, the amplification factors are functions of the input rock peak acceleration (0.05g, 0.1g, 0.2g, 0.4g, 0.75g, 1.0g, and 1.25g). In all, several thousand site-response calculations were run to cover all of the combinations of soil properties and ground motion levels.

Table 2. Site Categories Based on Surface Geology

Northern California	Southern California
Kjf (Franciscan)	Mxb (Granite)
TMzs (Tertiary Bedrock)	Ts (Saugus)
QTs (Quaternary/Tertiary)	Ts (Tertiary)
Qoa (older alluvium)	Qo (older alluvium)
Qal (Quaternary alluvium)	Qy (Quaternary alluvium)
Qm (Bay mud)	Qm (Holocene alluvium)

The large set of calculated amplification factors were then parameterized into simplified probabilistic models of the site amplification factors (e.g., median and standard deviation) for each of the surface geology site categories.

The amplification factors computed in this project were compared to the current National Earthquake Hazards Reduction Program (NEHRP) factors and to empirical amplification factors for both regions. Comparisons with the NEHRP amplification factors showed reasonable agreement for the San Francisco Bay area except for Bay mud. For the Los Angeles area, good agreement was seen with the NEHRP amplification factors at low ground motion levels (<0.1g) but the computed amplification factors were much lower than the NEHRP factors at high levels of shaking.

Application and Implementation

The site amplification models developed in this project will be used together with rock attenuation relations to define a model for the attenuation relations for the different surface geology classifications. Since surface geology information is available in map form, these new attenuation models can be immediately incorporated into ground motion evaluations. In addition, since the amplification factors are described probabilistically, these models can be used in both probabilistic and deterministic ground motion evaluations.

2.1.4 Evaluation of Uncertainties in Ground-Motion Estimates for Soil Sites

Background and User Needs

As discussed in Section 2.1.3, the primary tool used for predicting ground motions for engineering applications have been empirical attenuation relations, which have used very simple site classifications of soil and rock. Local site conditions can have a significant effect on ground motions and there can be large differences in the site response effects for different types of soils.

In the preceding project (Section 2.1.3), the generic soil site classification was subdivided into several categories based on surface geology as a way to improve the prediction of the site response. As an alternative to site categories, site-specific site response calculations can be made using analytical models of the site response that distinguish between different sites within a site category by having models of the site parameters for each individual site. Such site-specific site response calculations are commonly carried out for critical facilities, but they are typically not used for most facilities because of the cost of collecting the site information (e.g. shear-wave velocity profile).

Geotechnical engineers have long thought that the variability (standard deviation) of attenuation relations could be greatly reduced if the site-specific shallow site properties were taken into account (e.g. the 1-D shallow velocity structure and non-linear soil properties). There is a need to determine how much ground motion estimates can be improved if site-specific site response calculations are performed, rather than relying on attenuation relations for broad site categories. Are costly site exploration work and site-response analyses justified in terms of the reduction in the uncertainty of the estimated ground motion?

Project Approach

The objective of this project was to evaluate the benefit of site-specific site response analyses as compared to the use of generic soil attenuation relations.

The site response modeling was performed using the program SHAKE91, which represents the state-of-the-practice for site response calculations. The predicted ground motions were then compared to the observed ground motions to estimate the uncertainty of site-specific site response procedures. Standard empirical attenuation relations were also used to predict the ground motions at each site.

The predictive ability of the site-specific site-response analysis is compared to that of the empirical attenuation model by comparing the standard deviation of the residuals (the difference between the observed ground motion and the predicted ground motion) for subsets of soil categories. If the site-specific analysis leads to a significant reduction in the standard deviation, that would indicate that site-specific analyses can explain much of the variability of the ground motion within a soil category.

The project Principal Investigator is Professor J. Stewart of the Civil engineering Department at the University of California at Los Angeles. M. Baturay assisted him. The PG&E Technical Contact was Norm Abrahamson.

Results

Site-specific site response analyses were performed for 36 sites with widely varying geologic conditions that have recorded strong ground motions and that have site-specific information available (e.g. measured shear wave velocity profile). The sites were divided into four soil categories based on the geotechnical properties of the sites. (Note that these are different soil categories than were developed in Section 2.1.3) The soil categories are listed below:

C2 Shallow stiff soil over rock (soil thickness less than 30m)

C3 Moderate thickness stiff soil (soil thickness 45 to 90m)

D Deep stiff soil (soil depth greater than 120 m)

E Soft soil (Vs (Shear Wave Velocity) less than 150 m / s, soft soil thickness greater than 3 m)

A key issue for site-specific site response calculations for past earthquakes is the estimation of the ground motion that is input into the soil profile (input rock motion). In most cases, nearby rock ground motions are not available to be used as input motions. In this study, careful efforts were made to define a suite of input motions. Empirical ground motion recordings at rock sites for the appropriate magnitude and distance range were selected and then scaled to the median ground motion as predicted by empirical attenuation relations. These scaled motions were then modified to account for event-specific attenuation (this accounts for some earthquakes producing larger-than-average ground motions, and some earthquakes producing lower-than-average ground motions), site-specific rupture directivity effects for each event, and near-surface amplification effects at weathered rock sites.

Ten sets of input ground motions were developed for each of the 36 sites. The site response analysis was performed for each input ground motion and the resulting ground motions were compared to the observed ground motions at each site. The results of this suite of site response studies were grouped into the four site categories listed above and they were parameterized in terms of the median residual and the standard deviation of the residuals for each site class. As a base case, the median residual and standard deviation were also computed using empirical attenuation relations (without site-specific effects).

The evaluation found that there was a significant bias in the ground motion prediction for each soil category based on the generic soil attenuation relation; the bias was greatly reduced when the site-specific response was used. This supports using more refined soil categories (rather than just generic soil), which is consistent with the study by Silva et al. (Section 2.1.3)

The site-specific analysis led to a large reduction in the standard deviation for soft clay sites compared to generic soil attenuation models. At periods less than 1 second, the reduction in the standard deviation is from 0.68 to 0.28 natural log units. At long periods (T>1 second), the reduction is less (0.49 to 0.41).

For other site categories, the standard deviations are similar for the site-specific analysis and the generic attenuation relation, indicating that factors other than 1-D site response are randomly varying the ground motion from site-to-site. These other factors may include effects of the seismic source and the regional wave-propagation.

Application and Implementation

Based on this evaluation of a site response methodology, site-specific response methods need to be used for soft clay sites. Attenuation relations for broad categories are adequate for other soil sites, but these categories should be more refined than just generic soil.

2.1.5 Ground Motions for Site Response Estimates—Two Applications

Background and User Needs

In many instances, there are not relevant recorded ground motions near sites that are being studied for site response, liquefaction, or ground deformation. For example, often a site with liquefaction does not have a nearby ground motion recording that can be used as an estimate of the input motion into the soil column. To enable these data to be used in building models or ground-failure assessments, ground motions need to be estimated for these sites.

Project Approach

The objective of this project was to provide expertise for making estimates of the ground motions at sites being studied as part of the PG&E-PEER-Commission and PG&E-USGS seismic research programs. Numerical simulation methods are used to estimate the ground motion. Two of the better-validated methods that have extensive engineering application are the finite-fault stochastic model by Silva and the broadband empirical source function method by Somerville. These two methods are used to predict ground motions at sites as needed for the other projects.

Dr. Walt Silva of Pacific Engineering and Analysis, Berkeley and Dr. Paul Somerville of Woodward-Clyde Federal Services performed specific ground-motion calculations. Norm Abrahamson was the PG&E Technical Contact.

Results

Liquefaction was observed during the 1906 earthquake, but there were not strong motion instruments at that time. To estimate the input ground motions for these sites, Somerville applied his numerical simulation method to estimate the ground motion during the 1906 earthquake at the liquefaction site locations.

Silva generated representative ground motions for large earthquakes that could be used as input motions for analytical calculations of ground deformation. These ground motions are used to augment the sparse empirical database. Ground motions were generated for fault distances of 7.5 km and 37.5 km for magnitude 7.0 and 8.0 earthquakes. Both soft rock and deep firm soil conditions were modeled. Thirty sets of ground motions were generated to reflect the variability in the slip on the fault, in the location of the hypocenter on the fault plane, and in non-linear properties of the soil.

Application and Implementation

The simulated ground motion data from these projects are used as inputs for other evaluations of site response and ground deformation. These ground motions can also be used to define time histories from large earthquakes for structural engineering analyses.

2.1.6 Resolution of Site Response Issues for the Northridge Earthquake (ROSRINE IV-A)

Background and User Needs

It has long been known that local site conditions can have a significant effect on ground motions. However, for most sites that have recorded strong ground motions, the subsurface site information has not been collected due to the high cost of collecting the data. This lack of basic site characterization data has hindered the improvement and calibration of site response methods.

ROSRINE is a collaborative research project focused on improving engineering models for estimating site response effects. The central component of this project is the collection, synthesis, and dissemination of high-quality site characterization data from strong-motion instrument sites that recorded the 1994 Northridge Earthquake. Previous funding for this program has come from the National Science Foundation, Caltrans, Electric Power Research Institute, and PEER / PG&E. Other collaborations have been made by the U.S. Geological Survey, LADWP, LAWRD, and SCEC. This project represents Phase IV-A of the on-going ROSRINE program.

The user need is basic site characterization information that can be used to help in the interpretation of recorded ground motions and to improve empirical and analytical models of site response.

Project Approach

The objective of this project was to collect additional site characterization data for strong-motion sites that recorded the 1994 Northridge earthquake.

The site characterization includes measurement of the shear-wave velocity profile and some sampling of the soils that can be used to in laboratory evaluations to determine the non-linear properties of the soil.

The ROSRINE project has been administered through the Southern California Earthquake Center (SCEC). The PI for this project is T. Henyey, who is the SCEC representative, and R. Nigbor oversaw this part of the ROSRINE program. Norm Abrahamson was the PG&E Technical Contact.

