Arnold Schwarzenegger
Governor

ELECTRIC SYSTEM SEISMIC SAFETY AND RELIABILITY

PIER FINAL PROJECT REPORT

Prepared For:
California Energy Commission
Public Interest Energy Research Program

Prepared By:
Pacific Gas & Electric Company

January 2005
CEC-500-2005-007

Prepared By:
Pacific Gas and Electric Company
Stuart Nishenko, Norm Abrahamson, Kent Ferré,
Eric Fujisaki, and Lloyd Cluff
San Francisco, CA
Contract No. 700-99-002

Prepared For:

California Energy Commission

Public Interest Energy Research (PIER) Program

David Chambers,
Contract Manager

Laurie ten Hope,
Program Area Team Lead

Ron Kukulka,
Acting Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Robert L. Therkelsen
Executive Director

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ACKNOWLEDGEMENTS

The success of a research program of this size and complexity depends on the efforts of many individuals. The projects success was also the result of the alignment of interests and administrative support of the participating institutions: Corporate Real Estate, Geoscience, and Substation Engineering Departments of the Pacific Gas and Electric Company (PG&E); the Pacific Earthquake Engineering Research Center (PEER) administered by the University of California at Berkeley (UC Berkeley); and the Public Interest Energy Research (PIER) Program of the California Energy Commission (Commission). This work was supported in part by PEER through the Earthquake Engineering Research Center's program of the National Science Foundation under Award Number EEC-9701568. Common interest components of this program were cost-shared by the California Department of Transportation under the Program of Earthquake Applied Research for Lifelines (PEARL).

The participation of the following individuals is recognized and acknowledged:

Project Management:

Dr. Norman Abrahamson, Mr. Lloyd Cluff, Dr. Stuart Nishenko, and Dr. William Savage (2000-2001), PG&E

Professors Jack Moehle and Gregory Fenves, Dr. Michael Riemer, Dr. Yousef Bozorgnia, PEER

Mr. David Chambers, Ms. Laurie ten Hope, Mr. Terry Surles, Commission

Joint Management Committee (JMC)

PG&E Members

Dr. Norman Abrahamson, Senior Engineering Seismologist

Mr. Lloyd Cluff, Seismic Geologist and Director, Geosciences Dept.

Mr. Kent Ferré, Senior Structural Engineer

Mr. Eric Fujisaki, Senior Civil Engineer

Dr. Stuart Nishenko, Senior Seismologist (2001-2004)

Dr. William Savage, Senior Seismologist (2000-2001)

Dr. Joseph Sun, Senior Geotechnical Engineer

PEER Members

Professor Gregory Fenves, UC Berkeley, Chair of the JMC (2000-2002)

Professor Jack Moehle, UC Berkeley, Chair of the JMC (2002-2004)

Dr. Michael Riemer, Lifelines Program Manager (2000-2003)

Dr. Yousef Bozorgnia, PEER Associate Director for Sponsored Projects (2004)

Commission Members

Mr. Robert Anderson (2000-2001)

Mr. David Chambers (2002-2004)

Caltrans Members

Dr. Brian Chiou, Senior Seismologist

Dr. Clifford Roblee, Chief, Geotechnical Research (2000-2003)

Mr. Thomas Shantz, Senior Research Engineer

We particularly want to thank the following individuals for their voluntary time and effort in reviewing and commenting on this project as part of the PEER Lifelines Advisory Panel on Electric System Seismic Safety and Reliability:

Dr. William Savage, US Geological Survey (Chair)

Mr. Peter Aguila, Southern California Edison

Mr. Robert Anderson, California Seismic Safety Commission

Dr. Leon Kempner, Bonneville Power Administration

Mr. Edward Matsuda, Bay Area Rapid Transit

Mr. Phillip Mo, Southern California Edison

Dr. Dennis Ostrom, Consultant

Craig Riker, San Diego Gas and Electric

Ronald Tognazzini, Los Angeles Department of Water and Power

James Wight, San Diego Gas and Electric

Don Willoughby, Pacific Gas and Electric

Of the many others who assisted in the conduct of the research program, the following are particularly recognized:

PG&E: Mr. Marcus Carver, Mr. Henry Ho, and Mr. Micah Kauffman

PEER and UC Berkeley: Ms. Davinder Gabhi, Ms. Darlene Wright, and Mr. Parshaw Vaziri

Dr. Anshel Schiff, Consultant

Caltrans: Mr. Loren Turner, Senior Research Engineer

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 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:

- Building End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Energy Systems Integration

What follows is the final report for the Electric System Seismic Safety and Reliability project, Commission Contract # 700-99-002, conducted by the Pacific Gas and Electric Company (PG&E) and the Pacific Earthquake Engineering Research Center (PEER). This project contributes to the Energy Systems Integration 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 Commissions Publications Unit at 916.654.5200

ABSTRACT

The Pacific Gas and Electric Company (PG&E) under California Energy Commission contract 700-99-002 has conducted a four-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 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.

Seven topic areas involving 108 separate 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. Earthquake Ground Motions
2. Site Response
3. Permanent Ground Deformation
4. Seismic Performance of Substation Equipment
5. Electric System Building Vulnerability
6. Network System Seismic Risk
7. Emergency Response

Keywords: earthquake, seismic safety, electric utility, electric transmission and distribution, Pacific Earthquake Engineering Research Center (PEER) Lifelines Program.

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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 California Energy Commission's Five Year Transmission Research and Development Plan (CEC 500-03-104F) recognizes that growth of the California electric transmission system has not kept pace with demand over the last 20 years – threatening the integrity of the system and the health of the California economy.

The consequences of limited generation and transmission capacity under 'normal' or 'ordinary' operating conditions have included congestion, reliability problems and higher costs related to insufficient transmission infrastructure. In addition to these challenges, California faces 'extraordinary' demands on the electric system from extreme natural hazard events. The greatest single natural hazards threat to electric system reliability in California is the occurrence of a major urban earthquake. Given the inevitability of large earthquakes in California, evaluating and improving the post-earthquake functioning of electric power service is an important priority both for the providers of that service and for their customers.

Previous evaluations of earthquake risks to the electric power transmission system have been hindered by very large uncertainties in the both the earthquake forces (strength of shaking, ground deformation), and in the ability of key electric system buildings and substation components to withstand these earthquake forces. This report describes the results of a four-year coordinated applied research program to significantly improve the accuracy of evaluations of earthquake risks to the electric power transmission system in California. The research has been conducted by the Pacific Earthquake Engineering Research (PEER) Lifelines program, under the direction of Pacific Gas and Electric Company (PG&E) through the support of the California Energy Commission (Commission).

Application of research results has already benefited utility owners and ratepayers through 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.

Understanding and developing improved models of earthquake forces is important to other groups involved in earthquake engineering. Due to this common interest, Caltrans also provided funding for the earthquake forces part of the research program that provided leverage for the Commission funds.

The total PEER Lifelines program budget during the Phase III period 2000-2004 is $10,175,000 of which $4,600,000 is from the Commission, $4,500,000 is from Caltrans, $900,000 from PG&E, and $175,000 from the Federal Emergency Management Agency (FEMA). Out of a total of 101 PEER- Lifelines research projects conducted during this period, 49 (or 49%) were funded with PG&E/Commission support.

Objective

This project directly addresses the Commission's PIER goal to develop technologies and protocols to mitigate the vulnerability of electric components and systems to damage directly and indirectly caused by earthquakes by providing necessary data, models, and methods needed to reduce the earthquake vulnerability and to improve the earthquake safety of electric transmission and distribution systems.

Implementation of these research results enables 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.

In 2000, PG&E scientists, engineers, and operations specialists, in coordination with representatives from PEER and Caltrans, 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 are listed below.

- Topic 1: Earthquake Ground Motions
- Topic 2: Site Response
- Topic 3: Permanent Ground Deformation
- Topic 4: Seismic Performance of Substation Equipment
- Topic 5: Electric System Building Vulnerability
- Topic 6: Network System Seismic Risk
- Topic 7: Emergency Response

To facilitate a user-driven research focus, PG&E, PEER, Caltrans, and the Commission 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 projects, selecting highly qualified investigators to conduct the projects, and monitoring the work so that utility user needs would be met.

In the spring of 2003, the Joint Management Committee established the PEER Lifelines Advisory Panel on Electric System Seismic Safety and Reliability to perform a comprehensive review of the status of the PEER Lifelines Program research results and to provide recommendations for the future of the Program. The Advisory Panel consisted of seismic experts from large California and West Coast utilities and focused its review on the importance and usefulness of the applied research being conducted by the PEER Lifelines program to the electric power industry and its customers and regulators in California.

The Advisory Panel identified many benefits of this applied research to California ratepayers and utility owners and provided clear direction for further research that would meet the California's needs. Recognizing that future research projects need to be viewed from a broad

and integrated perspective, the Advisory Panel recommended that a comprehensive research plan be developed based on the results of an electrical network model sensitivity analysis. The sensitivity analysis would identify the greatest uncertainties in the network model and help focus research to address and reduce those uncertainties.

Research Topic Summary

The PEER Lifelines Program research topics cover broad areas of engineering seismology, as well as geotechnical, civil, structural, and electrical engineering and emergency response. Electric system network analysis planned for the next phase will integrate the information and results from the seven topic areas. The research in the seven topic areas has been planned so that the results will fit into a network system framework, as illustrated in Figure 1.

For example, research and data collection for earthquake strong motions in Topic 1 provided PEER researchers the ability to select the appropriate time-histories for the qualification testing of electrical substation equipment, as specified in the Institute of Electrical and Electronic Engineers (IEEE) 693 Standard (Recommended Practices for the Seismic Design of Substations), in Topic 4. The compilation of recommended sets of earthquake ground motions and guidance on how to use these data for building design and construction is another example of how research in Topic 1 has further research in Topic 5.

The following sections summarize the research goals and key outcomes for each topic area.

Topic 1: Earthquake Ground Motions

Objective

Based on results from previous seismic risk studies, the largest uncertainties in the seismic performance of structures and components result from the uncertainty in the ground motions. For networks of spatially distributed systems such as the electric system, there is greater sensitivity to the ground motion models than for individual (single location) structures because the distributed system is more sensitive to very large magnitude earthquakes.

The ground motion models available prior to this research program lead to very different estimates of ground motion from large magnitude earthquakes which result in very different evaluations of the seismic performance of the electric system. The main cause of the large uncertainty was a lack of observations from large magnitude earthquakes, The objectives of the projects under this topic are to use the greatly expanded set or recordings from large magnitude earthquakes to develop accurate ground motion models for large magnitude earthquakes including near source effects of directivity and fling, and 3-D basin effects.

Even with accurate ground motion and fault rupture models, there is a need for clear guidelines on the application of the models. In particular, the selection of ground motions for use in dynamic analyses of structures and components remains controversial. A second main objective under this topic was to develop application guidelines on the use of ground motions.

Outcome

Ground Motion Models

A coordinated program was organized to develop new ground motion prediction equations for earthquakes in the California with an emphasis on ground motions from large magnitude earthquakes. This program, called the Next Generation Attenuation (NGA) program integrates the results of over 40 individual project.

A key result of the NGA program is the development of that the most comprehensive and best documented strong ground motion data bases ever compiled. Two types of data bases were compiled: empirical ground motions and numerically simulated ground motions. The empirical ground motion data base includes over 3500 recordings from 175 earthquakes. Even with this extensive ground motion data base, there are still few recordings at short distance from very large magnitude earthquakes (e.g. M8). The analytical data base consists of over 180,000 computed ground motions from 880 potential future earthquakes for rock site conditions and over 96,000 computed ground motions from 60 earthquakes for sites in alluvial basins . The NGA program is the first time that empirical data and numerical simulations have been used together to develop ground motion models for California.

A second key outcome of this work is that the five new ground motion models are being developed that are significantly different from the existing models. These new models replace all of the ground motion models that are commonly used in California. These new ground motion models will have a large effect on all seismic studies in California for evaluations of the strength of the ground shaking that structures and components need to withstand. The short period (T< 1 sec) ground motions from the new models from large magnitude earthquakes at short distances are about half as large as existing models. This will have a large impact on the electric system network analyses, with much less damage expected during large magnitude earthquakes, reducing the seismic retrofits needed.

Surface Fault Rupture models

In previous studies, ground rupture hazard has been treated by simply replacing a ground motion attenuation relation with a fault rupture scaling relation based on generic world-wide data sets. The problem of this approach is that ground rupture is very fault specific so that global based data sets are not applicable to specific sites. The outcome of this work is that a new approach was developed specifically for site-specific ground rupture hazard. A method was developed to classify individual fault segments in terms accuracy of mapping and complexity of the fault rupture. Using a data base of fault ruptures compiled as part of this research, probabilistic models were developed for the amplitude of the ground rupture as a function of the earthquake magnitude and location of the site along fault. This model represents the first fault-specific model for ground rupture hazard.

Design Ground Motion Library

The ground motion data base used in the NGA program contained a large number of ground motions. The outcome of the Design Ground Motion Library (DGML) project is a set of application guideline for the selection and use of ground motions for engineering analyses. Specifically, a small subset of a set of recommended ground motions from the large NGA data

base were identified. In addition, the Design Ground Motion Library contains recommended scaling rules for adjusting these motions for all ranges of seismological conditions used for seismic design of critical infrastructure components in California, excluding subduction earthquakes.

Summary

The results of research in this topic have greatly improved the models for ground motion, and ground rupture that are used in California. These new models are expected to have a large impact on evaluations of earthquake hazards in California, particularly for locations near the large active faults. Proximity of California major cities to both large active faults and deep sedimentary basins place electrical infrastructure within these zones.

The development of convenient, standard and transparent methods for the selection and scaling of earthquake ground motions for use in engineering analyses and equipment qualification testing is critical for proper implementation of the results of this research.

Ground offsets caused by fault surface rupture can cause collapse of bridges or rupture of pipelines. This behavior has been demonstrated repeatedly in recent earthquakes in Turkey and Taiwan. The fault surface rupture estimation tool developed in this project will be useful for both the design of specific utility projects that cross faults, and will also serve to supplement planning information now provided by Alquist-Priolo maps.

Topic 2: Site Response

Objective

Geotechnical site effects are a period-dependent amplification, or de-amplification, of earthquake motions caused by near surface sediments (including soft rock and man-made fill). These effects depend on the stiffness and damping of the sediments, which in turn are a non-linear function of the amplitude of the motions. The non-linearity in site-effects is associated with the inelastic material behavior of the sediments, which become less stiff and more energy absorbing with increasing levels of strain.

The main obstacle to improving site response models has been a lack of accurate data on the soil properties at locations that have recordings of strong ground motion. Basic parameters such as the shear-wave velocity at the site were not available for the majority of stations. A central objective of the research is to collect soil characteristics at strong motion record sites to allow accurate classification of sites for use in the development of the ground motion models discussed in Topic 1.

Apart from the characterization of strong motion sites, tremendous amounts of geotechnical exploratory data have been, and continue to be generated for characterization of subsurface conditions and materials for engineering projects. For example, data sets for the Los Angeles region used by the California Geological Survey (CGS) for seismic hazard mapping exceed 12,500 borings. Hundreds of new borings generated statewide each year by Caltrans alone. These data sets have tremendous untapped potential for project designers and other geotechnical professionals, especially for early site reconnaissance phases of project development. A second objective under this topic is to develop a geotechnical data base for archiving subsurface conditions that is readily accessible to geotechnical engineers.

Information from nearby borings can be used to establish general subsurface conditions and identify problematic strata that could affect a new project site. Having this information before hand can help tailor a drilling program to assure good coverage of problematic zones or layers, and improved site characterization with reduced drilling costs.

Outcome

<u>Characterization of Strong Motion Recording sites.</u>

Because of the high cost of site characterization, initiatives in this area have sought to leverage related activities through partnerships and other opportunities as they arise. Examples include co-funding with National Science Foundation projects for sites that recorded the 1999 M 7.4 Koçaeli and M 7.1 Duzce earthquakes in Turkey

and with the National Center for research in Earthquake Engineering in Taiwan for sites that recorded the 1999 M 7.6 Chi-Chi earthquake.

In all, shear-wave velocities were measured at 330 locations. For sites that were not characterized, correlation models were developed to estimate the shear-wave velocity based on the surface geology. The key result of this work is that shear-wave velocities were either measured or estimated for all but six sites in the NGA data base. This marks the first time that accurate shear-wave velocities have been compiled for a strong motion data base.

Virtual Geotechnical Data Center

Currently access is the primary impediment to full utilization of the subsurface data. In addition, there are differing methods, both electronic and paper, for archiving data as well as institutional barriers that restrict sharing and dissemination of data. The outcome of this project is the Pilot Virtual Data Center, capable of serving subsurface data from CGS, USGS, Caltrans, and PG&E that was developed and implemented with co-funding from for a user-workshop from the Federal Highway Administration (FHWA). It is planned that the Virtual Data center will be operated by COSMOS.

Summary

The research in the site response topic provided the basic data that allows the NGA program to accurately characterize site effects on strong ground motions. It is a critical part of the ground motion data base that allows the ground motion models developed in the NGA program to use a site classification scheme that is consistent with the California Building code. The Pilot Geotechnical data base provides a standard method for archiving subsurface information from multiple institutions. The Virtual data center provides ready access to existing subsurface information from multiple institutions. The availability of this data will improve site characterization for projects and may reduce the number of borings that need to be drilled in the future, potentially saving several thousands to tens of thousands of dollars per boring.

Topic 3: Permanent Ground Deformation

Objective

In addition to strong ground shaking, earthquakes can also produce several different types of permanent ground deformations, or 'ground failure' that can impose additional loads on nearby built facilities. Ground failure mechanisms include fault surface rupture, liquefaction, and earthquake induced landslides. Fault surface rupture can result in large relative displacement of the ground surface across the fault. These displacements are largely a function of magnitude and can be as large as 5 to 10 meters across the fault. Liquefaction is the phenomena whereby saturated sediments soften due to pore pressure build up caused by shaking-induced strains. Foundation bearing in liquefied soils will experience a dramatic loss of capacity. Liquefied ground can also displace laterally large distances on very gentle slopes, a phenomenon known as 'lateral spread'. This lateral ground movement can produce extensive damage to underground as well as above ground utility structures.

The objective of research projects in this topic are to develop probabilistic based models for ground deformation due to liquefaction and fault rupture. Ground deformation due to landslides was not included in this phase of the research.

While models for ground deformation due to liquefaction have been available previously, they were not well constrained and did not have a sound probabilistic basis. There are two parts to the ground deformation due to liquefaction: the onset of liquefaction and the amount of deformation that occurs if there is liquefaction. The objective of the new research was to develop probabilistically based models for both the triggering of liquefaction and amplitude of the resulting ground deformation.

Previous models of fault rupture hazard have been based on global models that cannot be reliably applied to site-specific applications. Therefore, a second objective under this topic was to develop models for fault rupture hazard that could be applied to site-specific applications.

Outcome

<u>Liquefaction Triggering</u>

Liquefaction triggering assessment is the process of determining whether liquefaction is likely to occur at a particular site. A major achievement of the program has been the significant extension of the number of high-quality liquefaction case histories. The newly expanded database of case histories, plus new knowledge gained from fundamental research have made it possible to develop improved design tools for assessment of liquefaction triggering

Using the expanded data base, probabilistically based models for the onset of liquefaction were developed. This model represents a significant revision to the existing models. A key difference from previous models based on SPT blow counts is that the new model uses CPT which is the currently the preferred method of site characterization. The probabilistic nature of the models allows for liquefaction hazard to be incorporated into electric system risk calculations in a fully probabilistic manner.

<u>Ground Deformation</u>

The evaluation of the amplitude of the ground deformation given that liquefaction has occurred was based on empirical data. As part of this work, the empirical database of seismic ground motions has been greatly expanded, especially for smaller displacements. While still sparse, the data base developed in this project is a significant improvement over past data bases. New analysis tools have been developed to better model the probability of ground failures as a function of geologic and geotechnical data, and the level of strong ground shaking. The resulting ground deformation models have been used to develop regional liquefaction deformation hazard maps and can be used to estimate the loading on underground utility structures.

Summary

Liquefaction induced ground deformation is an important component of seismic hazard. The new models for onset of liquefaction and for the amount of deformation have greatly improved the accuracy at which this hazard can be evaluated.

Topic 4: Seismic Performance of Substation Equipment

Objective

The vulnerability of high-voltage substation equipment, including transformers and their components, circuit breakers, and switches has been the primary reason that power grids have failed in past earthquakes. The objectives of projects carried out under this Topic area were to improve the understanding of the response, vulnerability, and performance of various types of substation equipment and their components, develop methods for assessing the behavior of interconnected substation equipment, improve methods of seismic qualification, and to identify specific actions that can be taken to reduce significant vulnerabilities.

These results provided both immediate 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 have lead to improved industry standards, designs and procedures for substation equipment purchase and installation, directly providing increased safety and reduced outage times for the electric grid following earthquakes, benefiting both customers and optimizing equipment expenditures by utility.

Outcome

Analytic and Experimental Studies of Interconnected Equipment

This series of projects focused on a] experimentally investigating the interaction between components of substation equipment connected by re-designed (or improved) rigid bus connectors through quasi-static and shake table testing, and b] developing analytical models and methods for assessing the seismic response of electrical substation equipment connected by assemblies of rigid and flexible bus (RB, FB), flexible strap connectors (FSC) or slider connectors (SC). The purpose was to generate data that would provide guidance in the design of conductor assemblies with the improved connectors. The project resulted in mechanical models and dynamic analysis methods of equipment items connected by FB, RB-FSC or RB-SC. The model and analysis approach allow accurate prediction of the behavior of connected equipment items by properly accounting for the nonlinear behavior of the connectors and the interaction effect between equipment items. This study also introduced a new S-shaped FSC, called *S*-FSC, which has enhanced flexibility and is highly effective in reducing the adverse effect of dynamic interaction between the connected equipment items. Through extensive parametric investigations, simple design guidelines are suggested for reducing the hazardous effect of the seismic interaction in practice.

Seismic Qualification Requirements for Transformer Bushings

This research task investigates the factors that most greatly influence the dynamic response of high voltage bushings as well as attempts to quantify the ground motion amplification for various high voltage transformers. Numerical models of four different high voltage transformers were developed and used for modal and dynamic time-history analyses. In addition, system identification and seismic shake table tests were performed on a full-scale 525 kV transformer-mock bushing system. A numerical model of the test configuration was created to predict the seismic test results through dynamic time-history analyses.

Input Motions for Earthquake Simulator Testing

The main objective of the study was to develop a set of earthquake ground strong motion time histories suitable for seismic qualification testing of electrical substation equipment in accordance with the IEEE 693-1997 standard. Although the study's objective deals with shake table testing of a particular class of equipment, many of the issues investigated are equally relevant to the dynamic testing of other types of equipment and components. This study was motivated by a desire to introduce a standard set of input motions in three orthogonal directions, and thus achieve more consistency in earthquake simulator testing. The project is focused on developing an input strong motion based on a record of actual earthquake with a time-domain spectral matching procedure, so the spectrum-compatible strong motion time history would preserve the non-stationary behavior of the real record.

Seismic Qualification/ Fragility Tests of 500kV Disconnect Switches

This project is an example of common interest, collaborative testing that involved utilities, switch, structure, insulator manufacturers, and PEER personnel. Shake table testing at PEER facilities documented that 500 kV disconnect switches had acceptable performance (even though not fully qualified to IEEE 693-1997). Test results identified issues and pitfalls related to testing without support structure and resulted in improvement to Performance Level test requirements in next revision of IEEE 693. The performance of 500 kV insulators also highlighted need for better definition of "ultimate strength" of porcelain insulators. New standard porcelain insulators with the same strength, but lighter and cheaper than the old standard were identified. These design improvements were immediately implemented in the Path 15 transmission projects. Long term estimated avoided loss for future earthquakes is estimated to be $500,000/ yr for 3 California utilities.

Database of Seismic Parameters of Equipment in Substations

Electrical substations consist of many pieces of equipment that are vulnerable to earthquakes. Vulnerability depends on a variety of parameters including equipment type, voltage, manufacturer, seismic design criteria, installation and anchorage, foundations and soil conditions, and connection to other equipment. In order to be able to make accurate and standardized estimates of potential losses in earthquakes and to set priorities for equipment upgrades and replacements, an accurate database of the relevant seismic-performance parameters of substation equipment is needed. In this project, a comprehensive procedure for compiling seismic performance parameters of critical electrical components was developed and documented. The experience gained in assessing seismic vulnerability of substation equipment in previous PEER Lifelines Program research was incorporated. Development of a comprehensive procedure for compiling seismic performance data of electric substation equipment that is tied to a network-based earthquake loss estimation methodology will enable accurate and standardized estimates of potential losses to electrical systems in earthquakes and set priorities for equipment upgrades and replacements.

Summary

Interconnected equipment projects have resulted in an improved understanding of the fundamental behavior of interconnected equipment, and the behavior of various types of connector elements for rigid and flexible buses.

Dynamic tests of various types of substation equipment have yielded valuable qualification/ fragility data, and helped to improve current equipment qualification standards.

The objective of projects on development of input motions for testing (Task 408), and transformer bushing qualification (Task 406) was to provide inputs and improvements to the IEEE 693 standard. Results of these projects are expected to be implemented in the next revision of the standard, or will provide data that will support on-going work in these topics.

Topic 5: Electric System Building Vulnerability

Objective

Many substation buildings and service buildings are older, and their calculated seismic capacities do not meet current earthquake performance requirements for life safety and functionality. However, these types of buildings have performed reasonably well in past earthquakes. New data and models have been developed by PEER researchers to better assess the expected earthquake performance of these structures and enable better decision making by utilities regarding seismic retrofits and other mitigations for these buildings, if any are needed.

Outcome

<u>Rigid Wall/Flexible Diaphragm Buildings</u>

The goals of this research are to develop improved practical analysis procedures for evaluating the seismic performance of low rise buildings with rigid walls and flexible diaphragms and to use these procedures to evaluate current seismic design provisions. Representative of this type of building system are one story buildings with concrete tilt-up walls and low rise buildings with reinforced masonry walls.

<u>Methods to Estimate Displacements of Structures</u>

Dynamic inelastic time-history analyses of single-degree-of-freedom bilinear oscillators were undertaken to determine the ability of the Coefficient Method (CM) and the Capacity Spectrum Method (CSM) to predict the total displacement demands of structures. The CSM non-conservatively estimated median peak inelastic demands over most of the period range from 0-3 seconds. For some periods, the CSM estimated displacements that were only 60% of the actual median displacements. The CM method conservatively estimated peak inelastic demands over most of the period range of 0-3 seconds. For some periods, the CM estimated displacements more than 30% greater than the actual median displacements. For short period structures with fundamental periods less than 0.8 seconds, directivity effects from near-field shaking did not increase the displacement demands above that found for far field shaking.

<u>Mill Building</u>

A mill type substation was assessed using FEMA 356 guidelines. It was demonstrated that in all cases for the building, the recommended FEMA 356 design forces for the wall anchorage design were always conservative. It was shown that the distribution of the anchorage forces along the length of the wall is not uniform and decrease significantly as it moves away from the center of the wall. A revised design equation was developed for design of out-of-plane forces,

which included parameters for wall anchor location, wall out-of-plane stiffness, and attaching diaphragm stiffness.

Advanced Seismic Assessment Guidelines

This methodology provides a comprehensive tool for assessing key utility type buildings using non-linear dynamic analysis to determine if life safety and functionality performance objectives are obtained. These guidelines have been pilot tested on a mill-type building, and on a three- and an eight-story steel moment frame building. The methodology produces building specific fragility curves indicating the probability of a limit state (i.e., red, yellow, or green tagging) will be reached or exceeded as a function of the severity of the future ground motion at the site and provides a powerful decision analysis tool to assess mitigation needs. Building specific fragility curves reduce uncertainty and increase confidence in developing emergency planning and emergency response strategies, as well as electric system network modeling.

Application of the Advanced Seismic Assessment Guidelines

This project assessed three buildings using the Guidelines: 1) A 3-story steel moment frame building; 2) a concrete tilt-up building; and 3) a steel frame, concrete shear wall (mill type) building. Results provide building specific fragility curves indicating confidence of achieving a red, yellow, or green (building inspection) tag based on the damaged buildings' capacity to resist collapse in an aftershock.

Summary

The results of the Building Vulnerability Studies have resulted in improved state-of-the practice of performance-based earthquake engineering so that decisions can be better made regarding the need to seismically upgrade existing buildings. This was accomplished by improving the understanding of the effects of near-source ground motions on the seismic response of buildings and by developing an improved understanding of roles of various types of assessment methodologies. Research topics focused on: 1) developing new and evaluating existing assessment methodologies (i.e. performance prediction tools); 2) defining acceptable levels of damage to meet electric system operating goals (i.e. structural component testing); and 3) developing loss estimation tools to allow prediction of system impacts from earthquake effects (i.e. fragility curves).

Topic 6: Network System Seismic Risk

Objective

Electric utilities need to evaluate the likely functionality of customer services following earthquakes. A flexible and powerful tool to use for this analysis is a system seismic risk model, in which individual earthquake scenarios can be analyzed to probabilistically describe the post-earthquake operational state of the electric transmission and distribution system. System risk models integrate information about hazards and building/equipment fragility to estimate damage and functionality. This capability can be used to evaluate alternative earthquake mitigations, and to evaluate the current state of earthquake preparedness of the utility system from customers and regulators perspective.

Outcome

Scoping Study for Unified Lifeline Risk/Reliability Models

The objective of this project was to develop a program plan for a future PEER research program that will initially develop and demonstrate a modular, technically sound, and practical unified risk/reliability platform to: (a) evaluate seismic risks to as-built lifeline systems with no seismic improvements; (b) evaluate seismic risks to modified lifeline systems with physical and/or operational seismic improvements now included; and (c) provide results from the evaluations that can guide decision makers as they assess and then select seismic improvement strategies that limit risks to their system to acceptable levels. This initial research program will focus on the need for unification and commonalities of modeling methods for electric power and highway transportation systems. During future PEER research, this can be extended to other lifelines as well.

The research defined by this program plan will lead to a unified seismic risk/reliability platform that will: (a) be initially developed as separate but parallel packages for electric power and highway transportation systems (using procedures/models from current practice and research) during the first two years of this program; (b) be further developed into a more sophisticated platform (with improved procedures and models from new research) during the remaining years of this program; (c) focus on system performance rather than merely component performance; (d) be developed not as a decision-making tool, but instead as a decision-guidance toll that provides useful results for lifeline-system decision makers (e) accommodate a wide range of decision-making approaches and contexts; and (f) be applied in a demonstration application to an actual electric-power and highway-transportation system in California.

Earthquake Risk-Decision Making in Lifeline Organizations

In areas with earthquake potential, preparing for and responding to earthquakes is a significant responsibility of lifeline organizations. The decisions made by these organizations about how to manage and mitigate the risk of earthquakes are vital to both the organizations and the communities they serve. The overall purpose of PEER Lifelines research is to improve the understanding of how lifeline organizations make decisions about earthquake risk, identify critical issues and areas for potential improvement, and transfer general recommendations about decision-making to a broad range of lifeline organizations. This report describes the initial pilot phase of the research. The purpose of the pilot effort is to test data collection and analysis methods and to provide the participating organizations, the Pacific Gas & Electric Company (PG&E) and California Department of Transportation (Caltrans), with preliminary analysis on earthquake risk decision-making in their organizations.

This pilot study is primarily descriptive. It is an attempt to better describe and characterize earthquake risk mitigation decisions. It focuses on earthquake risk mitigation decisions in the lifeline organizations that are leaders in this area, and on the methods for studying these decisions. The pilot study is intended to identify key research issues and develop and assess the research methods to provide the basis for designing and conducting subsequent phases of research not to come to final conclusions.

Validation of Probabilistic Seismic Hazard Computer Codes

Probabilistic seismic hazard analysis (PSHA) is a methodology for establishing design ground-motion hazard level that is an alternative to the deterministic, or scenario-based, methodology. Advantages of PSHA include that it provides a consistent framework to incorporate contributions to hazard arising from multiple earthquake sources, poorly defined sources, and from a variety of uncertainties in hazard estimation ranging from variability in attenuation relationships to the likelihood of occurrence of a particular earthquake magnitude. Both national and California earthquake hazard maps used for building codes are based on PSHA. PSHA is also used to evaluate site-specific hazard for critical facilities such as power plants and dams, and is also used widely for risk analyses and loss estimation.

PSHA is a relatively sophisticated analysis, and a number of computer codes have been developed by a variety of organizations to implement the analysis. Design experience has shown that results of PSHA can vary widely depending upon both the analyst and the code employed. Differences in results can be attributed to input errors, numerical coding errors, errors in coding related to misinterpretation of component models, and differing approaches used for computational details (e.g. how to treat the distribution of uniform slip near fault edges, handling curved faults, etc.). The overall research goal for this project was to improve the consistency and transparency of results by assuring that computer codes are numerically correct, that consensus is established among code developers regarding the most appropriate implementation of component models and computational details, and that clear guidelines are available regarding proper usage and limitations of codes.

Summary

The objective of the scoping study for lifeline risk/reliability models is to develop a program plan for a future PEER research program that will initially develop and demonstrate a modular, technically sound, and practical unified risk/reliability platform to: (a) evaluate seismic risks to as-built lifeline systems with no seismic improvements; (b) evaluate seismic risks to modified lifeline systems with physical and/or operational seismic improvements now included; and (c) provide results from the evaluations that can guide decision makers as they assess and then select seismic improvement strategies that limit risks to their system to acceptable levels.

The overall purpose of the Decision-Making in Lifelines Organization project is to improve the understanding of how lifeline organizations make decisions about earthquake risk, identify critical issues and areas for potential improvement, and transfer general recommendations about decision-making to a broad range of lifeline organizations

The overall research goal for the validation of probabilistic seismic codes is to improve the consistency and transparency of results by assuring that computer codes are numerically correct, that consensus is established among code developers regarding the most appropriate implementation of component models and computational details, and that clear guidelines are available regarding proper usage and limitations of codes.

Topic 7: Emergency Response

Objective

Effective emergency response depends on obtaining accurate and rapid information about earthquake caused damage and system disruption. Strong motion and other data can be used to make rapid estimates of damage prior to getting input from experienced field operations personnel. Critical infrastructure and lifeline components are many times located in remote areas that are sparsely instrumented.

Outcome

Rapid Ground Motion Estimates

Developments in ground motion modeling capability are providing benefits to the emergency response community. PEER sponsored research on integrating finite fault and near field effects into the ShakeMap software developed by the U.S. Geological Survey provides improved estimates of near-field ground shaking immediately after an earthquake in areas that are currently only sparsely instrumented

Summary

This methodology was successfully applied as part of the California Integrated Seismic Network (CISN) response to the December 22, 2003 San Simeon earthquake. The earthquake occurred in a sparsely instrumented portion of central California coast, modeling in conjunction with available records improved description of ground shaking intensity and areas of potential damage (Hardebeck et al., 2004, Preliminary Report on the 22 December 2003 M 6.5 San Simeon California Earthquake, *Seismological Research Letters*, **75**, 155-172.)