Results

In this phase of the ROSRINE program, the standard site characterization data were collected at six sites (Table 3). In addition, index property testing of selected soil samples was performed and the data are disseminated through the ROSRINE website.

Table 3. ROSRINE Program Sites

Site	Work Performed
Saturn School	Drilling, sampling, logging
Dayton Heights School	Drilling, sampling, logging
Brentwood VA Hospital	Logging
LADWP Receiving Station East	Logging
ETEC RD-7	Logging
ETEC RD-20	Logging

Application and Implementation

The results of this study provide site characterization data that will be used in future projects that address site response.

2.1.7 Conclusions and Recommendations

The three objectives identified in Section 2.1.1 called for progress in addressing three needs related to predicting ground shaking at sites of utility interest.

- Improve methods to predict near-fault ground motions from large earthquakes incorporating site conditions.
- Improve accuracy and reduce uncertainties in predicting the effects of soil on site response estimates.
- Provide additional site characterization data for sites that have recorded strong ground motions.

The projects carried out to address these needs made significant progress. The results described in Sections 2.1.2 through 2.1.6 met these objectives in that:

- Numerical methods were calibrated with data from near-fault recordings of large earthquakes.
- Models were improved to refine the accuracy and reduce the uncertainty in estimates soil site response.
- Six sites of strong ground recordings in the 1994 Northridge earthquake were characterized according to the procedures used in the on-going ROSRINE project.

The results also provided clear direction for further studies on ground motions and site response.

2.2 Topic 2: Ground Motion Estimates for Emergency Response

2.2.1 Objective

The objective of this topic was the development and implementation of methods for rapidly estimating the pattern of strong ground shaking for a significant earthquake occurring anywhere in the state of California. This project brings highly valued benefits to portions of California that currently do not have dense networks of strong-motion instruments with which to measure potentially damaging ground shaking in earthquakes. Utilities, other emergency responders, and utility customers are eager to learn as quickly as they can where earthquake shaking effects are most severe, so they can take more effective and more rapid actions that can save lives and begin to recover from the earthquake.

2.2.2 Rapid Estimation of Ground Shaking for Emergency Response

Background and User Needs

Following a major earthquake, one of the important needs for emergency response is a rapid estimate of the extent of the damage. Currently, the magnitude and location of the epicenter are available quickly after an earthquake. While this information provides a general estimate of what happened, it does not provide enough detailed information on the locations that may have the greatest damage.

Maps of the strength of the ground motion over a region are called ShakeMaps. With estimates of the level of the shaking, preliminary estimates of the damage to the electric system and customer facilities can be made. In the Los Angeles region, rapid estimates of earthquake shaking are produced as part of the TRINET program. This program relies on a dense network of strong motion instruments to provide input to a ShakeMap.

In many parts of California, including the San Francisco Bay Area, there is not a sufficiently dense distribution of strong motion instruments for developing a ShakeMap from only strong motion data. Until adequate strong motion instrumentation is installed, the data need to be supplemented with predictions of the ground motion based on other information.

One source of information that is available throughout the state is regional broadband instruments. These are seismometers that provide high quality measurements of the ground motion from both weak and strong motions. The users need a method for computing ShakeMaps based on data recorded by the currently available regional seismic instrumentation.

Project Approach

The approach in this project was to develop a procedure for rapidly estimating the ground motions following a large earthquake using seismic data from broadband stations recorded at regional distances (e.g. 50 to 200 km) to infer the properties of the seismic source. The key source properties are rupture dimension, location, directivity, and velocity, and slip model. These source properties are then used to predict the ground motion using either empirical attenuation relations or numerical simulations.

This project developed a robust method to rapidly invert the regional seismic data to estimate the source properties. The key was to get a stable process that can be automated. In the past, this type of source inversion required hands-on analysis by a seismologist.

Given the source properties, the next step was to estimate the ground motions at a grid of locations that can be contoured to form a ShakeMap. For this purpose, a numerical simulation method that used the source characterization developed from the source inversion was refined from previously developed numerical simulation models. Again, the key was to automate the process so that the ShakeMap can be created in a timely manner.

Dr. Doug Dreger of the UC Berkeley Seismological Laboratory, with assistance from graduate student A. Kaverina, carried out the project. Norm Abrahamson was the PG&E Technical Contact.

Results

The essential source information needed for ground motions and ShakeMap estimation can be developed in 4 to 20 minutes following an earthquake. First, the estimates of the rupture dimension and rupture location are calculated in approximately four minutes following an earthquake. Knowing the rupture location (length, width, and dip), the earthquake magnitude, and the hypocenter location on the rupture plane, the ground motions are estimated using standard ground motion attenuation relations. From these estimates, a preliminary ShakeMap can be developed. Following this initial result, the estimate of the slip distribution on the fault plane is calculated in approximately 20 minutes following an earthquake. This slip distribution is then used as input to the numerical simulation program to compute revised ground motions. These numerical simulations provide an improved estimate of the ground motion that accounts for the variations in the slip on the fault (the empirical attenuation model just uses the distance from the site to the fault rupture). These simulated data are then used to produce an updated ShakeMap.

This method has been calibrated using regional and strong motion data from the 1992 Landers and 1994 Northridge earthquakes. The ground motion as estimated using only the regional data and the predictions were compared to the observed ground motions. The predictions using the regional data were generally only within 50 percent of the observed ground motions over distances up to 50 km from the fault. When the data were smoothed (spatially) to form a ShakeMap, the agreement between the simulations based on regional data and the observations is improved to within about 30 percent of the observations. This result indicated that this method makes it is possible to calculate robust ShakeMaps even in areas with sparse coverage of strong motion instruments.

2.2.3 Conclusions and Recommendations

The methodology for rapidly predicting ground motions based on regional seismic data provides a key tool for making ground-motion maps following an earthquake, and is successfully addressing the objective of the topic. For the results to be useable, this methodology next needs to automated and integrated into the routine provision of rapid earthquake information.

2.3 Topic 3: Ground Deformation Database

2.3.1 Objective

The objective of this topic was to develop a greatly improved empirical database of ground deformations in past earthquakes that can be used to calibrate statistical and numerical predictions of permanent ground deformation for future earthquakes. In past earthquakes, utilities and transportation systems with underground components have experienced minor to extensive damage due to earthquake-caused permanent ground deformation. The empirical database developed during this project will enable the development of improved predictive tools to better identify the locations of potential ground failure and to more accurately predict the expected amounts of ground deformation. These results will enable power customers, other utility customers, and the state in general to benefit from reduced outages due to improved utility designs that successfully avoid or resist earthquake-related ground deformation.

2.3.2 Enhanced Ground Deformation Database

Background and User Needs

Permanent ground deformations are the primary cause of the earthquake failure of pipelines and buried electric conduits. In addition, they can damage or deform the foundations of utility facilities. Therefore, parametric models of the amount of ground deformation as a function of magnitude, distance and site condition are needed for the evaluation of underground system damage.

In the past, empirically based models of liquefaction induced ground deformation have been developed, but they have focused on the largest deformations (greater than two meters). If such large deformations occur, then the underground facilities will very likely be damaged. If the deformations are less than 0.1 m, then it is very unlikely that modern buried pipe or modern foundations will fail. The key range of deformations for which improved models are needed is in the range of 0.1 to 2 m.

Much of the existing ground deformation data in this 0.1 to 2 m range also has errors in the standard reference database. In addition, the parametric models did not fit the data at small deformations well.

The user need is for a simplified parametric model of the liquefaction-induced ground deformation as a function of the earthquake magnitude, distance from the site to the fault, and geotechnical site conditions. Before such a model can be developed, a comprehensive database of ground deformation has to be developed.

Project Approach

The objective of this project was to develop a reliable database of liquefaction-induced ground deformations, including a characterization of the site conditions and input ground motions. This will then serve as input for subsequent model development tasks.

To deal with errors in ground deformation databases used in previous studies, the ground motion deformations data from pre-1995 earthquakes were re-evaluated using the original sources of data. To bring the database up to date, data from the 1994 Northridge and 1995 Kobe earthquakes were identified, collected, organized, and digitized.

Professor J. P. Bardet of the University of Southern California conducted this project. Norm Abrahamson was the PG&E Technical Contact.

Results

A relational database framework was developed for storing and structuring the large amount of data on liquefaction-induced ground deformations. These include data sets on the displacement vectors and soil properties including SPT and CPT. The database contains 16,000 displacement vectors, 902 SPT measurements, and 229 CPT soundings.

2.3.3 Conclusions and Recommendations

The database produced by this project will serve as the key input data for developing simplified parametric models of ground deformation as a function of magnitude, distance, and site condition that can be used to develop probabilistic maps of ground deformation due to liquefaction. Further data need to be added to the database, particularly those from the recent Taiwan and Turkey earthquakes in 1999. The database also needs to be provided to the research community so that workers can use this new resource to improve predictive models and methods for assessing the potential for permanent ground deformation in earthquakes.

2.4 Topic 4: Electrical Substation Equipment Performance

2.4.1 Objectives

The objective of this topic was to develop data and methods for accurately evaluating the expected earthquake performance of high-voltage substation equipment currently in use by major California utilities. The primary focus of the objective is on transformers, the most critical elements in a substation for restoring power after a major earthquake. The occurrence of a major earthquake in Turkey near the end of the research work provided an opportunity to verify the proper focus of this topic.

The projects in this topic improved the design of critical substation components to reduce earthquake damage and our understanding of the seismic capacity of existing components. Both aspects allow utilities to be able to reduce earthquake damages in substations, historically the leading cause of extensive power outages.

2.4.2 Seismic Evaluation of 550 kV Porcelain Transformer Bushings

Background and User Needs

A transformer typically consists of a closed steel tank, filled with oil, housing a massive core and coils. The bushings, mounted on top of the transformer tank, are used to house and insulate electrical conductors leading from overhead conductors to the inside of the tank. The insulating sections of bushings are almost exclusively made of porcelain, although in recent years some manufacturers have introduced composite polymer models.

Transformers provide the means for connecting power systems of different voltage levels and are one of the most vital components of an electrical substation. Following a significant earthquake, some types of damaged substation equipment might be temporarily bypassed to quickly restore electric service. This is not the case with transformers.

Past earthquake experience in California and other seismically active areas has shown that porcelain bushings are frequently the most vulnerable components of a transformer. Even at relatively low levels of shaking (about 0.3 g peak ground acceleration [pga]), shifting of the porcelain relative to the flange and oil leakage occurred on several 500 kV bushings during the 1983 Coalinga and 1989 Loma Prieta earthquakes, caused the transformers to be taken out of service for several weeks. Numerous failures occurred in 500 kV and 230 kV transformer bushings of Southern California utilities during the 1971 San Fernando, 1986 North Palm Springs, 1992 Landers, and 1994 Northridge earthquakes. During the 1978 Off-Miyagi Earthquake, Japanese utilities reported several porcelain bushing failures. Although utility practices may vary, a transformer will often be removed from service in the event of excessive bushing oil leaks or porcelain slippage because of the risk that internal damage to the bushing could result in fire or explosion.

Several alternative modifications have been proposed to improve the earthquake performance of transformer bushings. There is a need to collect data on the seismic performance of these alternatives. Two projects were carried out to collect data on how well the bushings perform as independent units with and without modifications:

- Seismic Evaluation of 550 kV Porcelain Transformer Bushings
- Performance of 230 kV and 500 kV Bushings

A second issue that affects seismic performance is the effect of equipment interactions. This issue is addressed by projects discussed in Sections 2.4.4 and 2.4.5.

Project Approach

The first of these projects addressed a class of large bushings that have evidenced vulnerability to even low levels of ground motion. The objectives of this project were to obtain information on the seismic capacity (called fragility) of 550 kV bushings through earthquake simulator testing and to assess the effectiveness of relatively simple design improvements on new bushings.

A previous PEER project investigated the seismic capability of 196 kV porcelain bushings (used on 230 kV transformers) through earthquake simulator tests conducted at the Richmond Field Station of the UC Berkeley. The present project investigates the performance of 550 kV bushings (used on 500 kV transformers). The methodology was very similar to that used in the previous study of 196 kV bushings.

Porcelain bushings generally consist of a metal flange assembly, core tube, and porcelain sections that are stacked in series. Insulating oil fills the annular space between the core tube and the inner surface of the porcelain sections. Gaskets are placed at the joints to contain the oil. During assembly, the bushing's core tube is pre-loaded to deliver a clamping force that holds the bushing together. It is from this clamping force that the bushing derives its strength against lateral loading caused by earthquake shaking.

Three 550 kV porcelain bushings were furnished by ABB Power T&D Company for use in testing. These bushings had the following key characteristics:

- Bushing 1: standard design
- Bushing 2: modified design, with higher core clamping force, and stiffer gaskets than standard design.
- Bushing 3: same modified design as Bushing 2, except electrically fully functional.

Tests on Bushing 1 were intended to provide a set of baseline data from which the performance of the modified bushings could be gauged. Higher clamping forces and stiffer gaskets were expected to improve performance of the Bushings 2 and 3 by increasing the friction forces at the gasketed joints and resistance to leakage. It was hoped that the relatively simple and inexpensive improvements made in Bushings 2 and 3 would be sufficient to achieve qualification at the IEEE Std 693-1997 Moderate level of ground motion. Because electrical functionality must typically be verified following shaking table tests, Bushing 3 was prepared for this purpose.

The Principal Investigator for this project was Professor Gregory Fenves of the University of California, Berkeley. Co-investigators were Andrew Whittaker and Amir Gilani. The same team performed shaking table tests on 196 kV porcelain bushings in the previous PEER project. Eric Fujisaki was the PG&E Technical Contact.

Results

Tests on Bushing 1 (standard design, unmodified) confirmed the vulnerability of this class of bushing. It failed because of oil leakage at a pga of about 0.5g. Bushings 2 and 3, which had an increased clamping force and improved gasket configuration, demonstrated a significant improvement in performance, and failed at close to 1.0g. Unfortunately, the modified bushings did not pass the IEEE Std 693-1997 Moderate level of qualification (1.0g, pga).

Application and Implementation

The testing of 550 kV bushings demonstrated the beneficial effect of increased clamping forces on the seismic performance of a bushing. These data will serve as critical benchmarks in the future development of analytical models for predicting the performance of these components. Data collected during the tests on the dynamic behavior of the bushings will also greatly contribute to the validation of analytical methods. The outcome of shaking table tests also points the way to the types of new designs improvements needed to achieve adequate performance in areas of high seismic hazard. The improvement in performance observed in these tests, although significant, does not appear to be sufficient for IEEE Std 693-1997 Moderate seismic level qualification and beyond. This outcome suggests that more drastic design changes should be pursued.

2.4.3 Performance of 230 kV and 500 kV Bushings

Background and User Needs

The background for this project is the same as that for the project described in Section 2.4.2.

Project Approach

This project investigated the effectiveness of simple field retrofits to improve the seismic capacity of bushings in utilities' installed inventories. We selected a bushing type that was observed to have failed in past earthquakes for testing with and without the strengthening retrofit. In addition, this project was intended to yield an improved understanding of the behavior of transformer bushings under lateral load.

Utilities maintain a large inventory of porcelain transformer bushings, many of which appear to be vulnerable to strong earthquake motions. Although more seismically rugged bushings have now become available, the wholesale replacement of vulnerable bushings with these models is cost-prohibitive. As a result, an inexpensive retrofit that could be applied in the field to improve the seismic capacity of installed bushings would be very attractive. This project arose as a way to meet these needs.

In addition to PG&E, Bonneville Power Adminstration (BPA), Southern California Edison (SCE), and BC Hydro supported this project. In addition to funding contributions, the utility partners provided the technical assistance of their engineering staffs, bushing specimens for use in testing, and retrofit devices. Bushing manufacturers also participated in the project by providing specification data on test specimens, and reviewing and commenting on the approaches considered in the project.

This project included the following major activities:

- Identify vulnerable types of bushings, and obtain test specimens.
- Perform shaking table test on unmodified bushings.
- Perform static/cyclic tests on unmodified bushings.
- Develop retrofit scheme, and install on bushing.
- Perform static/cyclic tests on modified bushing.
- Perform shaking table tests on modified bushing to prove concept.

Based upon the observed performance of porcelain transformer bushings in past earthquakes, a vulnerable model of bushing was identified. Several identical specimens of a 196 kV bushing model were provided by BPA. SCE provided one model of a 550 kV bushing. Because of the relative ease of handling a 196 kV bushing compared to the much larger 550 kV model, the 196 kV model was chosen for testing.

Shaking table tests were first performed on unmodified bushings to obtain a set of baseline data for comparison purposes. Since the key objective of the project was to develop an effective retrofit, it was necessary to achieve a better understanding of the behavior of bushing when subjected to earthquake motions. Unlike previous tests on bushings, this project included a set of static/cyclic tests that were intended to study the behavior of the bushing when subjected to controlled lateral loads. In the static/cyclic tests, the bushing specimen was mounted on a stiff stand and subjected to forces applied by hydraulic actuators. Static/cyclic tests permit controlled rates of loading or displacements in order to gain an improved understanding of mechanical behavior. A retrofit ring similar to a pipe clamp, with the annular space filled with an epoxy grout, was developed and applied to the bushing. Static/cyclic and shaking table tests were conducted with the ring in place.

The Principal Investigator for this project was Professor Gregory Fenves of the University of California, Berkeley. Co-investigators were Andrew Whittaker and Amir Gilani. The same team performed shaking table tests on 196 kV porcelain bushings in the previous PEER project. BPA ($25,000), SCE ($20,000), and BC Hydro ($20,000) cofunded the project. Key industry participants were Dr. Anshel Schiff (consultant to SCE), Dr. Leon Kempner, Jr. (BPA), Mr. James T. Kennedy (SCE), and Mr. Alan J. King (BC Hydro). Eric Fujisaki was the PG&E Technical Contact.

Results

Shaking table tests of unmodified 196 kV bushings were unable to cause failure. The performance of the specimen tested exceeded the expectations of utility participants and the investigators. Consequently, it was necessary to use the static/cyclic tests to assess the effectiveness of the retrofit. Static/cyclic tests also demonstrated the high lateral load capacity of these bushings. However, the improvement in performance of the retrofitted bushing was found to be marginal.

A modified retrofit ring, using better attachment clamps to the bushing flange and a smaller gap to the porcelain, was applied to a 196 kV bushing that was then subjected to shaking table tests. In these latter tests, a flexible mounting plate was used to support the bushing as opposed to the rigid support previously used. The flexible support was intended to better simulate actual bushing support conditions. The modified ring resulted in a capacity of 2.0g pga before major slip, compared to 1.4g pga without the ring.

Application and Implementation

The retrofit for 230 kV and 500 kV bushings developed in the second of these projects achieved limited success. The modified retaining ring resulted in a significant improvement in bushing fragility for the porcelain slip failure mode. However, its capacity even without the ring was somewhat higher than a prediction based upon earthquake experience data. Significant differences in the dynamic behavior of bushings were observed compared to expected behavior based on current knowledge. This implies that the interactions of the mechanical parts of a bushing, and with its supports and attachments, are complex and still not well understood. The favorable performance of 196 kV bushings in tests compared to poor performance in past earthquakes highlights the need for improvements in the qualification procedures of IEEE 693-1997. As a direct result of this project, the committee responsible for the standard is currently considering such changes. In particular, the use of more realistic support conditions during testing (i.e., flexible versus rigid stand) and improved methods to account for the effects of interaction with adjacent equipment are needed. The dynamic characteristics of bushings investigated in this project also have a direct bearing on the effects of equipment interaction, which are discussed in Sections 2.4.4 and 2.4.5.