Conclusions and Recommendations

Conclusions

The goal of this applied research program is 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 research results would directly address utility needs in preparing for future earthquake occurrences, and that the results could be quickly implemented by utility personnel or their consultants.

The 101 projects have provided useful results that meet utility needs in the seven 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 a narrative form, the cumulative connections between the topics that address this goal. [Ref to Figure 1]

- Topic 1 results (earthquake ground motions) are used as input to Topic 2 (site response) and Topic 3 (permanent ground deformation) studies.
- Topic 1 results are used as input to assess the vulnerability of substation components and interconnected equipment, as well as equipment qualification testing (Topic 4).

Severe ground shaking and ground failure are the direct causes of substation damage that can disrupt power transmission to customers.

- Topic 1, 2, and 3 results improve the assessment of building damage (Topic 5) before earthquakes occur to help identify appropriate mitigation and risk management strategies, and immediately following an earthquake (with Topic 7) to aid in emergency response and recovery activities.
- System earthquake risk models (Topic 6) integrate information about hazards (Topics 1, 2, and 3) and building/equipment fragility (Topics 4 and 5) to estimate damage and functionality of the electric transmission and distribution system.

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, changes in the procurement procedures and requirements for new equipment, upgrading old 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, vulnerabilities related to aging infrastructure, and unknown or unexpected response of equipment. However, 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

Significant progress has been made in achieving the ultimate goal of the project, to improve electric system safety and reliability in earthquakes. 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 this report was prepared, some of the results were being implemented in managing the equipment inventory at several utilities and in modifications of the national seismic qualification procedures for substation equipment (IEEE-693).

Ratepayers (who have funded this research) and other members of society are already benefiting from the research conducted by PEER Lifelines program through 1] improved life safety, 2] receiving more rapid restoration of service following an earthquake due to less utility damage and improved emergency response capability, 3] avoiding possible utility rate increases because there is less damage to equipment and facilities, and 4] experiencing more rapid overall recovery of societal functioning following an earthquake due to rapid power restoration and use of the research results by other organizations to recover their functionality more quickly.

Progress towards achieving these goals can also be measured in terms of avoided costs and losses. One example of an **avoided cost** or cost savings is the reduced 'up front' costs for the purchase of new equipment.

- Qualification testing of 230 kV disconnect switches demonstrated that a stiff, low profile support structure is effective in achieving good performance of 230 kV switches with minor modifications. Cost savings of approximately ~$250,000 per year are achieved at PG&E, for example, by not having to purchase more expensive disconnect switches (at a 30-50% premium) that were shake table tested using an ultra-conservative Los Angeles Department of Water and Power (LADWP) testing protocol.
- Seismic qualification testing of 500 kV disconnect switches identified a new standard porcelain insulator with the same strength, but lighter and cheaper than old standard. Replacement with newer insulators is estimated to result in a cost savings of ~ $40,000 per year for the three California utilities.
- Not having to retrofit specific buildings (or building types) that have been shown to have greater capacity to resist earthquake ground motions than previously recognized is another example of cost avoidance. Estimated savings for mill-type and rigid wall/flexible diaphragm buildings are ~$500,000 and $100,000 per building, respectively.

Avoided losses include reduced earthquake related utility damage and reduced outage times for customers.

- Shake table qualification testing of 500 kV bushings resulted in improved knowledge about the ruggedness of porcelain bushings in this voltage class. These results led PG&E to specify 500 kV composite transformer bushings in lieu of porcelain for all future bushing replacements. Replacement of vulnerable 500 kV porcelain bushings with composite bushings will significantly reduce the number of bushings that have to be replaced after an earthquake – resulting in a savings in repair time, outage time, and replacement costs (~$45,000 per bushing) following the next major earthquake. Through 2004, approximately 40 per cent of these vulnerable porcelain bushings have been replaced as part of the PG&E risk management program, resulting in total loss avoidance of ~$1 million, to date. Composite bushings also provide additional savings from reduced maintenance costs for cleaning bushings in high pollution areas, while providing improved safety compared to center-clamped porcelain bushings.

In addition to these examples of economic loss avoidance by utilities, far greater loss avoidance in achieved by minimizing customer business interruption due to delays in the restoration of service. The value of electricity (in kWh) is much greater, up to 250 times, when a business cannot produce their product due to a lack of electricity (Roger Grey, personal communication, 2002).

The research program provides several additional benefits to utilities and 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, both nationally and internationally. 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 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 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 programs future work or to perform separately funded but closely coordinated studies that fit together nearly seamlessly. The California Department of Transportation (Caltrans) and the Federal Emergency Management Agency (FEMA) are examples of two such partners. It is likely that a number of others will participate during the next several years.

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. Clear directions for further applied research were identified by the PEER Lifelines Advisory Panel, and provide the basis for planning the next phase of work. They include the following major research areas for high-priority research that extends the progress of Phase III work to capture immediate benefits.

1) Continue the Next Generation Attenuation project (Topic 1) to include vertical motions and numerical modeling of near-fault, large-earthquake motions that lack extensive empirical recordings. Extend these results into practice through the Design Ground Motion Library, which is a very important and practical product for the engineering design community.

2) Continue efforts to implement the Virtual Geotechnical Data Center (Topic 2) with the current and new partners. This is a highly leveraged activity that has large, long-term economic benefits to California utilities and many others.

3) Continue to develop regional-scale liquefaction and landslide deformation hazard maps (Topic 3). This development directly addresses a significant gap in design practice for lifelines systems.

4) Continue to carry out equipment testing and analysis to improve fragility (vulnerability) models and the IEEE-693 performance specifications (Topic 4). These activities in past phases of the Program have produced dramatic cost savings and improvements in the seismic performance of new equipment. Specific project activities include further studies of porcelain and composite insulators, pilot studies on the use of base isolation and dampers for substation equipment, and the seismic design guidelines for transformer appendages.

5) Continue efforts to create user-friendly design procedures and practices related to seismic qualification and evaluation. Specific needs are for interaction of equipment and component qualification procedures (Topic 4). Additional topics include the development of guidelines for simplifying the qualification test procedure for equipment mounted on support structures, and test protocols for the shake table testing of transformer bushings

6) Continue to improve performance assessment procedures for the typical stock of common utility buildings (Topic 5). Specific project activities include expansion of the seismic assessment guidelines developed in Phase III to allow assessment of generic classes of common utility building types and dynamic testing of utility building components.

7) Continue to improve electric utility procedures and practices to collect rapid post-earthquake damage information and perform rapid damage assessment (Topic 7).

The scopes of future research projects need 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, based on results of a network model based sensitivity analysis. This analysis is recommended to 1] identify the primary causes of power network damage and operational disruption given current level of information regarding hazards to and vulnerabilities of the system, and 2] identify the greatest uncertainties in the analysis and develop focused research to address and reduce those uncertainties. This type of analysis will allow the development of a comprehensive research task plan that will address the improved earthquake performance of electric power systems in California.

An addition, an increased emphasis is needed on research information and technology transfer for widespread application by the electric utilities of the State and by other utility and transportation organizations in the State and the Nation. These needs can be addressed through the development of Applications Guides to transfer research results into the practice of the electric power industry, and professional training through topical seminars for utility personnel, utility consultations and other professionals. The publication of derivative professional papers on the use of Application guides and the continued development of the PEER Internet site will also help facilitate access to information generated by the PEER Lifelines Program.

It is also recommended that the next phase of the program continue to provide for and optimize the involvement of multiple co-funding organizations, particularly Caltrans. The JMC member organizations (PG&E-PEER-Commission) should identify prospective additional partners and

enlist their participation. Such efforts will enable significant leveraging of available funding and make possible rapid gains in knowledge and applications to significantly reduce earthquake risk to utilities and transportation systems in California.

1.0 Introduction

1.1. Purpose of Research

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 California Energy Commission's Five Year Transmission Research and Development Plan (CEC 500-03-104F) recognizes that growth of the California electric transmission system has not kept pace with demand over the last 20 years – threatening the integrity of the system and the health of the California economy. The consequences of limited generation and transmission capacity under 'normal' or 'ordinary' operating conditions have included congestion, reliability problems and higher costs related to insufficient transmission infrastructure. The August 2003 Northeast power outage, which affected 5 states and approximately 50 million people, and resulted in an estimated $4-10 billion in business interruption losses (Electricity Consumers Resource Council, 2004) provided a dramatic 'wake-up call' concerning the vulnerability of electric systems and the resultant regional and national consequences.

In addition to these challenges, California faces 'extraordinary' demands on the electric system from extreme natural hazard events. The greatest single natural hazards threat to electric system reliability in California is the occurrence of a major urban earthquake. The 1989 and 1994 earthquakes in California are a warning of the potential for even larger and more severe earthquakes to affect the state. Within the San Francisco Bay area, the US Geological Survey has stated a 62% chance of a large $M \geq 6.7$ earthquake in the next 30 years (USGS, 2003). In southern California, the probability for a large $M>7$ earthquake in the next 30 years is estimated to be 85% (SCEC, 2001). 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. Given the inevitability of another significant California earthquake during the next few decades, evaluating and improving the post-earthquake functioning of electric power service is an important priority both for the providers of that service and for their customers.

This report describes the results of an applied research program to systematically reduce earthquake risks to electric power in California that has been conducted by the Pacific Earthquake Engineering Research (PEER) Lifelines program, under the direction of Pacific Gas and Electric Company (PG&E) through the support of the California Energy Commission (Commission).

This project directly addresses the Commission's Public Interest Energy Research (PIER) goal to develop technologies and protocols to mitigate the vulnerability of electric components and systems to damage directly and indirectly caused by earthquakes by providing necessary data, models, and methods needed to reduce the earthquake vulnerability and to improve the earthquake 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 effects in California and elsewhere.

In typical academic-based research, there is a time interval of as long as 10 to 20 years between the start of 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 the accelerated schedule for getting the research into use, a framework has been developed to organize the types of research. This framework, as illustrated in Figure 1, also enables the integration and transfer of research results from one Topic area to another. We developed three classifications for the research conducted under this program: data, models, and methods.

- Research projects classified as **data** produce 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 described below. Two examples of data projects are the Design Ground Motion Library (1F01) and the Virtual Geotechnical Data Center (2L02).
- Research projects classified as **models** produce simplified descriptions of data. Models can either be parametric descriptions of data (such as equations) or maps. Examples include the Next Generation Attenuation model (1L01) and analytical models describe equipment interactions for rigid and flexible bus (401 and 403).
- Research project 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 computer programs for performing probabilistic seismic hazard assessment (PSHA) (607) and other ground motion simulation procedures (1A01 and 1C02).

1.2. Background

1.2.1. Program History and Management

Since 1997, three funding cycles of the PEER Lifelines Program have taken place. The first, or Phase I, began in 1997 when 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 system's safety and reliability, 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, scientists, and their students in the research program. PEER is a consortium of 9 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 Founding Partner in the Utility Component of the PEER Business and Industry Partnership helped secure National Science Foundation funding for PEER. PG&E's support and involvement in PEER helped to focus the research of California utility infrastructure, important because of the life-safety issues and economic consequences that significant seismic events cause to this infrastructure. The initial budget was $2,400,000. 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.

In the second phase, PG&E funding was augmented by a one-year contract with the California Energy Commission (Commission) through their Public Interest Energy Research (PIER) Program. The PIER Program was established as part of the implementation of Legislative Act AB 1890, and coincided with the termination of most investor-owned utility ratepayer funded research and development (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 provided $1,000,000 to fund the continuation of the earthquake studies under the PIER Transition Research Program during the period 1998-2000.

The Commission PIER Program provided $4,600,000 for Phase III of the PEER Lifelines Program to address an expanded scope of work that was identified during Phase II. This work was carried out over a period of three years plus a one-year extension (2000-2004). Additional funding from the Caltrans Program of Earthquake Applied Research for Lifelines (PEARL) provided the opportunity to leverage funding from both organizations to conduct common interest lifelines research during Phase III.

The total PEER Lifelines program budget during the Phase III period 2000-2004 is $10,175,000 of which $4,600,000 is from the Commission, $4,500,000 from Caltrans, $900,000 from PG&E, and $175,000 from the Federal Emergency Management Agency (FEMA) (see Figure 2). The ability to leverage common interest funding enabled 101 individual research projects to be carried out during this phase of the PEER Lifelines program, 49 of which were funded with PG&E/Commission support. As seen in Figure 3, these 49 PG&E/Commission projects represent a 50-50 spit in research emphasis. Research in substation equipment, electric systems buildings, and emergency response (Topics 4, 5, and 7) was funded solely by PG&E/Commission. Research on site effects and network system seismic risk (Topics 2 and 6) was funded through PG&E, Caltrans, and FEMA support. Research in earthquake ground motion and permanent ground deformation (Topics 1 and 3) was jointed funded by both PG&E/Commission and Caltrans. The recognition that improved earthquake ground motion data, models, and methods were required for more robust lifelines engineering research defined many of the common interest research goals of these organizations. Figure 3 also shows the overall percentage and actual dollar amount of PG&E/Commission funds expended in each Topic area.

Table 1 lists all 101 projects by topic area and provides the Principal Investigator, the institution and the title of each project. Commission funded projects are highlighted in boldface. More complete descriptions of the projects and their results are presented in Section 2 – Research Results. Overall, 89% of PG&E/Commission funds were used to support lifelines research with the remaining 11% for technical and project management expenses at PG&E and PEER (see Figure 4). The next sections describe the PEER Lifelines Program management process in more detail.

1.2.2. Joint Management Committee

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, PG&E and Caltrans 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 PG&E/PEER research activities and complimentary 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 (CRADA). A representative from the California Department of Transportation joined the JMC during the course of the program to provide input and coordination with their ongoing Program of Earthquake Applied Research for Lifelines (PEARL).

1.2.3. PEER Lifelines Advisory Panel

In the spring of 2003, the Joint Management Committee formed the PEER Lifelines Advisory Panel on Electric System Seismic Safety and Reliability to perform a comprehensive review of the status of the PEER Lifelines Program research results and to provide recommendations for the future of the Program. The objective in the formation of the Advisory Panel was to establish a group that is well qualified to provide comprehensive and representative review and recommendations regarding the importance and usefulness of the applied research being conducted by the PEER Lifelines program to the electric power industry and its customers and regulators in California. The Joint Management Committee decided to ask members of the Inter-Utility Seismic Working Group (IUSWG) to serve on the Panel.

The IUSWG was formed in 1990 as an ad hoc organization of earthquake experts in the major California gas and electric utilities, and met as needed to address technical earthquake problems and issues facing the California utilities. Other utility organizations outside of California participated at times, including Bonneville Power Authority and BC Hydro. Some of the IUSWG technical issues evolved to be handled by the IEEE-693 Working Group, which continues to establish seismic guidance for substation equipment. The Seismic Safety Commission encouraged the involvement of the IUSWG at several points in addressing utility

aspects of the Commission's five-year plans. The IUSWG was also identified as a useful source of advice for the PEER Lifelines Program in Phases I and II, and individuals involved in the Working Group have participated, both formally and informally, in providing advice on research needs and individual research projects since the inception of the Lifelines Program.

The PEER Lifelines Advisory Panel is composed of individuals who have participated in the IUSWG, along with additional individuals who are current and appropriate technical experts in electric power and earthquake engineering and science. The members are predominantly from the large California electric power utilities. The members of the Panel are listed in Table 2. The Panel chairman, Woody Savage, served as chair of the IUSWG for a number of years.

The Joint Management Committee provided the following four charges to the Advisory Panel:

1. Review current PEER Lifelines research activities and projects in order to evaluate and comment on the applicability of this research towards helping achieve the goals of improved electric component and network performance and public safety
2. Recommend new directions or topics for research for the next phase of the PEER Lifelines program, including recommendations for either increasing or decreasing emphasis on specific topic areas
3. Comment on the sharing and distribution of information and research results from the PEER Lifelines program with California electric utilities and related organizations
4. Provide comments and recommendations on the coordination and leveraging of PEER research with other research programs, either currently being conducted or planned, by California electric utilities

To carry out this charge, the Advisory Panel held two meetings. The first meeting on June 16 and 17, 2003, was held in conjunction with a research coordination meeting for Topic 4, Substation Equipment, at the PEER Center offices in Richmond, CA. The second and final meeting was held on April 1 and 2, 2004, also at the PEER Center. Substantial discussions among the Panelists were conducted at the two meetings, and e-mail exchanges and conference calls were used to review draft reports. The Final Report (see Appendix I) incorporates the results of both meetings and provides detailed responses to the charges listed above. Recommendations for topics of research in the next phase of the PEER Lifelines program and for the distribution of information and research results from the Lifelines program with California utilities are discussed further in Section 3.3.

1.2.4. Research Topics

The research needs identified by PG&E consisted of a set of topics that addressed the broad 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. The topics from the Phase II PG&E/PEER research were reviewed and the following were chosen as a focus for the next phase of work (Phase III)

- Topic 1: Earthquake Ground Motion
- Topic 2: Site Effects
- Topic 3: Permanent Ground Deformation

- Topic 4: Seismic Performance of Substation Equipment
- Topic 5: Electric System Building Vulnerability
- Topic 6: Network System Seismic Risk
- Topic 7: Emergency Response

1.2.5. Project Selection

The JMC prepared and issued Requests for Proposals (RFP) that addressed these seven topics and described in detail the desired research. Responses to these RFPs resulted in a total requested amount that was greater than the available funding. The JMC had to both evaluate and rate the proposals and then prioritize the projects that would be funded. This process resulted in the selection of 108 projects. The project titles, Principal Investigators and their institutions, and expenditures for these projects are listed in Table 1.

Section 2 of this report summarizes the need, project description, results, and applications of the Phase III research projects and investigations. 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 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 II contains the complete final reports for each project on a Digital Video Disk (DVD) in Adobe Acrobat PDF format.

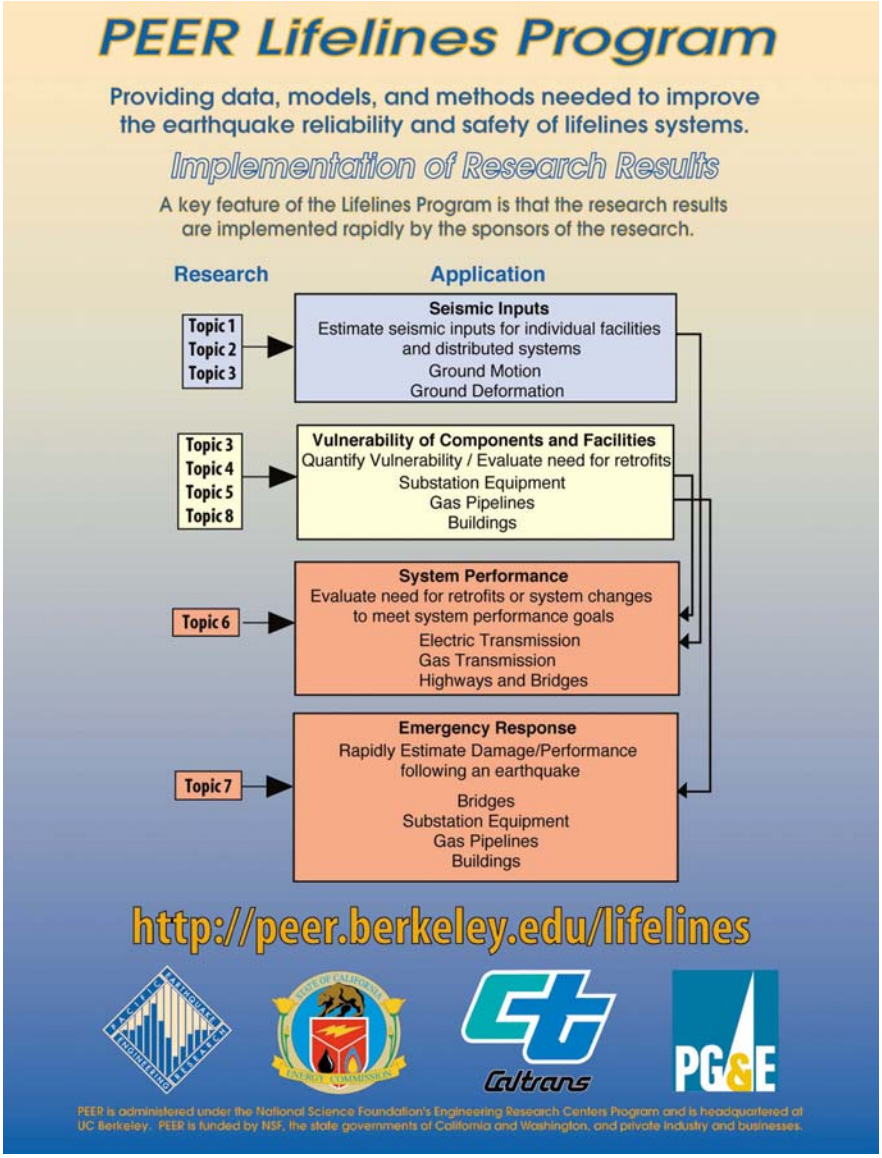

PEER Lifelines Program
Providing data, models, and methods needed to improve the earthquake reliability and safety of lifelines systems.
Implementation of Research Results
A key feature of the Lifelines Program is that the research results are implemented rapidly by the sponsors of the research.
Research
Application
Topic 1
Topic 2
Topic 3
Seismic Inputs
Estimate seismic inputs for individual facilities and distributed systems
Ground Motion
Ground Deformation
Topic 3
Topic 4
Topic 5
Topic 8
Vulnerability of Components and Facilities
Quantify Vulnerability / Evaluate need for retrofits
Substation Equipment
Gas Pipelines
Buildings
Topic 6
System Performance
Evaluate need for retrofits or system changes to meet system performance goals
Electric Transmission
Gas Transmission
Highways and Bridges
Topic 7
Emergency Response
Rapidly Estimate Damage/Performance following an earthquake
Bridges
Substation Equipment
Gas Pipelines
Buildings
http://peer.berkeley.edu/lifelines
Caltrans
PG&E
PEER is administered under the National Science Foundation's Engineering Research Centers Program and is headquartered at UC Berkeley. PEER is funded by NSF, the state governments of California and Washington, and private industry and businesses.

Figure 1.

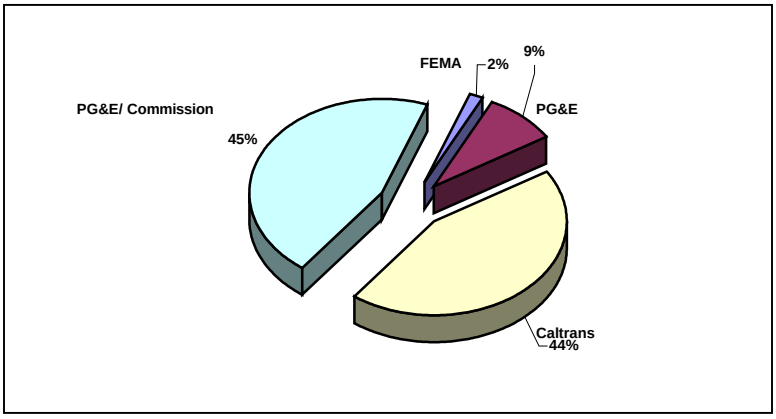


Figure 2. PEER Lifelines Program Phase III Budget (2000-2004)

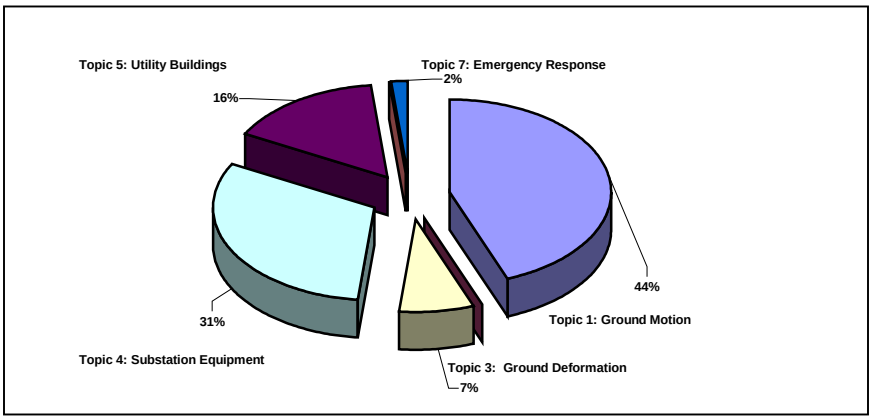


Figure 3. PG&E/Commission PEER Phase III Research Budget by Topic Area

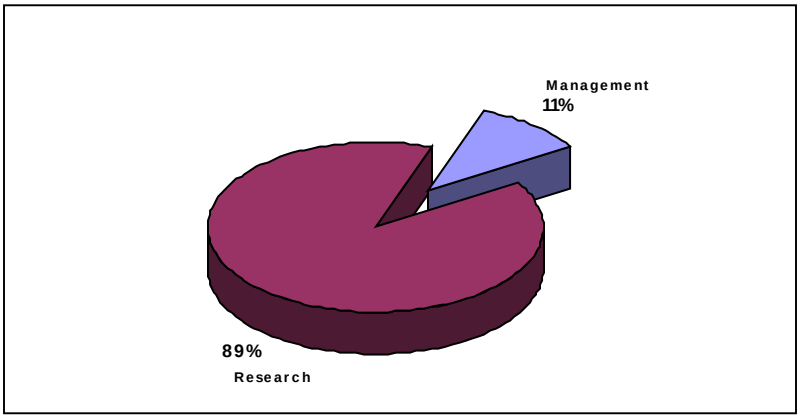


Figure 4. PG&E/Commission PEER Phase III Project Management/Research Budget

Table 1. PEER Lifelines Funded Research Projects 2000-2004

Topic #	Project Title	PI	Institution	Dates	Budget Amount
Topic 1	**Earthquake Ground Motion**				
1A01	Validation of Basin Response Codes	Henyey /S. Day	USC/SCEC	9/1/99 9/30/00	$100,000
1A02	**Calibration of Basin Simulations**	**Henyey / Day**	**USC/SCEC**	**10/1/00 12/31/02**	**$162,000**
1A02a	**Calibration of Basin Simulations (UCB Portion of 1A02)**	**Dreger**	**UCB**	**10/1/01 6/30/02**	**$38,000**
1A03	**Calibration of Basin Simulations**	**Henyey / Day Dreger**	**USC/SCEC**	**8/1/02 3/31/04**	**$160,000**
1A03a	**3D Ground Motion Simulation in Basins (UCB Portion of 1A03)**	**Dreger**	**UCB**	**8/1/02 3/31/04**	**$35,000**
1C01	**Interim Spectral Attenuation Relations**	**Chiou**	**Geomatrix**	**05/01/00 04/31/02**	**$56,750**
1C02a	**Validation of 1-D Numerical Simulation Procedures**	**Silva**	**PE&A**	**05/01/00 11/30/01**	**$50,000**
1C02b	**Validation of 1-D Numerical Simulation Procedures**	**Somerville/ Graves/ Pitarka**	**URS**	**05/01/00 03/31/02**	**$49,992**
1C02c	**Validation of 1-D Numerical Simulation Procedures**	**Zeng/ Anderson**	**UNR**	**05/01/00 08/30/01**	**$50,000**
1C02d	1D Simulation Analysis and Surface Fault Check	Somerville	URS	7/19/04 8/31/04	57898
1C03	**Rupture model of the Duzce, Turkey EQ**	**Somerville**	**URS**	**4/4/01 3/31/02**	**$49,947**
1C07	**Contribution to Ground Motion Synthesis Report**	**Somerville**	**URS**	**1/1/01 5/30/01**	**$9,935**
1C08	**Physically Based Source Input for Strong Ground Motion Simulation**	**Beroza**	**Stanford**	**6/01/02 5/31/03**	**$63,262**

Table 1. PEER Lifelines Funded Research Projects 2000-2004 (con't)

Topic #	Project Title	PI	Institution	Dates	Budget Amount
Topic 1	**Earthquake Ground Motion**				
1D01	Experimental Model for Rupture Directivity Effects	Brune/ Anooshehpoor	UNR	05/01/00 8/30/03	$121,877
1D02	**Utilization of Physical Model Data to Validate Numerical Procedures for Near-Field Motions**	**Day**	**SCEC**	**9/1/01 10/31/03**	**$120,000**
1E01	**Update Ground Motion Database with Data from Turkey and Taiwan**	**Silva**	**PE&A**	**06/1/00 6/30/01**	**$30,000**
1E02	**Attenuation Relations for Velocity and Displacement**	**Silva**	**PE&A**	**06/1/00 11/30/01**	**$30,000**
1E04	Database for 1999 Chi-Chi (Taiwan) Earthquake	Kiremidjian/ Lee	Stanford	1/1/01 12/31/01	$60,000
1E06	**Seismic Moment Tensors and Finite-Source Analysis of Chi-Chi Aftershocks**	**Dreger**	**UCB**	**1/1/02 12/31/02**	**$44,899**
1E07	**Comparison of Ground Motion Characteristics between Taiwan & California**	**Silva**	**PE&A**	**9/30/02 6/30/04**	**$64,966**
1F01	**Design Ground Motion Library**	**Power**	**Geomatrix**	**7/01/02 6/30/04**	**$60,005**
1F01a	**Design Ground Motion Library**	**Power**	**Geomatrix**	**7/01/02 12/31/04**	**$35520**
1G00	**Parameterization of Non-Stationary Accelearation Time History**	**Bazzurro**	**Applied Insurance**	**12/1/01 12/31/03**	**$142,839**
1J01	Surface Fault Rupture Design Model: Hazard Model Inputs	Schwartz	USGS	3/1/02 3/31/04	$184873
1J02	Surface Fault Rupture Design Models: Hazard Models	Petersen	USGS	2/1/02 6/30/04	$20,000
1J03	Surface Fault Rupture Design Models: Statewide Mapping Products	Wills	CDMG	2/1/02 6/30/04	$50,000

Table 1. PEER Lifelines Funded Research Projects 2000-2004 (con't)

Topic #	Project Title	PI	Institution	Dates	Budget Amount
Topic 1	**Earthquake Ground Motion**				
1L01	Next Generation Attenuation (NGA) Models, WUS Shallow Crustal Earthquake	Power	Geomatrix	8/1/02 6/30/04	$352630
1L01a	NGA travel &expenses	M. Riemer	UCB	8/1/02 6/30/04	$20,000
1L02	**NGA Data Sets**	**Silva**	**PE&A**	**11/1/02 12/31/03**	**$215,722**
1L03	**D. Boore participation with NGA modeling**	**Boore**	**USGS**	**3/1/03 6/30/04**	**$50,000**
1L04a	USGS Participation in NGA		USGS		
1L04b	SCEC Participation in NGA		SCEC		
1L05	**NGA: Site Condition Metadata from Geology**	**Wills**	**CDC-CGS**	**4/1/03 6/30/04**	**$59,359**
1L06	Ground Motion Models for Fling step	R. Graves	URS	5/1/03 6/30/04	$64,603
1L07a	**Statistical Methods for Attenuation Modeling**	**Youngs**	**Geomatrix**	**10/1/03 3/31/04**	**$56,470**
1L08	**1-D Rock Motion Simulations**	**Silva**	**PE&A**	**12/1/03 6/30/04**	**$80,000**
1L09	**Checking and Augmentation of NGA Database**	**Collins**	**URS**	**5/1/03 4/30/04**	**$54,498**
1L10	**Supplemental USGS Work for NGA Project**	**Spudich**	**USGS**	**11/18/03 6/30/04**	**$36,761**
1L10b	Supplemental SASW Work by USGS for NGA Project	Kayen	USGS	11/25/03 6/30/04	$36,039

Table 1. PEER Lifelines Funded Research Projects 2000-2004 (con't)

Topic #	Project Title	PI	Institution	Dates	Budget Amount
Topic 2	**Site Response**				
TBA	Using the DFSD to Characterize dynamic Properties of Bay Mud Sites with Nonlinear Seismic Response	Riemer	UCB	12/1/04 11/30/05	$61,000
2A01	ROS 5b Characterization of U.S. Sites	Nigbor	USC	05/01/00 09/30/01	$299,875
2A02a	Site Characterization at Strong-Motion Stations & Liquefaction Sites in Turkey	Stokoe/Rathje	UT at Austin	05/01/00 09/30/01	$49,470
2A02b	Site Characterization at Strong-Motion Stations & Liquefaction Sites in Turkey	Bay	Utah State	05/01/00 09/30/01	$25,530
2A02c	SMA Site Characterization in Taiwan-SASW	Stokoe/Rathje	UT at Austin	7/01/02 5/31/04	$108,092
2A02d	Coordination of SMA Site Data from Taiwan: Phase 1	Nigbor	USC	9/1/01 4/30/03	$112,890
2B01& 2B02	Laboratory Testing of Nonlinear Properties: I & II	Donald Anderson	CH2M	06/01/00 11/30/03	$135,000
2B03	Workshop on Uncertainties in Nonlinear Soil Properties and impact on modeling response	M. Riemer	UCB	9/1/03 6/30/04	$30,000
2C01	Application of SASW to US SMA Sites	Stokoe	UT	06/01/01 05/31/03	$125,000
2F01	Design Guidelines for Site Response Analysis for Vertical Ground Motion	Silva	PE&A	05/01/00 11/30/01	$65,026
2G01	Calibration Sites for Validation of Non-Linear Geotechnical Models	Stewart	UCLA	05/01/00 9/30/03	$81,952
2G02	Benchmarking of Nonlinear Geotechnical Ground Response Analysis Procedures	Stewart	UCLA	07/01/04 6/30/06	$253,317
2K01	Workshop on Ground Motions for Treasure Island National Geotechnical Experimental Site	De Alba	UNH	09/01/01 6/30/04	$30,000
2L01	COSMOS-GEOINFO Standards for Archiving & Dissemination of Geotechnical Data	J. Carl Stepp	COSMOS	5/15/01 11/15/01	$45,208

Table 1. PEER Lifelines Funded Research Projects 2000-2004 (con't)