2.4.4 Analytic Studies of Substation Equipment Interaction

Background and User Needs

Electrical substation equipment is connected by different types of electrical conductors. In broad terms, these conductors may be categorized as rigid and flexible buses. Rigid buses usually consist of aluminum pipes that are attached to equipment and other sections of the bus by various types of connectors. Flexible buses are usually made up of cables composed of a number of aluminum wires with end fittings used for making the connection to equipment terminals.

Rigid buses find wide use among utilities because they maintain a fixed shape and provide better control of clearances to adjacent equipment, buses, or the ground necessary for safety and operability. Maintaining control over clearances is particularly important when limited space is available, such as when a substation of a fixed size requires additional equipment to accommodate load growth. Flexible connector fittings are employed to relieve stresses induced by thermal expansion and contraction of a rigid bus system, but these connectors also influence the behavior of the system during earthquakes. Rigid bus systems provide a stiff mechanical link between adjacent equipment, which raises concerns about how connected equipment might interact with one another.

To mitigate interaction effects, utilities have often installed flexible bus systems. If sufficient slack in the cables is provided, flexible buses should have a minimal effect on the behavior of the connected equipment, effectively making them behave as if they were not connected. The disadvantage of flexible bus systems is that by their very nature, they allow more movement. Consequently, their design involves issues such as maintaining electrical clearances and transverse stability under wind and other loads.

One obvious way for connected equipment to interact during an earthquake is for one to collapse, pulling down connected equipment. Perhaps less apparent but equally important is the fact that the connected equipment, including the conductors, form a mechanical system that does not behave in the same manner as when the equipment is unconnected. In past earthquakes, interaction between adjacent connected equipment has been suspected of contributing to equipment damage. Unfortunately, damage assessments by trained observers are done after the fact, making it difficult, if not impossible to reach a firm conclusion about the importance of interaction effects. IEEE Std 693-1997, the new national standard for the seismic qualification of substation equipment, recognizes the importance of interaction effects, but only provides qualitative design guidance. Furthermore, equipment seismic qualification tests or analyses have always been done with the equipment in an unconnected condition. Clearly, this topic is one of great interest and importance to utilities in high seismic areas.

Project Approach

The objective of the analytical studies was to develop mathematical models to predict interaction effects on two pieces of equipment connected by a specified type of bus / connector system. This project was an extension of previous work on the same topical area, but focused on specific connector types and properties.

A previous PEER project developed the basic framework for interconnected equipment. Models and critical parameters were identified generically for equipment and rigid and flexible conductors. Rigid bus systems were limited to linear elastic elements. Models for flexible bus systems did not consider the bending stiffnesses of cables. This project continued the development of analytical models to predict the response of equipment connected by conductors, focusing on two specific types:

- Spring connectors (called flexible strap connectors or) with rigid bus, including nonlinear behavior of connector
- Cable conductors, including bending stiffness properties.

The spring connector is frequently used in rigid bus installations by several utilities. Several different styles of this connector are used, but all consist of several copper current-carrying straps formed into a ‘U’ shape to provide some flexibility and bolted to terminal pads at each end. Since these connectors were tested in the experimental studies portion of this topic (Section 2.4.5), some of the basic mechanical properties were available for use in the analytical studies. These basic properties were used to develop detailed mathematical models of the connector, which were then converted to a simpler representation for use in the analysis of the bus system. Because of the large displacement demands that might be imposed on such a spring connector during a major earthquake, a great deal of nonlinear behavior would be expected, which would be expected to affect the response of the connected system. This nonlinear behavior was included in the bus system analyses.

Models for cable conductors including bending stiffness properties were also considered in the analytical studies. The bending stiffness of cables would be expected to have a more important effect on the behavior of shorter cables. Cable conductors have been used by a number of utilities to provide more flexible connections between equipment. IEEE Std 693-1997 suggests several shapes of short jumper cables for this purpose. During previous developments, however, design guidance has been limited to qualitative suggestions. One of the reasons for the scarcity of specific design guidance is the complexity and nonlinearities characteristic of the problem. Available information on the properties and behavior of cables was gathered and used in the development of analytical models. The results of experiments on cables previously conducted by Dastous and Pierre of Hydro Quebec were also investigated for comparison with the analysis results. Detailed analytical models were developed and analyzed with several ground motion inputs and varied slack.

The Principal Investigator for the analytical project was Professor Armen Der Kiureghian of the University of California, Berkeley, assisted by Professor (Emeritus) Jerome Sackman of the University of California, Berkeley. K-J Hong was a co-investigator. This same team developed the basic framework for analytical methods in a previous PEER project. Eric Fujisaki was the PG&E Technical Contact.

Results

The analytical studies demonstrated a method for modeling a spring type bus connector, including nonlinear effects. A detailed finite element model for each of three connectors was developed. A sample analysis of one of the spring connectors indicates that a de-amplification (i.e., reduction in response of the connected equipment compared to the unconnected equipment) occurs for both equipment items, due to the flexibility of the spring connector and the energy dissipated by yielding of the spring connector. The results of analyses are reported in terms of non-dimensional Response Ratios.

For the analysis of flexible bus systems, good qualitative agreement was obtained from the analytical model compared to experimental results reported by Dastous and Pierre. Parametric studies were performed to assess the importance of flexural stiffness and damping of the cable, and ground motion variability. Non-dimensional Response Ratios were calculated and reported as a function of an interaction parameter that describes the amount of slack provided in a flexible bus system.

Application and Implementation

One of the most important contributions of the analytical studies was the structuring of the interaction problem and the development of the concept of Response Ratios to quantify the effects of interaction. Because the Response Ratio for given equipment is defined as the maximum displacement of the equipment in the connected condition compared to that in the unconnected condition, this quantity represents the total load demand on the equipment. As discussed earlier in this section, equipment is seismically qualified in the unconnected condition. Consequently, Response Ratios provide a convenient means of relating equipment qualification levels to the expected performance of the equipment in a connected condition. The suitability and simplicity of this description of interaction make it an attractive measure for use in the specification, analysis, and testing of connected equipment. Similarly, the development of the interaction parameter for flexible cables in terms of readily available design quantities represents a major step forward in designing for the effects of interaction.

The development of analytical models of one type of rigid bus connector suggests that it is even feasible to perform such analyses with computer codes commercially available in the industry. The analytical studies also resulted in a method for estimating the slack required in a cable to prevent the effects of interaction, considering bending and axial stiffness properties, and several different earthquake ground motions. With an appropriate amount of parametric variation, these values can provide valuable design guidance for flexible bus systems in substations.

2.4.5 Experimental Studies of Substation Equipment Interaction

Background and User Needs

The background and user needs for this project are the same as that for the project described in Section 2.4.4.

Project Approach

The experimental studies were intended to complement the analytical studies described in Section 2.4.4, and to obtain basic mechanical properties of connectors, provide data to validate analytical methods developed previously as well as in the concurrent project, and investigate the effectiveness of different types of rigid bus connectors. In addition, similar experiments on flexible cable jumpers were planned. Rigid and flexible bus assemblies and connectors were fabricated by PG&E and provided for testing. A flexible connector that BPA has installed with rigid buses in some of their substations was also provided for testing.

The experimental portion of this project included static/cyclic or shaking table tests of the following bus/connector assemblies:

- Spring connector with rigid bus (3 types)
- Expansion slider with rigid bus
- BPA flexible connector with rigid bus
- Three types of flexible cable assemblies.

The spring connectors are the same components that were evaluated in the analytical portion of the project. The expansion slider consists of a plunger that slides inside of the bus tube to maintain alignment and aluminum cable jumpers that carry electrical current. The cables also act as springs to restore the connector to its original position. The BPA flexible connector is constructed of three vertical aluminum cables that are welded to two horizontal terminal pads. The bending stiffness of this connector is large enough to support the weight of the bus assembly connected to it and maintain stability against lateral loading, but small enough to keep forces between the equipment low during earthquake motions. Single and bundled (two cables side-by-side tied by clamping bars) cable jumper specimens of two lengths (15 feet and 25 feet) were prepared for the tests.

Static/cyclic tests were conducted using all of the listed connectors and the flexible cable assemblies. These tests gathered force versus displacement data on each connector type to use as inputs to analytical models. Material tests were conducted to obtain basic data, also for use in analytical studies, on the spring connector.

Shaking table tests were conducted on one type of spring connector, the expansion slider, and the BPA connector. The rigid bus assemblies were approximately 10 feet long, with the connector attached at one end. To study the interaction behavior of equipment connected by these bus assemblies, cantilever posts with provisions for adjusting the mass at their tops were constructed to simulate the equipment. A range of frequencies and masses for each piece of simulated equipment were developed for use in testing. Five different equipment pairs were selected for testing. The simulated equipment and buses were subjected to different intensities of motion from two different earthquakes. Stand-alone equipment tests were also conducted to establish the responses of the unconnected equipment. About 160 different shaking table tests were performed for different combinations of equipment pair, bus connector type, ground motion, and intensity of motion. Flexible cable assemblies of the lengths chosen were found to have such low bending stiffness that shaking table tests were not performed.

The Principal Investigator for the experimental project was Professor Andre Filiatrault of the University of California, San Diego (UCSD). Spyridon Kremmidas, Ahmed Elgamal, and Frieder Sieble were co-investigators. Eric Fujisaki was the PG&E Technical Contact.

Results

The spring type rigid bus connectors exhibited good energy dissipation characteristics during static/cyclic tests. Their displacement capacity was shown to be from six to eight inches in each direction, depending on the style of spring connector. The expansion slider connector demonstrated the characteristics of a friction-damper type device in static/cyclic tests. Its behavior is characterized by low stiffness (due to the flexibility of the cables) and good energy dissipation (resulting from friction forces generated at the plunger/pipe interface). Static/cyclic tests on the flexible cable assemblies showed that for the lengths chosen, the bending stiffness of the cables was insignificant. No other tests were performed with the cable assemblies.