Topic #	Project Title	PI	Institution	Dates	Budget Amount
Topic 2	**Site Response**				
2L02	Archiving & Web Dissemination of Geotechnical Data	J. Carl Stepp	COSMOS	3/31/2004	$141,649
2L02a	Archiving & Web Dissemination of Geotechnical Data II	J. Carl Stepp	COSMOS	3/31/04 6/30/04	$65,257
2M01	Examining Site Response issues for NGA	Z. Wang	Geomatrix	8/1/03 3/1/04	59,570
Topic 3	**Permanent Ground Deformation**				
3A01a	Liquefaction and Ground Motion Deformation Data from Turkey	Bray/Youd	UCB/BYU	06/01/00 06/30/02	$141,000
3A01a	**Liquefaction and Ground Motion Deformation Data from Turkey**	**Stewart**	**UCLA**	**06/01/00 09/30/01**	**$9,000**
3A01b	Ground Deformation Due to Faulting & Liquefaction, 1999 Kocaeli & Duzce EQs	Bardet	USC	10/01/00 08/31/02	$40,000
3A02	Liquefaction Site Characterization in Taiwan	Stewart	UCLA	9/01/01 6/30/03	$78,217
3A04	Update Database for Liquefaction Data	Bardet	USC	05/01/00 04/30/02	$94,377
3D01	SPT Triggering Models for Liquefaction	Seed	UCB	02/01/00 07/01/00	$40,467
3D02	Probabilistic CPT Based Triggering Model for Liquefaction	Seed	UCB	1/1/01 6/1/03	$118,914
3D03	**Probabilistic Liquefaction Assessment by Shear Wave velocity**	**Robert Kayen**	**USGS/UCB**	**4/1/01 6/30/04**	**$47,450**

Table 1. PEER Lifelines Funded Research Projects 2000-2004 (con't)

Topic #	Project Title	PI	Institution	Dates	Budget Amount
Topic 3	**Permanent Ground Deformation**				
3D04	CPT Testing of Deposits in Imperial Valley	J. Stewart	UCLA	5/1/03 3/31/04	$6,361
3F01	Performance of Lifelines Subjected to Lateral Spreading: Full-Scale Experiment	Ashford/Elgamal/Uang	UCSD	6/13/01 6/30/02	$622,597
3F02	Foundation Loads due to Spreading Ground	Elgamal	UCSD	6/01/03 6/30/04	$75,000
3F03	Inertial & Kinematic Load Combinations on Pile Foundations in Liquefying and Laterally Spreading Ground	Boulanger	UC Davis	4/1/04 6/30/04	$250,000
3G01	**Pilot Application of Regional Liquefaction Ground Deformation Models**	**Keith Knudsen**	**CDMG**	**7/1/01 1/30/04**	**$103,999**
3G02	Improved Assessment of Liquefaction-Induced Lateral Spreading Hazard	Seed	UCB	6/1/03 5/31/04	$64,476
3H01	Liquefaction Advisory Panel	Coord: Riemer	UCB	7/1/01 6/30/02	$26,000

Table 1. PEER Lifelines Funded Research Projects 2000-2004 (con't)

Topic #	Project Title	PI	Institution	Dates	Budget Amount
Topic 4	**Seismic Performance of Substation Equipment**				
401	Substation Equipment Interaction - Analytical Models of Rigid Bus Connectors	Der Kiureghian	UCB	02/01/00 12/31/02	$130,000
401b	**Analytical Models for Electrical Equipment Connected by Rigid Buses**	**Der Kiureghian**	**UCB**	**5/1/02 6/30/04**	**$82,121**
402	**Substation Equip. Interaction-Experimental Models of Rigid Bus Connectors**	**Filiatrault**	**UCSD**	**4/1/02 3/31/03**	**$100,000**
403	**Substation Equip. Interaction - Experimental Models of Flexible Bus Connectors**	**Filiatrault**	**UCSD**	**07/01/00 12/31/02**	**$160,000**
403b	**Substation Equipment Interaction -- Analytical Models of Flexible Bus Connectors**	**Der Kiureghian**	**UCB**	**07/01/00 12/31/02**	**$100,000**
404	**Improvements to Modeling Substation Equipment**	**Pardoen**	**UCI**	**07/15/01 3/31/04**	**$130,000**
406	**Seismic Qualification Requirements for Transformer Bushings**	**Whittaker**	**UCB**	**5/1/00 4/31/01**	**$100,270**
406	**Seismic Qualification Requirements for Transformer Bushings**	**Filiatrault**	**UCSD**	**10/1/01 9/30/03**	**$120,000**
408	**Input Motions for Earthquake Simulator Testing of Electric Substation Equipment**	**John Anderson**	**UNR**	**05/01/00 09/30/01**	**$40,000**
408	**Input Motions for Earthquake Simulator Testing of Electric Substation Equipment**	**Fenves**	**UCB**	**05/01/00 3/31/04**	**$90,720**

Table 1. PEER Lifelines Funded Research Projects 2000-2004 (con't)

Topic #	Project Title	PI	Institution	Dates	Budget Amount
Topic 4	**Seismic Performance of Substation Equipment**				
409	**Equipment Overturning**	**Makris**	**UCB**	**5/01/00 09/30/01**	**$65,000**
410	**Feasibility for Large-Scale Testing of Electrical Equipment**	**Nigbor**	**USC**	**5/1/00 12/31/01**	**$49,655**
411	**Seismic Qualification and Fragility Testing of 500 kV Disconnect Switches**	**Fenves**	**UCB**	**8/1/02 6/30**	**$210,012**
413	Database of Seismic Parameters of Equipment in Substations	Ostrom	Dennis Ostrom Consulting	3/1/03 3/1/04	$35,250
415	**Advisory Panel from Inter-Utility Seismic WG**	**Riemer**	**PEER**	**6/1/03 5/31/04**	**$15,000**
Topic 5	**Electric System Building Vulnerability**				
504	**Development of Improved Methodology for Buildings w/ Rigid Walls & Flexible Diaphragms**	**James Anderson**	**USC**	**05/01/00 1/31/03**	**$129,991**
505	**Methods for Estimation of Target Displacement**	**MacRae**	**UW**	**05/01/00 08/30/01**	**$65,000**
506	**Application of Simplified Model to Assess Structural Behavior of Mill Type Bldg**	**Niaz Nazir**	**EQE Intn'l**	**3/19/01 8/31/01**	**$10,000**

Table 1. PEER Lifelines Funded Research Projects 2000-2004 (con't)

Topic #	Project Title	PI	Institution	Dates	Budget Amount
Topic 5	**Electric System Building Vulnerability**				
507	**Advanced Seismic Assessment Guidelines**	**Cornell**	**Stanford**	**1/1/01 12/31/03**	**$266,301**
508	**Test Applications of Advanced Seismic Assessment Guidelines**	**Maffei**	**Rutherford & Chekene**	**7/1/02 2/28/04**	**$79,138**
509	**Evaluation and Application of Concrete Tilt-up Assessment Methodologies**	**Malley**	**Degenkolb**	**4/1/03 3/31/04**	**$68,130**
Topic 6	**Network System Seismic Risk**				
601	Scoping Study for Unified Lifeline Risk/Reliability Models	Werner	SSEC	10/1/00 6/31/01	$64,996
604	Earthquake Risk Decision-Making in Lifeline Organizations	David Seaver	Battelle	6/1/01 4/30/02	$173,972
605	*Follow up project(s) to 604 project*				*$144,595*
607	Validation of Probabilistic Seismic Hazard Computer Programs	Wong	URS	11/1/01 4/30/04	$93,692
6D01	Influence of Design Ground Motion Level on Highway Bridge Costs	Ketchum	OPAC	7/15/02 2/14/04	$149,980
Topic 7	**Emergency Response**				
701	**Rapid Ground Motion Estimates**	**Dreger**	**UCB**	**05/01/00 04/30/01**	**$65,000**

Table 1. PEER Lifelines Funded Research Projects 2000-2004 (con't)

Topic #	Project Title	PI	Institution	Dates	Budget Amount
Topic 8	**Pipeline Reliability**				
n/a	Assessment and Feasibility	Watanabe	EEI		$23,200
n/a	Bathymetry Surveys in Izmit Bay and Lake Sapanca, Turkey	Lettis	Lettis & Assoc		$12,000
		Total Awards			**$9,054,562**

Table 2. Members of the PEER Lifelines Advisory Panel on Electric System Seismic Safety and Reliability

Robert Anderson, Seismic Safety Commission

Peter Aguila, Southern California Edison

Leon Kempner, Bonneville Power Administration

Edward Matsuda, Bay Area Rapid Transit

Philip Mo, Southern California Edison

Dennis Ostrom, Consultant (resigned from the Panel in March 2004)

Craig Riker, San Diego Gas and Electric

William "Woody" Savage, US Geological Survey (Chair)

Ronald Tognazzini, Los Angeles Department of Water and Power

James Wight, San Diego Gas and Electric (resigned from the Panel in May 2004)

Don Willoughby, Pacific Gas and Electric

2.0 Research Results

Introduction

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 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 II contains the complete final reports for each project on a Digital Video Disk (DVD) in Adobe Acrobat PDF format.

Research results are presented in two formats,

- Topic area and individual project summaries (Section 2)
- Final project reports (contained on DVD as Appendix II)

Topic area discussions address the objectives and outcomes of research for each Topic area in a global sense. Detailed summaries for each individual project address the following eight areas

- Projects goals and objectives
- Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.
- Brief description of the accomplishments of the project
- Instances where project results have been used in industry
- Methodology employed
- Other related work conducted within and/or outside PEER
- Recommendations for future work
- Author(s), Title and Date for the Final Project Report

2.1. Topic 1: Earthquake Ground Motions

Topic 1: Earthquake Ground Motions

For previous seismic risk studies, the largest uncertainties in the seismic performance of structures and components result from the uncertainty in the ground motions. For networks of spatially distributed systems such as the electric system, there is greater sensitivity to the ground motion models than for individual (single location) structures because the distributed system is more sensitive to very large magnitude earthquakes (e.g. M7-M8). This occurs because large magnitude earthquakes affect a large area and can result in multiple failures. For example, in the electric transmission system, if a single substation is damaged, redundancy in the grid may allow the damaged substation to be by-passed and the resources are available to make the necessary repairs in a timely manner; however, it multiple substations are damaged in a large earthquake (e.g. multiple failures), then the redundancy in the system would not be sufficient to allow continued operation and there may not be enough resources available for timely repairs. The current ground motion models predict very different ground motions from large magnitude earthquakes that will result in very different system performance. To develop reliable system performance evaluations and thus make good risk management decisions, accurate ground motion assessments from large magnitude earthquakes are needed. The research projects in this topic area have provided needed data, models, and methods to reduce uncertainties in ground motions, particularly for locations near large magnitude earthquakes.

The research projects in Topic 1 can be grouped into three main subtopics: ground motion models, fault rupture models, and application guidelines. Of these three subtopics, the majority of the projects were for the ground motion models. The coordination and integration of the projects related to ground motion model was called the Next Generation Attenuation (NGA) program.

- Next Generation Attenuation (NGA) models (Data/Models) (1A01 – 1L10)
- Design Ground Motion Library (Data/Methods) (1F01, 1F01a)
- Surface Fault Rupture models (Models) (1J01, 1J02, 1J03)

Outcome

- <u>Next Generation Attenuation (NGA) models (Data/Models) ((1A01 – 1L10)</u>

Simply stated, attenuation relationships are the backbone of modern earthquake hazard assessment. These relationships are used in *all* earthquake hazard assessment ranging from the national and California seismic hazards maps, produced jointly by the USGS and CGS, to site-specific assessments, both deterministic and probabilistic, used for specific facilities ranging from bridges to dams to power plants. Hazard assessment results are used to establish design strategies and details of the built environment and to

predict their performance. Significant recent seismological advances including new earthquake data, new computer simulation capabilities, and improved scientific understanding warrant the development of next generation attenuation models.

Although leading attenuation modelers have periodically updated their design models, these updates were typically performed using independently assembled data sets and varying assumptions regarding optimal combinations of predictor variables and functional forms to account for particular seismological and geotechnical effects. Simultaneously, numerous research seismologists and engineers have developed a wide array of theories to better account for observed effects, and numerous adjustments to the models have been proposed. Unfortunately, these proposed adjustments are not fully consistent, and proposed usage is not necessarily compatible with existing attenuation models. The end result is that designers lack clear and consistent guidance from the research community as to best methods for hazard estimation. This can lead to widely varying estimates of hazard for a particular facility as different individuals often apply different combinations of attenuation models and adjustments.

The overarching goal of the NGA program is to develop broad consensus among attenuation model developers and researchers as to which seismological effects and predictive models are sufficiently mature to warrant their incorporation into routine hazard estimation. The NGA project represents a capstone initiative that is undoubtedly the most complex research coordination and consensus-building effort initiated to date by PEER-LL. It involves coordination of over 30 individuals and synthesis of results from over 40 projects. Partnerships have been established with SCEC and USGS to assure broad technical participation and review, additional research capabilities, and assistance in the leadership and coordination of key working group activities. The NGA program represents the first major coordinated effort to develop ground motion prediction equations for the western U.S. The NGA program aims to develop general "consensus" among five leading model development teams (identified below as "developers") and a broad array of leading researchers (identified below under "Task PI's", "Co-PI's" and "Review"). In this case, "consensus" is not focused on development of a single attenuation model; rather, it is meant to fully recognize and support multiple valid views that allows for individual expert judgment to be exercised regarding optimal means of modeling complex ground-shaking phenomena. However, to facilitate consensus building, each development team has been provided with common resources and exposed to the same resources and research findings.

The individual projects that comprise the NGA program can be grouped into three main categories: empirical data base development, analytical ground motion data base development, and ground motion model development. These projects are listed below along with a classification of the project into one or more of the three categories.

Although the NGA program is developing attenuation relations primarily based on attenuation relations, half of the projects in the NGA program are in the analytical model category. The reason for this emphasis on analytical models is that the developers are required to define their model for all design cases in California (excluding subduction earthquakes). This requires extrapolating the models beyond the range that is well constrained by empirical data. The ground motion model developers

can use the results of the analytical models to constrain the extrapolation of their models. This use of both empirical data and analytical models is a key feature of the NGA program that has not been part of previous ground motion models developed for California.

Projects in the NGA Program

	Project	PI	Empirical Data Base Development	Analytical Model Data Base Development	Ground Motion Model Development
1A01	Validation of Basin Response Codes	Henyey /S. Day		X	
1A02	Calibration of Basin Simulations	Henyey / Day		X	
1A02a	Calibration of Basin Simulations (UCB Portion of 1A02)	Dreger		X	
1A03	Calibration of Basin Simulations	Henyey / Day Dreger		X	
1A03a	3D Ground Motion Simulation in Basins (UCB Portion of 1A03)	Dreger		X	
1C01	Interim Spectral Attenuation Relations	Chiou			X
1C02a	Validation of 1-D Numerical Simulation Procedures	Silva		X	
1C02b	Validation of 1-D Numerical Simulation Procedures	Somerville / Graves/ Pitarka		X	
1C02c	Validation of 1-D Numerical Simulation Procedures	Zeng/ Anderson		X	

1C03	Rupture model of the Duzce, Turkey EQ	Somerville	X		
1C07	Contribution to Ground Motion Synthesis Report	Somerville		X	
1C08	Physically Based Source Input for Strong Ground Motion Simulation	Beroza		X	
1D01	Experimental Model for Rupture Directivity Effects	Brune/ Anooshehpoor		X	
1D02	Utilization of Physical Model Data to Validate Numerical Procedures for Near-Field Motions	Day		X	
1E01	Update Ground Motion Database with Data from Turkey and Taiwan	Silva	X		
1E02	Attenuation Relations for Velocity and Displacement	Silva			X
1E04	Database for 1999 Chi-Chi (Taiwan) Earthquake	Kiremidjian/ Lee	X		
1E06	Seismic Moment Tensors and Finite-Source Analysis of Chi-Chi Aftershocks	Dreger	X		
1E07	Comparison of Ground Motion Characteristics between Taiwan & California	Silva	X		
1L01	Next Generation Attenuation (NGA) Models, WUS Shallow Crustal Earthquake	Power			X
1L01a	NGA travel &expenses	M. Riemer	X	X	X
1L02	NGA Data Sets	Silva	X		
1L03	D. Boore participation with NGA modeling	Boore			X

1L04a	USGS Participation in NGA		X	X	
1L04b	SCEC Participation in NGA		X	X	
1L05	NGA: Site Condition Metadata from Geology	Wills	X		
1L06	Ground Motion Models for Fling step	R. Graves			X
1L07a	Statistical Methods for Attenuation Modeling	Youngs			X
1L08	1-D Rock Motion Simulations	Silva		X	
1L09	Checking and Augmentation of NGA Database	Collins	X		
1L10	Supplemental USGS Work for NGA Project	Spudich		X	
1L10b	Supplemental SASW Work by USGS for NGA Project	Kayen	X		
2M01	Examining Site Response issues for NGA	Z. Wang	X	X	

Empirical Data Base

The NGA program has developed the most comprehensive and most reviewed strong motion data base ever developed for seismic hazard analyses. The data base consists of over 3500 recordings from 175 earthquakes. For comparison, commonly used attenuation relations are typically based on only a few hundred recordings. In particular, the NGA data base contain about a factor of 10 increase in the number of recordings from earthquakes over magnitude 7 at distances less than 20 km as compared to previous data bases.

The database projects included compiling and processing the recorded ground motions, compiling and collecting the meta data for the recorded ground motions. One key effort for the meta data was the information on the site. In previous studies, very few sites had information on the shear-wave velocity available even though shear-wave is the basis for site classification in the building code. The NGA data base includes estimates of the shear-wave velocity at nearly every site.

Analytical Models

Three main types of analytical models were used in the NGA: seismological simulations for rock site conditions (flat layered crust), seismological models for deep alluvial basins, and geotechnical simulations for shallow site response effects. The seismological simulation procedures involve relatively complex computer codes that incorporate a range of assumptions about the earthquake source and wave propagation. While the computer codes had been widely used in academic exercises, they needed to be verified, calibrated, and validated before they were used in engineering applications. The NGA program included a major effort to validate the seismological models and a smaller effort to validate the geotechnical simulations. These validation exercises were successful in that they identified some errors in the simulation codes as well as inappropriate assumptions on source parameters.

The validated simulation methods were then used to generate suites of simulated ground motions from potential future earthquakes. These results were compiled in a series of plots and tables to address the following specific issues faced by the ground motion developers:

- Extrapolation to distances less than 10 km
- Extrapolation to distances greater than 100 km
- Extrapolation to spectral periods up to 10 seconds
- Scaling for magnitudes greater than 7
- Scaling for directivity effects
- Scaling for hanging/wall footwall effects
- Scaling for static stress-drop
- Scaling for rupture aspect-ratio
- Scaling for 3-d basin effects
- Scaling for non-linear site response

Ground Motion Model Development

The fundamental result from the NGA program is the ground motion prediction equations. To allow for early evaluations of the impacts of the NGA data base on ground motion models, two projects developed preliminary ground motion models early in phase III. The main effort has been on the development of five new sets of attenuation relations that will replace all of the existing models that are commonly used currently. While good progress has been made, the final NGA ground motion models are not yet completed. An extension to the Caltrans part of the PEER/LL program has provided some additional funding and time to complete the work. The final NGA ground motion models will be presented Dec 2-3, 2004 and the final reports will be completed in January 2005.

Preliminary results from the NGA program show that there will be a large change in the ground motions for large magnitude earthquakes as compared to existing models. Specifically, the short period (T< 1 sec) ground motions from the new models are about

half as large as existing models. If, as expected, such a reduction is in the final models, there will be a large impact on the electric system network analyses, with much less damage. This would greatly reduce the seismic retrofits needed.

Fling step – In addition to standard ground motion models, another key element of the NGA program is the development and evaluation of "fling step" displacement models. Fling step is that component of ground motion that is associated with irreversible, or static, fault offset. That is, it is related to tectonic deformation as compared to vibratory ground motion. Fling step affect the long period (e.g. T>2 sec) ground motion. Ground motion very near a fault is composed of a combination of fling step and dynamic shaking components. Currently, fling step is not considered in design. Therefore, the inclusion of fling step will increase the long period ground motions for sites located close (e.g. < 10 km) to large magnitude earthquakes that rupture the surface.

- Design Ground Motion Library (Data/Methods) (1F01, 1F01a)

Although high quality strong motion databases are currently available, selection of the most appropriate subset of motions for a specific design application remains a challenge. Designers need a convenient, transparent, and standard mechanism to select record sets that will produce the level of seismic demand intended for the specific design assessment. They also need clear guidance on how to properly scale the selected motions to meet design-level hazard. The Design Ground Motion Library (DGML) aims to develop a convenient electronic database for the selection and download of recommended sets of motion and their metadata. The Design Ground Motion Library will contain recommended sets of motions and scaling rules for adjusting these motions, for all ranges of seismological conditions used for seismic design of critical infrastructure components in California

The first phase, focusing on general library development and populating the library for shallow crustal earthquakes using only recorded data. The second phase of the project will address data gaps by adding supplemental motions generated using a variety of simulation techniques. This second phase is scheduled to be completed in Spring 2005. The second phase will also add records and simulations for subduction events.

- Surface Fault Rupture (Models) (1J01, 1J02, 1J03)

The NGA program addresses ground motions. A second hazard is ground rupture, which causes differential movement across the fault. Ground rupture hazard is restricted to facilities that cross the fault main trace or secondary traces. This can affect buried systems such as underground transmission lines, pipelines, and other critical infrastructure.

In previous studies, ground rupture hazard has been treated by simply replacing a ground motion attenuation relation with a fault rupture scaling relation based on generic world-wide data sets. The problem of this approach is that ground rupture is very fault specific and even location on the fault-specific so global based data sets are

not applicable to specific sites. In the PEER/LL work, a new approach was developed specifically for site-specific ground rupture hazard. Specially, a method was developed to classify fault segments in two ways: accuracy of mapping, and complexity of the fault rupture. These two parameters are used to assess the chance that there will be rupture off of the mapped main fault trace. For complex fault rupture or poor accuracy of mapping, then there is a larger chance that there could be rupture off of the mapped trace. Detailed empirical studies of the variation of the fault rupture both along strike and perpendicular to strike were conducted using California earthquakes. Using these empirical data sets, models were developed to parameterize the amplitude of the rupture on the main trace, the amplitude of the rupture on secondary fault traces and the location of the main trace.

A new probabilistic fault rupture hazard computer program was developed that uses these new models. An example application was conducted by the CGS to demonstrate that the procedure is working. The result of this project is that there is now a calibrated site-specific procedure for evaluation fault rupture hazard.

Summary

Research in this topic area provided needed data and models to reduce uncertainties in ground motions, particularly for locations near large magnitude earthquakes. Reduced uncertainty, reduction of unnecessary conservatism in existing design practice and identify areas where current practice may be unconservative.

Development of convenient, standard and transparent methods for the selection and scaling of earthquake time-histories for use in non-linear dynamical structural analysis and equipment qualification testing

Ability to predict the risk and distribution of fault offset will allow utility personnel to develop appropriate displacement tolerant designs and details to accommodate these motions.

The fault surface rupture estimation tool will be useful for both the design of specific utility projects that cross faults, and will also serve to supplement planning information now provided by Alquist-Priolo maps.

SEE TOPIC 1 SUMMARY SHEETS

2.2. Topic 2: Site Response

Objective

Geotechnical site effects are a period-dependent amplification, or de-amplification, of earthquake motions caused by near surface sediments (including soft rock and man-made fill). These effects depend on the stiffness and damping of the sediments, which in turn are a non-linear function of the amplitude of the motions. The non-linearity in site-effects is associated with the inelastic material behavior of the sediments, which become less stiff and more energy absorbing with increasing levels of strain.

Recent well-recorded earthquakes have graphically demonstrated the large effects that soils have on the ground shaking response at individual sites. Current databases and models for predicting site response have limitations and uncertainties that research projects in this Topic area have addressed. A good understanding of reliable methods for assessing site response is an essential part of assessing site-specific ground motions for utility buildings, equipment, and facilities.

- Characterization of Strong Motion Recording Sites (Data) (2A02a, 2A02c, 2A02d, 2C01)
- Laboratory Testing for Non-Linear Material Properties (Data) (2B01, 2B02)
- Geotechnical Virtual Data Center (Data) (2L01, 2L02, 2L02a)

Outcome

- <u>Characterization of Strong Motion Recording Sites (Data) (2A02a, 2A02c, 2A02d, 2C01)</u>

Accurate assessment of geotechnical site effects hinges on the availability of high-quality subsurface data. However, there remain very significant data gaps in subsurface information at strong-motion recording (SMR) sites, the data from which form the basis for all ground-motion estimation procedures. Over 1700 sites are in the current NGA database, but only a small fraction (less than 20%) of these have been thoroughly characterized. Approximately half of the sites investigated had been previously misclassified using one or more schemes used for assessment of site effects. Where data is absent, correlations and extrapolations need to be employed, resulting in possible misclassification and unnecessary scatter and bias in attenuation relationships used for design.

Because of the high cost of site characterization, initiatives in this area have sought to leverage related activities through partnerships and use of "holes of opportunity" as they arise. Since its inception, the ROSRINE project has worked closely with related and sustained efforts by the USGS. ROSRINE also worked in collaboration with SCEC's

borehole initiative that installed downhole and surface SMR pairs at key reference sites around the Los Angeles region. Very deep 300-meter monitoring wells drilled by the Los Angeles Water Reclamation District are excellent examples of "holes of opportunity" that provided tremendous new geophysical data sets at no added drilling cost. More recent partnerships include: 1) a collaboration with Kajima Corporation of Japan to share results from characterization of a US SMR site, 2) a project co-funded with NSF to characterize SMR and aftershock sites that recorded the 1999 M7.4 Kocaeli and M7.1 Duzce earthquakes in Turkey, and 3) two joint projects with NCREE of Taiwan to characterize sites that recorded the 1999 M7.6 Chi Chi earthquake.

- Laboratory Testing of Non-Linear Material Properties (Data) (2B01, 2B02)

In addition to velocity profiles, the other essential input required for quantitative analysis of geotechnical site effects is a non-linear material model for the sediments. The most common of these models involve families of two strain-dependent parameters: modulus reduction (G/G_{max}) and hysteretic damping (D) that are commonly presented as curves on a semi-log plot. Two alternative models developed in the early 1990's that are commonly used in design are derived from statistical analysis of results from sophisticated, and expensive, laboratory tests on soil samples. Unfortunately, only a very limited data set of (a few hundred) lab-test results have been available for model development. This data set is insufficient to clearly separate trends with standard geotechnical parameters such as depth, soil plasticity, and grain size.

Similar to the SMR site characterization program, the primary accomplishment of the lab-testing program has been a major expansion and extension of the fundamental database used to develop material properties models. The expansion includes new test results for 126 samples taken from 22 SMR locations and 2 deep vertical SMR arrays. Results were obtained from 48 coarse-grained soils and 78 fine-grained samples having plasticity index values ranging from 0 to 46. The extension toward greater confining stress includes results for 44 samples taken at depths greater than 30 meters including 11 samples taken from depths beyond 100 meters. The extension toward greater strain is provided through 48 DSDSS tests. These test results have been made publicly available on the ROSRINE web site.

The new data created under this testing program have been used in combination with additional data sources to develop new engineering models for non-linear material behavior. The new models can be used directly in equivalent-linear site response analyses or as constraints for more complex non-linear material models.

- Virtual Geotechnical Data Center (Data) (2L01, 2L02, 2L02a)

Tremendous amounts of geotechnical exploratory data have been, and continue to be generated for characterization of subsurface conditions and materials. For example, data sets for the Los Angeles region used by the California Geological Survey (CGS) for seismic hazard mapping exceed 12,500 borings. Hundreds of new borings generated

statewide each year by Caltrans alone. These data sets have tremendous untapped potential for project designers and other geotechnical professionals, especially for early site reconnaissance phases of project development. Information from nearby borings can be used to establish general subsurface conditions and identify problematic strata that could affect a new project site. Having this information before hand can help tailor a drilling program to assure good coverage of problematic zones or layers, and improved site characterization with reduced drilling costs. Each boring that does not need to be drilled results in savings on the order of several thousands to tens of thousands of dollars.

Access is the primary impediment to full utilization of these data. Lack of knowledge regarding data availability; differing methods, both electronic and paper, for archiving data; and institutional barriers that restrict sharing and dissemination of data have been addressed during this project.

The project has two phases: 1) a completed feasibility study, and 2) the current development of a pilot VDC. The feasibility investigation culminated in a workshop where user needs were discussed, alternative development case histories were presented, and both technical and institutional issues were examined. The general conclusion of the workshop was that development of a geotechnical VDC is indeed timely and feasible from both technical and institutional perspectives. Key issues identified to move forward with a pilot VDC were a clearer definition of users and use scenarios, the need for a standard "data dictionary" and associated data structures, and an IT architecture that meet technical and institutional constraints. The three working groups described above were formed to address these needs. The second phase of the project, recently completed, developed a pilot geotechnical VDC capable of serving selected data sets from CGS, USGS, Caltrans, and PG&E. The mixture of public and private entities participating in the pilot is thought to mirror the range of organizations that would ultimately serve as data providers and provide a realistic test case to assure that the functional requirements of the system can meet the expectations of diverse users.

Summary

The research in the site response topic provided the basic data that allows the NGA program to accurately characterize site effects on strong ground motions. It is a critical part of the ground motion data base that allows the ground motion models developed in the NGA program to use a site classification scheme that is consistent with the California Building code. The Pilot Geotechnical data base provides a standard method for archiving subsurface information from multiple institutions. The Virtual data center provides ready access to existing subsurface information from multiple institutions. The availability of this data will improve site characterization for projects and may reduce the number of borings that need to be drilled in the future, potentially saving several thousands to tens of thousands of dollars per boring.

SEE TOPIC 2 SUMMARY SHEETS

2.3. Topic 3: Permanent Ground Deformation

Objective

In addition to strong ground shaking, earthquakes can also produce several different types of permanent ground deformations, or 'ground failure' that can impose additional loads on nearby built facilities. Ground failure mechanisms include fault surface rupture (see Topic 1), liquefaction, and earthquake induced landslides. Fault surface rupture can result in large relative displacement of the ground surface across the fault. These displacements are largely a function of magnitude and can be as large as 5 to 10 meters across the fault. Liquefaction is the phenomena whereby saturated sediments soften due to pore pressure build up caused by shaking-induced strains. Foundation bearing in liquefied soils will experience a dramatic loss of capacity. Liquefied ground can also displace laterally large distances on very gentle slopes, a phenomenon known as 'lateral spread'. This lateral ground movement can impose large loads on buried facilities such as utility pipelines and underground cables.

Permanent ground deformations due to earthquake induced-liquefaction and lateral spreading, soft clay shear failure, landslides, and related phenomena can produce extensive damage to underground as well as above ground utility structures. The empirical database of seismic ground motions has been expanded, especially for smaller displacements through case histories of recent earthquakes in Taiwan and Turkey. New analysis tools have been developed to better model the probability of ground failures as a function of geologic and geotechnical data, and the level of strong ground shaking. When combined with fragility models for underground conduits, pipelines, and foundation structures, improved prediction of utility damage can be obtained and appropriate mitigation strategies identified.

- Liquefaction Triggering (Data/Models) (3D01, 3D02, 3D03)
- Lateral Spread Case Histories (Data) (3A01a, 3A01b, 3A02, 3A04)
- Regional Liquefaction Deformation Hazard Mapping (Models/Methods) (3G01)
- Soil-Foundation-Structure Interaction (Models) (3F01, 3F02, 3F03)

Outcome

- <u>Liquefaction Triggering (Data/Models) (3D01, 3D02, 3D03)</u>

Liquefaction triggering assessment is the process of determining whether liquefaction is likely to occur at a particular site. It is the first step in a comprehensive liquefaction hazard assessment, and possible consequences are assessed only if liquefaction triggering is considered likely. In its simplest form, liquefaction triggering assessment is

determined by comparison of the expected levels of ground shaking, expressed as a cyclic stress ratio (CSR), against various measures of the soils capacity to withstand shaking, expressed as a cyclic resistance ratio (CRR). Thresholds of liquefaction susceptibility are determined through empirical regression of observed behavior using worldwide case studies. The threshold is a function of the soil type and earthquake magnitude (i.e. as a proxy for duration or number of large strain cycles). The baseline threshold curve is normally expressed for clean sandy soils and a magnitude of 7.5. Adjustments to CSR are made to account for duration effects associated with different earthquake magnitude. Threshold boundaries are adjusted for different soil types, with increasing fines contents leading to lower likelihood of liquefaction.

- Lateral Spread Case Histories (Data) (3A01a, 3A01b, 3A02, 3A04)

Lateral spread is the phenomena where liquefied ground can displace laterally large distances on very gentle slopes. Lateral spread can impose extremely large loads on underground facilities including bridge foundations and buried utilities. Although the fundamental mechanics of lateral spread are reasonably well understood, analytical calculation of the amount of spread is not well constrained. Currently, designers typically rely on empirical approaches derived from examination of case histories. Studies of liquefaction and ground deformation in the 1999 Taiwan and Turkey earthquakes, as well as full-scale field experiments in Japan (3F01) have added to this empirical database. Advancements in numerical simulation capabilities will also rely on calibration against well-documented case histories.

- Regional Liquefaction Deformation Hazard Mapping (Models/Methods) (3G01)

Liquefaction hazards exist over large areas, such as many urban regions of California, that have a combination of young saturated sediments and high shaking hazard. Identification of whether a site may be subject to liquefaction hazard is needed for facility planning and a first screening step for design. In California, liquefaction hazards are being mapped by the California Geological Survey (CGS) under authority of the Seismic Hazards Mapping Act of 1990. The zone maps classify a site on a binary basis as either within or outside of a zone that is potentially susceptible to liquefaction hazards. No gradation is provided to identify relative hazard within the zones that are considered susceptible. Therefore, planners and designers use these maps primarily to identify where they *do not* have a liquefaction hazard, and site-specific assessments are required for all other locations. Another resource for identification of liquefaction hazards is "liquefaction susceptibility" maps produced by USGS. These maps do identify different levels of hazard, but the differentiation is based strictly on geologic criteria so all sites within the same surface geology unit are assigned the same hazard level. This approach provides valuable insight, but does not account for different seismic hazards or important variations within units, and does not incorporate knowledge of basic engineering principles driving the liquefaction process.

- Soil-Foundation-Structure Interaction (Models) (3F01, 3F02, 3F03)

Once a site has been identified as susceptible to liquefaction-induced ground displacement, a designer can elect to either remove or improve the poor soils, or design the facility to withstand the additional loads imposed by the ground displacement. The latter strategy requires use of engineering models that account for the interaction of the displacing soil with the foundation and, ideally, also with inertial loads caused by the earthquake-induced vibratory motions of the structure. This general problem is called "soil-foundation-structure interaction (SFSI)", and the special case of liquefaction-induced soil loads is a particularly important SFSI problem that seriously impacts the design of buried utilities and bridge foundations.