In shaking table tests, the expansion slider consistently exhibited the most favorable behavior of the three connectors tested. Response Ratios (discussed earlier in this section), determined from quantities measured during the tests, showed that the seismic responses of both equipment items were de-amplified during virtually every test. This means that the responses of the equipment when connected are lower than the unconnected equipment. The de-amplification of responses is attributed to the energy dissipated by frictional forces in the connector, which are generated even at low levels of motion. At the highest intensities of ground motion, however, the displacement capacity of the slider was exceeded, causing the plunger to come out of the tube.

At lower levels of shaking, the BPA flexible connector seemed to perform reasonably well to mechanically isolate the connected components. In general, both the spring connector and the BPA flexible connector caused amplification in the higher frequency equipment, while de-amplifying the response of the lower frequency equipment. This behavior is in agreement with one of the general trends identified in previous analytical studies and occurred even though significant levels of inelastic behavior occurred in the spring connector.

Application and Implementation

Experiments validated previous analytical studies, which suggested that a flexible connector with significant energy dissipation would be effective in reducing the responses of the connected equipment. The expansion slider was shown in experiments to be consistently effective in de-amplifying the responses of both pieces of equipment. This type of behavior was not observed in the other two connectors tested. Such a result suggests that more attention should be focused on the use of such a connector. PG&E has discussed increasing the displacement capacity of the expansion slider with one of its suppliers for future validation tests. Experimental results for the spring connector and the BPA flexible connector were not as favorable as the expansion slider. Response Ratios determined from tests will provide valuable data for benchmarking analytical methods, and guiding future actions on connector selection for use with rigid buses. Tests involving the BPA connector showed that amplification still occurred in at least one equipment item, particularly at high intensities of shaking. This result raises some question about the effectiveness of flexible connectors with low damping, which traditionally has been the preferred approach in connection design to prevent interaction. Previous analytical work taken together with these experimental results provides an indication of the magnitude of stiffness required for these connectors to prevent or minimize the effects of interaction.

2.4.6 Amplification of Ground Motions at the Base of Transformer Bushings

Background and User Needs

As discussed in Section 2.4.2, transformers are one of the most vital types of equipment in a substation, and porcelain bushings have been shown to be a weak link in past earthquakes. Seismic qualification requirements for bushings given in IEEE 693-1997 specify shaking table tests for bushings to simulate earthquake ground motions. Because the structures that support a transformer bushing (the transformer tank, turret, or other support structure) are not rigid, earthquake motions applied at the base of a transformer are amplified at the bushing support point. Physical limitations and the expense of shaking table tests preclude testing a transformer with the bushing mounted on it. Consequently, test standards require that the bushing be mounted on a rigid test stand and subjected to motions amplified by a factor of two.

Very little experimental or analytical data exists on the adequacy or appropriateness of the amplification factor of two for bushing qualification. Different manufacturers of transformers configure the tank and bushing support structures differently, resulting in a variety of bushing support conditions. In the past, little attention has been paid to the structural design of the bushing support structures. Research efforts to estimate the magnitude of the amplification factor and the reasonableness of the value given in specifications were considered to be of great value.

Project Approach

The objective of this project was to obtain experimental data from field measurements, to better define the dynamic characteristics of large transformers, develop simple mathematical models to predict the transformer and bushing responses, and estimate the amplification factors appropriate for different transformers. The following major activities occurred in this project:

- Select transformers (spares or new equipment that is de-energized) for investigation.
- Install instrumentation and shake the equipment by impact hammer or portable shaker and record responses.
- Develop simple analytical models and benchmark against experimental data.
- Estimate amplification factors and assess reasonableness of factor of two.

Four transformers located in PG&E substations were selected for testing. We selected transformers with high-side voltages of 230 kV and 500 kV because, based on past experience, bushings of this class are the most vulnerable to earthquakes. Different styles of transformers and bushing supports were chosen for testing. Two 500 kV single-phase units, one 230 kV single-phase unit, and one 230 kV three-phase unit were tested. Two of the transformers were older spare units located in substations, and two were new units just about to enter service. In all cases, the transformers were not connected to the station buses while testing was performed. For each transformer, instrumentation was installed. A 160-pound electromagnetic shaker mounted on the transformer tank and controlled by a PC-based signal analyzer applied low-level input.

Based upon outline and limited structural drawings of the equipment, simple mathematical models for two of the four transformers were developed. These models were benchmarked against experimental data gathered through field tests, and adjustments made to achieve similar behavior. These mathematical models were then used to study the dynamic behavior of the transformer and bushing system and to estimate amplification factors at the bushing support points.

The Principal Investigators for this project were Professors Roberto Villaverde and Gerald Pardoen of the University of California, Irvine. Eric Fujisaki was the PG&E Technical Contact.

Results

Experimental data on the important frequencies of vibration for the four transformers were gathered during testing. Simple lumped mass and stick analytical models were developed for the two 500 kV transformers. Frequencies ranged from about 3 to 4 Hz for the 500 kV bushings and about 4.5 to 6 Hz for the 230 kV bushings. Measurements made at low levels of shaking indicate damping ratios of about 1.5 percent to 4 percent of critical. Analytical models for the two 230 kV transformers were not developed; however, it appears that the frequencies of vibration of the 230 kV bushings would be in a similar range to that described above.

The simple mathematical models of the two transformers were adjusted to achieve a reasonable match with the results of measured field responses. Amplification factors for the responses of the bushings were computed from these models and reported as approximately two for the 500 kV bushings and about four for the 230 kV bushings. However, due to the unavailability of detailed data on transformer structures and components, and a lack of understanding of the basic properties of bushings (such as those discussed in the projects on high voltage transformer bushings described in Sections 2.4.2 and 2.4.3), there is significant uncertainty in accuracy of these calculated values. It was also suspected that the small magnitude of forces imparted by the shaker might not have adequately excited some parts or components of the transformer, introducing further uncertainty into the results.

Application and Implementation

This project resulted in two important and useful outcomes. First, the frequencies of vibration measured in field tests were substantially lower than those measured for similar bushings in seismic qualification tests. For example, 500 kV bushings in field tests had frequencies of vibration of 3 to 4 Hz compared to about 8 Hz in shaking table tests; 196 kV bushings had frequencies in field tests of 4.5 to 6 Hz compared to 14 to 20 Hz in shaking table tests. Although a reduction in frequencies of vibration was expected due to the different support conditions when these measurements were made, the magnitude of the reduction is significant. This suggests that other sources of flexibility, such as several rubber gaskets at cover plates and flanges, need to be considered in the analysis and design of the bushing support structure.

The second important outcome of this project deals with the basic approach specified in IEEE Std 693-1997 to account for the bushing support amplification. Although the amplification factor method prescribed by the standard is simple to apply for bushing qualification tests, it may be inadequate for dealing with the wide variation in bushing support responses and the complex behavior of the bushing/support system. The difficulties and uncertainties encountered in this project highlight the need for a more integrated design of the bushing and its support and for more definitive guidance in the design of the bushing support structure in IEEE Std 693-1997.

2.4.7 Rocking Response and Overturning of Equipment

Background and User Needs

California utilities maintain a large number of substations in high seismic hazard areas. Within these substations is a significant amount of equipment that is poorly anchored, and in some cases, unanchored. At PG&E and other utilities, equipment anchorage strengthening efforts have focused on transformers because of their importance to substation operation. Equipment anchorages are designed to restrain the equipment from sliding and overturning, the latter generally producing more damage.

Rocking or toppling of equipment or the equipment and its foundation has been observed in past earthquakes. Analytical studies performed by others have suggested that objects have a much higher capacity against toppling during earthquakes than assumed in conventional engineering design because of the limited amount of energy supplied by the earthquake. While previous studies and methods of assessing vulnerability to overturning have been limited to actual toppling, rocking is also of interest to the utility since equipment would likely be severely damaged by equipment impact with the ground even before toppling occurs. A better understanding of the rocking phenomenon and identification of factors that contribute to the vulnerability to rocking and toppling would help to prioritize future anchorage strengthening efforts.

Project Approach

Previous analytical studies investigated the rocking response of freestanding rigid blocks and their response to pulse-type motions. The current project continued this work and investigated the following major issues:

- Influence of anchorages of varying strength
- Effect of variation in coefficient of restitution on rocking response
- Contribution of vertical seismic input to overturning
- Characterization of rocking response (uplift or angular velocity).

The investigations conducted in this project were intended to address several practical aspects of the overturning problem. Because actual substation equipment are connected to foundation slabs on soil, an important consideration in the rocking problem are the effects of inelastic collision with the ground (influence of coefficient of restitution) and anchorages of varying strength. Previous analytical work considered only horizontal input motions; vertical input motions generally have been considered to be detrimental to rocking response, since upward motion tends to reduce the restoring forces that would return the object to its initial stable position. Finally, as discussed previously, rocking as opposed to actual toppling is of interest in order to ensure that the equipment does not sustain severe damage from impact loading.

The Principal Investigator for this project was Professor Nicos Makris of the University of California, Berkeley. Jian Zhang was Co-Investigator. Professor Makris was the Principal Investigator in a previous PEER project on equipment overturning. Eric Fujisaki was the PG&E Technical Contact.