Summary

- A major achievement of the PEER-LL program has been the significant extension of the number of high-quality liquefaction case histories.
- The newly expanded database of case histories, plus new knowledge gained from fundamental research have made it possible to develop improved design tools for assessment of liquefaction triggering

SEE TOPIC 3 SUMMARY SHEETS

2.4. Topic 4: Seismic Performance of Substation Equipment

Objective

The vulnerability of high-voltage substation equipment, including transformers and their components, circuit breakers, and switches has been the primary reason that power grids have failed in past earthquakes. The objectives of projects carried out under this Topic area were to improve the understanding of the response, vulnerability, and performance of various types of substation equipment and their components, develop methods for assessing the behavior of interconnected substation equipment, improve methods of seismic qualification, and to identify specific actions that can be taken to reduce significant vulnerabilities.

These results provided both immediate 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 have lead to improved industry standards, designs and procedures for substation equipment purchase and installation, directly providing increased safety and reduced outage times for the electric grid following earthquakes, benefiting both customers and optimizing equipment expenditures by utility.

- Analytic and experimental studies of interconnected equipment (Data/Models/Methods) (401, 402, 403, 403b)
- Seismic Qualification Requirements for Transformer Bushings (Data/Models) (406)
- Input Ground Motion for Equipment Qualification Testing (Data/Models) (408)
- Seismic Qualification/ Fragility Tests of 500kV Disconnect Switches (Data) (411)
- Database of Seismic Parameters of Equipment in Substations (Data/ Methods) (413)

Outcome

- <u>Analytic and Experimental Studies of Interconnected Equipment (Data/Models/Methods) (401, 402, 403, 403b)</u>

This series of projects focused on a] experimentally investigating the interaction between components of substation equipment connected by re-designed (or improved) rigid bus connectors through quasi-static and shake table testing, and b] developing analytical models and methods for assessing the seismic response of electrical substation equipment connected by assemblies of rigid and flexible bus (RB, FB), flexible strap connectors (FSC) or slider connectors (SC). The purpose was to generate data that would provide guidance in the design of conductor assemblies with the improved connectors. The project resulted in mechanical models and dynamic analysis methods

of equipment items connected by FB, RB-FSC or RB-SC. The model and analysis approach allow accurate prediction of the behavior of connected equipment items by properly accounting for the nonlinear behavior of the connectors and the interaction effect between equipment items. This study also introduced a new S-shaped FSC, called *S*-FSC, which has enhanced flexibility and is highly effective in reducing the adverse effect of dynamic interaction between the connected equipment items. Through extensive parametric investigations, simple design guidelines are suggested for reducing the hazardous effect of the seismic interaction in practice.

- Seismic Qualification Requirements for Transformer Bushings (Data/Models)(406)

This research task investigates the factors that most greatly influence the dynamic response of high voltage bushings as well as attempts to quantify the ground motion amplification for various high voltage transformers. Numerical models of four different high voltage transformers were developed and used for modal and dynamic time-history analyses. In addition, system identification and seismic shake table tests were performed on a full-scale 525 kV transformer-mock bushing system. A numerical model of the test configuration was created to predict the seismic test results through dynamic time-history analyses.

- Input Motions for Earthquake Simulator Testing (Data/Models)(408)

The main objective of the study was to develop a set of earthquake ground strong motion time histories suitable for seismic qualification testing of electrical substation equipment in accordance with the IEEE 693-1997 standard. Although the study's objective deals with shake table testing of a particular class of equipment, many of the issues investigated are equally relevant to the dynamic testing of other types of equipment and components. This study was motivated by a desire to introduce a standard set of input motions in three orthogonal directions, and thus achieve more consistency in earthquake simulator testing. The project is focused on developing an input strong motion based on a record of actual earthquake with a time-domain spectral matching procedure, so the spectrum-compatible strong motion time history would preserve the non-stationary behavior of the real record.

- Seismic Qualification/ Fragility Tests of 500kV Disconnect Switches (Data) (411)

This project is an example of common interest, collaborative testing that involved utilities, switch, structure, insulator manufacturers, and PEER personnel. Shake table testing at PEER facilities documented that 500 kV disconnect switches had acceptable performance (even though not fully qualified to IEEE 693-1997). Test results identified issues and pitfalls related to testing without support structure and resulted in improvement to Performance Level test requirements in next revision of IEEE 693. The performance of 500 kV insulators also highlighted need for better definition of "ultimate

strength" of porcelain insulators. New standard porcelain insulators with the same strength, but lighter and cheaper than the old standard were identified. These design improvements were immediately implemented in the Path 15 transmission projects. Long term estimated avoided loss for future earthquakes is estimated to be $500,000/ yr for 3 California utilities.

- Database of Seismic Parameters of Equipment in Substations (Data/Methods)(413)

Electrical substations consist of many pieces of equipment that are vulnerable to earthquakes. Vulnerability depends on a variety of parameters including equipment type, voltage, manufacturer, seismic design criteria, installation and anchorage, foundations and soil conditions, and connection to other equipment. In order to be able to make accurate and standardized estimates of potential losses in earthquakes and to set priorities for equipment upgrades and replacements, an accurate database of the relevant seismic-performance parameters of substation equipment is needed. In this project, a comprehensive procedure for compiling seismic performance parameters of critical electrical components was developed and documented. The experience gained in assessing seismic vulnerability of substation equipment in previous PEER Lifelines Program research was incorporated. Development of a comprehensive procedure for compiling seismic performance data of electric substation equipment that is tied to a network-based earthquake loss estimation methodology will enable accurate and standardized estimates of potential losses to electrical systems in earthquakes and set priorities for equipment upgrades and replacements.

Summary

- Interconnected equipment projects have resulted in an improved understanding of the fundamental behavior of interconnected equipment, and the behavior of various types of connector elements for rigid and flexible buses.
- Dynamic tests of various types of substation equipment have yielded valuable qualification/ fragility data, and helped to improve current equipment qualification standards.
- The objective of projects on development of input motions for testing (Task 408), and transformer bushing qualification (Task 406) was to provide inputs and improvements to the IEEE 693 standard. Results of these projects are expected to be implemented in the next revision of the standard, or will provide data that will support on-going work in these topics.

SEE TOPIC 4 SUMMARY SHEETS

2.5. Topic 5: Electric System Building Vulnerability

Objective

Many substation buildings and service buildings are older, and their calculated seismic capacities do not meet current earthquake performance requirements for life safety and functionality. However, these types of buildings have performed reasonably well in past earthquakes. New data and models have been developed by PEER researchers to better assess the expected earthquake performance of these structures and enable better decision making by utilities regarding seismic retrofits and other mitigations for these buildings, if any are needed.

- Rigid Wall/Flexible Diaphragm Buildings (Data/Model) (504)
- Near Source Ground Motions (Data) (505)
- Mill Building (Model) (506)
- Advanced Seismic Assessment Guidelines (Methodology) (507)
- Application of the Advanced Seismic Assessment Guidelines (508/509)

Outcome

- <u>Rigid Wall/Flexible Diaphragm Buildings (Data/Model) (504)</u>

The goals of this research are to develop improved practical analysis procedures for evaluating the seismic performance of low rise buildings with rigid walls and flexible diaphragms and to use these procedures to evaluate current seismic design provisions. Representative of this type of building system are one story buildings with concrete tilt-up walls and low rise buildings with reinforced masonry walls.

- <u>Methods to Estimate Displacements of Structures (Data) (505)</u>

Dynamic inelastic time-history analyses of single-degree-of-freedom bilinear oscillators were undertaken to determine the ability of the Coefficient Method (CM) and the Capacity Spectrum Method (CSM) to predict the total displacement demands of structures. The CSM non-conservatively estimated median peak inelastic demands over most of the period range from 0-3 seconds. For some periods, the CSM estimated displacements which were only 60% of the actual median displacements. The CM method conservatively estimated peak inelastic demands over most of the period range of 0-3 seconds. For some periods, the CM estimated displacements more than 30% greater than the actual median displacements. For short period structures with fundamental periods less than 0.8 seconds, directivity effects from near-field shaking did not increase the displacement demands above that found for far field shaking.

- Mill Building (Model) (506)

A mill type substation was assessed using FEMA 356 guidelines. It was demonstrated that in all cases for the building, the recommended FEMA 356 design forces for the wall anchorage design were always conservative. It was shown that the distribution of the anchorage forces along the length fo the wall is not uniform and decrease significantly as it moves away from the center of the wall. A revised design equation was developed for design of out-of-plane forces which included parameters for wall anchor location, wall out-of-plane stiffness, and attaching diaphragm stiffness.

- Advanced Seismic Assessment Guidelines (Methods) (507)

This methodology provides a comprehensive tool for assessing key utility type buildings using non-linear dynamic analysis to determine if life safety and functionality performance objectives are obtained. These guidelines have been pilot tested on a mill-type building, and on a three- and an eight-story steel moment frame building. The methodology produces building specific fragility curves indicating the probability of a limit state (i.e., red, yellow, or green tagging) will be reached or exceeded as a function of the severity of the future ground motion at the site and provides a powerful decision analysis tool to assess mitigation needs. Building specific fragility curves reduce uncertainty and increase confidence in developing emergency planning and emergency response strategies, as well as electric system network modeling.

- Application of the Advanced Seismic Assessment Guidelines (Methods) (508/509)

This project assessed three buildings using the Guidelines: 1) A 3-story steel moment frame building; 2) a concrete tilt-up building; and 3) a steel frame, concrete shear wall (mill type) building. Results provide building specific fragility curves indicating confidence of achieving a red, yellow, or green (building inspection) tag based on the damaged buildings' capacity to resist collapse in an aftershock.

Summary

The results of the Building Vulnerability Studies have resulted in improved state-of-the practice of performance-based earthquake engineering so that decisions can be better made regarding the need to seismically upgrade existing buildings. This was accomplished by improving the understanding of the effects of near-source ground motions on the seismic response of buildings and by developing an improved understanding of roles of various types of assessment methodologies. Research topics focused on: 1) developing new and evaluating existing assessment methodologies (i.e. performance prediction tools); 2) defining acceptable levels of damage to meet electric system operating goals (i.e. structural component testing); and 3) developing loss

estimation tools to allow prediction of system impacts from earthquake effects (i.e. fragility curves).

SEE TOPIC 5 SUMMARY SHEETS

2.6. Topic 6: Network System Seismic Risk

Objective

Electric utilities need to evaluate the likely functionality of customer services following earthquakes. A flexible and powerful tool to use for this analysis is a system seismic risk model, in which individual earthquake scenarios can be analyzed to probabilistically describe the post-earthquake operational state of the electric transmission and distribution system. System risk models integrate information about hazards and building/equipment fragility to estimate damage and functionality. This capability can be used to evaluate alternative earthquake mitigations, and to evaluate the current state of earthquake preparedness of the utility system from customers and regulators perspective.

- Scoping Study for Unified Lifeline Risk/Reliability Models (Models/Methods) (601)
- Earthquake Risk-Decision Making in Lifeline Organizations (Models/Methods) (604)
- Validation of Probabilistic Seismic Hazard Computer Codes (Models/Methods) (607)

Outcome

- Scoping Study for Unified Lifeline Risk/Reliability Models (Models/Methods) (601)

The objective of this project was to develop a program plan for a future PEER research program that will initially develop and demonstrate a modular, technically sound, and practical unified risk/reliability platform to: (a) evaluate seismic risks to as-built lifeline systems with no seismic improvements; (b) evaluate seismic risks to modified lifeline systems with physical and/or operational seismic improvements now included; and (c) provide results from the evaluations that can guide decision makers as they assess and then select seismic improvement strategies that limit risks to their system to acceptable levels. This initial research program will focus on the need for unification and commonalities of modeling methods for electric power and highway transportation systems. During future PEER research, this can be extended to other lifelines as well.

The research defined by this program plan will lead to a unified seismic risk/reliability platform that will: (a) be initially developed as separate but parallel packages for electric power and highway transportation systems (using procedures/models from current practice and research) during the first two years of this program; (b) be further developed into a more sophisticated platform (with improved procedures and models from new research) during the remaining years of this program; (c) focus on system performance rather than merely component performance; (d) be developed not as a

decision-making tool, but instead as a decision-guidance toll that provides useful results for lifeline-system decision makers (Figure 1 illustrates the role of this platform in one possible seismic risk reduction decision-making process.); (e) accommodate a wide range of decision-making approaches and contexts; and (f) be applied in a demonstration application to an actual electric-power and highway-transportation system in California.

- Earthquake Risk-Decision Making in Lifeline Organizations (Models/Methods) (604)

In areas with earthquake potential, preparing for and responding to earthquakes is a significant responsibility of lifeline organizations. The decisions made by these organizations about how to manage and mitigate the risk of earthquakes are vital to both the organizations and the communities they serve. The overall purpose of PEER Lifelines research is to improve the understanding of how lifeline organizations make decisions about earthquake risk, identify critical issues and areas for potential improvement, and transfer general recommendations about decision-making to a broad range of lifeline organizations. This report describes the initial pilot phase of the research. The purpose of the pilot effort is to test data collection and analysis methods and to provide the participating organizations, the Pacific Gas & Electric Company (PG&E) and California Department of Transportation (Caltrans), with preliminary analysis on earthquake risk decision-making in their organizations.

This pilot study is primarily descriptive. It is an attempt to better describe and characterize earthquake risk mitigation decisions. It focuses on earthquake risk mitigation decisions in the lifeline organizations that are leaders in this area, and on the methods for studying these decisions. The pilot study is intended to identify key research issues and develop and assess the research methods to provide the basis for designing and conducting subsequent phases of research not to come to final conclusions.

- Validation of Probabilistic Seismic Hazard Computer Codes (Models/Methods) (607)

Probabilistic seismic hazard analysis (PSHA) is a methodology for establishing design ground-motion hazard level that is an alternative to the deterministic, or scenario-based, methodology. Advantages of PSHA include that it provides a consistent framework to incorporate contributions to hazard arising from multiple earthquake sources, poorly defined sources, and from a variety of uncertainties in hazard estimation ranging from variability in attenuation relationships to the likelihood of occurrence of a particular earthquake magnitude. Both national and California earthquake hazard maps used for building codes are based on PSHA. PSHA is also used to evaluate site-specific hazard for critical facilities such as power plants and dams, and is also used widely for risk analyses and loss estimation.

PSHA is a relatively sophisticated analysis, and a number of computer codes have been developed by a variety of organizations to implement the analysis. Design experience has shown that results of PSHA can vary widely depending upon both the analyst and the code employed. Differences in results can be attributed to input errors, numerical coding errors, errors in coding related to misinterpretation of component models, and differing approaches used for computational details (e.g. how to treat the distribution of uniform slip near fault edges, handling curved faults, etc.).

The overall research goal for this project was to improve the consistency and transparency of results by assuring that computer codes are numerically correct, that consensus is established among code developers regarding the most appropriate implementation of component models and computational details, and that clear guidelines are available regarding proper usage and limitations of codes.

Summary

The objective of the scoping study for lifeline risk/reliability models is to develop a program plan for a future PEER research program that will initially develop and demonstrate a modular, technically sound, and practical unified risk/reliability platform to: (a) evaluate seismic risks to as-built lifeline systems with no seismic improvements; (b) evaluate seismic risks to modified lifeline systems with physical and/or operational seismic improvements now included; and (c) provide results from the evaluations that can guide decision makers as they assess and then select seismic improvement strategies that limit risks to their system to acceptable levels.

The overall purpose of the Decision-Making in Lifelines Organization project is to improve the understanding of how lifeline organizations make decisions about earthquake risk, identify critical issues and areas for potential improvement, and transfer general recommendations about decision-making to a broad range of lifeline organizations

The overall research goal for the validation of probabilistic seismic codes is to improve the consistency and transparency of results by assuring that computer codes are numerically correct, that consensus is established among code developers regarding the most appropriate implementation of component models and computational details, and that clear guidelines are available regarding proper usage and limitations of codes.

SEE TOPIC 6 SUMMARY SHEETS

2.7. Topic 7: Emergency Response

Objective

Effective emergency response depends on obtaining accurate and rapid information about earthquake caused damage and system disruption. Strong motion and other data can be used to make rapid estimates of damage prior to getting input from experienced field operations personnel. Critical infrastructure and lifeline components are many times located in remote areas that are sparsely instrumented.

- Rapid Ground Motion Estimates (Models/Methods)(701)

Outcome

- Rapid Ground Motion Estimates (Models/Methods) (701)

Developments in ground motion modeling capability are providing benefits to the emergency response community. PEER sponsored research on integrating finite fault and near field effects into the ShakeMap software developed by the U.S. Geological Survey provides improved estimates of near-field ground shaking immediately after an earthquake in areas that are currently only sparsely instrumented

Summary

This methodology was successfully applied as part of the California Integrated Seismic Network (CISN) response to the December 22, 2003 San Simeon earthquake. The earthquake occurred in a sparsely instrumented portion of central California coast, modeling in conjunction with available records improved description of ground shaking intensity and areas of potential damage (Hardebeck et al., 2004, Preliminary Report on the 22 December 2003 M 6.5 San Simeon California Earthquake, *Seismological Research Letters*, **75**, 155-172.)

SEE TOPIC 7 SUMMARY SHEETS

3.0 Conclusions and Recommendations

3.1. Conclusions

The goal of this applied research program is 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 research results would directly address utility needs in preparing for future earthquake occurrences, and that the results could be quickly implemented by utility personnel or their consultants. PG&E and PEER JMC representatives, technical and administrative personnel in the two organizations, members of the PEER Lifelines Advisory Panel, and individual researchers were very satisfied with the results achieved by these 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 exceptional.

The 101 projects have provided useful results that meet utility needs in the seven 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 a narrative form, the cumulative connections between the topics that address this goal.

- Topic 1 results (earthquake ground motions) are used as input to Topic 2 (site response) and Topic 3 (permanent ground deformation) studies.
- Topic 1 results are used as input to assess the vulnerability of substation components and interconnected equipment, as well as equipment qualification testing (Topic 4). Severe ground shaking and ground failure are the direct causes of substation damage that can disrupt power transmission to customers.
- Topic 1, 2, and 3 results improve the assessment of building damage (Topic 5) before earthquakes occur to help identify appropriate mitigation and risk management strategies, and immediately following an earthquake (with Topic 7) to aid in emergency response and recovery activities.
- System earthquake risk models (Topic 6) integrate information about hazards (Topics 1, 2, and 3) and building/equipment fragility (Topics 4 and 5) to estimate damage and functionality of the electric transmission and distribution system.

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, changes in the procurement procedures and requirements for new equipment, upgrading old 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, vulnerabilities related to aging infrastructure, and unknown or unexpected response of equipment. However, 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.

3.2. Commercialization Potential

Commercial interest in PEER research is evident from the collaborative testing that has involved utilities, switch, structure, and insulator manufacturers during the 4 year program. Identification of improved transformer bushing materials (composite vs. porcelain) and disconnect switch assemblies coupled with improvements to the IEEE–693 standards is creating a market for seismically qualified electric substation equipment.

Specific PEER innovations, such as the Flexible Strap Connector (PEER 401), offer promise in helping to reduce interactions between substation equipment connected by rigid bus.

In addition, the development of the Virtual Geotechnical Data Center (PEER 2L01, 2L02, 2L02a) holds great commercial potential by providing designers and other geotechnical professional access to boring logs from a number of host institutions. The development of tools for design professionals, such as the Design Ground Motion Library (PEER 1F01, 1F01a) and the Advanced Seismic Assessment Guidelines (PEER 507) also has commercial benefit by contributing to improvements the designs of building and facilities subject to earthquake effects.

3.3. 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. Clear directions for further applied research were identified by the PEER Lifelines Advisory Panel, and provide the basis for planning the next phase of work. They include the following major research areas for high-priority research that extends the progress of Phase III work to capture immediate benefits.

1) Continue the Next Generation Attenuation project (Topic 1) to include vertical motions and numerical modeling of near-fault, large-earthquake motions that lack extensive empirical recordings. Extend these results into practice through the Design Ground Motion Library, which is a very important and practical product for the engineering design community.

2) Continue efforts to implement the Virtual Geotechnical Data Center (Topic 2) with the current and new partners. This is a highly leveraged activity that has large, long-term economic benefits to California utilities and many others.

3) Continue to develop regional-scale liquefaction and landslide deformation hazard maps (Topic 3). This development directly addresses a significant gap in design practice for lifelines systems.

4) Continue to carry out equipment testing and analysis to improve fragility (vulnerability) models and the IEEE-693 performance specifications (Topic 4). These activities in past phases of the Program have produced dramatic cost savings and improvements in the seismic performance of new equipment. Specific project activities include further studies of porcelain and composite insulators, pilot studies on the use of base isolation and dampers for substation equipment, and the seismic design guidelines for transformer appendages.

5) Continue efforts to create user-friendly design procedures and practices related to seismic qualification and evaluation. Specific needs are for interaction of equipment and component qualification procedures (Topic 4). Additional topics include the development of guidelines for simplifying the qualification test procedure for equipment mounted on support structures, and test protocols for the shake table testing of transformer bushings

6) Continue to improve performance assessment procedures for the typical stock of common utility buildings (Topic 5). Specific project activities include expansion of the seismic assessment guidelines developed in Phase III to allow evaluation of other building classes including, but not necessarily limited to, generic classes of buildings (e.g., generic wood frame buildings), medium- to high-rise steel moment frame buildings, and short-period, rigid wall, flexible diaphragm buildings; and shake table testing of utility building components to develop component acceptance criteria for connection hardware to meet building performance objectives.

7) Continue to improve electric utility procedures and practices to collect rapid post-earthquake damage information and perform rapid damage assessment (Topic 7).

The scopes of future research projects need 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, based on results of a network model based sensitivity analysis. This analysis is recommended to 1] identify the primary causes of power network damage and operational disruption given current level of information regarding hazards to and vulnerabilities of the system, and 2] identify the greatest uncertainties in the analysis and develop focused research to address and reduce those uncertainties. This type of analysis will allow the development of a comprehensive research task plan that will address the improved earthquake performance of electric power systems in California.

An addition, an increased emphasis is needed on research information and technology transfer for widespread application by the electric utilities of the State and by other

utility and transportation organizations in the State and the Nation. These needs can be addressed through the development of Applications Guides to transfer research results into the practice of the electric power industry, and professional training through topical seminars for utility personnel, utility consultations and other professionals. The publication of derivative professional papers on the use of Application guides and the continued development of the PEER Internet site will also help facilitate access to information generated by the PEER Lifelines Program.

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

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

3.4 Benefits to California

Significant progress has been made in achieving the ultimate goal of the project, to improve electric system safety and reliability in earthquakes. 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 this report was prepared, some of the results were being implemented in managing the equipment inventory at several utilities and in modifications of the national seismic qualification procedures for substation equipment (IEEE-693).

Ratepayers (who have funded this research) and other members of society are already benefiting from the research conducted by PEER Lifelines program through 1] improved life safety, 2] receiving more rapid restoration of service following an earthquake due to less utility damage and improved emergency response capability, 3] avoiding possible utility rate increases because there is less damage to equipment and facilities, and 4] experiencing more rapid overall recovery of societal functioning following an earthquake due to rapid power restoration and use of the research results by other organizations to recover their functionality more quickly.

Progress towards achieving these goals can also be measured in terms of avoided costs and losses. One example of an **avoided cost** or cost savings is the reduced 'up front' costs for the purchase of new equipment.

- Qualification testing of 230 kV disconnect switches demonstrated that a stiff, low profile support structure is effective in achieving good performance of 230 kV switches with minor modifications. Cost savings of approximately ~$250,000 per year are achieved at PG&E, for example, by not having to purchase more

expensive disconnect switches (at a 30-50% premium) that were shake table tested using an ultra-conservative Los Angeles Department of Water and Power (LADWP) testing protocol.

- Seismic qualification testing of 500 kV disconnect switches identified a new standard porcelain insulator with the same strength, but lighter and cheaper than old standard. Replacement with newer insulators is estimated to result in a cost savings of ~ $40,000 per year for the three California utilities.
- Not having to retrofit specific buildings (or building types) that have been shown to have greater capacity to resist earthquake ground motions than previously recognized is another example of cost avoidance. Estimated savings for mill-type and rigid wall/flexible diaphragm buildings are ~$500,000 and $100,000 per building, respectively.

Avoided losses include reduced earthquake related utility damage and reduced outage times for customers.

- Shake table qualification testing of 500 kV bushings resulted in improved knowledge about the ruggedness of porcelain bushings in this voltage class. These results led PG&E to specify 500 kV composite transformer bushings in lieu of porcelain for all future bushing replacements. Replacement of vulnerable 500 kV porcelain bushings with composite bushings will significantly reduce the number of bushings that have to be replaced after an earthquake – resulting in a savings in repair time, outage time, and replacement costs (~$45,000 per bushing) following the next major earthquake. Through 2004, approximately 40 per cent of these vulnerable porcelain bushings have been replaced as part of the PG&E risk management program, resulting in total loss avoidance of ~$1 million, to date. Composite bushings also provide additional savings from reduced maintenance costs for cleaning bushings in high pollution areas, while providing improved safety compared to center-clamped porcelain bushings.

In addition to these examples of economic loss avoidance by utilities, far greater loss avoidance in achieved by minimizing customer business interruption due to delays in the restoration of service. The value of electricity (in kWh) is much greater, up to 250 times, when a business cannot produce their product due to a lack of electricity (Roger Grey, personal communication, 2002).

The research program provides several additional benefits to utilities and 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, both nationally and internationally. 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 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 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 programs future work or to perform separately funded but closely coordinated studies that fit together nearly seamlessly. The California Department of Transportation (Caltrans) and the Federal Emergency Management Agency (FEMA) are examples of two such partners. It is likely that a number of others will participate during the next several years.

APPENDIX I

PEER Lifelines Advisory Panel on
Electric System Seismic Safety and Reliability
Final Report

PEER Lifelines Advisory Panel on Electric System Seismic Safety and Reliability

Final Report
September 23, 2004

Summary

The PEER Lifelines Advisory Panel on Electric System Seismic Safety and Reliability was convened by the Joint Management Committee of the PEER Lifelines Program in the spring of 2003. The objective in the formation of the Advisory Panel was to establish a well-qualified group that would provide comprehensive review and recommendations regarding the importance and usefulness of the applied research being conducted by the PEER Lifelines Program to the electric power industry and its customers and regulators in California. The Charge to the Panel addressed four topics, and the Panel provided detailed responses to each Charge.

Charge 1: Evaluate the applicability of the research in improving the earthquake safety and reliability of electric power.

Panel Response: PEER Lifelines research is directly applicable to improving the earthquake safety and reliability of California electric utilities. The results have already improved utility practices and industry codes, have solved specific problems, have been used by other lifelines and critical infrastructure in California and elsewhere, and have informed and involved faculty at major universities to establish a long-term interest in meeting utility research needs.

Charge 2: Recommend new directions or topics for future research.

Panel Response: A next phase of research work is needed. The Panel identified seven high-priority areas of research that should be continued in the next year to two years to capture clear and immediate benefits. In parallel, an electric system network analysis using the current Program results should be performed to identify the specific research results that are still needed to improve electric system earthquake performance as measured by greater reliability and reduced financial and human losses. Tasks to obtain these results should be carried out during the latter part of the next phase of the Program.

Charge 3: Comment on sharing and distribution of research results

Panel Response: Expanded sharing and distribution of research results is urgently needed to enable California to receive the greatest benefit of the PEER Lifelines research. The

Panel recommended conducting an integrated program to prepare Application Guides and perform professional training using the Guides to transfer the research results into the practice of the electric power industry.

Charge 4: Provide recommendations on coordination and leverage with other research programs.

Panel Response: Research coordination should be enhanced with other research, educational, professional, and industrial organizations. There are many opportunities for likely cooperation that will leverage the funding resources of the PEER Lifelines Program and will increase the production of applied research results.

Introduction

This report presents the comments and recommendations of the PEER Lifelines Advisory Panel on Electric System Safety and Reliability that address the Charge to the Advisory Panel. This effort was carried out in the past 14 months through two working meetings accompanied by conference calls and e-mail reviews. The report summarizes the formation of the Advisory Panel and presents its Charge, then discusses the Panel's comments and recommendations in detail. Information about the two working meetings is provided in two appendices.

Background of the PEER Lifelines Program

The PEER Lifelines Program was established in 1997 as a multi-year, multi-discipline applied research effort to improve the safety and reliability of electric power in earthquakes. Since the inception of the Program, the conduct of the research as been managed by the Joint Management Committee, comprised of representatives from the funding agencies and the Pacific Earthquake Engineering Research Center (PEER). By requiring agreement on scope, budget, and schedule between the funders and the researchers prior to beginning every research task, the funders are assured that the research results are well aligned with the needs of the users of the research, and the researchers are satisfied that the studies they are conducting are compatible with their academic needs and interests. This mode for conducting user-driven applied research has been successful and productive.

Since 1997, three funding cycles of the Peer Lifelines Program have taken place. In Phase I, PG&E rate-payer funding initiated the Program, and 23 individual research tasks were carried out that addressed utility needs for improved earthquake hazard characterization along with better understanding of the seismic performance of utility buildings and substation equipment. In the second phase, in 1998-1999, PG&E funding was augmented by a one-year contract with the California Energy Commission (CEC) through their Public Interest Energy Research Program. The CEC funded Phase III for three years plus a one-year extension (2000-2004) to address an expanded scope of work. The CEC and PG&E participation was greatly augmented by the Phase III partnership with the California Department of Transportation (Caltrans), which co-funded tasks primarily addressing earthquake hazards characterizations.

During the entire period from 1997 to 2004, the Joint Management Committee has met frequently (every four to eight weeks) and has organized topical coordination meetings on a quarterly basis among the researchers and funding representatives in an effort to keep the research activities on scope and schedule, and to maximize the integration of results from previous tasks into the current tasks and into planning for future tasks. Thus, as Phase III comes to an end, the research results represent more than seven years of well-organized effort.

PEER Lifelines Program Advisory Panel

In the spring of 2003, the Joint Management Committee formed an Advisory Panel to perform a comprehensive review of the status of the PEER Lifelines Program research results and to provide recommendations for the future of the Program. The objective in the formation of the Advisory Panel was to establish a group that is well qualified to provide comprehensive and representative review and recommendations regarding the importance and usefulness of the applied research being conducted by the PEER Lifelines program to the electric power industry and its customers and regulators in California. The Joint Management Committee decided to ask members of the Inter-Utility Seismic Working Group (IUSWG) to serve on the Panel.

The IUSWG was formed in 1990 as an ad hoc organization of earthquake experts in the major California gas and electric utilities, and met as needed to address technical earthquake problems and issues facing the California utilities. Other utility organizations outside of California participated at times, including Bonneville Power Administration and BC Hydro. Some of the IUSWG technical issues evolved to be handled by the IEEE-693 Working Group, which continues to establish guidance for the seismic design of substation equipment. The Seismic Safety Commission involved the IUSWG several times in addressing utility aspects of the Commission's five-year plans.

The IUSWG was also identified as a useful source of advice for the PEER Lifelines Program. Individuals involved in the Working Group have participated, both formally and informally, in providing advice on research needs and individual research projects since the inception of the Lifelines Program.

The PEER Lifelines Advisory Panel is composed of individuals who have participated in the IUSWG, along with additional individuals who are current and appropriate technical experts in electric power and earthquake engineering and science. The members are predominantly from the large California electric power utilities. The members of the Panel are listed in Table 1. The Panel chairman, Woody Savage, served as chair of the IUSWG for a number of years.

Table 1. Members of the PEER Lifelines Advisory Panel

Robert Anderson, Seismic Safety Commission
Peter Aguila, Southern California Edison
Leon Kempner, Bonneville Power Administration
Edward Matsuda, Bay Area Rapid Transit
Philip Mo, Southern California Edison
Dennis Ostrom, Consultant (resigned from the Panel in March 2004)
Craig Riker, San Diego Gas and Electric
William "Woody" Savage, US Geological Survey (Chair)
Ronald Tognazzini, Los Angeles Department of Water and Power
James Wight, San Diego Gas and Electric (resigned from the Panel in May 2004)
Don Willoughby, Pacific Gas and Electric

Charge to PEER Advisory Panel

The following four charges were provided to the Advisory Panel by the Joint Management Committee as the proposed scope of their activities to be conducted during the twelve months period until the end of the current phase of work on June 30, 2004. The Panel accepted these charges at its meeting on June 16, 2003.

1. Review current PEER Lifelines research activities and projects in order to evaluate and comment on the applicability of this research towards helping achieve the goals of improved electric component and network performance and public safety

2. Recommend new directions or topics for research for the next phase of the PEER Lifelines program, including recommendations for either increasing or decreasing emphasis on specific topic areas

3. Comment on the sharing and distribution of information and research results from the PEER Lifelines program with California electric utilities and related organizations

4. Provide comments and recommendations on the coordination and leveraging of PEER research with other research programs, either currently being conducted or planned, by California electric utilities

Advisory Panel Meetings

To carry out its Charge, the Panel had two meetings. The first meeting on June 16 and 17, 2003, was held in conjunction with a research coordination meeting for Topic 4, Substation Equipment, at the PEER Center offices in Richmond, CA. A report on the meeting results, including the agenda, is provided in Appendix 1. The second meeting was held on April 1 and 2, 2004, also at the PEER Center. The agenda for the second meeting is provided in Appendix 2, and this report incorporates the results of the meeting. Substantial discussions among the Panelists were conducted at the two meetings, and e-mail exchanges and conference calls were used to review draft reports.

Panel Comments and Recommendations

The Advisory Panel has developed extensive comments and recommendations in response to the Charge to the Panel. Many detailed comments are included in the interim report of the Panel in Appendix 1. For this final report, a more comprehensive and integrative view has been taken by the Panel. These comments and recommendations are described in four headings that correspond to the topics of the four charges.

Response to Charge 1: PEER Lifelines research is highly applicable to improving the earthquake safety and reliability of California electric utilities.

The following specific examples illustrate four types of application of the research results.

- Research results are applicable to utility practices and industry codes, and have resulted in seismic performance improvements in California.
    - Input motions for testing. A new input motion specification for shake table testing was developed by a PEER research project, and will be included in the next revision to the Institute of Electrical and Electronic Engineers (IEEE) 693 standard (Recommended Practices for the Seismic Design of Substations). This project developed empirically-based input motion time histories that meet the IEEE 693 requirements, as well as validated a set of numerically generated time histories that will be made available for download at the IEEE West Coast Committee website. Filtering recommendations, executables for implementing the new specification, and examples have also been provided for users to download. This project is expected to improve the reliability and consistency of shake table tests, and lead to improved seismic performance of electrical equipment qualified by such tests.
    - Transformer bushing response. Previous PEER projects have identified the need for changes in the qualification procedures for testing transformer bushings. The most recent PEER project on this subject made important new steps in gaining a more complete understanding of the problem through a combination of analytical and experimental investigations. In addition to quantifying the magnitude of amplifications experienced by bushings mounted on transformers, the project also highlighted the possibility of resonances that have previously not been adequately considered.
    - 230 kV disconnect switch performance. A previous PEER project investigated the seismic performance of 230 kV disconnect switches through experimental and analytical studies. These tests demonstrated the ruggedness of typical switches without special seismic enhancements, when mounted on stiff supports, allowing procurement of less costly equipment. This project identified the weakness of cast aluminum fittings at the insulator bases, which could be inexpensively replaced by stronger, more ductile materials. This allowed PG&E and other utilities to obtain seismically qualified switches at a much lower cost in future procurements. Prior to the tests, PG&E had paid 30% more to obtain seismically qualified 230 kV disconnect switches. The project also yielded valuable seismic response data that PG&E continues to use for the evaluation of switches by analytical procedures.
    - 500 kV transformer bushings. Tests on a standard porcelain 500 kV transformer bushing and a porcelain bushing modified to meet IEEE 693

criteria verified that porcelain bushings are vulnerable to earthquake damage, and 500 kV porcelain transformer bushings could probably not be built or modified to meet IEEE 693 requirements. This result helps utilities and vendors to more fully understand the vulnerabilities of porcelain 500 kV transformer bushings and to promote consideration of less vulnerable, seismically qualified, 500 kV composite transformer bushings. Composites are safer, easier to install and maintain because they are much lighter and washing is not required, more rugged seismically, and are approaching the price of porcelain.

  - Improved identification of remaining performance uncertainties. Testing has identified specific areas, such as transformer bushing failure modes, response of bushings with supports, and porcelain strength determination, that require additional research to provide a better understanding of high-voltage equipment performance when subjected to strong earthquake input motions.

- Research has solved specific problems
  - Interaction of connected equipment. Several analytical and experimental PEER projects on this subject have resulted in an improved understanding of the behavior of interconnected substation equipment. The methods of analysis developed in these projects, and validated by experiments, provide better estimates of requirements for conductor slack, some of which have been implemented by IEEE 693. Although the current methods remain somewhat unwieldy, they serve as a guide for future development of tools that can more easily be implemented by utility engineers for design.
  - 500 kV disconnect switch seismic performance. A 500 kV disconnect switch was seismically tested in a collaborative project that involved three California utilities and three manufacturer partners. This project filled an important utility need by demonstrating (1) the seismic capability of the equipment after making some relatively minor design changes, and (2) the effectiveness of qualifying equipment through the collaboration of multiple users. These new switches have been procured for PG&E's Path 15 project as well as other recent projects in California (Path 15 has been found to be an extremely critical link for the transmission of power between northern and southern California during periods of electrical energy shortage in the State). In addition, tests highlighted some deficiencies in the IEEE 693 requirements for performance level testing, which will be revised in the upcoming edition of the standard. The tests also resulted in the adoption of new stronger and lighter insulators for installation in these switches by the California utilities.
  - Consistent design ground motions. The PEER Lifelines Program's Next Generation Attenuation project is resulting in more consistency in design response spectra. It is helping to resolve the problem of having greatly varying response spectra for the same site depending on the consultant

used to develop design ground motions. In the past, peak ground accelerations have varied by 50% at the same sites.

- Results have been used for other lifelines and critical infrastructure in California
  - Fault displacement hazard. There has been significant variation in how displacements at fault crossing are evaluated. The consistent approach developed by PEER Lifelines research, which has concurrence by the leading experts, will help ensure that appropriate fault displacements are used in design and analysis. The results of the research will help prevent designing for displacements that have an extremely low likelihood of being exceeded, which can be very costly. The results will also help prevent under design, which could result in safety and/or operational problems. BART is using the results of this research for retrofit decisions at a number of existing fault crossings and for design at a number of future fault crossings. Water and gas utilities and Caltrans are also using this research.
  - Consistent time histories for engineering analysis. Time history analysis has been found to control the design of a number of types of structures including bridges and tunnels. Time-history characteristics for design, including the size of a velocity pulse, can greatly vary depending on the consulting firm and individual developing them. Not only are the clients getting vastly different time histories, but also the cost for development is generally quite high. It appears developing reasonable time histories is more of an art, which takes a great deal of experience and insight, than a science. The PEER Lifelines project to develop a library of time histories for various conditions that has been peer reviewed by leading seismologists will be used by BART, Caltrans, and other lifelines and critical infrastructure. This library will result in more consistency, use of the appropriate time histories, and saving the cost to develop project-specific time histories. BART has found that some of the time histories used in the past are excessively severe and have resulted in unnecessarily expensive designs.

- Academia is more informed about and involved in meeting electric utility needs for applied research.
  - Faculty at major universities in California and other states are now aware of issues of concern to electric power and other utilities, and are addressing these issues in their research and student advisement.
  - Graduate students have been trained in engineering analyses of substation equipment, and represent an investment in future expertise that will be available to the electric utility industry.
  - The PEER Lifelines Program has engaged in inter-university communications within California and outside the State on common-interest earthquake research on electric power equipment and systems. A

well-attended workshop involving the three NSF engineering centers in 2003 was an effective initial exchange of information about each center's lifeline-related research and planned directions.

Response to Charge 2: A next phase of research work is needed.

In considering future work, the Advisory Panel stepped outside of the previous structure of the research program, which was organized into seven topics. This change in perspective allows a greater focus on the integration of research into applications within the electric power industry that make the most improvement in future earthquake performance. The Panel recommends the following three-step strategic plan for additional PEER Lifelines applied research in which the progress already made in the Program is used to carefully analyze and identify the most significant topics and tasks of more research that will lead to the greatest improvements in earthquake safety and reliability of the electric power network.

Step A: At the start of the next phase, conduct research that extends the progress of Phase 3 work to capture clear and immediate useful results. There are seven specific areas recommended for such high-priority research. These activities should be carried out in about one to one-and-a-half years, to mesh effectively with the completion of Step B and the start of Step C.

1. Continue the Next Generation Attenuation project to include vertical motions and numerical modeling of near-fault, large-earthquake motions that lack extensive empirical recordings. Extend these results into practice through the consistent development of ground-motion time histories to be included in the Design Ground-motion Library, which is an important and practical product.
2. Continue efforts to implement the Virtual Geotechnical Data Center with the current and new partners. This is a highly leveraged activity that has large, long-term economic benefits to California utilities and many others.
3. Continue to develop the regional-scale liquefaction and landslide deformation hazard maps. This development directly addresses a significant gap in design practice for lifeline systems.
4. Continue to carry out equipment testing and analysis to improve fragility (vulnerability) models and IEEE-693 performance specifications. These activities in past phases of the Program have produced dramatic savings in the cost of improved seismic performance of new equipment.
5. Continue efforts to create user-friendly design procedures and practices related to seismic qualification and evaluation. Specific needs are for interaction of equipment and component qualification procedures.
6. Continue to improve performance assessment procedures for the typical stock of common utility buildings.
7. Continue to improve electric utility procedures and practices to collect rapid post-earthquake damage information and perform rapid damage assessment.

In each of these seven areas, there are important opportunities to continue to develop working relationships with industry and with other universities interested in research regarding the seismic performance of electric power facilities.

Step B: Use a network-model-based sensitivity analysis to identify the primary causes of power network damage and operational disruption, given the current level of information regarding ground-motion and ground-failure hazards to the system and vulnerabilities in the system. From this analysis, research tasks can be identified that provide the greatest benefit to improving earthquake performance as measured by greater reliability and reduced financial and human losses. This effort should be carried out in parallel with the continuing work of Step A, so that during the second year of the next phase, when the results of this sensitivity analysis are available, the further research efforts can be focused on the most beneficial tasks for risk reduction.

Step C: Carry out the specific tasks and sets of tasks identified in Step B for the remaining term of the next phase. This procedure will allow a robust research task plan that is assured to be the most essential to achieving improved earthquake performance of electric power systems in California.

Response to Charge 3. Expanded sharing and distribution of research results is urgently needed to enable California to receive the greatest benefit of the PEER Lifelines research.

The Advisory Panel, along with many individuals and groups in California and nation-wide, is profoundly impressed with the high quality, great breadth of scope, and focus on practical needs that have been achieved in the research results obtained by the PEER Lifelines Program. The full transfer of these research results into widespread applications by the electric utilities of the State and by other utility and transportation organizations in the State and the Nation, however, needs more attention. To that end, the Panel recommends two specific activities that augment the research efforts themselves and that will assure effective utilization of the results.

A. Prepare Application Guides based on research results

The research results as they are documented and compiled in the Program are not practically available to users within the electric power industry. At best, the results can be digested and used by industry consultants and a few specialists within the industry. The Panel recommends that a series of Application Guides be prepared under the direction of the PEER Lifelines Program to lay out the clear application within the utility industry of new ground-motion and ground-failure hazards characterizations, improvements in design inputs, equipment performance tests, and other research products. These Application Guides would likely need to be written by well-qualified individuals from consulting engineering organizations, with input from the academic researchers. An industry advisory group could work with the Joint Management Committee to identify the scope and content of each Application Guide, and then review the draft Guides at

several stages of development. The Guides should be written in a fashion that allows for periodic updates as additional research is done or as users have experience in practical applications of the Guides. Optimally, such Application Guides could be adopted by Standards Development Organizations (such as IEEE and ASCE) to be maintained and distributed. The American Lifelines Alliance is a project of FEMA that could assist in this conversion of industry practices to national guidance.

B. Plan and conduct professional training.

Effective means of training to use the Application Guides can take several forms:

- Topical seminars for utility personnel, utility consultants and other professionals would create a fast track to interaction and application in California. Once such training is established, other utilities may be more interested in supporting the PEER Lifelines research itself. Modest charges could help offset the out-of-pocket costs of the training.
- Publication of derivative professional papers on the use of Application Guides in peer-reviewed journals and professional conference proceedings would promote long-term education of students and professionals nationally and internationally.
- Web sites with dynamic links could create "one-stop shopping" for current research results, Application Guides, seminar offerings, and other information of interest to the broad community. Likely long-term hosts for such web sites would be professional societies.

The professional training element of promoting the application of the research results likely should be established through partnerships and cooperative agreements, since this activity, although very important, is not the primary focus of the PEER organization.

Response to Charge 4: Research coordination should be enhanced with other research, educational, professional, and industrial organizations.

The Advisory Panel concurred with the concept of the fourth Charge that there are good opportunities to leverage the PEER Lifelines Program with other research, both fundamental research and highly applied research, to the benefit of interests in the State of California. Some research is actively being carried out that could be productively coordinated with the Program, while in other cases the opportunities for others to participate in the Program need to developed and persuasively articulated to prospective partners. Three areas of likely coordination are discussed below.

- Refresh and expand coordination and cooperative agreements with the Electric Power Research Institute, US Geological Survey, California Geological Survey, BC Hydro, Bonneville Power Administration, Department of Energy, other California utilities, and others.

In marketing terms, this is the "warm market." These organizations all have active research and development interests, and have been involved with the PEER Lifelines Program in the past, to at least some extent. Effort directed to renewing contacts and holding informational meetings to look for opportunities for collaboration and co-funding would likely be productive.

The California utilities offer a particularly beneficial opportunity, due to their many common interests associated with the shared political and seismic hazards settings. Two possible actions are suggested: (1) The PEER Lifelines Program could host annual meetings involving California electric utilities as well as consulting engineers, institutes and other non-profits, and governmental agencies to discuss technical topics of common interest, such as the performance of transmission substations in scenario earthquakes around the State; and (2) following the next significant earthquake in the State, the Program could hold a post-earthquake conference to share information among industry partners and the research community on findings from that event in a public forum, prior to publication, when interest in electric utility performance is highest. Other utilities connected through the Pacific Coast Intertie would also be interested.

- Attract cooperative funding and in-kind support from other utilities, transportation systems, and such critical infrastructure as financial and medical networks.

  Support for the development of Applications Guides, and for the research that underlies the Guides, could be sought from other critical infrastructure elements (e. g. other utilities) that depend on reliable electricity and face the same earthquake hazards. Other utilities that could be partners for funding and in-kind support include water, communications, and natural gas. Water utilities have a dependence on electric utilities for pump storage systems. Communication utilities depend on electric utilities to perform their lifeline function. Electric utilities are very dependent upon gas utilities as an energy source. One common area of mutual interest is large-scale soil-structure interaction, which can affect pipelines and buried cables, as well as closely interconnected surface facilities such as large substations.

- Expand exchanges with the MCEER and MAE NSF Centers

  Each of the three NSF centers is more comfortable working alone without involvement from their regional counterparts, but the most productive research will likely come when they work together in an integrated fashion. PEER in particular is strong in ground motion and geotechnical areas and can contribute to both MCEER and MAE in hazard analysis. PEER is also strong in development of substation component vulnerability analysis, which is needed by MCEER for their models on electric system resilience. MAE, on the other hand, has developed models for emergency management in the transportation sector that MCEER could adapt for the electric sector. The MAE model would also be improved with hazard and vulnerability research from PEER. These comments illustrate how the three Centers can integrate. PEER is well positioned to contribute significantly to infill research results needed by the other two centers,

and to advance all three Centers' goals to improve seismic reliability. The PEER Lifelines Program could provide the mechanism and motivation to expand the Tri-Centers' exchanges and collaboration.

Conclusions

The PEER Lifelines Program has accomplished major progress in improving the scientific and engineering knowledge of both the earthquake hazards that threaten the electric power infrastructure and the seismic vulnerability of that infrastructure. Because of this progress, the Advisory Committee finds that the PEER Lifelines Program is highly valuable to the power industry in California, and outside of the State.

For the future, the Panel recommends continuing seven high-benefit research tasks from the end of Phase III. At the same time, it is recommended to conduct a sensitivity analysis to identify, for subsequent focused research, the major remaining risk factors. The Program should expand sharing and distribution of research results to assure more rapid and effective application of the research results. Expanded cooperation among researchers and among funding agencies and in-kind supporters will increase the productivity and application of the program.

The members of the PEER Lifelines Program Advisory Panel appreciate the insight they have gained into the Program. They hope that the recommendations and comments that are contained in this report can be well applied to encourage ongoing funding for the Program, and to encourage broadened industry involvement.

Appendix 1

PEER Lifelines Advisory Panel on Electric System Seismic Safety and Reliability

Report on Meeting of June 16-17, 2003
PEER Center Offices, Richmond, CA
June 25, 2003

Roster of Attendees

Present: Robert Anderson, Seismic Safety Commission
Edward Matsuda, Bay Area Rapid Transit
Philip Mo, Southern California Edison
Dennis Ostrom, Consultant
Craig Riker, San Diego Gas and Electric
William Savage, US Geological Survey (Chair)
Ronald Tognazzini, Los Angeles Department of Water and Power
Don Willoughby, Pacific Gas and Electric

Absent: Peter Aguila, Southern California Edison
Leon Kempner, Bonneville Power Administration
James Wight, San Diego Gas and Electric

Agenda

A copy of the agenda for the meeting is provided as Attachment 1.

Review of Advisory Panel Charge and Election of Advisory Panel Chair

Stu Nishenko opened the discussion of the formation and the role of the Advisory Panel. The background of the Inter-Utility Seismic Working Group (IUSWG) and the formation of the Advisory Panel was discussed by Stu Nishenko, David Chambers, Lloyd Cluff, Woody Savage, and others. The IUSWG was started in 1990 as an ad hoc organization of earthquake experts in California gas and electric utilities, and met as needed to address technical problems and issues facing the California utilities. Other utility organizations outside of California participated at times, including Bonneville Power Authority and BC Hydro. Some of the IUSWG technical issues evolved to be handled by the IEEE-693 Working Group, which continues to establish seismic guidance for substation equipment. The Seismic Safety Commission encouraged the involvement of the IUSWG at several points in addressing utility aspects of the Commission's five-year plans. The IUSWG was also identified as a useful source of advice for the PEER Lifelines Program, and individuals who have been involved in the Working Group have participated, either formally or informally, in providing advice on research needs and individual research projects since the inception of the Lifelines Program. The PEER Lifelines Advisory

Panel is formed from the individuals who have participated in the IUSWG, along with additional individuals who are current and appropriate technical experts within the California electric power utilities. The objective in the formation of the Advisory Panel was to establish a group that is well qualified to provide comprehensive and representative review and recommendations regarding the importance and usefulness of the applied research being conducted by the PEER Lifelines program to the electric power industry and its customers and regulators in California. The IUSWG was selected as a suitable source of members for the Advisory Committee.

Stu Nishenko initiated the selection of a chairman for the Advisory Panel, and suggested consideration of Woody Savage, who had been the Chairman of the IUSWG. No other names were proposed, and the selection was unanimous.

It was noted that the Advisory Panel did not have a member who represented the electric power operations of PG&E, while the other major utilities did have such representatives. The Advisory Panel members and the PEER Lifelines Joint Management Committee members who were present agreed that adding such a person would strengthen the Panel, and Don Willoughby, Manager of Substation Civil Engineering, was thereby added to the Advisory Panel.

PEER Advisory Panel Scope

The following four charges were provided to the Advisory Panel as the proposed scope of their activities to be conducted during the next twelve months, until the end of the current phase of work on June 30, 2004.

1. Review current PEER Lifelines research activities and projects in order to evaluate and comment on the applicability of this research towards helping achieve the goals of improved electric component and network performance and public safety

2. Recommend new directions or topics for research for the next phase of the PEER Lifelines program, including recommendations for either increasing or decreasing emphasis on specific topic areas

3. Comment on the sharing and distribution of information and research results from the PEER Lifelines program with California electric utilities and related organizations

4. Provide comments and recommendations on the coordination and leveraging of PEER research with other research programs, either currently being conducted or planned, by California electric utilities

The Panel agreed to accept the four charges as the scope of its advisory activities. The Panel recognizes the significance of the PEER Lifelines Program to improving the safety

and reliability of electric power, and appreciates the opportunity to assist the Program in reaching its goals.

Advisory Panel Observations and Recommendations

During the course of the two-day meeting, the Panel observed presentations of the purpose, content, and current status of the research topics that constitute the PEER Lifelines Research Program, and participated in the Coordination Meeting for Topic 4, Seismic Performance of Substation Equipment. These presentations and discussions provided the Panel with a broad overview of the research plan and progress, and an in-depth look at the recent results from eight research tasks in Topic 4.

The following comments, observations, and recommendations are compiled under the four charges of the Panel. These results of the Panel's meeting are interim in that they represent the initial thinking of the panel based on the presentations and discussions at the meeting and on the Panelists' previous knowledge of the PEER Lifelines Program and their expertise in matters relevant to the Program. These views will be refined after the Panel receives more information and has additional meetings during the coming 12 months.

1. Observations on the Applicability of the Lifelines Program
   - Overall, the Peer Lifelines Program has a lot of important work underway that can lead to increased understanding of the earthquake performance of existing electric power systems and to improved seismic design and performance of those systems in the future.
   - The Program research has a good chance of achieving a satisfactory balance between academic rigor and utility need. A focus should be maintained on the objective of providing knowledge and procedures that can improve utility practices and decision-making.
   - The results from Topics 1 and 2 are clearly necessary to complete the development of ground motions for simulator testing (Task 408), and can improve the ability of utilities to estimate ground motions for site-specific design criteria. The results of Task 408 are important to the IEEE-693 Working Group.
   - The ground response and ground deformation information from Topics 2 and 3 is valuable for analyzing underground facilities like buried electric lines and gas pipelines.
   - The Program needs to facilitate more dialog between the hazard characterization (Topics 1, 2, and 3) and the engineering tasks (Topics 4, 5, 6 and 7) to develop earthquake hazard parameters that can be used for fragility models that are specific to electric utilities, which can then be used for risk analysis and emergency response. Hazard characterization by others that do develop this dialog are not likely to consider the unique requirements of the electric utility industry in the State of California. There is a strong need to exchange specific information on the seismic loads that have caused or can cause various existing models of equipment to fail, and hazard parameters observed in earthquake shaking and ground deformation. For example, shake-table tests of equipment

fragility use modified recordings of real earthquakes for input; what are the damage-causing parameters for that input that can be related to parameters measured for other earthquakes?

- The research in Topic 4 is developing a lot of useful information that has already been implemented
    - Testing of connectors is valuable and leading to better connector designs and standard configurations to mitigate interconnection problems. The tasks on equipment interconnection are producing valuable results. In particular, the development of improved analytical models for interconnections between pieces of equipment is notable. These analytical models need to be advanced to a state that they can be formed into an engineering standard or a practice that can by used by utility engineers. .
    - 500 kV transformer bushing testing has revealed difficulties in meeting the IEEE-693 criteria with ceramics, and has focused vendors toward developing composite bushings that do meet the criteria.
    - The field measurements associated with substation equipment performance (Task 404) are interesting, and should provide a way to assess the dynamic response of the existing inventory of installed bushings. Some of the measurement activities seem to lack clear purpose, and might be better achieved by using measurements of natural frequencies and other properties derived from previous tests. The result from this task will build on Task 406 by gathering response data for other configurations of transformer tanks and bushing supports for validation of finite-element models. This information could contribute to definition of transformer tank design parameters to ensure consistency between bushing qualification test and tank design. Tasks 404 and 406 should be closely coordinated. This project may not reach its intended goals due to difficulties in acquiring the tank specimen, but is a topic of great interest among the utilities facing the threat of strong earthquake shaking, and the current results are promising.
    - The 500 KV disconnect switch tests, even with the porcelain overstress, have satisfied PG&E's needs for a standard structure/insulator/switch configuration.
- The Topic 5 research should focus more on smaller buildings like those used for control buildings rather than high-rise buildings. The goal should be a tool for streamlined assessment of all types (typically mill-type and simple one-story) of utility buildings that house equipment that is critical to the operational requirements of the utility. The industry needs to not be content with generic FEMA procedures, but to focus on procedures that meet utility-specific performance specifications, particularly the need for specific functionality of individual structures and their contents during and after severe earthquakes.
- The general areas of network analysis and validations of hazard codes (in Topics 6 and 1, respectively) are important and needed for current industry work. Advancement of research in this area is critical to the development of seismic mitigation programs and the damage assessment and situation analysis required in the initial phases of emergency response.

- The substation and system model being developed in Topic 6 (using data formatted and compiled in Task 413) wisely focuses on the most important components for system operation and restoration. Site-specific component fragilities should be included, particularly those of relatively vulnerable components. It would be useful to be able to identify the locations of all at-risk components in a system, such as vulnerable control buildings or older series capacitor banks. The use of this tool for network analysis enables utilities to prioritize resource allocation to improve system seismic reliability and recovery.

2. New Directions and Topic Emphasis
   - The engineering research (Topics 4 and 5) and network analysis studies (Topic 6) in the Program need accurate and comprehensive hazard information that is specific to the electric utility (Topics 1, 2, and 3) for their inputs. If the type of hazard inputs needed by electric utilities cannot be obtained from other agencies, then continued funding of research in these topics is needed.
   - Applied research is needed in improved fragilities across a range of functional states and classes of equipment, and in developing and testing methods for establishing equipment acceptance criteria.
   - As long as PEER is producing results that are useful to the electric utility industry and that are not being provided by others, the research program should continue.
   - Suggestions for future projects:
     - Evaluate energy absorption devices, including base isolation that has been researched by others such as MCEER.
     - Test additional interconnected equipment sets until test results better approximate analytical solutions.
     - Develop disconnect switch test protocols with emphasis on streamlining the procedures without loss of accuracy in predicting their behavior during seismic shaking (e.g., use equivalent supports, test only one pole of a switch).
     - Develop composite insulator acceptance criteria, following up on observations made during CCVT tests funded through EPRI by the Utility Consortium. This is needed by the IEEE-693 Working Group.
     - Continue transformer body/bushing performance investigations to achieve the planned goal of validation or change in the IEEE-693 criteria. This will likely result in guidance to transformer vendors for mitigating high bushing amplifications. The current project (task 406) may be unable to come to a reliable, generalized conclusion without more work.
     - Investigate existing transformer radiators to identify parameters that are critical to their function during and after strong ground motion.
     - For underground high-voltage electrical conduits, develop deformation capacities, and develop design features to mitigate deformation and lateral soil pressures due to interactions with adjacent structures, liquefaction and lateral spreading.
     - Study ground-motion effects at ridge-tops that may be responsible for transmission line tower failures.

- Investigate and develop vertical ground-motion attenuation relationships that can be used for electric system components.
- Investigate ground deformations in earthquakes as a function of soil depth and characteristics.
- Develop appropriate ground-motion and ground-deformation parameters for fragility studies.
- Improve NEHRP site classification scheme for electric utilities: finer scale classification, use of shear-wave profiles, include soil depths greater than 30 meters.
- Develop improved system performance metrics (coordinate with the American Lifelines Alliance electric power reliability guideline project)
- Establish specific and systematic procedures to document damage to substations and other facilities that will capture valuable performance data needed to improve both component fragility and system reliability models.

3. Sharing and Distributing Research Results

- The results of the research need to be packaged into practical recommendations and tools that can be used by the utility engineering community.
- Other organizations to involve in distribution of research results include Sacramento Municipal Utility District, Western Area Power Administration, California Independent System Operator, US Bureau of Reclamation, and the larger irrigation districts that produce and/or transmit power.
- Work with the IEEE-693 Working Group and the ASCE Technical Council on Lifeline Earthquake Engineering to receive and apply the results.
- Encourage researchers to publish their results in ASCE and IEEE journals. Articles in trade journals such as *T&D World* can raise awareness among utility engineers, equipment manufacturers, and utility customers.
- Regular presentation of the Program research results on hazards and engineering is needed to reach the intended user groups and to generate more interest in (and possible new funding for) the Program.
- Workshops are a useful means to reach specific target audiences, and are needed to distribute results in such areas as network performance and emergency response for the entire energy arena.
- Workshops with consultants to the utilities would be effective in communicating the research results in hazards, substation equipment performance, and building performance.
- A handy reference and useful compendium of PEER Lifelines results would be a single volume that included examples of the application of the results and an overview of complementary results from research done at the other NSF engineering research centers, Electric Power Research Institute, and others.

4. Coordination and Collaboration Opportunities

- There are opportunities for collaborative research with the state Office of Emergency Services (OES) and the California Utilities Emergency Association (CUEA) in addressing Topics 6 and 7.

- Network analysis (Topic 6) results can be used to identify and prioritize mitigations and to support benefit/cost, time of recovery, customer outage or cash flow analysis.
- A practical and ongoing process is needed to coordinate the PEER Lifelines Program with other relevant academic (NSF Centers, etc.) and industry (the Utility Consortium project at EPRI, with Anshel Schiff as the Principal Investigator) research efforts so that the electric utility industry and their consultants can be informed of research results and how they can be applied.
- Coordination with Bonneville Power Administration (BPA), who funds its own seismic research, should be pursued; one co-funded project with PEER was carried out in Phase 2.
- Coordination among utilities, power generators, and the CEC licensing staff regarding the need for reliable performance of transformers and other critical equipment is needed. The CEC staff should be made aware of the advancements being made in the PEER Lifelines Program so that they can determine whether those advancements should be reflected in the generator licensing requirements.

PEER Lifelines Advisory Panel on
Electric System Seismic Safety and Reliability

June 16-17, 2003
Bldg. 451, Richmond Field Station

Agenda

June 16 PEER Lifelines Research Program

10:00	Welcome/Introductions		
	Stu Nishenko	(PG&E)	
	David Chambers	(CEC)	
	Michael Riemer	(PEER)	
10:15	Review of Meeting Agenda		
10:30	Review of Advisory Panel Charge/Election of Advisory Panel Chair		
10:45	Review of PEER Lifelines Research, by Topic Areas		
	Topic 1	Earthquake Ground Motions	Norm Abrahamson (PG&E)
	Topic 2/3	Response and Deformations	Cliff Roblee (Caltrans)
	Topic 4	Substation Equipment	Eric Fujisaki (PG&E)
	Topic 5	Electric system buildings	Kent Ferré (PG&E)
	Topic 6/7	Network Analysis / Response	Norm Abrahamson (PG&E)
12:30	Lunch		
1:30	Advisory Panel Executive Session		
	General Discussion		
	Draft Advisory Panel Report / Observations & Recommendations		
4:30	Adjourn		
6:00	Group Dinner (Details TBD)		

June 17 PEER Topic 4 Coordination Meeting

9:30	Welcome/Introductions
	Eric Fujisaki (PG&E)
9:40	Task 401/403 – Rigid / Flexible Bus Interactions - Analyses (Der Kiureghian)
10:00	Task 402/403 – Rigid / Flexible Bus Interactions - Experimental (Filiatrault)
10:20	Task 404 – Improvements to Modeling (Pardoen)
10:40	Task 406 – Seismic Qualification Requirements for Transformer Bushings (Filiatrault)
11:00	Task 408 – Ground Motions for Simulator Testing (Fenves)
11:20	Task 411 – Seismic Qualification and Testing of 500 kV Disconnect Switch (Fenves)
11:40	Task 413 – Substation Equipment Database Development (Ostrom)
12:00	General Discussion

12:30	Lunch
1:15	Advisory Panel Executive Session
	General Discussion
	Draft Advisory Panel Report / Observations & Recommendations
3:45	Next Working Group Meeting
4:00	Adjourn

Appendix 2

PEER Lifelines Advisory Panel on Electric System Seismic Safety and Reliability

April 1-2, 2004
PEER Center Offices, Bldg. 451,
Richmond Field Station, Richmond, CA

Agenda

April 1	Open Session	
10:00	Welcome/Introductions	
	Woody Savage	(Panel Chairman)
	Stu Nishenko	(PG&E)
	David Chambers	(CEC)
	Jack Moehle	(PEER)
10:20	Review of Meeting Agenda	
10:30	Review of Advisory Panel Charge, June 2003 Minutes and Recommendations	
11:00	Review of PEER Lifelines Research,	
	Topic 1 Earthquake Ground Motions	Norm Abrahamson (PG&E)
12:30	Lunch	
1:30	Review of PEER Lifelines Research (continued),	
	Topic 2/3 Site Response and Permanent Ground Deformation	
	Cliff Roblee (Caltrans)	
3:00	Update on PEER Activities in Topics 4, 5, and 6	Stu Nishenko (PG&E)
4:00	Review of EPRI Lifelines Research	Anshel Schiff (EPRI)
4:30	Review of NSF Tri-Center Activities in Lifeline Engineering	Jack Moehle (PEER)
5:00	Adjourn	
6:00	Group Dinner (Details TBD)	

April 2	**Closed Session**	
8:30	Welcome	
8:45	Draft Advisory Panel Report / Observations & Recommendations	
12:00	Lunch	
	Open Session	
1:00	General Discussion	
	Brief (10-15 min) presentations by Advisory Panel members on the benefits of the PEER Lifelines program to their utility and how this information has been implemented	
2:00	Summary of Advisory Panel Observations and Recommendations to JMC	
3:00	Adjourn	

APPENDIX II

PEER Lifelines Program
Individual Project Final Reports

(See Accompanying DVD)

TOPIC SUMMARIES

Topic Summaries Index

Topic 1. Earthquake Ground Motions

Topic 2. Site Response

Topic 3. Permanent Ground Deformation

Topic 4. Seismic Performance of Substation Equipment

Topic 5. Electric System Building Vulnerability

Topic 6. Network System Seismic Risk

Topic 7. Emergency Response

Final Project Summary— PEER Lifelines Program

Project Title—**ID Number**	*Validation of Basin Response Codes*—**1A01**		
Start/End Dates	9/1/99 – 9/30/00	Budget/ Funding Source	$100,000 / PG&E
Project Leader (boldface) and Other Team Members	**Henyey/Day (SCEC/SDSU)**		

1. Project goals and objectives

Numerical simulations of wave propagation can now be done in three dimensions for models with sufficient realism (e.g., three-dimensional geology, propagating sources, frequencies approaching 1 Hz) to be of engineering interest. However, before numerical simulations can be applied in the context of engineering studies or seismic hazard analysis, the numerical methods and the models associated with them must be thoroughly validated. Task 1A01 focused on validation of the underlying numerical methodologies and computer programs employed in numerical modeling of earthquake ground motion from propagating earthquakes in 3D earth models. The emphasis in 1A01 was on idealized sources in simple earth structures. Code verification was carried out through a systematic, coordinated program of test simulations.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The project provided an essential foundation for simulation-based ground motion estimation in urban sedimentary basins.

3. Brief description of the accomplishments of the project

Tests verified the accuracy of basic equation solvers, source formulations and free surface boundary conditions, through comparisons with analytic solutions for uniform elastic halfspace problem. Further tests verified the accuracy and limitations of absorbing boundary conditions used to simulate radiation conditions at grid boundaries. Additional tests verified accuracy of material interface representation through comparisons with analytic solutions for layered a halfspace problem. Finally, test simulations were done to verify code accuracy for propagating earthquake sources. Test problems were documented and made available to any interested investigators.

4. Describe any instances where you are aware that your results have been used in industry

5. Methodology employed

Five different earthquake ground-motion simulation codes were tested. Of these, four are finite difference (FD), and one is finite element (FE). All of the FD codes use uniform, structured grids, with staggered locations of the velocity and stress components and fourth-order accurate spatial differencing of the elastodynamic equations. The codes were independently programmed. The main variations among them include: degree of computational parallelism, type of memory management (e.g., main-memory contained operation versus roll-in/roll-out from disk), free-surface boundary condition formulation, absorbing boundary formulation, material interface representation (e.g., type of averaging of material properties in vicinity of properties gradients or interface), and source formulation.

6. Other related work conducted within and/or outside PEER

The PI and several of the co-PIs conducted related SCEC research, including developmental work on the codes that were the subjects of this validation study.

7. Recommendations for the future work: what do you think should be done next?

(1) Testing of the methods for earth structure models with realistic levels of complexity, such as the SCEC Community Velocity Model, and for earthquake models with realistic levels of complexity, such as the published kinematic models of the 1994 Northridge, California, Earthquake. (2) Application of the methods to estimate basin amplification effects on seismic ground motion.

8. <u>Author(s), Title, and Date</u> for the final report for this project

Authors: S. M. Day, J. Bielak, D. Dreger, S. Larsen, R. Graves, A. Pitarka, and K. B. Olsen

Title: Tests of 3D Elastodynamic Codes

Date: September 10, 2001

9. Figures

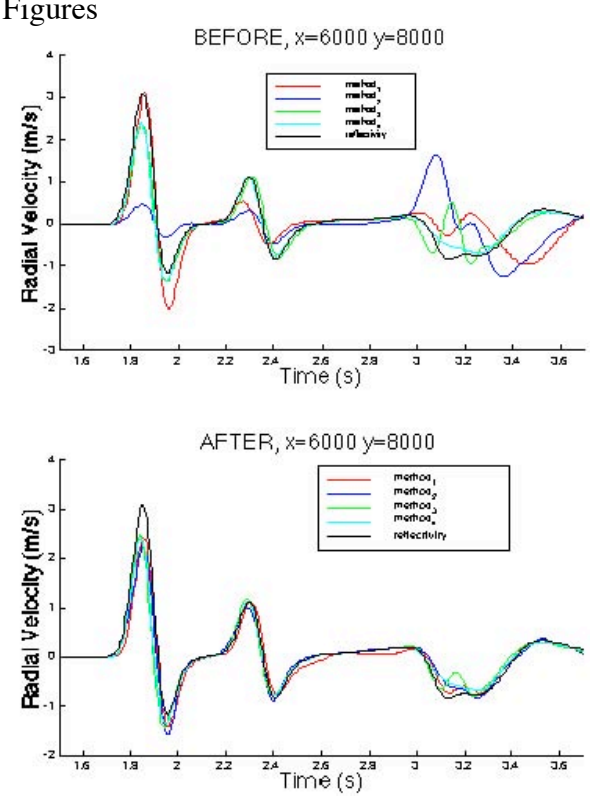


Figure 1. Comparison of results from 4 FD and FE wave propagation codes, at beginning (above) and end (below) of the validation study 1A01. Solutions are for uniform halfspace. Semi-analytic solution by integral tranform methods ("reflectivity") is also shown, for reference.