Results

Analytical models were developed to investigate the rocking behavior of various blocks with anchorages of varying strength. In a manner similar to previous studies, an impulsive motion was used as an input, and rocking spectra were computed. These spectra related the pulse frequency / block size to the amplitude of the pulse acceleration required to cause toppling to occur. These spectra indicated that there is high capacity against overturning for small blocks, or at high pulse frequency. For large blocks or low pulse frequencies, overturning capacities are lower. These spectra also indicated that for some frequency ranges, the conventional engineering evaluation would tend to predict a higher capacity for resisting overturning than suggested by this study. Some limited investigations were performed on the influence of the coefficient of restitution. These show that although the magnitude of the uplift decreases with more inelastic collisions (which is expected), the impact velocities are sometimes higher. Vertical seismic input was found to have an insignificant influence on rocking response.

Application and Implementation

This project demonstrated that conventional engineering methods using static coefficient analysis provide, in most cases, a safe design. However, rocking spectra also identified a frequency range where the conventional approach underestimates the potential for overturning. Because vertical input motions were shown to have an insignificant effect on overturning, they can be safely ignored in engineering evaluations. These results can be incorporated into engineering design criteria.

Rotation and angular velocity spectra for blocks of different slenderness parameters were calculated and plotted for two sample earthquakes and different values of the coefficient of restitution. These results give an indication of the importance of the coefficient of restitution on rocking response. These results also directly provide uplift displacements and impact velocities, which can be compared to values established by equipment manufacturers. An extension of these calculations to include the effects of foundation slabs would result in data on the uplift and impact velocities for the equipment / foundation system. Results from both of these cases (equipment uplift and equipment / foundation uplift) can be used to establish the vulnerability of equipment to rocking, given input motion records appropriate for the site.

For a given site near a fault zone, predictions of pulse frequency and amplitude, and equipment size parameters can be coupled with the calculated overturning spectra to provide an indication of the vulnerability of equipment. Prior to use, however, these spectra should be recast to define failure as rocking uplift or impact velocity of a specified magnitude. This information can then be used to prioritize strengthening modifications for equipment anchorage.

2.4.8 Field Investigation of Effects of the Kocaeli, Turkey, Earthquake

Background and User Needs

On August 17, 1999, at 3:01 AM, a magnitude 7.4 earthquake hit the industrial heart of the country of Turkey (the Izmit Bay area). The earthquake was accompanied by severe ground shaking, more than 100 km of surface fault rupture of several meters, and shaking-induced ground failure in urbanized areas. In the days following the earthquake, as televised reports and information on the Internet flowed out of the densely urbanized Kocaeli Province and adjacent provinces in western Turkey, it became clear that significant information on the performance of the Turkish electric power system could be gained by studying this earthquake. This information would bring increased relevance to the Commission-supported research program.

Project Approach

PG&E organized a reconnaissance team to travel to Turkey and gather critical, time-sensitive data and information regarding the earthquake and its effects on electric power reliability and on the electric utility customers. The team was in Turkey from September 2 to September 13. Table 4 lists members of the team. The team included very knowledgeable collaborators from Turkey, who greatly added to the effectiveness of the PG&E-Commission team in the field.

Table 4. Kocaeli Earthquake Investigation Team and Collaborators

Name	Primary Topics of Investigation	Organization
Lloyd Cluff, Team Leader	Seismic Geology, Damage Assessment and Structural performance	PG&E, Manager, Geosciences Dept.
Norman Abrahamson	Engineering Seismology	PG&E, Geosciences Dept.
Robert Panero	Utility risk management	PG&E, Insurance Dept.
William Savage	Seismic Hazards, Electric Power Systems	PG&E, Geosciences Dept.
Robert Anderson	Engineering Geology, Power Systems	CEC, Energy Facilities Siting & Environmental Protection Division
Aykut Barka	Seismic Geology	Istanbul Technical University, Geology Dept.
Fakir Erdogan	Electric Power Systems	TEAS, Nuclear Engineering Dept.
Muzaffer Genc	Geology	TEAS, Nuclear Engineering Dept.

The team visited the Turkish Electric Generation and Transmission Company (TEAS) in Ankara to receive detailed briefings on the performance of the utility systems in the earthquake. Several field tours allowed the team to inspect many features of the surface fault rupture and its effect on structures and utility and transportation systems. In particular, the Adapazari substation near the epicenter of the earthquake was inspected, and valuable information about damage to substation components was obtained. Travel through some of the heavily damaged areas permitted a close look at the interaction between building damage and electric utility damage. Inspection of the surface fault features at selected locations illustrated many examples of poor and good performance of buildings, pipelines, and transportation corridors. The trip ended with a four-hour helicopter overflight of much of the entire length of the fault rupture, permitting close visual inspection and photography of geologic and man-made features associated with the earthquake.

Results

In spite of the severe earthquake conditions, the Turkish electric power transmission system was quickly restored on the day of the earthquake, promoting the timely restoration of customer service in all but the most severely damaged urban areas. The team made several important observations:

- The extensive damage to several 380 kV substations was not a major factor in transmission power restoration due to the existence of 380 kV transmission lines that bypassed the damaged stations. Power could then be rerouted to the distribution system via the 154 kV transmission system, whose substations were much less damaged. The redundant system design used by TEAS performed successfully in this earthquake, even though explicit planning for such earthquakes had not been done.
- The power generation and transmission personnel were responsive and organized in their efforts to stabilize the post-earthquake situation, rapidly assess critical damage, and restore system operations. In general, the crisis management actions taken by TEAS were effective.
- The distribution company actions were also responsive and effective. Of particular importance was the coordination between local government representatives and the local distribution companies to safely restore power. This avoided the danger of restoring power into damaged or collapsed buildings.

The physical damage to generation, transmission, and distribution equipment was consistent with the experiences of past earthquakes in California, Japan, and elsewhere and included the following typical observations:

- Generating plants are usually resistant to significant damage in earthquakes, provided their foundations do not undergo large deformations.
- Transmission towers and lines are highly resistant to earthquake damage even when displaced by surface fault rupture.
- Porcelain insulators used in high-voltage substation equipment are generally vulnerable to strong earthquake shaking and loading caused by interconnection with other equipment, unless high-strength insulators and appropriate seismic designs are used.
- Unanchored equipment is seismically vulnerable, particularly transformers sitting on rails or inadequately attached pole-mounted transformers. Transformer damage can significantly delay customer service restoration.

- Distribution power poles and towers are vulnerable to damage due to liquefaction and other ground failures, particularly in urban areas where buildings are likely to be damaged as well and can fall into the poles and towers.
- Pole-mounted transformers fail if shaking causes the poles to break, or if they are not adequately anchored to the poles.
- Underground cables are prone to damage where they connect to surface electrical supplies or buildings because of subsequent degradation in cable insulation due to physical or electrical effects. Such damage can lead to long delays in power restoration because of the relative difficulty in repairing underground cables compared to overhead lines.

Application and Implementation

The observations made of earthquake damage and its impact on restoration of customer service in the electric and natural gas systems in the Izmit region of Turkey were quite consistent with the types of damage and service disruptions observed in past earthquakes in California. The damage to high-voltage substation equipment confirmed the wisdom of the diverse testing and analysis program that is being carried out in the PG&E-Commission program. In past earthquakes in California there has not been extensive damage to underground electric cables, nor has there been the need for rapidly constructed utility services to refugee camps. However, these issues could arise in future earthquakes in selected localities, and their implications will be incorporated in future research planning. The immediate post-earthquake response of TEAS to the earthquake damage provided important lessons for emergency response and system risk analysis. It took many hours to gather information on what the level of damage was at individual utility facilities, and to begin to comprehend the huge societal impact of the damage. Research efforts to accelerate this information-gathering using ground motions and vulnerability curves is properly directed. Similarly, the benefit of pre-earthquake understanding of the role of redundant transmission paths and operational alternatives given various states of equipment damage is incorporated in the topics for future research that address modeling seismic risk.

In addition, the personal experiences gained by the investigation team have had a large impact in their convictions about the importance of the PG&E-Commission research program, and has reinforced their resolve to continue to focus on the critical issues that affect safety and reliability of electric power in California. Along with the detailed observations and data collected, the lessons they learned during and following the field investigation are being incorporated into planning ongoing and future research activities covering all program topics.

2.4.9 Conclusions and Recommendations

A well-integrated range of projects provided results that address the Electrical Substation Equipment Performance topic, and incorporated field experiments, laboratory testing on shake tables, and sophisticated analysis and modeling. The extensive observations made following the Kocaeli earthquake helped confirm the appropriateness of the projects and emphasized the benefits and urgency of the work. As noted in the discussion of each of the project results, there were numerous specific data sets and analysis results that can in some cases be used immediately. These results also point to additional studies necessary to fulfill the topic objective of understanding the seismic vulnerabilities of substation equipment so that appropriate improvement in existing equipment and installation of well-performing new equipment can lead to predictable and acceptable electric system performance in future earthquakes.

2.5 Topic 5: Earthquake Fire Safety Associated with Gas and Electric Systems

2.5.1 Objective

The objective of this topic is to systematically identify the bases for assessing fire safety issues related to natural gas and electric power systems, considering both utility-owned facilities (pipes, wires, and meters) and customer-owned facilities (residences and businesses). Although fires have not typically been a severe consequence of earthquakes in modern Californian cities, the threat of fire, including conflagration, is a prominent factor in planning for earthquake safety. This study provided an overview of this complex and variable hazard in earthquakes, and then focused on key issues dealing with residential structures and life safety. These results are a beneficial step toward informing the various parties responsible for fire safety, including building owners and occupants, about the causes of earthquake-related fires and alternative safety improvement actions.

2.5.2 Ignition of Fires Following Earthquakes Associated with Natural Gas and Electric Distribution Systems

Background and User Needs

Utility providers of natural gas and electric power work diligently to provide safe and reliable services. Nonetheless, concerns about potential safety threats accompanying the occurrence of earthquakes have been raised regarding both gas and electric power. The ignition of gas leaks inside buildings resulting from damage to customer-owned piping and appliances, or ignition of natural gas escaping from damaged pipelines in streets or near buildings, could lead to property damage and threaten the life safety of individuals. These occurrences have led to suggestions for reducing fire risk by reducing the occurrence of leaks through numerous measures, including strengthening buildings, anchoring appliances and other gas-burning devices, and installing gas shutoff valves that respond to earthquake shaking, excessive gas flow, or the presence of leaked gas. However, each of these alternatives has various adverse consequences, including high installation costs, long implementation time, prolonged service outage durations, and potentially dangerous customer behaviors that may negatively effect gas safety or reliability if actually implemented.

Statistics from earthquakes in the past decade indicate that electric power can be as significant as natural gas in causing post-earthquake fires. The source of ignition may be due to electric appliance and wiring failures causing a spark in a damaged building or downed, energized overhead distribution lines. Recent and ongoing improvements in the post-earthquake reliability of high-voltage electric transmission systems have increased the potential for electric distribution service to continue to be provided to areas containing seismically damaged buildings or contents.

Utilities, their customers, government agencies, and regulators need to understand and consider the issues and implications associated with various alternatives to reduce earthquake risk due to natural gas and electric power when preparing for future emergencies.

Project Approach

During the initial PG&E-PEER research program, a project to study these topics, focused on natural gas, was conducted. A second phase of this research was carried out to incorporate electric power issues, since work during the first phase indicted that electric power was also a primary ignition source for fires following earthquakes. The two studies have been integrated herein and are reported together.

The scope of the project involved reviewing the causes of fires in earthquakes beginning with the Great San Francisco earthquake of 1906 and concluding with the Kobe, Japan event in 1995. The review includes consideration of facilities and structural performance, human factors, and organizational factors. The project created an inventory of fire ignition scenarios. These scenarios were used to identify and consider alternative means to reduce the safety threats posed by fires, including appliance anchorage and flexible gas connections, gas and electric shutoff devices for residences and businesses, and gas and electric distribution shutdowns. Public education and service restoration coordination in the aftermath of a major earthquake were also considered.

The project was conducted by Dr. R. Brady Williamson, professor of Engineering Science in the Fire Safety Engineering Science Program, a part of the Department of Civil and Environmental Engineering at the University of California, Berkeley. Dr. Norman Groner assisted Dr. Williamson. William Savage was the PG&E Technical Contact.

Results

The causes of fires in eleven twentieth-century earthquakes were reviewed. From this review, the degree of structural damage was found to be a direct indicator of the potential incidence of fires following an earthquake. Using the earthquake fire history and other information, a list of fire ignition scenarios was developed involving gas and electric service. The scenarios incorporate the necessary presence of a fuel source and a source of ignition.

- A gas pipe in a building is broken, **and** an electric spark from damaged electrical wiring is present near the released gas to cause ignition.
- Bottles or open cans of flammable liquids are thrown to the floor by the earthquake, **and** an open gas flame or an electric spark is present to ignite the vapors from the spilled liquid.
- A water heater is overturned by the earthquake, **and** the customer’s house gas piping is ruptured, **and** released gas is ignited by a flame or spark.
- A gas pipe in a building is broken due to building structural damage, **and** the delayed ignition of the released gas occurs when an ignitable mixture of gas and air is reached in the presence of a source of ignition.
- Cooking oils and other kitchen fuels are spilled during the earthquake, **and** either electrical- or gas-based cooking equipment ignites these fuels.
- Electrical service to a structure is interrupted by the earthquake, **and** an electric-powered device is displaced or damaged by the earthquake **and** comes into contact with a quantity of fuel that is in a flammable state, **and** when the electric power is restored to

the building, this device causes the ignition of the flammable fuel. (An example of such a scenario might be a high-intensity light falling onto a polyurethane mattress or couch.)

- A person ignites a fire by means such as arson or turning on light switches in the presence of a gaseous fuel.

The study focused on the life-safety implications of these fire scenarios for residential structures, specifically R-1 (three or more dwelling units) and R-3 (one or two dwelling units). From the standpoint of fire threatening people trapped inside a structure following an earthquake, R-1 occupancies are considered to be the more serious concern due to the greater number of occupants with a smaller number of exits. This is particularly true for buildings of more than two stories than for single-family or duplex residences. Schematic goal decomposition models and influence diagrams for gas and electric utility-related earthquake fires were developed to aid in understanding the logical relations among factors affecting gas and other sources of fuel; gas flames, electric sparks or heating elements, and other ignition sources; and life-safety issues such as injuries or egress blockage due to building damage.

Finally, alternative means to reduce fire risks following earthquakes were analyzed. The interrelated performance in an earthquake is very complex among residential structures, customer and utility gas lines, electric distribution and residence wiring, electric safety systems, gas and electric appliances, gas and electric shutoff devices in the building, and people affected by or responding to the earthquake. While this study does not reach conclusions about all these relationships, it does provide a logical framework to analyze them. For some situations involving life-safety issues, there were several conclusions reached regarding the most effective measures to reduce life-safety threats due to post-earthquake fires.

- Older multifamily residential buildings (R-1 occupancies) that are susceptible to structural damage and potential collapse appear to represent the most likely setting for people to be trapped and exposed to life-safety threats from fire. Improvement of structural performance of these structures could significantly improve fire safety. Gas flow interruption devices, such as seismically activated valves or excess flow valves, can also make improvements in safety, provided that they have appropriate performance characteristics for the seismic hazard exposure and for the level of seismic vulnerability of each structure and its contents.
- For one- or two-family residences (R-3 occupancies) of good, earthquake-resistant design and construction, life-safety is provided by such current practices as water-heater and other appliance anchorage, strong attachment of the structure to its foundation, and multiple means of egress. For older R-3 occupancies, important first steps to improve safety are to anchor water heaters and other gas appliances, and install flexible connectors.
- The report discusses alternative means to shut off gas to a structurally damaged residential building to stop gas leaks that could lead to fires. The first alternative is to manually shut off the building gas valve, which building occupants are recommended to do if they smell gas. This has proven effective in past earthquakes. The second alternative is to install automatic gas shutoff devices either activated by earthquake shaking above a set level or by gas flow rate above a set level. Performance characteristics of the two types of devices were reviewed, and their respective

advantages and disadvantages summarized. It was noted that a new standard for the activation of seismic shutoff valves, ASCE 25-97, has been developed for R-3 occupancies, but it does not apply to R-1 occupancies. Adoption of current standards for seismically activated shutoff valves and excess flow valves is pending in California.

- Electric power service will most likely be interrupted to the earthquake-affected area. To prevent power from being restored into areas with gas leaks or other damage that could lead to fire ignitions, there should be an exchange of information between emergency responders (fire protection, police, and utility field personnel) and the utility emergency control center.

Application and Implementation

This report provides a logical framework for identifying and analyzing earthquake-related fire safety issues involving gas and electric utilities. It is clear that these issues are multi-disciplinary and multi-jurisdictional, involving utilities, regulators, public officials, fire departments, building owners, and manufacturers of gas and electric safety devices, appliances, and building and utility components. Improvements in fire safety involve a complex process of risk identification, evaluation of safety alternatives under various scenarios, and implementation of effective choices. This study represents progress in this process and is a useful review of current knowledge about earthquake fire safety.

The study is restricted in scope to consideration of residential life safety issues, and has identified two focus areas for the application of the findings of the study.

- The study notes that earthquake fire safety is strongly dependent on the structural integrity of buildings and their contents, and that older multi-family residential units are likely the highest life-safety risk structures. Using its experience and expertise, PG&E is assisting in the preparation of gas and electric safety information to be made available to local governments and building owners and occupants to assist them in making informed decisions about the best actions to take to reduce earthquake-related fire safety risks.
- PG&E recognizes the importance of coordinating electric power restoration with gas safety checks. This was demonstrated during the power restoration of San Francisco and other localities following the Loma Prieta earthquake. In addition, PG&E is working with the local and national offices of the Federal Emergency Management Agency (FEMA) and California's Office of Emergency Services (OES) and Division of Mines and Geology to enhance the application of FEMA's HAZUS software within a few hours following an earthquake to identify areas of severe building damage in the greater San Francisco Bay area. As currently envisioned, this information would be distributed by OES and could augment initial field reports to improve the safety of power restoration and other post-earthquake responses.

2.5.3 Conclusions and Recommendations

The report for this project contains a useful framework for further analysis of fire safety. However, at the present time, this framework and the scope of possible additional studies need further consideration in the context of the large amount of information available before further work is pursued.

3.0 Project Administration

PG&E and PEER carried out the administration of the project. The two organizations maintained close and effective coordination in preparing contracts, subcontracts, and subawards through their respective project managers, Dr. William U. Savage and Professor Gregory L. Fenves. The following paragraphs describe the administrative functions of the program of research.

Pacific Gas and Electric Company

As the prime contractor with the Commission for this project, PG&E provided project management and financial services for the project. Dr. Savage was the principal contact with Ms. Judy Grau and her successor Mr. Robert Anderson, Commission Project Manager, and with others at the Commission. He prepared contractual Quarterly Progress Reports and Quarterly Status Reports and forwarded them to the Commission Project Manager, approved invoices before their submission to the Commission, and provided other information and attended meetings as requested by the Commission.

PG&E subcontracted with PEER to perform the research activities as approved by the JMC. Dr. Savage also maintained primary project management relations with Dr. Fenves and others at PEER, in support of their subcontract to PG&E to conduct the research projects. PEER personnel were very responsive in providing information as needed during the course of the program. Their administrative activities are described in the next section.

Key PG&E personnel participated in the JMC, including Mr. Lloyd Cluff, Seismic Geologist and Manager of PG&E's Geosciences Department; Dr. Norman Abrahamson, Senior Engineering Seismologist; Mr. Edward Matsuda, Supervising Civil/Structural Engineer; Mr. Eric Fujisaki, Civil/Structural Engineer; Mr. Kent Ferre, Civil/Structural Engineer; and Mr. Robert White, Geotechnical Engineer. These individuals also served as Technical Contacts for the individual PEER research projects, providing technical information, guidance, and advice as needed to help the Principal Investigators and projects to be successful.