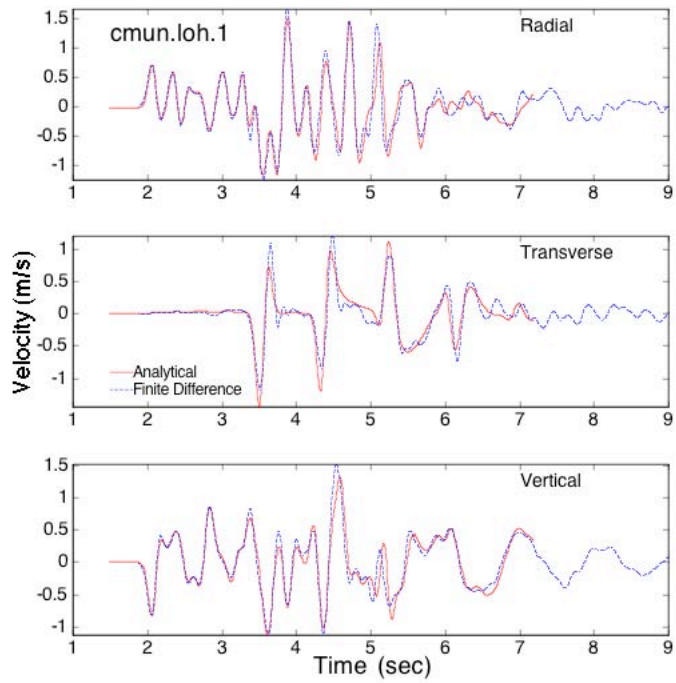


Figure 2. Comparison of FD and semi-analytic solutions for layer-over-halfspace test (point dislocation source), demonstrating accuracy of FD code.

Final Project Summary— PEER Lifelines Program

Project Title—**ID Number**	*Calibration of Basin Simulations*—**1A02/1A02a**		
Start/End Dates	10/1/00 – 12/31/02	Budget/ Funding Source	$200,000 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**Jordan/Day (SCEC/SDSU)**		

1. Project goals and objectives

Numerical simulations of wave propagation can now be done in three dimensions for models with sufficient realism (e.g., three-dimensional geology, propagating sources, frequencies approaching 1 Hz) to be of engineering interest. However, before numerical simulations can be applied in the context of engineering studies or seismic hazard analysis, the numerical methods and the models associated with them must be thoroughly validated. Task 1A02 focused on the following: (1) Test accuracy of codes in presence of complex earth structure, as represented by the SCEC Reference 3D Seismic Velocity Model (2) Test accuracy and limitations of anelastic attenuation models. (3)Test accuracy of propagating thrust fault source representation. (4) Perform simulations of Northridge earthquake.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The project provided an essential foundation for simulation-based ground motion estimation in urban sedimentary basins.

3. Brief description of the accomplishments of the project

Six new test problems were designed and carried under Task 1A02. Together, these test simulations complement an additional 4 which were carried out as part of the initial phase of the project (Task 1A01). They document very close agreement among the codes for perfectly elastic problems, and for anelastic problems over the frequency range in which the prescribed Q model is well represented by the respective codes. At the low and high frequency ends of the prescribed frequency band, those methods employing a broadband attenuation scheme agree closely among themselves and with the analytical solution, while significant departures from the analytical solution are evident for other methods.

4. Describe any instances where you are aware that your results have been used in industry

Enter text here.

5. Methodology employed

Five different earthquake ground-motion simulation codes were tested. Of these, four are finite difference (FD), and one is finite element (FE). All of the FD codes use uniform, structured grids, with staggered locations of the velocity and stress components and fourth-order accurate spatial differencing of the elastodynamic equations. The codes were independently programmed. The main variations among them include: degree of computational parallelism, type of memory management (e.g., main-memory contained operation versus roll-in/roll-out from disk), free-

surface boundary condition formulation, absorbing boundary formulation, material interface representation (e.g., type of averaging of material properties in vicinity of properties gradients or interface), and source formulation.

6. Other related work conducted within and/or outside PEER

The PI and several of the co-PIs conducted related SCEC research, including developmental work on the codes that were the subjects of this validation study.

7. Recommendations for the future work: what do you think should be done next?

Application of the methods to estimate basin amplification effects on seismic ground motion.

8. <u>Author(s), Title, and Date</u> for the final report for this project

Authors: S. M. Day, J. Bielak, D. Dreger, S. Larsen, R. Graves, A. Pitarka, and K. B. Olsen

Title: Tests of 3D Elastodynamic Codes

Date: October 10, 2003

9. <u>Figures</u>

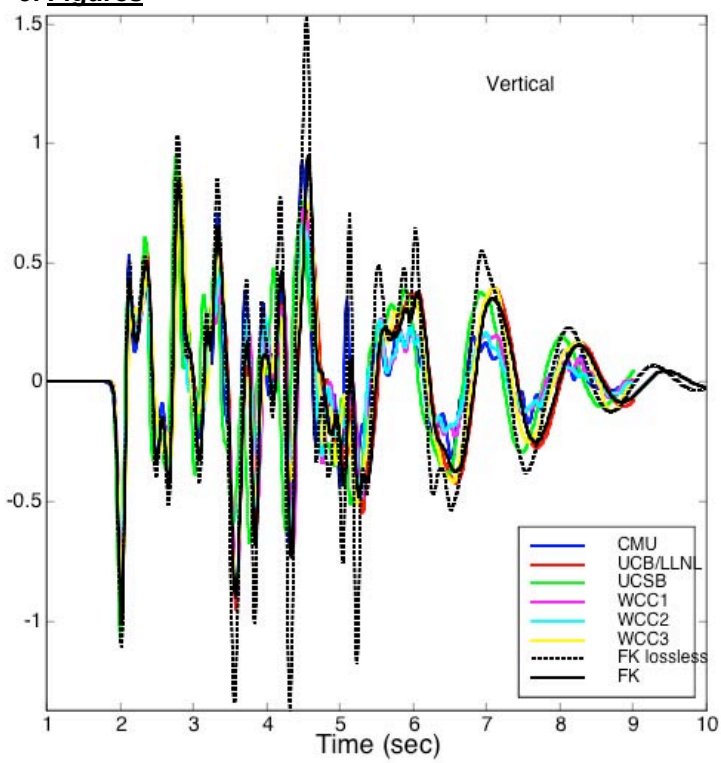


Figure 1. Comparison of FE and various FD codes for point-source problem with anelastic attenuation, showing good level of agreement among methods.

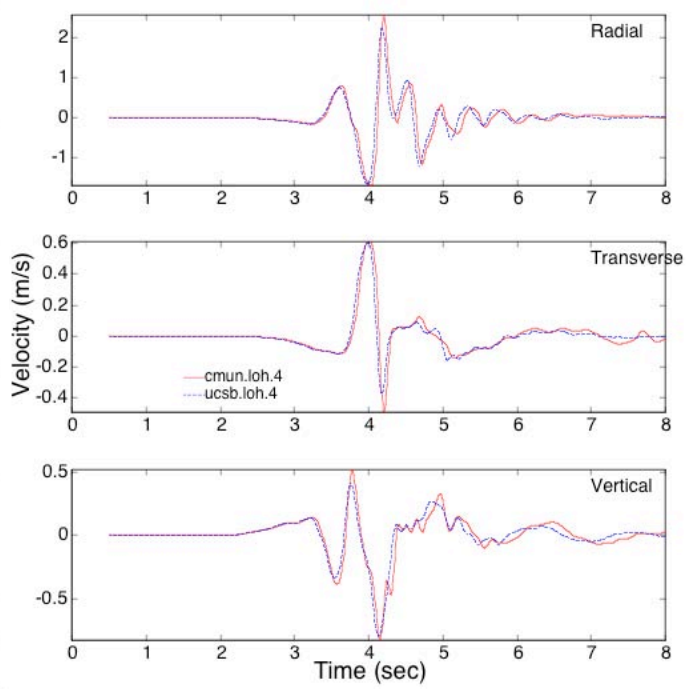


Figure 2. Comparison of FE (red) and FD (blue) solutions for propagating thrust fault source in layer-over-halfspace model.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Interim Spectral Attenuation Relations*—**1C01**		
Start/End Dates	05/01/00 – 04/31/02	Budget/ Funding Source	$56,750 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**Chiou (Geomatrix)**		

1. Project goals and objectives

There are two goals: 1. To update the Sadigh and others (SAO) attenuation model, which has been a major tool used for seismic design in California. 2. To conduct a preliminary evaluation of the potential impacts of three major 1999 earthquakes on the attenuation models used in current practice for seismic design in California.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The outcome of this project improves our understanding of the characteristics of shaking due to large magnitude earthquakes, which have a high probability to occur in California in the next 50 years. This is particularly important given that California hasn't experienced large earthquake (M>7.5) since strong-motion observatory system was established in the 1930s.

3. Brief description of the accomplishments of the project

We completed several major improvements to the Sadigh attenuation models, including the use of mixed-effects statistical model for regression analysis, overhaul of the modeling of soil effects to better capture the soil non-linear behavior and its effect on spectral shape (Figure 1), period-dependence of the style-of-faulting effect (Figure 2).

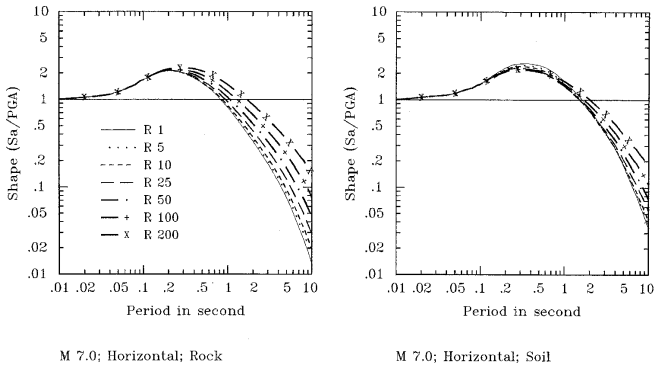


Figure 1

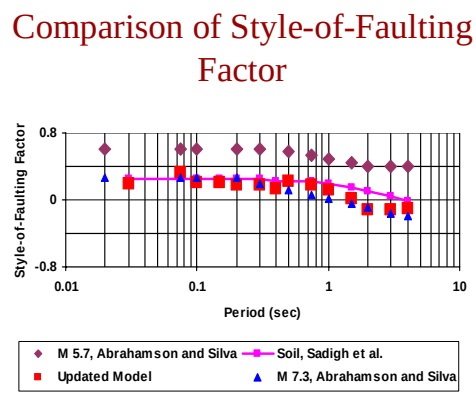


Figure 2

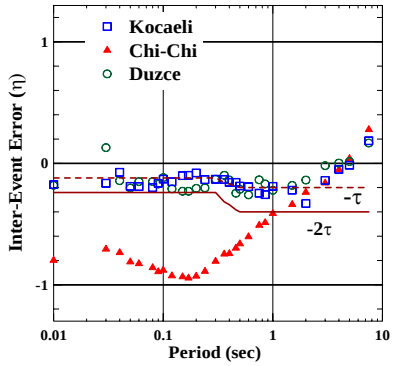


Figure 3

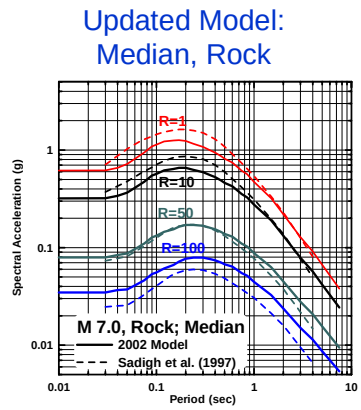
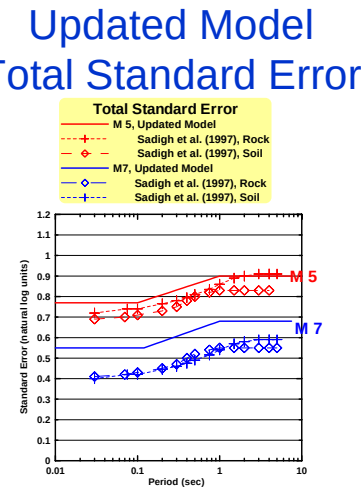


Figure 4



We evaluated the 400+ recordings from the 1999 Kocaeli (M7.4) and Duzce (M7.2) earthquakes from Turkey and the 1999 ChiChi Taiwan earthquake (M7.6). The objective is to explore their potential impacts on the predictive relationship of ground shaking in terms of both the median and the standard deviation. The main results are summarized in Figures 3 and 4. All three earthquakes generated lower-than-average shaking (Figure 3), but ChiChi is clearly an outlier in the context of SAO. Our attempt to model the 1999 data set leads to the results shown in Figure 4. The inclusion of these 1999 data increase the total standard error by about 20% due to the reduced magnitude-dependence of earthquake-to-earthquake variation stemming from the unusually low shaking of ChiChi earthquake. On the other hand, the median value (Figure 4) of high frequency motion decreases by also about 20% at distances less than 50 km. It is noted that, even with this reduction, ChiChi is still, on average, two standard errors below the median predicted for typical M7.6 earthquake. The same can be anticipated when other attenuation models are considered.

It is concluded that the attenuation models used in current practice cannot satisfactorily explain ChiChi data. The observed low level of shaking may be explained by new explanatory source parameters and/or regional differences in source/path/site effects between California and other seismically active regions.

4. Describe any instances where you are aware that your results have been used in industry

The data and supporting information collected during this project has been incorporated into the PEER strong-motion database, which has been an important resource for both industry and academy.

5. Methodology employed

(See section 3)

6. Other related work conducted within and/or outside PEER

This project sets the stage for the major research initiative of Next Generation of Attenuation Model (NGA), which is a national, multi-agencies collaboration aimed to dramatically improve our ability to predict ground-motion hazard of future major earthquake in California.

7. Recommendations for the future work: what do you think should be done next?

This study concludes that the attenuation models used in current practice cannot satisfactorily explain the lower-than-average shaking of the recent large earthquakes, particularly the ChiChi earthquake. Better understandings of the behavior of these recent large earthquakes would greatly benefit California in the area of earthquake hazard mitigation. Search for new explanatory source parameters and understanding of regional variation in source/path/site effects are thus highly recommended for the future work to be conducted under the NGA project.

8. <u>Author(s), Title, and Date</u> for the final report for this project

"Update of the attenuation relationships of Sadigh and others for shallow crustal earthquakes", Brian Chiou & Robert Youngs.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Validation of 1-D Numerical Simulation Procedures*—**1C02a**		
Start/End Dates	05/01/00 08/30/01	Budget/ Funding Source	$50,000/ PG&E-CEC
Project Leader (boldface) and Other Team Members	**Walter Silva (PEA)**		

1. Project goals and objectives

Compare the stochastic finite rupture simulations to recorded motions for five earthquakes to quantify prediction error.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

Finite rupture scenarios can be used to supplement actual earthquake recordings to provide guidance in characterizing seismic loads to engineered structures.

3. Brief description of the accomplishments of the project

All five earthquakes and specified recording sites were modeled.

4. Describe any instances where you are aware that your results have been used in industry

The simulation methodology was used to develop seismic demands for analyses at some twenty sites.

5. Methodology employed

The methodology uses a grid of small point sources distributed on a rupture surface sequentially ruptured to simulate a large propagating rupture and includes equivalent-linear site response.

6. Other related work conducted within and/or outside PEER

This same effort was performed by two other groups reflecting distinct simulation methodologies.

7. Recommendations for the future work: what do you think should be done next?

The validation should be extended to many more earthquakes.

8. <u>Author(s), Title, and Date</u> for the final report for this project

Walter Silva, Nick Gregor, Bob Darragh.
Validation of 1-D Numerical Simulation Procedures. 6/12/02.

Final Project Summary— PEER Lifelines Program

Project Title—**ID Number**	*Validation of 1-D Numerical Simulation Procedures*—**1C02b**		
Start/End Dates	05/01/00 – 11/30/01	Budget/ Funding Source	$49,992 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**Somerville (URS Corporation)**		

1. Project goals and objectives

The objective of this project is to validate procedures for numerically calculating ground motions generated during moderate and larger earthquakes. A set of target earthquakes was chosen to compare the ground motion simulation procedures against. The data were essentially limited to rock sites. The primary goal of this work was to establish the adequacy of the simulation procedures, so that they can then be used to assist in the extrapolation of existing ground motion data (e.g., to very near fault distances) within the NGA (Next Generation Attenuation) program.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The simulation methodologies analyzed in this project are being used in the NGA program to help guid the development of new ground motion attenuation models. These models will have broad application for engineering purposes throughout the Western US.

3. Brief description of the accomplishments of the project

We have validated our ground motion simulation procedure against a target set of earthquake data. The simulation procedure performs well across a broad frequency band (0.1-10 Hz), and captures many of the important features of strong ground motions, including directivity effects, basin effects, footwall / hanging wall effects, and shallow vs buried rupture effects.

4. Describe any instances where you are aware that your results have been used in industry

Our ground motion simulation procedure is currently being used in the NGA program. In addition, the methodology is being applied by the URS group within engineering projects where broadband ground motion time histories are required for specific scenario earthquake situations.

5. Methodology employed

We present a methodology for generating broadband (0 - 10 Hz) ground motion time histories for moderate and larger crustal earthquakes. Our hybrid technique combines a stochastic approach at high frequencies with a deterministic approach at low frequencies. The broadband response is obtained by summing the separate responses in the time domain using matched filters centered at 1 Hz. We use a kinematic description of fault rupture, incorporating spatial heterogeneity in slip, rupture velocity and rise time by discretizing an extended finite-fault into a number of smaller subfaults. The stochastic approach sums the response for each subfault assuming a random phase, an omega-squared source spectrum and generic ray-path Green's functions. Gross impedance effects are incorporated using quarter wavelength theory to bring the response to a reference baserock velocity level. The deterministic approach sums the response for many point sources distributed across each subfault. Wave propagation at frequencies below 1 Hz is modeled using a 3D viscoelastic finite difference algorithm with the minimum shear wave velocity set between 600 and 1000 m/s, depending on the scope and complexity of the velocity structure. To account for site-specific geologic conditions, short- and mid-period empirical amplification factors provided by Borcherdt [1994] are used to develop frequency-dependent non-linear site response functions. The amplification functions are applied to the stochastic and deterministic responses separately since these may have different (computational) reference site velocities. We note that although the amplification factors are strictly defined for response spectra, we have applied them to the Fourier amplitude spectra of our simulated time histories. This process appears to be justified because the amplification functions vary slowly with frequency and the method

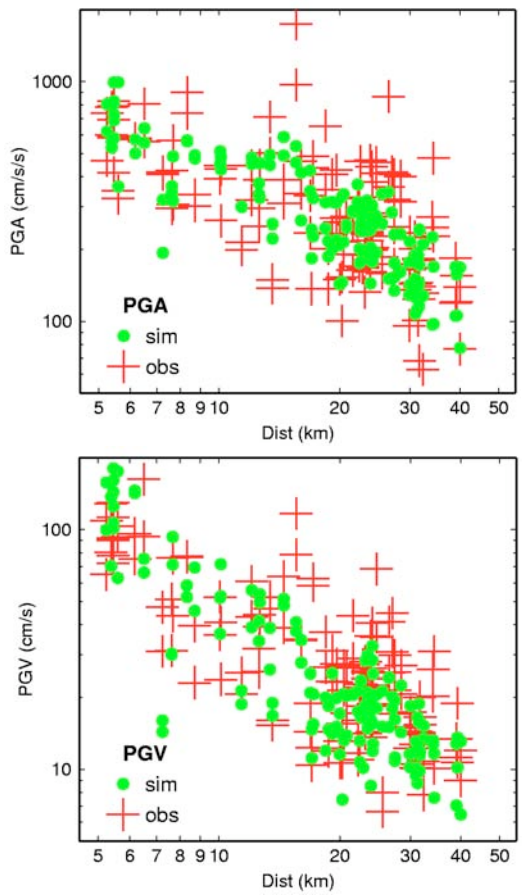


Figure 1. Observed (red crosses) and simulated (green circles) peak ground acceleration (top) and peak ground velocity (bottom) plotted as a function of closest distance to fault rupture at 69 sites for the Northridge earthquake. PGA and PGV values are measured from the observed and simulated time histories.

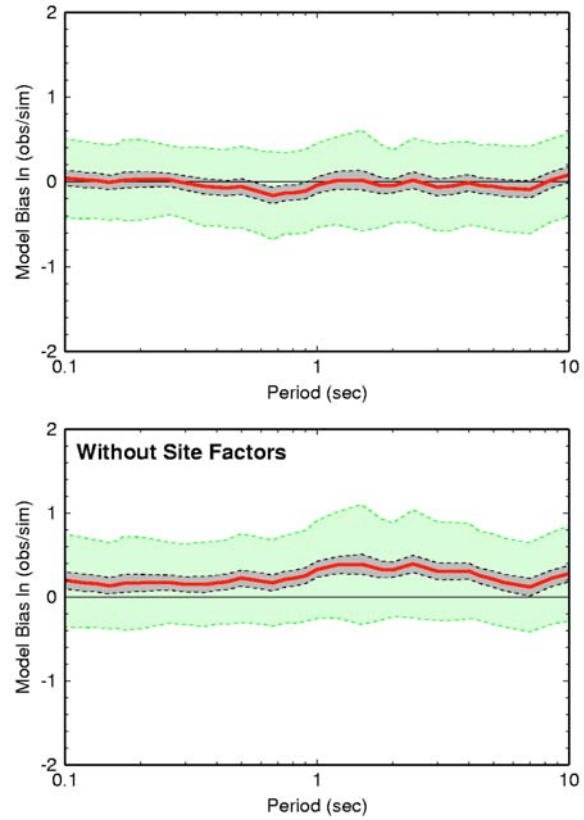


Figure 2. (Top) Spectral acceleration goodness-of-fit computed for the average of both horizontal components for the Northridge earthquake. Red line plots mean model bias averaged over 69 sites. Gray shading denotes 90% confidence interval of the mean and green shading denotes interval of one standard deviation. (Bottom) Same as top except simulation does not incorporate site-specific amplification factors.

produces favorable comparisons with observations. We demonstrate the applicability of the technique by modeling the broadband strong ground motion recordings from the 1989 Loma Prieta and 1994 Northridge earthquakes.

6. Other related work conducted within and/or outside PEER

The ground motion simulation procedure described here results from the efforts of an ongoing process to better understand the physics of earthquake rupture and seismic wave propagation. Specifically, the PIs are actively involved in projects conducted by the Southern California Earthquake Center to develop and test more robust methodologies of earthquake rupture, wave propagation and site response.

7. Recommendations for the future work: what do you think should be done next?

Continued testing of the methodology is certainly warranted. In particular, the transition between the deterministic and stochastic methodologies should be pushed to higher frequencies (currently at 1 Hz). This requires a better understanding of earthquake rupture processes and geologic structure at much shorter length scales than is current available.

8. <u>Author(s), Title, and Date</u> for the final report for this project

Paul Somerville, Robert Graves, and Nancy Collins "Validation of 1D Numerical Simulation Procedures", 2004.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Validation of 1-D Numerical Simulation Procedures*—**1C02c**		
Start/End Dates	05/01/00 – 03/31/02	Budget/ Funding Source	$50,000 / PG&E/CEC
Project Leader (boldface)	**Zeng/ Anderson (UNR)**		

1. Project goals and objectives

Our goal is to develop physically based broadband synthetic ground motion database using validated ground motion simulation procedure. This synthetic database will complement the existing observation on magnitude, distance, and frequency range. The objective of this project is to validate our composite source model using strong motion data from the 1999 Turkey and Taiwan earthquakes.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes.

Using the 1-D ground motion simulation procedure validated through this project, we have a synthetic ground motion database that includes 10 strike-slip scenarios earthquakes and 12 reverse-slip scenarios earthquakes with magnitude ranging from 6.5 to 8.5, distance from 0 to 200 km, and period from 0.01 to 10 seconds. The synthetic databases are currently used for the purpose of providing guidance to the selection of functional forms used in developing the next generation ground motion attenuation relations and to constrain the extrapolation of the relations outside the range of empirical data.

3. Brief description of the accomplishments of the project

We have computed a joint GPS static deformation and strong motion waveform inversion for the Kocaeli and the Chi-Chi earthquakes to obtain the composite source rupture processes of the events (Figure 1a and 2a) using the genetic algorithm procedure developed by Zeng and Anderson (1996). For both earthquakes, we used a fault model with curved fault planes based on the field surface rupture data. We found evidence of supershear rupture velocity for the Kocaeli earthquake fault rupture. For both events, the subevent of the composite sources shows significant slow rupture or long rise time comparing with other earthquakes we have previous studied. The total moment is 2.1×10^{27} dyne-cm for the Kocaeli earthquake and 2.9×10^{27} dyne-cm for the Chi-Chi earthquake.

We found that a variable rupture velocity for the subevent rupture of the composite sources provided an overall unbiased fit to the observed ground motion response spectra in the frequency range of 0.1 to 25 Hz. In general, we found that the composite source model has generated very realistic ground motion in comparison with the observations. For the Chi-Chi earthquake, there is systematic underprediction for stations to the south of the epicenter and slight overprediction for stations to the north of the epicenter. Overall, the composite source simulations agree very well with the observations over a broad frequency band for the ground motion amplitudes and duration (Figure 1b and 2b). This research has lead to the improved kinematic rupture model for scenario earthquake strong ground motion predictions.

4. Describe any instances where you are aware that your results have been used in industry

Result of this project has not been used directly in industry, but the simulation procedure developed from this project has been used for other applications, i.e., the DOE Yucca Mountain ground motion simulation, PEER/SCEC/USGS NGA ground motion simulation, etc.

5. Methodology employed

We have used an improved composite source model (Zeng et al., 1994) to compute synthetic strong motion seismogram. The composite source model assumes a large earthquake is a superposition of smaller subevents that all break during the earthquake rupture processes. The number and radius of the subevents follow the Guttenberg and Richter frequency-magnitude relation given in form of a power law distribution of radii, $N(r) \sim r^{-p}$ where p is the fractal dimension. Given the source parameters of a large earthquake, we can numerically generate the subevents following the power law relation. We then place these events within the fault plane and allow them to overlap. The random nature of the heterogeneities on a complex fault is achieved by distributing the subevents randomly on the fault plane. Rupture propagates from the hypocenter, and each subevent radiates a displacement pulse of a rupture crack when the rupture front reaches the subevent. Once the source has been specified, we can propagate the motion generated at the source to the site using layered crustal model (Luco and Apsel, 1983) or 3-D

inhomogeneity structure using finite difference method. The method has been successful in generating realistic strong motion seismograms. The realism is demonstrated by comparing synthetic strong motions with observations from the recent California earthquakes at Landers, Loma Prieta (Su et al., 1994a,b) and Northridge (Zeng and Anderson, 1996; Anderson and Yu, 1996; Su et al., 1998), earthquakes in the eastern US (Ni et al., 1999) and earthquakes in Guerrero, Mexico (Yu, 1994; Zeng et al., 1994; Johnson, 1999), Turkey (Anderson et al., 1997) and India (Khattri et al, 1994; Zeng et al, 1995).

6. Other related work conducted within and/or outside PEER

We have related projects funded by SCEC/PEER titled "1-D Rock Ground Motion Simulation to the SCEC/PEER NGA Initiative" and by USGS titled "Improving ground motion attenuation relation in the Great Basin", etc.

7. Recommendations for the future work: what do you think should be done next?

Current model is based on kinematic earthquake source model. Future improvement should include features of dynamic earthquake source rupture.

8. Author(s), Title, and Date for the final report for this project

Final Technical Report of the project titled "Validation of 1-D Numerical Simulation Procedures of the 1999 Turkey and Taiwan earthquakes" by Yuehua Zeng on August 29, 2002.

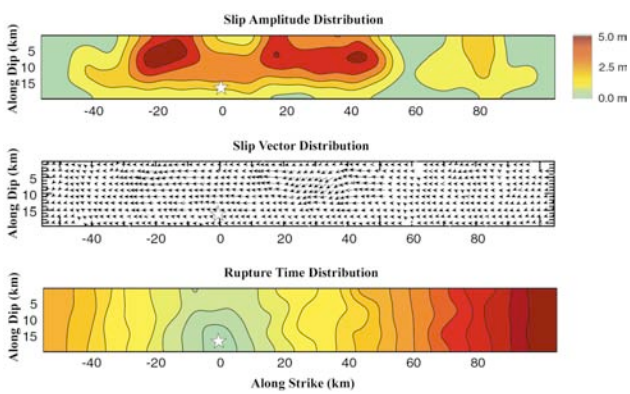


Figure 1a. The Kocaeli earthquake composite source slip amplitude, slip vector, and rupture time distributions over the fault plane.

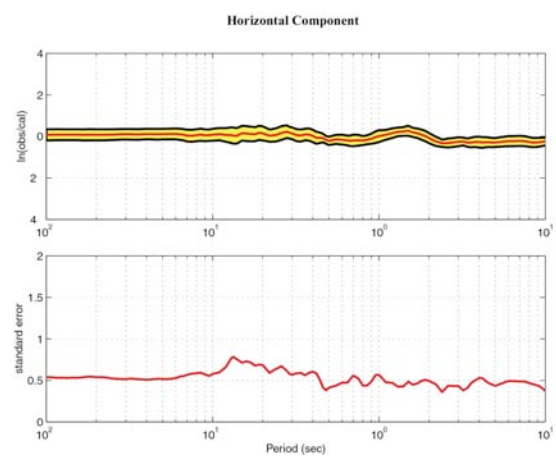


Figure 1b. The upper panel plots biases (red) and its 90% confidence limits (black) of the Kocaeli prediction for the horizontal component. The lower panel plots the standard errors.

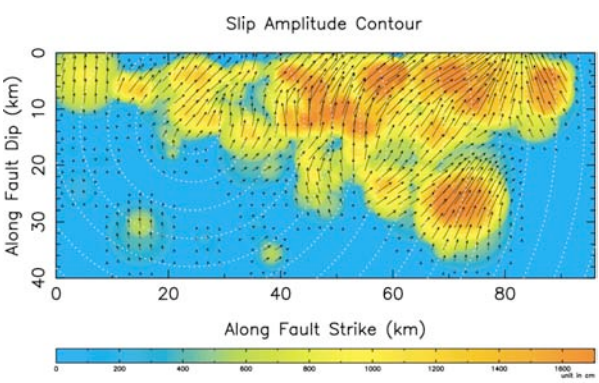


Figure 2a. The final slip amplitude and slip vector distributions of the Chi-Chi earthquake composite soruce model.

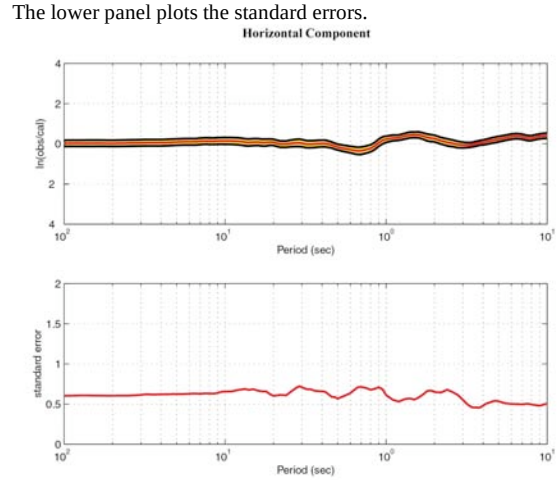


Figure 2b. The upper panel plots biases (red) and its 90% confidence limits (black) of the prediction for the horizontal component. The lower panel plots the standard errors.

Final Project Summary— PEER Lifelines Program

Project Title—**ID Number**	*Rupture model of the Duzce, Turkey EQ*—**1C03**		
Start/End Dates	4/4/01 – 3/31/02	Budget/ Funding Source	$49,947 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**Somerville (URS Corporation)**		

1. Project goals and objectives

The main purpose of this project is the determination of the slip distribution and rupture history of the 1999 Duzce (Turkey) earthquake from teleseismic body waves and local strong motion data.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The results of this project help us to understand and predict the ground shaking associated with large strike-slip earthquakes.

3. Brief description of the accomplishments of the project

Slip model

Our slip model inversion results are shown in Figure 1a The Düzce earthquake had a relatively simple slip distribution consisting of a single main asperity slightly eastward of the hypocenter and a centroid depth of approximately 10 km. The source-time function (Figure 1b) has a total duration of 20 seconds, but the moment release after the first 15 seconds is very low and insignificant. We therefore adopt a duration of 15 seconds for this event. The moment of 8.8×10^{26} dyne.cm corresponds to a moment magnitude (M_W) of 7.2. The waveform fits are plotted in Figures 1c and 1d.

4. Describe any instances where you are aware that your results have been used in industry

The resulting rupture model is used by the NGA project.

5. Methodology employed

We represented the rupture as a propagating band of slip across the fault plane that is subdivided into subfaults (4x4 km). The slip history in any of these subfaults was determined through a non-negative least squares inversion of the observed waveforms using Green's functions that were computed for a local velocity model.