The costs of the PG&E administrative and technical management, amounting to more than three man-years, have been borne by PG&E. This funding was provided in the expectation that the results of the research would be quickly incorporated into ongoing utility activities and result in safer and more reliable electric power provided to customers. Earthquake specialists in other utilities in the state have been either directly involved in research projects or have been kept informed of results that they can apply to their own systems.

Pacific Earthquake Engineering Research Center

Based at the University of California, Berkeley, PEER was responsible for managing the user-directed research program under a contract with the Pacific Gas & Electric Company. As described previously, the JMC established policies and made the major decisions affecting the program. Professor Gregory L. Fenves, assistant director at PEER, chaired the JMC and served as program manager for PEER. As chair of the JMC, Dr. Fenves organized the meetings and their agendas, in consultation with the staff of PG&E, Commission, and the other utilities involved in the research program. Dr. Fenves kept in close contact with Dr. Savage at PG&E to assure smooth operation of the program.

After the JMC approved the 18 projects, PEER administered them. Working under the supervision of Dr. Fenves, Administrative Assistant Joanne Cortez prepared the subaward contracts from UC Berkeley to the project investigators. After signed approval of the subaward by voting members of the JMC, UC Berkeley issued the subaward. Generally this process went smoothly. With projects underway, the major administrative task was to monitor progress of the projects and review and approve invoices for payment. The following payment process was established. A subaward organization sent an invoice to UC Berkeley. Ms. Cortez prepared a summary table showing expenditures to date and receipt of quarterly reports. Dr. Fenves reviewed the request for payment, the quarterly report, and presentations at quarterly coordination meetings. If progress was adequate, Dr. Fenves approved invoice payment. If there were questions, Dr. Fenves spoke with the technical contact for the project and investigator. Once Dr. Fenves approved the invoices, they were sent to UC Berkeley Accounting for payment. Invoices to PG&E were issued by Accounting based on payments to subawardees.

During the course of the project, PG&E identified a significant problem in the low amount of invoices, well below the projected cash flow, from UC Berkeley. After investigation with UC Berkeley Accounting, Dr. Fenves discovered that Accounting did not prepare invoices to PG&E in a timely manner because of the manual business systems. Although discovered late in the process, PEER has received assurance from UC Berkeley Accounting that they will prepare and send invoices to PG&E in a more timely manner.

As the individual projects reached their end, PEER withheld 10 percent of the total payment until the investigators submitted the final report and it had been accepted. The technical contact and one or two other reviewers reviewed all final reports. Based on those comments, Dr. Fenves determined whether a report was acceptable or required modification. After the final report was approved, the withheld sum from the contract was paid to the subawardee. Summaries of the reports were provided to the JMC in addition to copies of the reports requested by JMC members.

4.0 Conclusions and Recommendations

4.1 Conclusions

The goal of this applied research program was to improve the earthquake safety and reliability of electric power transmission and distribution in California. The research program was organized by the JMC to assure that the research results would directly address electric utility needs in preparing for future earthquake occurrences, and that utility personnel or their consultants could quickly implement the results.

As described in the previous sections of this report, the 18 projects have provided useful results that meet utility needs in the five topic areas. However, it is important to also note the integration of the projects to meet the goal of the program, namely to improve utility earthquake performance. The following bullets summarize, in narrative form, the cumulative connections between the topics that address the goal.

- **Topic 1** results (improved ground motion and site response models and methods) are used as input to **Topic 2** (ground motion estimates for emergency response)
- Topic 1 results are used as input to **Topic 3** (ground motion database) to improve the assessment of locations and amounts of post-earthquake permanent ground deformation caused by ground shaking.
- Topic 1 results, along with Topic 3 results, are used as input to **Topic 4** projects (assessing the vulnerability of pieces of substation equipment and the vulnerability of interconnected equipment). Severe ground shaking and ground failure are the direct causes of substation damage that can disrupt power transmission to customers.
- Topic 1 and 3 results improve the assessment of building damage (damaged buildings are the structures within which most earthquake-caused fires start), and thus underlie and are input to **Topic 5** (earthquake fire safety of gas and electricity). Levels of ground shaking can be used to control utility service shutoff valves and to quickly identify likely locations of damaged buildings where fires could start and people could be trapped.

Although the connections among the individual projects are multi-faceted, a broad picture can be seen of the research results linking up to enable utility personnel (and their regulatory counterparts) to have significantly improved information for taking actions regarding earthquake risks. These actions often include retrofitting a vulnerable building that houses office workers, upgrading equipment and improving anchorages in substation yards, and modifying emergency response procedures to take advantage of new information. The customer benefits from these actions following an earthquake in terms of greater electric power reliability, and faster and less expensive recovery of the overall functioning of society. Of course, there will always be some utility system damage due to random failures of components or facilities. However, the redundant electric system design and the operation skill of utility personnel can make the extent and duration of outages no worse than those of a winter storm.

4.2 Benefits to California

The measure of the success of this user-driven, applied research program is the extent to which the results are being put to use to directly benefit the California electric power ratepayers and others in the state. Even before the reports were prepared, some of the results, such as the substation equipment seismic performance data and analyses, were being implemented in managing the equipment inventory at several utilities and in preparing to modify the national seismic qualification procedures for substation equipment. Significant progress has been made in the ultimate goal of the project, to improve electric system safety and reliability in earthquakes. Clear directions for further applied research were also identified, and provide the basis for planning the next phase of work.

When the results have been implemented in the utility system, then the ratepayers (who have funded this research) and other members of society will benefit from the research by (1) receiving more rapid restoration of service following an earthquake due to less utility damage and improved emergency response capability, (2) avoiding possible utility rate increases because there is less direct damage to equipment and facilities, and (3) experiencing more rapid overall recovery of societal functioning following the earthquake due to rapid power restoration and use of the research results by other organizations to recover their functionality more quickly.

This research program provides several additional benefits to utilities and to the State of California. Although they are secondary to the goal of this program, these benefits have substantial long-term value.

- Enhanced academic expertise: This research program has created an expanded group of university faculty who have gained extensive knowledge about electric utility systems and who have demonstrated interest and talent in addressing utility research needs and problems. In the future, they will have opportunities to continue research in these areas, and to guide their students into graduate work involving utility systems and earthquakes. This reservoir of academic experience will provide ongoing benefits to the utility industry and the State.
- The establishment of the PG&E-PEER-Commission research program has attracted great interest nationally. Other organizations, both public and private at the local to national level, have observed the success of the program, and are influenced by its research goals and project topics. Thus, by providing strong technical leadership, well-defined research project scopes, and results that have clear value and applicability, the PG&E-PEER-Commission program is helping to shape the direction and topics of other research activities. Over the next several years, there will be more coordination of research among the funding agencies, if not among the individual researchers. This coordination will significantly leverage the results of the studies reported herein.
- The PG&E-PEER-Commission program has also attracted highly motivated research partners who are willing to co-fund this program's future work or to perform separately funded but closely coordinated studies that fit together nearly seamlessly. The California Department of Transportation (Caltrans) is the first such partner. It is likely that in the next several years a number of others will join.

4.3 Recommendations

Although the results of the individual research projects reported herein have successfully met their objectives, it is clear that there are additional research activities whose results would provide further improvements in the earthquake performance of utility systems. Many of these opportunities for further study and implementation have been identified in previous sections. They include the following major research areas:

- Ground Motion and Site Response: More accurate ground-motion assessments for utility sites are critical to evaluate the seismic hazard at those sites and to make good risk management decisions. Data and models to reduce uncertainties in ground motions are needed, particularly for locations near large-magnitude seismic events. Because current databases and models for predicting site response have limitations and uncertainties, improved and reliable methods for assessing site response are needed for assessing site-specific ground motions.
- Ground Deformation Database: Expanded empirical databases and new analysis tools need to be developed to better model the probability of permanent ground deformation as a function of geologic and geotechnical data and level of strong ground shaking, so that potential extensive damage to underground as well as above-ground utility structures can be reduced or avoided.
- Electrical Substation Equipment Performance: Further efforts are needed to accurately understand the seismic performance of existing high-voltage equipment to be able to either use elsewhere or replace equipment that is unacceptably vulnerable in its current locations. Seismic performance data obtained from shaking table tests and analytical models of substation equipment, their interconnections, and their system functionality under various earthquake scenarios would be important products of this research.
- Ground Motion Estimates for Emergency Response: Advanced instrumentation capabilities and methods for using them are needed so that strong-motion data and other data can be used to make rapid estimates of damage and functionality prior to getting input from experienced field operations personnel.
- Building Vulnerability: Additional data and models are needed to better assess expected earthquake performance of older substation buildings and service buildings to enable better decision-making by utilities regarding seismic retrofits or other mitigation measures for these buildings.
- Seismic Risk Analysis: A flexible and powerful capability to evaluate the likely functionality of customer services following earthquakes is needed. This capability could be used to evaluate alternative earthquake mitigation actions, and to evaluate the current state of earthquake preparedness of the utility system from the perspective of the utility, customer and regulator.

It is recommended that this successful earthquake research program be continued to address these and other topics.

The scope of further research projects needs to be viewed from a broad and integrated perspective to ensure that other related opportunities are not being missed. It is recommended that the continuation of this program should incorporate a comprehensive planning effort by the JMC.

It is also recommended that the next phase of the program be structured to provide for and to optimize the involvement of multiple co-funding organizations, particularly Caltrans. The JMC member organizations (PG&E, PEER, and Commission) should identify prospective additional partners and enlist their participation. Such efforts will enable significant leveraging of the available funding and make possible rapid gains in knowledge and applications to profoundly reduce earthquake risk in California.

Appendix I
Phase I Research Projects

Appendix II
Request For Proposals

Appendix III
Final Reports of Research Projects