6. Other related work conducted within and/or outside PEER

7. Recommendations for the future work: what do you think should be done next?

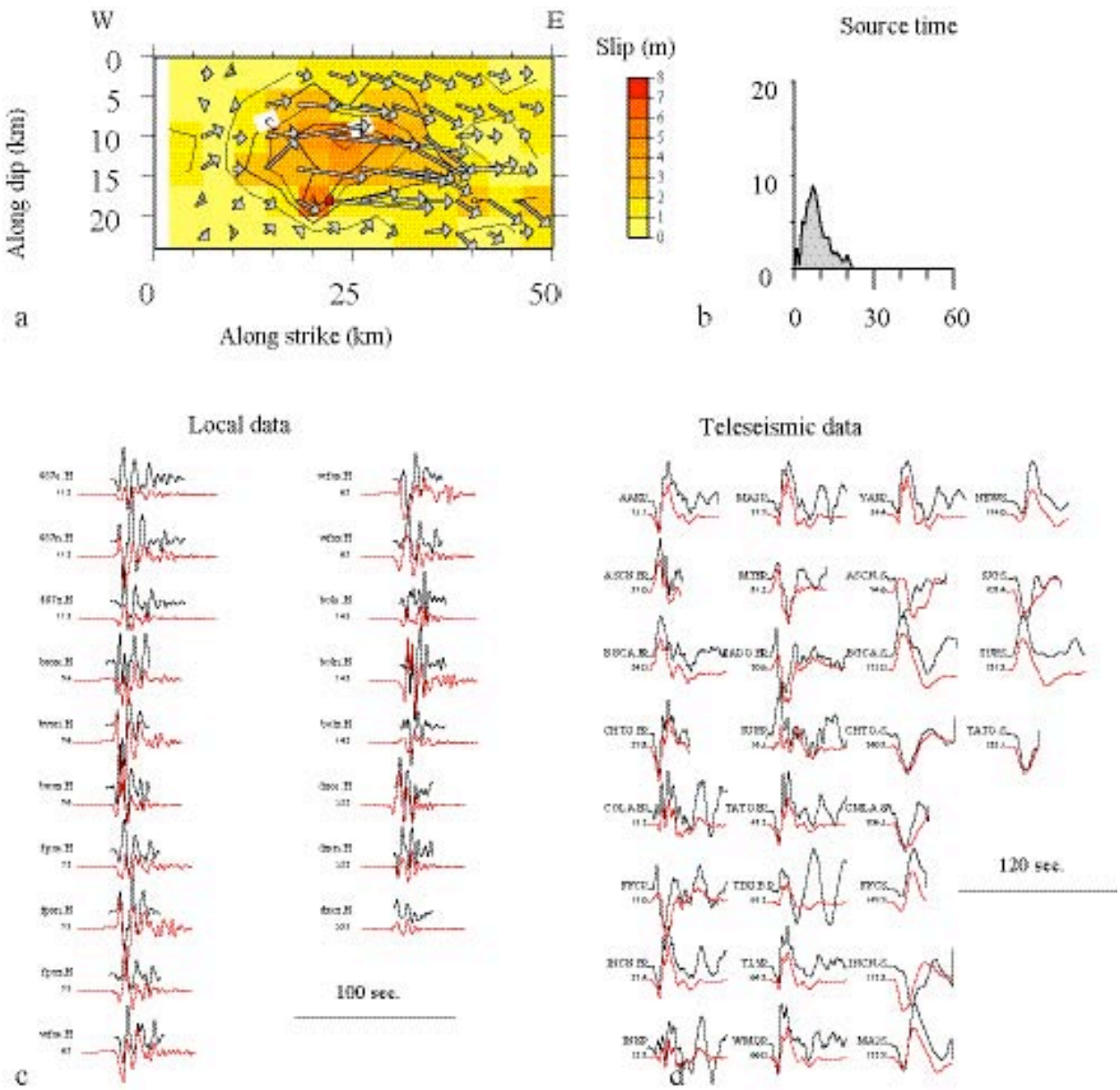


Figure 1. a - slip distribution and slip vectors on the fault plane. b - surce time function, c - strong motion waveforms (black) and synthetics (red). d - teleseismic waveforms (black) and synthetics (red).

8. <u>Author(s), Title, and Date</u> for the final report for this project

Hong Kie Thio, Robert Graves, Paul Somerville, US corp, april 6, 2002.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Contribution to Ground Motion Synthesis Report*—**1C07**		
Start/End Dates	1/1/01 – 5/30/01	Budget/ Funding Source	$9,935 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**Somerville (URS Corporation)**		

1. Project goals and objectives

The objective of the project was to collaborate with other PEER investigators in a synthesis of contemporary procedures for ground motion evaluation within a performance-based design framework. The report addresses source characterization, attenuation relations, near-fault ground motions, site effects, ground motion simulation, and time history selection.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The report described below is an up-to-date reference that explains how ground motion estimates are developed for use in performance based design.

3. Brief description of the accomplishments of the project

Dr Robert Graves and Dr Paul Somerville made contributions to the report listed below in 8. The two figures that follow this text illustrate the nature of the information that was contributed to the report.

4. Describe any instances where you are aware that your results have been used in industry

5. Methodology employed

Review of current state of practice.

6. Other related work conducted within and/or outside PEER

None.

7. Recommendations for the future work: what do you think should be done next?

Recommendations are given on pages x and xi of the report.

8. <u>Author(s), Title, and Date</u> for the final report for this project

Stewart, J.P., S.-J.-Chiou, J.D. Bray, R.W. Graves, P.G. Somerville and N.A. Abrahamson. "Ground Motion Evaluation Procedures for Performance-Based Design." Report PEER 2001/09.

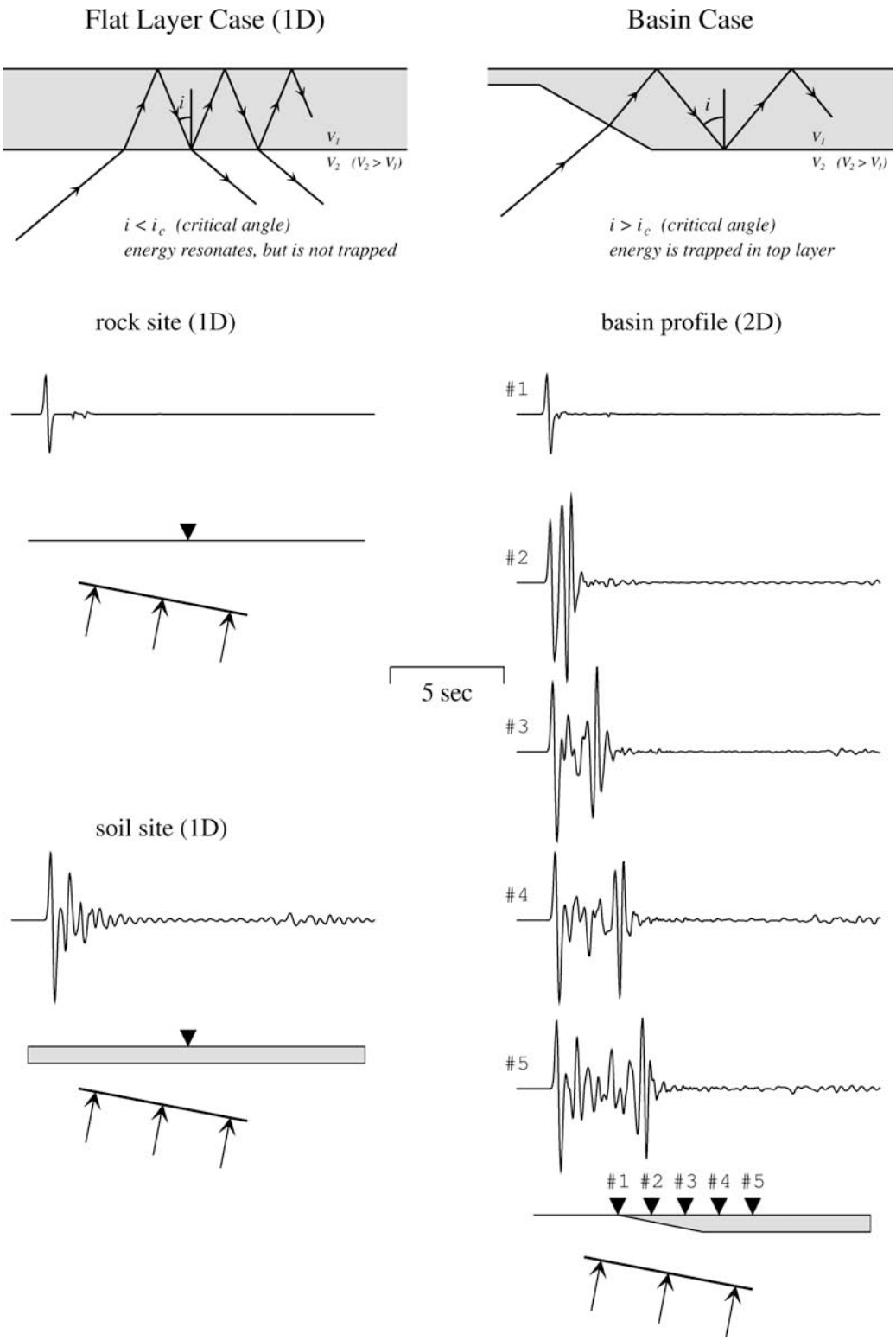


Figure 5.24. Schematic diagram showing that seismic waves entering a sedimentary layer from below will resonate within the layer but escape if the layer is flat (left) but become trapped in the layer if it has varying thickness and the wave enters the layer through its edge (right). Source: Graves (1993).

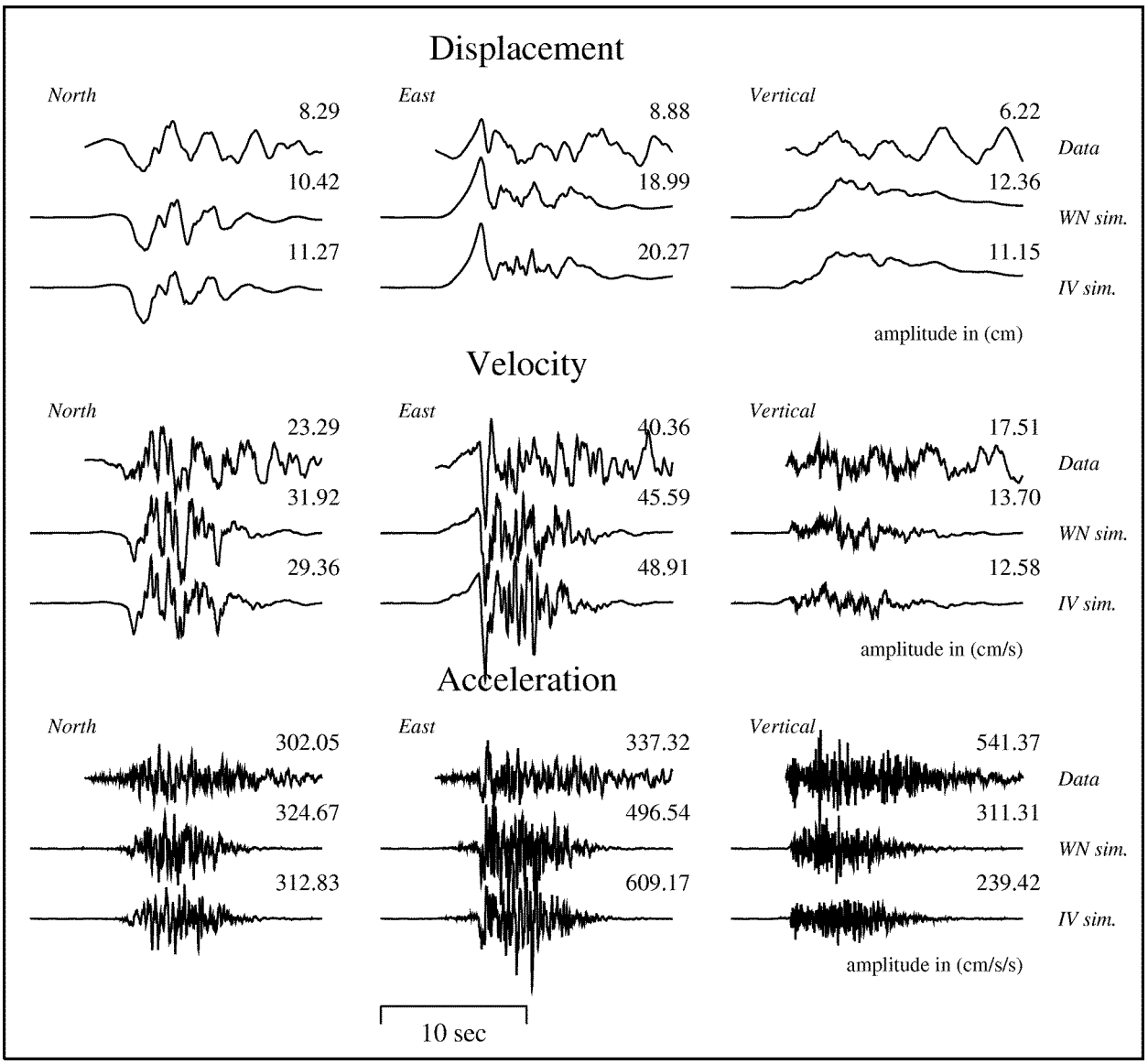


Figure 6.2. Comparison of recorded (top row) and simulated (middle and bottom rows) displacement, velocity, and acceleration time histories at Arleta from the 1994 Northridge earthquake, plotted on a common scale, with the peak value given in the top left corner. Source: Somerville et al., 1995.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Physically Based Source Input for Strong Ground Motion Simulation*—**1C08**		
Start/End Dates	6/01/02 – 5/31/03	Budget/ Funding Source	$63,262 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**Beroza (Stanford) Guatteri (Stanford – now at Swiss Re)**		

1. Project goals and objectives

The goal of this project is to develop a library of rupture models for scenario earthquakes that are consistent with the scaling and spatial variability of slip determined for past earthquakes and with simple notions of the physics of earthquake faulting.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The output of the project is being used to simulate seismograms from large earthquakes. These are in turn being used as input to the modeling component of the Next Generation Attenuation project under the PEER Lifelines Program.

3. Brief description of the accomplishments of the project

We carried out dynamic rupture modeling using the boundary integral method (BIM) algorithm [*Quin and Das*, 1989]. The pseudo-dynamic source model we developed is based on the output of this dynamic rupture modeling algorithm. We have demonstrated that we can accurately reproduce the effects of the free surface and horizontal layering in dynamic rupture modeling within the framework of the BIM using approximations that are valid for vertical faults. This was presented at a PEER/Lifelines workshop. We have also developed a library of source models for scenario strike-slip earthquakes. This was presented at the March quarterly PEER/Lifelines Workshop. A paper on the approach has been submitted to *BSSA* for publication [Guatteri, M., P. M. Mai, and G. C. Beroza, A Pseudo-Dynamic Approximation to Dynamic rupture Models for Strong Ground Motion Prediction, *Bull. Seismol. Soc. Am.*, (in press), 2004]

4. Describe any instances where you are aware that your results have been used in industry

None known.

5. Methodology employed

We have used a spatial random field model developed by *Mai and Beroza* [2002] to create realizations of scenario earthquakes. From these we create dynamic models that are consistent with them using the method of *Guatteri et* al. [2003] based on a modified boundary integral formulation. These inputs are used as a basis for predicting an approximate, physically consistent source model (*viz.*, the pseudo-dynamic approximation).

6. Other related work conducted within and/or outside PEER

We had funding from SCEC to work on the initial development of this model. We have also used it to develop seismograms in the extreme near field for a project funded by the NSF sponsored US-Japan Urban Earthquake Hazards Program.

7. Recommendations for the future work: what do you think should be done next?

Our approach was developed for earthquakes in the magnitude range of 6.5 to 7.2. We have extrapolated it to earthquakes as large as magnitude 8.2. This extrapolation is problematic for several reasons, so a project to extend and validate our method for larger earthquakes would be a natural next project. Also, if the hybrid NGAH project gets underway, then pseudo-dynamic modeling would be a natural way to treat the source as the starting point for simulating strong ground motion.

8. <u>Author(s), Title, and Date</u> for the final report for this project

Gregory C. Beroza and Mariagiovanna Guatteri (Department of Geophysics, Stanford University)
1C08: "Physically Based Source Input for Strong Ground Motion Simulation"
November 18, 2003

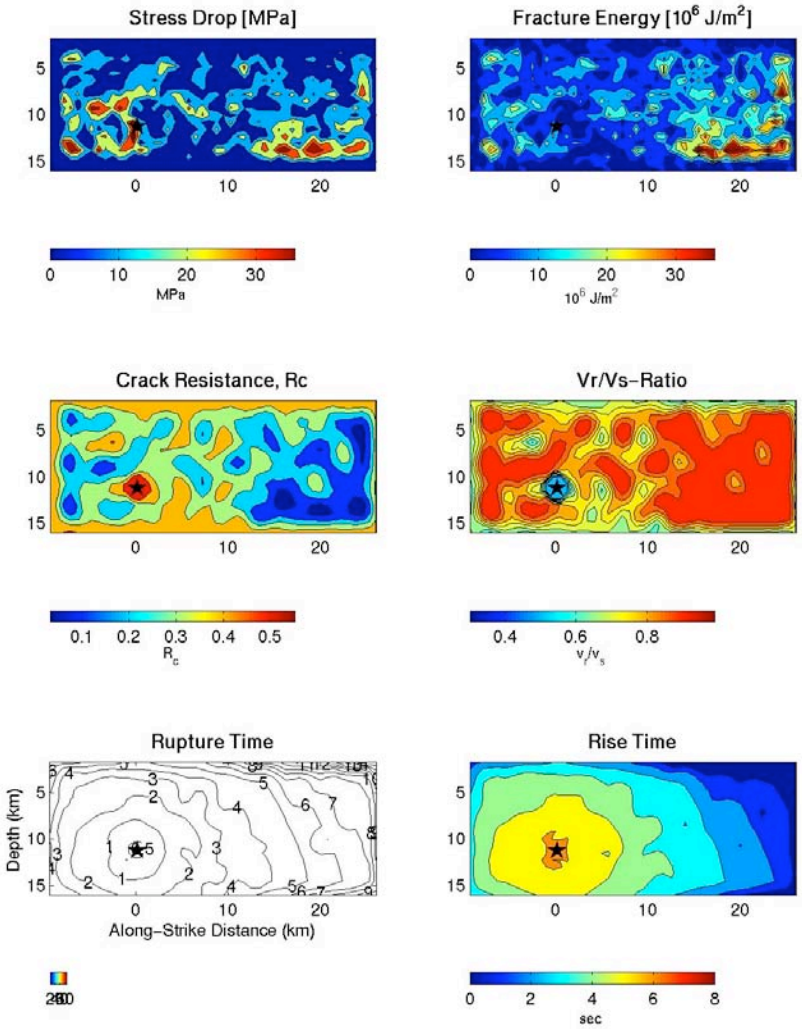


Figure 1: Example representing the pseudo-dynamic procedure [. The starting point is a slip realization generated as a spatial random field [Mai and Beroza, 2002], which yields a corresponding stress drop distribution computed using the method of Andrews [1981] shown in the upper left panel. Upper right panel shows a fracture energy distribution determined in such a way the the average rupture velocity is subshear. The crack resistance (middle left) determines a direct mapping to an approximate local rupture velocity (middle right). Rupture time (lower left) is determined from this and rise time is estimated based on the overall dimensions of the slipped region.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Experimental Model for Rupture Directivity Effects*—**1D01**		
Start/End Dates	05/01/00 – 8/30/03	Budget/ Funding Source	$121,877 / Caltrans
Project Leader (boldface) and Other Team Members	**Brune/ Anooshehpoor (UNR)**		

1. Project goals and objectives

Understanding earthquake rupture dynamics, especially forward rupture directivity, is crucial in determining the seismic hazard for critical structures located near major active faults. Numerical models currently in use have too many unconstrained parameters to allow confidence in predictions, and may not even be realistic from a physical point of view. The overall objective of this project is to use foam rubber modeling experiments to provide constraints on parameters that control rupture dynamics, and consequently, forward directivity effects.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

This project has the potential for better understanding of the rupture process and ground motion effects in the near field, and validation of simulation methods which can be applied to a wide variety of cases and eventually provide realistic forward simulations for time-history based design. Developing an in-depth understanding of this particular physical (and thus physically realistic) model allows us to greatly improve our understanding of the various modeling parameters involved, and consequently improve our understanding of the true seismic hazard near large active faults.

3. Brief description of the accomplishments of the project

Data from experiments simulating unilateral strike-slip motion agreed well with 3D numerical simulations of the shape, duration, and absolute amplitude of the direct acceleration pulses. Directivity was evident in both peak accelerations and pseudo-spectral accelerations, the amplitude of the fault-normal component of acceleration generally larger than the associated fault-parallel component. Waveforms agree with an empirical directivity model for earthquake strong-motion spectra at long periods. We investigated the effects of shallow weak layer on the near-fault ground motions by introducing plastic strips of different widths on the fault plane, near the surface. Accelerations recorded on or close to the weak layer show significant reduction in amplitudes, even though the total slip is similar to the case without a weak layer (increased slip rise-time). Surface acceleration amplitudes decrease rapidly with increasing depth of the weak layer. We also recorded results from a variety of anti-asperity (weak patch) models.

4. Describe any instances where you are aware that your results have been used in industry

Not aware of any.

5. Methodology employed

The strike-slip model consists of two large blocks of foam rubber, one driven horizontally past another by a hydraulic piston (Fig. 1). As the upper block is forced to slide over the lower block, the strain in the blocks increases until the stress at the interface exceeds the frictional resistance and a stick-slip event occurs over the entire fault plane.

Fig. 1 (left) shows the locations of the sensors. There are 76 recording channels, of which 35 are on the fault plane and 41 on the free surface. Fig 2. (right) shows a stick-slip event recorded on all 76 channels.

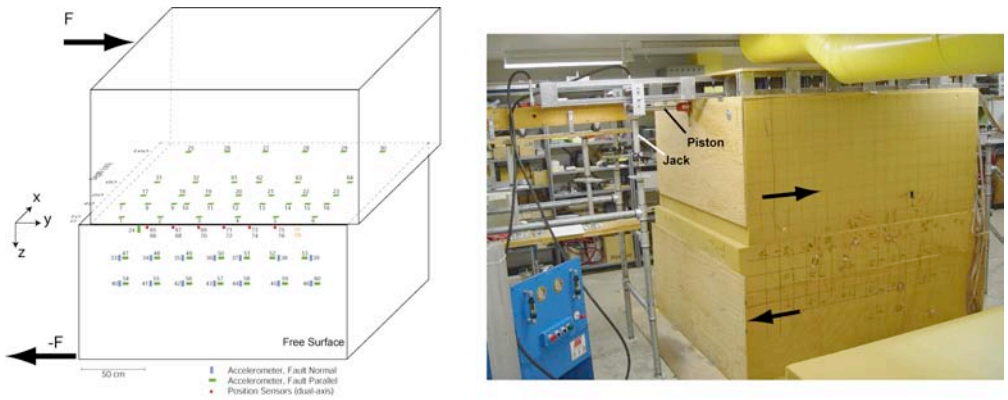


Figure 1: A photograph of the foam rubber model of strike-slip faulting (right) and a diagram showing the type and location of the sensors.

The numbers next to each trace match those in Fig. 1. The first 64 traces are accelerations and the last 12 displacements. Plots on the left side of Fig. 2 show fault-parallel and fault-normal components of ground motions on the surface along two profiles parallel to the fault trace at distances of 25 and 45 cm. Increasing acceleration amplitudes at stations in the rupture direction indicate a strong forward directivity. Note that the fault-normal components are generally larger than the corresponding fault-parallel components.

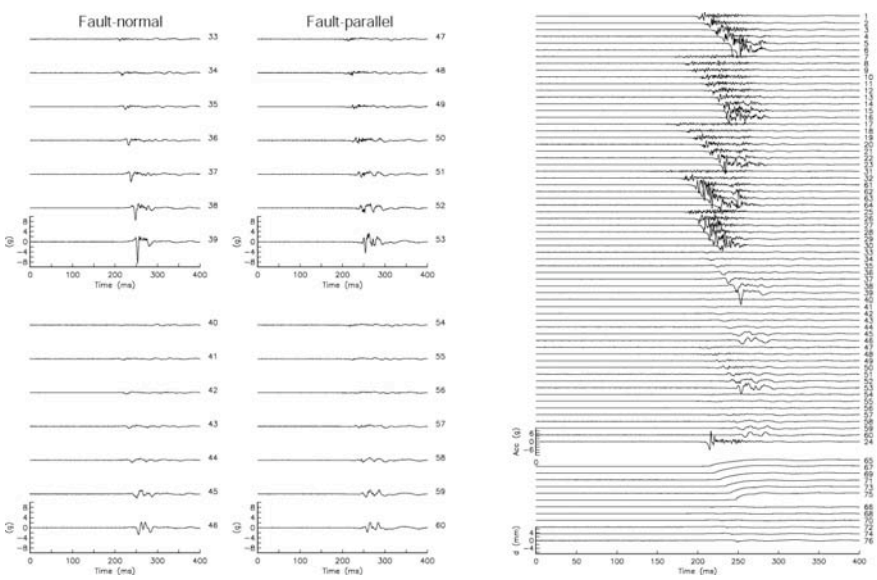


Figure 1

6. Other related work conducted within and/or outside PEER

There is not similar work outside PEER, but within PEER, data was used for comparison with simulation methods, 1D02 project.

7. Recommendations for the future work: what do you think should be done next?

Further studies of more complex asperities on the fault and use of a layered model to study rupture dynamics and the resulting strong ground motions.

8. <u>Author(s), Title, and Date</u> for the final report for this project

Rasool Anooshehpoor and James N. Brune, Study of Rupture Directivity in a Foam Rubber Physical Model, July 2004.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Utilization of Physical Model Data to Validate Numerical Procedures for Near-Field Motions*—**1D02**		
Start/End Dates	9/1/01 – 10/31/03	Budget/ Funding Source	$120,000 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**S. M. Day,** R. Graves, A. Pitarka, Y. Zeng, W. Silva		

1. Project goals and objectives

The objective of Project 1D02 was to determine whether numerical procedures for simulating ground motions are capable of capturing the near-field effects of an earthquake. Ground-motion time histories generated from the rupture of a foam rubber model were used as the "data" against which several widely used simulation procedures were tested.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

Earthquake modeling using a foam rubber model automatically accounts for the source and wave propagation effects in a controlled environment. Data obtained from the foam rubber modeling not only directly provides important insights into the near-field effects, but also provides a set of time histories against which numerical procedures can be validated.

3. Brief description of the accomplishments of the project

The analysis and numerical modeling of the data led to an improved understanding of the foam rubber experiments. Two types of experimental events were identified, for which the directivity effects were very different: those events that ruptured mainly along strike, and those with highly oblique incidence, respectively (Fig 1). Model rupture velocities were determined and found consistent with predictions from numerical modeling with dynamic rupture code DFM. Measured directivity effects (as quantified by the slope of a spectral-ordinate-versus-Xcos(theta) regression) on response spectra are comparable to predictions from earthquake regression models at periods comparable to and greater than the S transit time across the fault (Fig 2). However, the foam data have higher directivity slopes than real earthquakes at shorter periods. The latter suggests that, in real earthquakes, disordering effects such as frictional and elastic heterogeneity reduce short-period directivity relative to simple models. In addition, comparison of DFM simulations and recorded waveforms aided in the identification and correction of reported model parameters (S and P velocities). Simulation of recorded waveforms by kinematic modeling techniques, after a numerical model calibration using a subset of the recorded data, had good predictive capability for the remainder of the data. A calibration error (factor of two amplitude scale factor) in the data was reported to us after completion of the technical work, limiting our ability to draw firm quantitative conclusions from the numerical simulations at present.

4. Describe any instances where you are aware that your results have been used in industry

5. Methodology employed

The scale-model earthquakes were done under separate support and are described elsewhere. Project 1D02 used an explicit, 3D finite difference code, DFM, to model the dynamics of the foam experiments. The kinematic simulation component of the project used 4 different methods: 2 kinematic models based upon different frequency-wavenumber transform methods, a kinematic-source finite difference method (explicit, fourth-order in space, second-order in time) and a primary-only ray-theory approach. The former 3 include elastic waves of all types (in the context of isotropic elasticity), while the latter includes only far-field terms, and only those associated with primary body-wave arrivals.

6. Other related work conducted within and/or outside PEER

The foam rubber experiments were performed by University of Nevada, Reno, under separate PEER support. The kinematic simulation methods were calibrated to earthquake data under separate PEER Lifelines projects.

7. Recommendations for the future work: what do you think should be done next?

Subsequent to the completion of the technical work for this project, the foam rubber data supplied to the project were determined to be mis-calibrated by a factor of two. The numerical simulations done for this project therefore needs to be updated, using new kinematic and dynamic simulations appropriate to the correctly calibrated foam rubber data. Further numerical modeling of data from foam rubber experiments has great potential for testing dynamic rupture models and proposed finite-source inversion methods, both of which are important to ground motion simulation methods in use or under development.

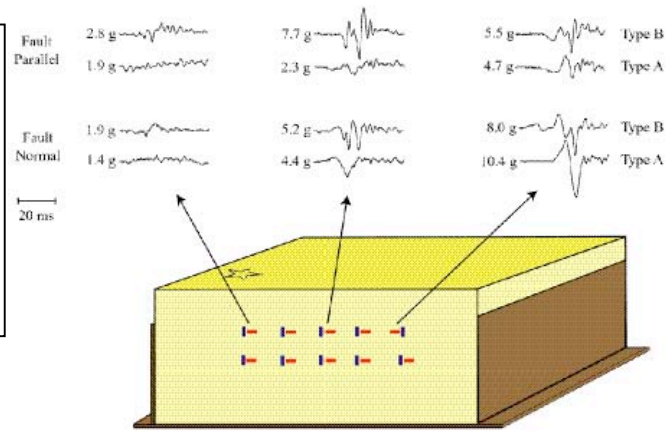
8. Author(s), Title, and Date for the final report for this project

Authors: Steven M. Day, Robert Graves, Arben Pitarka, Walter Silva, Yuehua Zeng, Rasool Anooshehpoor, and James N. Brune

Title: Utilization of Physical Model Data to Validate Numerical Procedures for Simulating Near-Field Motions

Date: Pending

Fig 1. Comparison of fault parallel and fault normal acceleration records for sensors located 25 cm from fault trace (fault plane in dark yellow; sensors are on free surface plane, shown in light yellow). Events labeled "Type A" were found to have predominantly along-strike rupture direction. "Type B" events had highly oblique rupture direction. Note very different waveforms and directivity patterns for the 2 types of events.



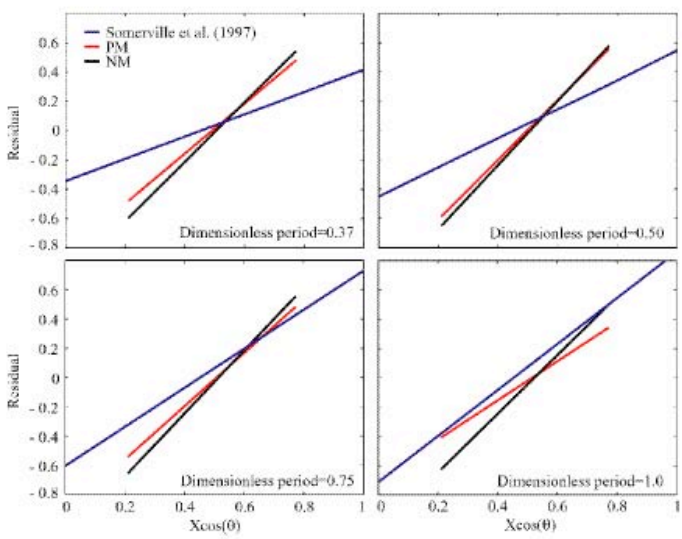


Fig 2. Regression lines for residuals as function of directivity variable Xcos(θ), for DFM numerical model (black), foam model (red), and empirical earthquake model (blue—from Somerville et al, 1997, *Seism. Res. Letters*). A dimensionless period is used as basis of comparison between scale-model and real earthquake data, where a dimensionless period of 1 corresponds to S wave transit time across fault width.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Update Ground Motion Database with Data from Turkey and Taiwan*—**1E01**		
Start/End Dates	06/1/00 — 6/30/01	Budget/ Funding Source	$30,000 / PG&E-CEC
Project Leader (boldface) and Other Team Members	**Walter Silva (PEA)**		

1. Project goals and objectives

This project was to provide additional strong motion data for the PEER NGA project. Specifically to process and make available data from the recent Chi-Chi, Taiwan as well as Koaceli and Duzce, Turkey earthquakes.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

Data from these earthquakes increased five fold the world wide recordings of earthquakes with magnitude greater than 7 and distances within 20 km, typical design cases for California.

3. Brief description of the accomplishments of the project

Addition of some 400 processed recordings to the PEER strong motion database to constrain near fault motions at large magnitude as well large distance fall-off of motions, both necessary for the PEER NGA project.

4. Describe any instances where you are aware that your results have been used in industry

Data set of processed records have been used on several projects to characterize time histories for engineering design.

5. Methodology employed

Records were processed to remove instrument response and both high and low-frequency noise.

6. Other related work conducted within and/or outside PEER

This data set complements a larger data set which comprises the PEER strong motion data base, also developed by Pacific Engineering for PEER.

7. Recommendations for the future work: what do you think should be done next?

Data from subduction zone earthquakes as well as eastern North America should be added to have, in one place, a complete repository of consistently processed data of strong ground motions.

8. <u>Author(s), Title, and Date</u> for the final report for this project

Walter Silva

Update Ground Motion Database with Data from Turkey and Taiwan.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Attenuation Relations for Velocity and Displacement*—**1E02**		
Start/End Dates	06/1/00 – 11/30/01	Budget/ Funding Source	$30,000/ PG&E-CEC
Project Leader (boldface) and Other Team Members	**Walter Silva (PEA)**		

1. Project goals and objectives

Based on newly added data from recent large earthquakes as well as existing data in the PEER strong motion database, attenuation relations were developed for several intensity measures: peak acceleration, peak particle velocity, and peak displacement. To properly characterize peak particle velocities and peak displacements, special effort was made to preserve static displacements at close distances (< 20 km) to large (**M** > 7.4) earthquakes.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

These intensity measures are used to characterize seismic loads on engineered structures such as lifelines. Lifelines are particularly distressed by static displacements, particularly bridges and pipelines.

3. Brief description of the accomplishments of the project

Magnitude, distance, and site dependencies of these peak intensity measured were captured along with their uncertainties. Figures 1 and 2 show resulting attenuation relations for data processed to retain static displacements and relations developed (which filters out any static displacements) with traditional processing, respectively.

4. Describe any instances where you are aware that your results have been used in industry

Not aware of any usage as yet.

5. Methodology employed

Nonlinear regression analyses was used to determine values for the coefficients in the regression equation. Independent variable were magnitude and rupture distance. Site conditions were soft rock and deep firm soil.

6. Other related work conducted within and/or outside PEER

Results of this project will be updated with the PEER NGA project.

7. Recommendations for the future work: what do you think should be done next?

The effects of spatial correlation in strong ground motion should be included in defining seismic loads on lifelines. Spatial correlation models need to be developed with the same data used in developing attenuation relations.

8. <u>Author(s), Title, and Date</u> for the final report for this project

Nick Gregor, Walter Silva, Bob Darragh.

Attenuation Relations for Velocity and Displacement. June 12, 2002.

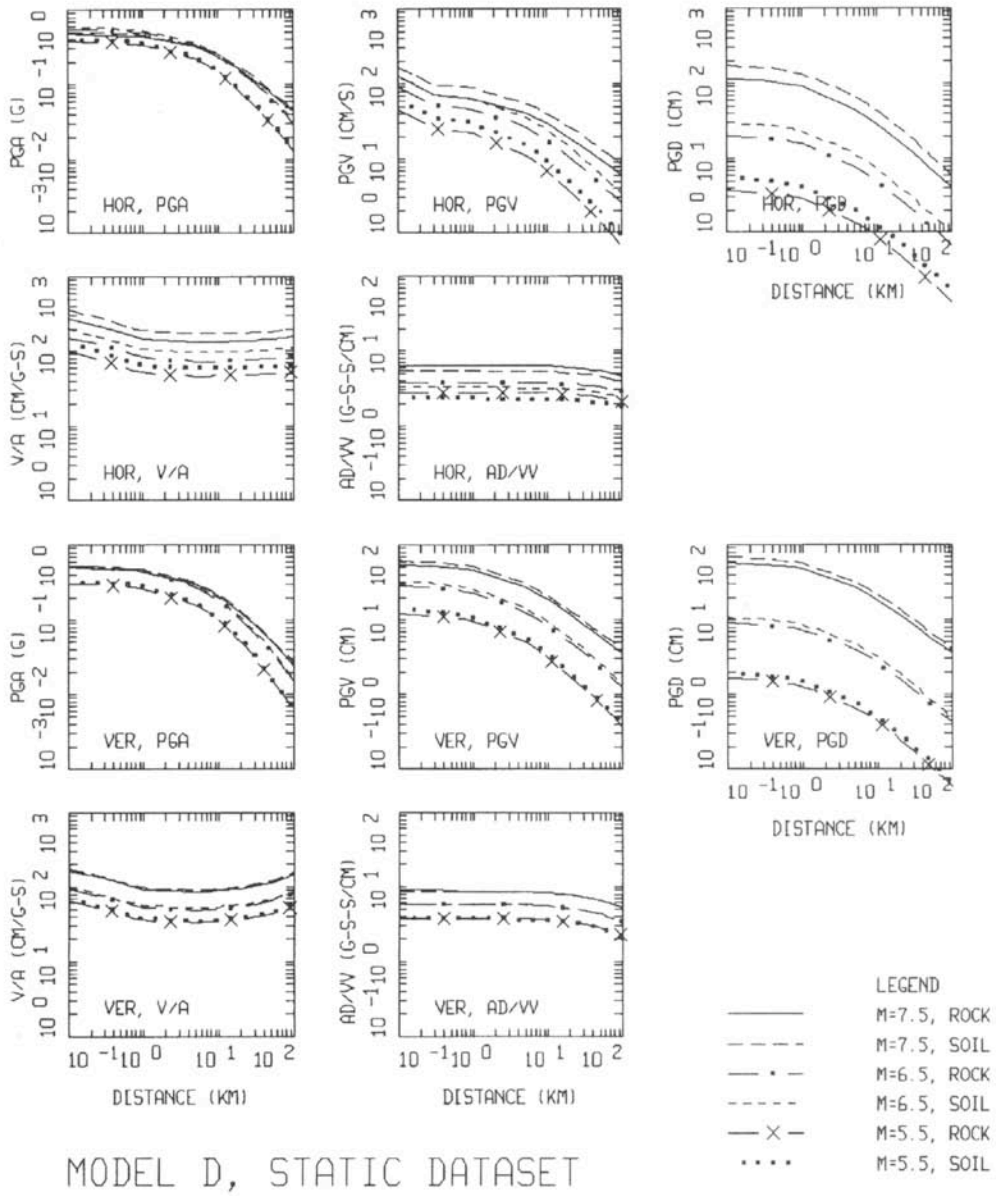


Figure 1. Peak ground motion estimates for **M** = 5.5, 6.5, and 7.5 based on the functional Model D form and the static dataset assuming a strike-slip mechanism.

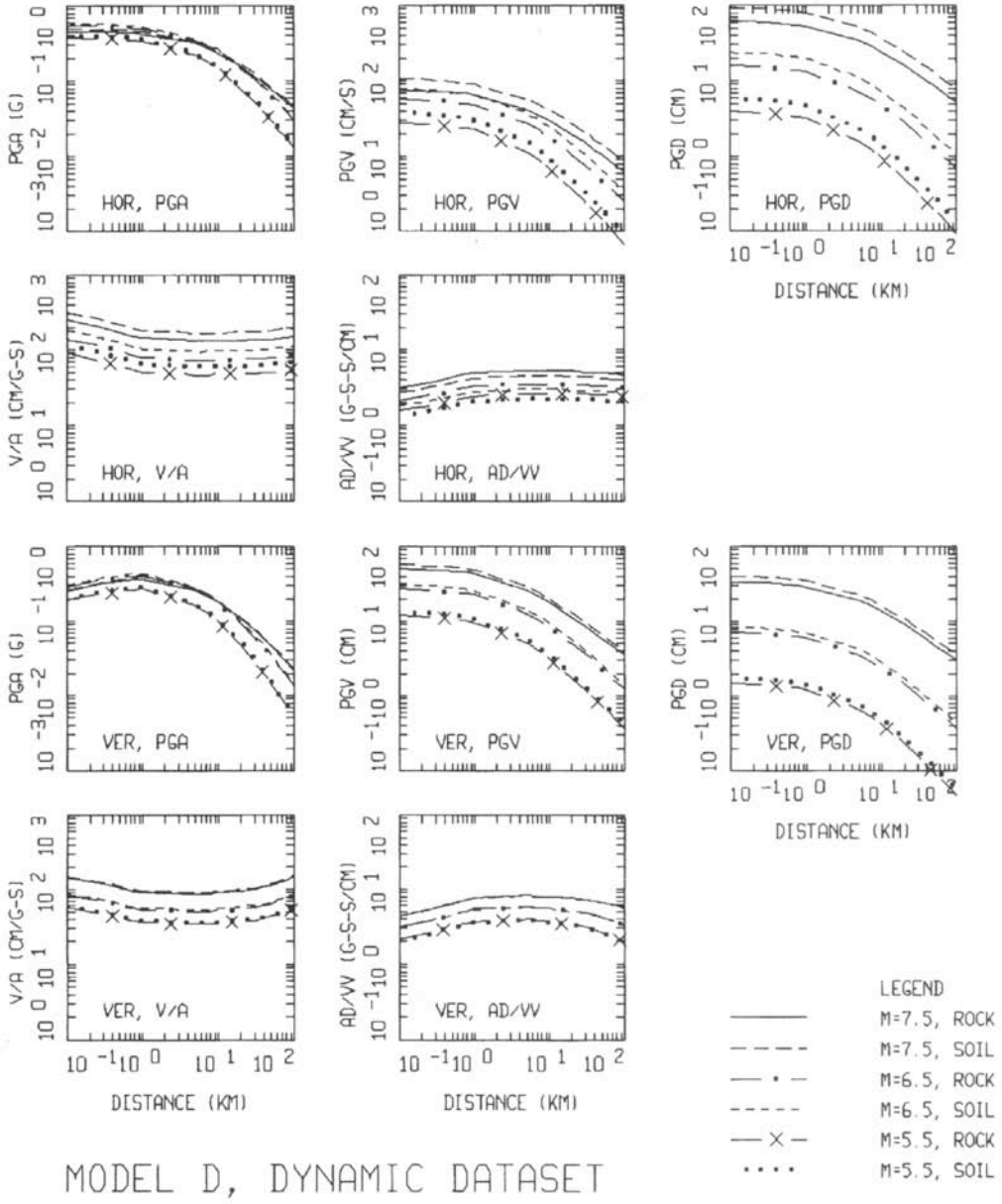


Figure 2. Peak ground motion estimates for **M** = 5.5, 6.5, and 7.5 based on the functional Model D form and the dynamic dataset assuming a strike-slip mechanism.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Database for 1999 Chi-Chi (Taiwan) Earthquake*—**1E04**		
Start/End Dates	1/1/01 – 12/31/01	Budget/ Funding Source	$60,000 / Caltrans
Project Leader (boldface) and Other Team Members	**Kiremidjian (Stanford)**		

1. Project goals and objectives

The purpose of this proposal is to select and process at least 20 large aftershocks (M>4) at 20 or more well recorded stations form the September 20, 1999 Chi-Chi (Taiwan) earthquake. The recordings will result in a database that will augment the existing strong motion database currently available from the main shock of that event.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The aftershock database represents the first such database for a major earthquake. Since the aftershocks were also of significant size, the database combined with the mainshock database can provide the opportunity for a variety of ground motion studies. These include various directivity affects, local soil effects, ground motion propagation effects among the many. Correlations between mainshock and aftershock ground motions can also be investigated – something that has never been studied, but can have serious implications for building performance in large earthquakes followed by significant aftershocks.

3. Brief description of the accomplishments of the project

The strong motion data for 33 aftershocks from the 1991 Chi-Chi, Taiwan earthquakes were processed and synthesized in a database. A total of 3,153 strong motion records including 5 aftershocks with magnitude greater than 6 and 9 aftershocks with magnitude greater than 5. Of these, 400 records were rejected due to dead component trace, belated triggering or 12-bit accelerographs, a total of 2,753 acceptable strong motion records were obtained. They are organized in a set of two CD-ROMs. The CD's also contain software that makes it easy to search the database and retrieve strong motions according to magnitudes, component direction and record number. Included in the database is also information on each aftershock for subsequent referral. The CD-ROMs are available upon request. A report describing the strong motion database was also published.

4. Describe any instances where you are aware that your results have been used in industry

This database is now available as part of the general ground motion database that can be used in site specific ground motion estimation. We are not aware of specific instances where these ground motions may have been used in practice.

5. Methodology employed

The following steps were used in the development of the database:

1. *Initial processing:* All records were converted into the same format called PC-SUDS and errors in the header information were corrected.

2. *Time correction and file association with an earthquake:* Most Taiwan Central Bureau (CWB) accelerographs did not have accurate GPS time synchronization, and their internal clocks night have been manually set incorrectly and/or drifted substantially over time. Lee et al. (2001a) procedure was used to correct the timing of records to at most 2 seconds for stations within 100 km.
3. *Quality assurance*: An interactive program called SMQC by Dodge and Lee (2000) was used to perform quality assurance of the associated strong-motion data files for a given earthquake. An analyst verifies that the predicted P and S arrival times are agreeable with the actual observed arrivals, DC-offsets are removed, spikes (if present) are removed, and any unusual appearance of the recorded accelerograms is noted.
4. *Final processing*: Strong-motion records are then plotted and visually inspected. Any records with defects (e.g. triggered late, or recording has defects, or timing is uncertain) are rejected. The remaining records are placed in a file under sub-directory called SUDfiles.
5. *ASCII files*: Readable ASCII text files corresponding to those under the sub-directory SUDfiles are created using the SUD2ASC program. These ASCII text files are placed under the sub-directory call ASCfiles.
6. *Auxiliary information*: A station map showing the location of the accelerographs with acceptable records is plotted along with the location of the aftershocks. In addition, two tables of station information are generated to aid the users with the selection of the data files: one table is listed according to increasing epicentral distance, and the other is alphabetical by station name.

6. Other related work conducted within and/or outside PEER

N/A

7. Recommendations for the future work: what do you think should be done next?

Conduct extensive correlation studies on the mainshock-aftershock data from these databases; investigate phase angle and directivity effects; develop complete Fourier transform information for ground motions simulation purposes …

8. Author(s), Title, and Date for the final report for this project

Lee, W. H. K., Lai, J. and Kiremidjian, A. S., "Development of Aftershock Strong-Motion Database for the 1999 Chi-Chi (Taiwan) Earthquake", Final Report with Processed Data flies for 33 Aftershocks on Two CD-ROMs, The John A. Blume Earthquake Engineering Center, Stanford University, Stanford, California, August 26, 2001.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Seismic Moment Tensors and Finite-Source Analysis of Chi-Chi Aftershocks*—**1E06**		
Start/End Dates	1/1/02 – 12/31/02	Budget/ Funding Source	$44,899 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**Dreger (UCB),** Chi (UCB), Rhie (UCB)		

1. Project goals and objectives

The objective of this project was to estimate the earthquake source parameters for aftershocks of the Chi-Chi earthquake and other Taiwanese events for use by researchers participating in the Next Generation Attenuation (NGA) project. Revised locations, style of faulting from first motion focal mechanisms and seismic moment tensors, moment magnitude and finite-source parameters such as the distribution of fault slip are necessary parameters for the development of new strong motion attenuation relationships. The finite-source parameters are of particular importance since they allow the determination of the distance to the closest point of the fault with appreciable slip rather than simply the distance to an epicenter, assumed fault plane, or the surface projection of the fault.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The 1999 Chi-Chi, Taiwan earthquake sequence produced the most complete strong motion data set to date with observations ranging from 100s of meters from the fault to 100s of kilometers. Strong motion data was obtained for the Mw7.6 mainshock and numerous large Mw>6 aftershocks. This data set will contribute significantly to the revision of existing attenuation relationships and the development of new relationships that take additional source information into account, such as directivity, which is one objective of the Next Generation Attenuation (NGA) relationship project. The results of this project provide the necessary information for using Chi-Chi aftershocks to update these relationships.

3. Brief description of the accomplishments of the project

Strong motion data for 30 aftershocks of the September 1999 Chi-Chi, Taiwan earthquake sequence, compiled by PEER Lifelines, were investigated to determine seismic moment tensors, finite-source models, and to evaluate event locations. This data set provided by the Taiwan Central Weather Bureau consisted of strong motion accelerograms from 30 aftershocks with local magnitudes (M_L) between 4 to 6.8. Finite-source parameters were obtained for 6 of the large (M6+) aftershocks, seismic moment tensors for 4 of the M5+ aftershocks, and style of faulting information for 15 of the aftershocks. A relationship between the reported local magnitude and moment magnitude was determined. Analysis of event locations using both P and S-wave picks and a grid search routine indicates that the locations provided with the data set are adequate for NGA purposes.

For each of the 6 M6+ aftershocks approximately 1000 inversions were performed to determine the orientation of the rupture plane, as well as the rupture velocity, dislocation rise time, and hypocenter location parameters. The resulting slip models have been delivered to Brian Chiou and can be obtained from; http://www.seismo.berkeley.edu/~dreger/peer_chichiaftershocks.zip.

Figure 1 gives an example of the sensitivity analysis for fault orientation and rupture velocity, and Figure 2 shows the best fitting slip distribution for one of the events. The obtained slip models may be used to estimate the distance of strong motion stations to the closest point of the fault that actually slipped during

the earthquake. In the particular example (Figure 2) the approximately 15 km by 5 km slip patch extending updip and to the south of the hypocenter is interpreted as the ruptured fault area.

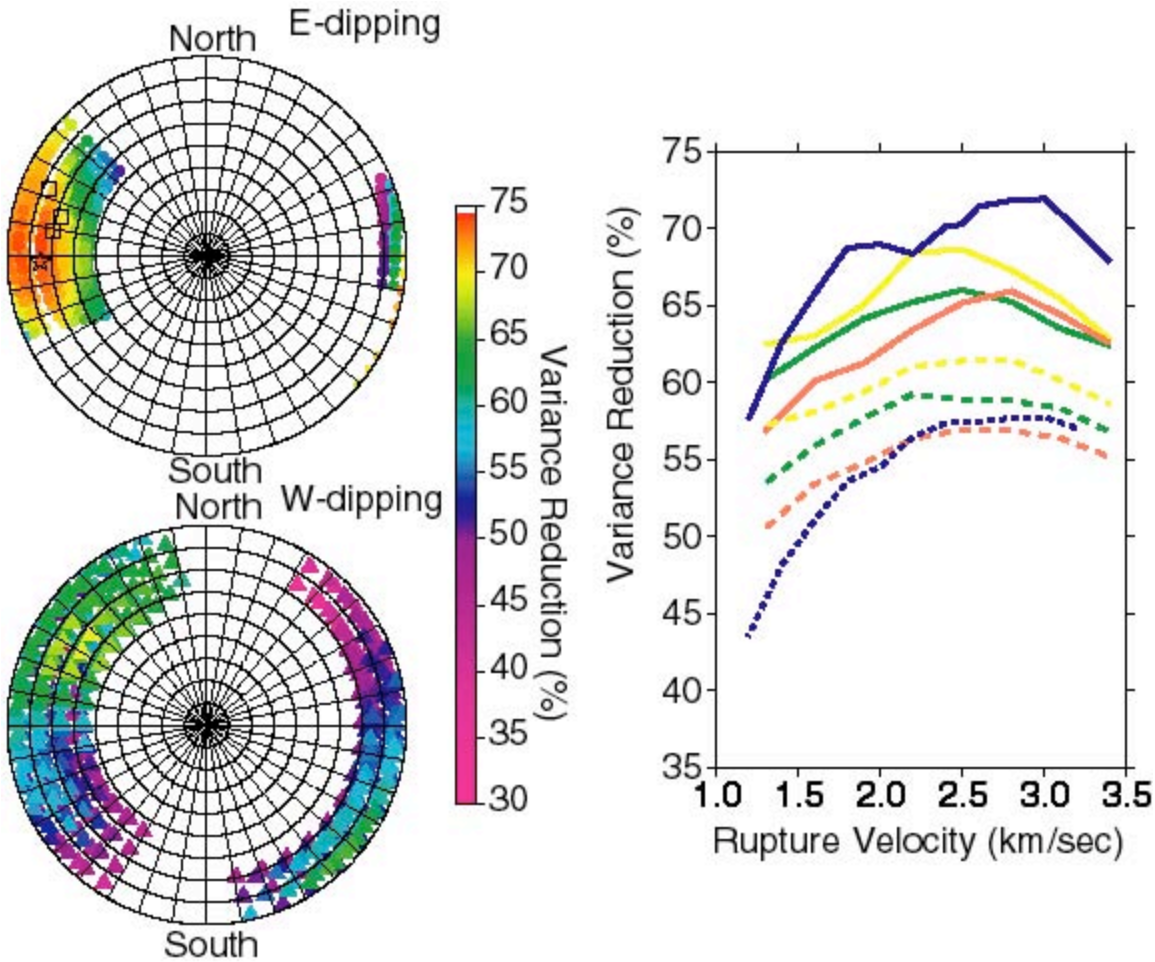


Figure 1. The left shows P-axes for east-dipping (top) and west-dipping (bottom) planes for the M6.3 aftershock on 1999/09/25. Each symbol represents a finite-source inversion. The color is scaled to a measure of fit to the seismic velocity waveforms in the 0.02 to 0.5 Hz passband. The sensitivity analysis shows clearly that the east-dipping plane provides a superior fit to the data, and gives an idea of the uncertainty in the fault orientation. On the right several east-dipping (solid lines) and west-dipping (dashed lines) fault orientations are examined in terms of the rupture velocity. The best solution obtained shows that the rupture velocity of 3 km/s is well constrained.

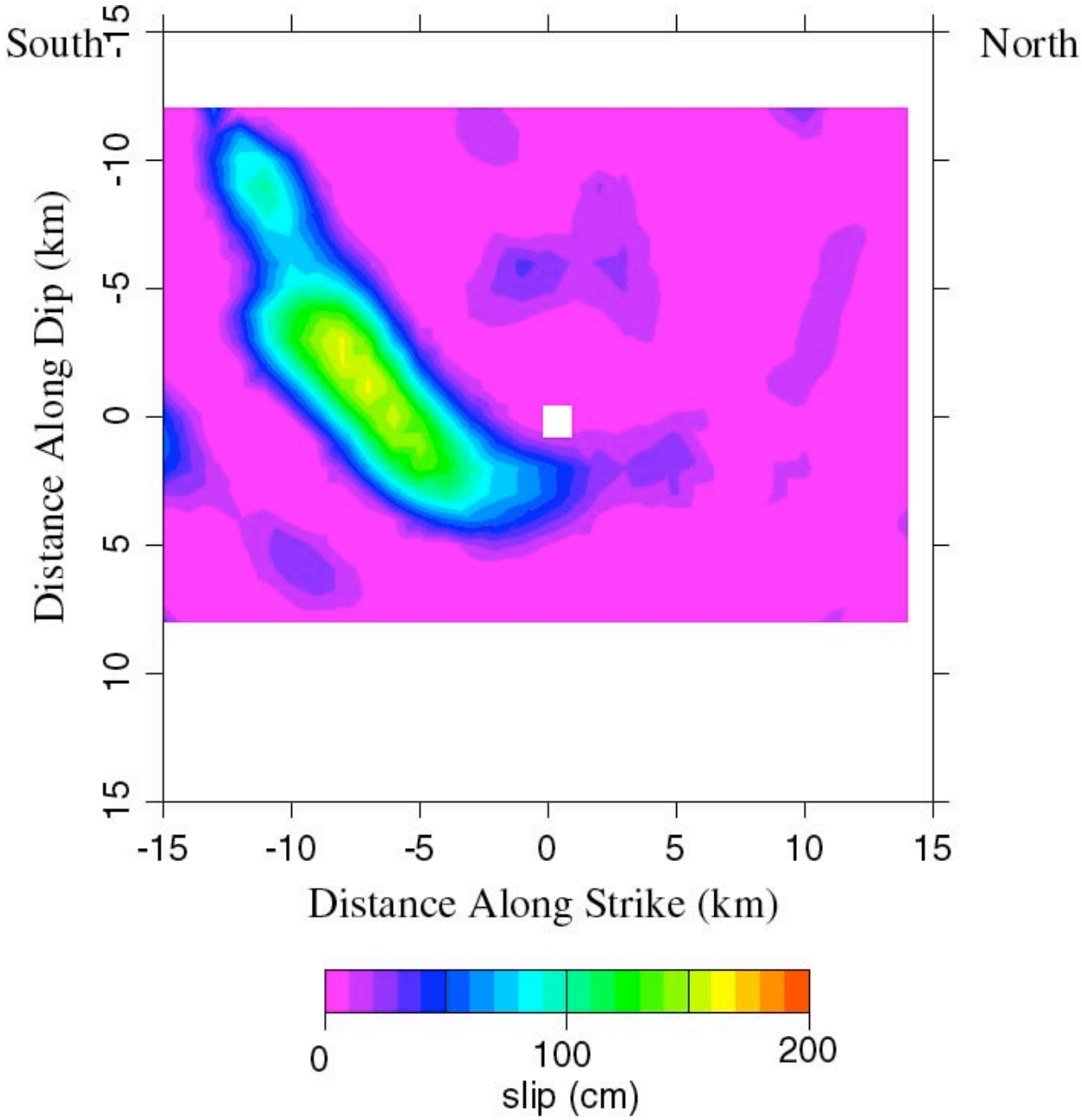


Figure 2. Slip distribution for the the M6.3 aftershock on 1999/09/25. The hypocenter is shown as a square and is at a depth of 16 km. The fault is oriented with a strike of 5 degrees, a dip of 30 degrees to the east and a slip-vector (rake) of 100 degrees.

Beyond the practical objectives of this study the results also contribute to improved understanding of the fault network in central Taiwan including segmentation of the Chelungpu fault zone, the orientation of ancillary faults and the style of the collisional tectonics.

Two peer-reviewed publications and a Ph.D. thesis resulted from this study:

- Chi, W-C, and D. Dreger (2004). Finite fault inversion of the September 25, 1999 (Mw6.4) Taiwan earthquake: Implications for GPS displacements of the Chi-Chi, Taiwan sequence, Geophys. Res. Lett., 29(14), 1694, doi:10.1029/2002GL015237.

- Chi, W-C (2003). From subduction to collision: Results from seismic profiling, gravity modeling, and earthquake finite-fault inversions in the Taiwan region, Ph. D. thesis, University of California, Berkeley, 200p.
- Chi, W-C, and D. Dreger (2004). Crustal deformation in Taiwan: Results from finite source inversions of six Mw>5.8 Chi-Chi aftershocks, Journ. Geophys. Res., 109, B07305, doi:10.1029/2003JB002606.

These publications may be obtained online from;

http://www.seismo.berkeley.edu/~dreger/ChiandDreger2002GRL.pdf
http://www.seismo.berkeley.edu/~dreger/ChiDreger2004JGR_ChiChi.pdf

4. Describe any instances where you are aware that your results have been used in industry
The finite-source parametric information that we have obtained for the large aftershocks as well as the moment magnitudes for the moderate aftershocks is being used by researchers participating in the Next Generation Attenuation (NGA) project.

5. Methodology employed
To determine seismic moment tensors the method of complete, low frequency waveform inversion was used. This method is described in Pasyanos et al. (1996). Event locations were evaluated using a grid search method (Dreger et al., 1998; Uhrhammer et al., 2001). Finite-source parameters were determined using the method described in (Dreger and Kaverina, 2000; Kaverina et al., 2002; and Chi et al., 2001). This method was developed under the Lifelines project 701.

- Chi, W-C, D. Dreger and A. Kaverina (2001). Finite-source modeling of the 1999 Taiwan (Chi-Chi) earthquake derived from a dense strong motion network, Bull. Seism. Soc. Am., 91, 1144-1157.
- Dreger, D., R. Uhrhammer, M. Pasyanos, J. Franck, and B. Romanowicz (1998). Regional and Far-Regional Earthquake Locations and Source Parameters using Sparse Broadband Networks: A Test on the Ridgecrest Sequence, *Bull. Seism. Soc. Am*., 88, 1353-1362.
- Dreger, D. S. and A. Kaverina (2000). Seismic remote sensing for the earthquake source process and near-source strong shaking: a case study of the October 16, 1999 Hector Mine earthquake, *Geophys. Res. Lett.,* 27, 1941-1944.
- Kaverina, A., D. Dreger and E. Price (2002). The combined inversion of seismic and geodetic data for the source process of the 16 October 1999 Mw7.1 Hector Mine, California, earthquake, Bull. Seism. Soc. Am., 92, 1266-1280.
- Pasyanos, M. E., D. S. Dreger, and B. Romanowicz (1996). Toward real-time estimation of regional moment tensors, *Bull. Seism. Soc. Am*., 86, 1255-1269.
- Uhrhammer, R. A., D. Dreger and B. Romanowicz (2001). Best practice in earthquake location using broadband three-component seismic waveform data, Pure. Appl. Geophys., 158, 259-276.

6. Other related work conducted within and/or outside PEER
N/A

7. Recommendations for the future work: what do you think should be done next?
There are a number of other M6 aftershocks not contained on the project event list that now have available seismic waveform data. Future studies of these events can provide additional constraints on the fault structure activated by the mainshock and also on the nature of strong ground motion attenuation in Taiwan.

8. <u>Author(s), Title, and Date</u> for the final report for this project

Dreger, Chi, and Rhie, Seismic Moment Tensors and Finite-Source Analysis of Chi-Chi Aftershocks, January 2004.

Final Project Summary— PEER Lifelines Program

Project Title—**ID Number**	*Comparison of Ground Motion Characteristics between Taiwan & California*—**1E07**		
Start/End Dates	9/30/02 – 6/30/04	Budget/ Funding Source	$64,966/ PG&E-CEC
Project Leader (boldface) and Other Team Members	**Walter Silva (PEA)**		

1. Project goals and objectives
In the PEER NGA project, data from Taiwan are to be combined with data from California to develop attenuation relations for California. The project was specifically to address the appropriateness of this combination.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.
None. Project was cancelled due to delays in getting started.

3. Brief description of the accomplishments of the project
Initial stage of project of updating profile database with Taiwan velocity profiles was begun.

4. Describe any instances where you are aware that your results have been used in industry
None.

5. Methodology employed
Project intended to compare stress drops, kappa values, Q(f), and crustal propagation parameters for Taiwan with those of northern and southern California.

6. Other related work conducted within and/or outside PEER
Response spectral shapes and absolute levels of response spectra for earthquakes in Taiwan have been compared to California attenuation relations.

7. Recommendations for the future work: what do you think should be done next?
The original project should be completed.

8. <u>Author(s), Title, and Date</u> for the final report for this project
No report available.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Design Ground Motion Library*—**1F01/1F01a**		
Start/End Dates	7/01/02 – 6/30/04	Budget/ Funding Source	$95,520 / PG&E/CEC & Caltrans
Project Leader (boldface) and Other Team Members	**Power (Geomatrix)**		

1. Project goals and objectives

The objective of the Design Ground Motion Library (DGML) project is to form an electronic library of recorded acceleration time histories suitable for use by engineering practitioners for the time history dynamic analysis of various facility types in the western United States, including lifelines, buildings, bridges, dams, base isolated structures, and other infrastructure facilities. The DGML is distinctly different from a ground motion data base. Data bases contain large numbers of time history records but no guidance on how to select records for specific applications. On the other hand, the DGML contains small groups of time histories considered by the expert project team to be suitable for use for defined categories of the seismic environment and structure characteristics.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

To accurately predict the damageability and performance of lifelines and other infrastructure facilities when analyzed using time history analysis methods, the time histories must be representative of the seismic environment with respect to those time history characteristics most important to causing structural damage. This project applies knowledge gained through research by PEER, PEER-LL, and other research of the time history characteristics that correlate with structure damage and selects time histories that, in aggregate, represent the variability in these characteristics to be expected for the design earthquake for a facility.

3. Brief description of the accomplishments of the project

In the current phase, the project has focused on developing criteria for the selection of time histories and quantification of their characteristics. The implementation of the criteria and finalization of the DGML will be accomplished using an expanded and improved data base of ground motion records, which has just been completed as part of the Next Generation Attenuation (NGA) project (project 1L01). Elements of the criteria include: (1) definition of magnitude (M)-distance (R)-site (S) condition bins (M-R-S bins) and period-range sub-bins for which key time history characteristics are evaluated and sets of time histories are selected (Tables 1 and 2); (2) detailed criteria for selecting time history record sets based on capturing the variability of ground motion response spectral shape and, for near-source record sets, the variability of pulsive ground motion characteristics; and (3) definition of ground motion parameters and supporting information to be quantified and tabulated for selected time history records (Tables 3 and 4).

Ground motion response spectral shape over a period range of significance to structural response has been found to be correlated with inelastic response and behavior in research by PEER and PEER-LL. The period range of significance includes periods shorter than the structure fundamental period because of higher mode effects and periods longer than the fundamental period because of structure softening as inelastic response occurs. Therefore, the development of quantitative measures to evaluate the variability of response spectral shape from a median spectral shape for each M-R-S bin and period range sub-bin has been an important element of criteria for time history selection. Figures 1 and 2 illustrate how the variability in response spectral shape of a larger data set can be captured in a smaller set of time histories through quantitative analysis of spectral shapes. Research has also indicated that the time-domain pulsive characteristics (pulse velocity, pulse period, and number of pulses) associated with near-fault ground motions can be damaging to structures. Therefore, criteria has been developed to include these ground motion characteristics and their variability for near-source record sets.

4. Describe any instances where you are aware that your results have been used in industry

When the selection of time history record set is fully complete, it is expected that the library will be used in practice to select records for the analysis of a wide range of facilities.

5. Methodology employed

The methodology broadly consists of, first, development of criteria for forming time history sets and identifying parameters and information to be quantified and tabulated for selected time history records; and, second, implementation of these criteria for records selected from an expanded and improved ground motion data base. A key element of the overall approach to forming the DGML has been to utilize a multi-disciplinary team of structural engineers, geotechnical engineers, and seismologists who are expert both in selecting time histories and in utilizing these time histories in analyses for new and existing facilities. The team develops the criteria for the DGML and selects and reviews the time history record sets.

6. Other related work conducted within and/or outside PEER

It is believed that similar projects are not being conducted outside PEER. In contrast to the collection of large numbers of records in a ground motion data base, the DGML focuses on the identification of sets of smaller time history records that are judged to be appropriate for time history analyses of different types of structures.

7. Recommendations for the future work: what do you think should be done next?

The present project is limited to formation of time history record sets representative of shallow crustal earthquakes in the western United States. A future project extension is envisioned to develop time history record sets for subduction zone earthquakes such as occur in northwest California, Oregon, Washington, and Alaska. The DGML should be periodically reviewed and updated with records from future earthquakes. The addition of simulated earthquake recordings to fill gaps in the recorded data should also be considered.

8. Author(s), Title, and Date for the final report for this project

Authors of the final report will be members of the DGML project team. Project team members and their respective organizations include: Maurice Power, Robert Youngs, Faiz Makdisi, and Chih-Cheng Chin, Geomatrix Consultants, Inc.; Ronald Hamburger and Ronald Mayes, Simpson Gumpertz & Heger; Roupen Donikian, T.-Y. Lin International; Yusof Ghanaat, Quest Structures; Walter Silva, Pacific Engineering & Analysis; Paul Somerville, URS Corporation; Ignatius PoLam, Earth Mechanics; Professor Allin Cornell, Stanford University; Professor Stephen Mahin, University of California, Berkeley.

Table 1

Preliminary M-R Bins for DGML

Moment Magnitude, M	Earthquake Closest Source-to-Site Distance, R (km)
5.5 – 5.9	0 – 15, >15 – 30
6.0 – 6.4	0 – 15, >15 – 30, >30 – 50
6.5 – 7.0	0 – 15, >15 – 30, >30 – 50, >50 – 100
6.9 – 7.9	0 – 15, >15 – 30, >30 – 50, >50 – 100

Table 2

Preliminary Period Range Sub-Bins for DGML (seconds)

0.05 – 0.5
0.5 – 5.0
0.1 – 5.0

Table 3

Ground Motion Record Parameters (Intensity Measures) Considered for Quantification in DGML

Parameter	Published Attenuation Relationship Available	Presently Proposed to be Quantified for Records in DGML
• PGA, PGV, PGD	☐	☐
• Elastic response spectra	☐	☐
• Inelastic response spectra	*	☐
• Duration	☐	☐
• Cumulative Absolute Velocity (CAV)	*	☐
• Energy		
• Damage indices		
• Arias Intensity	☐	☐
• Housner Spectrum Intensity		☐
• Near-source record characteristics		
- pulse velocity	☐	☐
- pulse period	☐	☐
- no. of pulses	☐	☐

* Relationships developed, not yet published.

Table 4

Supporting Information about Records Considered for Quantification in DGML

Parameter or Characteristic	Presently Proposed to be Quantified for Records in DGML
• Earthquake moment magnitude	☐
• Faulting mechanism (strike slip, reverse, normal, reverse-oblique, normal-oblique)	☐
• Hanging wall vs. foot wall	☐
• Source-to-site distance (closest distance to rupture surface, Joyner-Boore distance)	☐
• Near-fault directivity parameters: Somerville et al. (1997): s or d, X or Y, cos ☐, cos ☐, X cos ☐, Y cos ☐	☐
• Site classification(s): Geomatrix; NEHRP	☐
• Basin response influence	

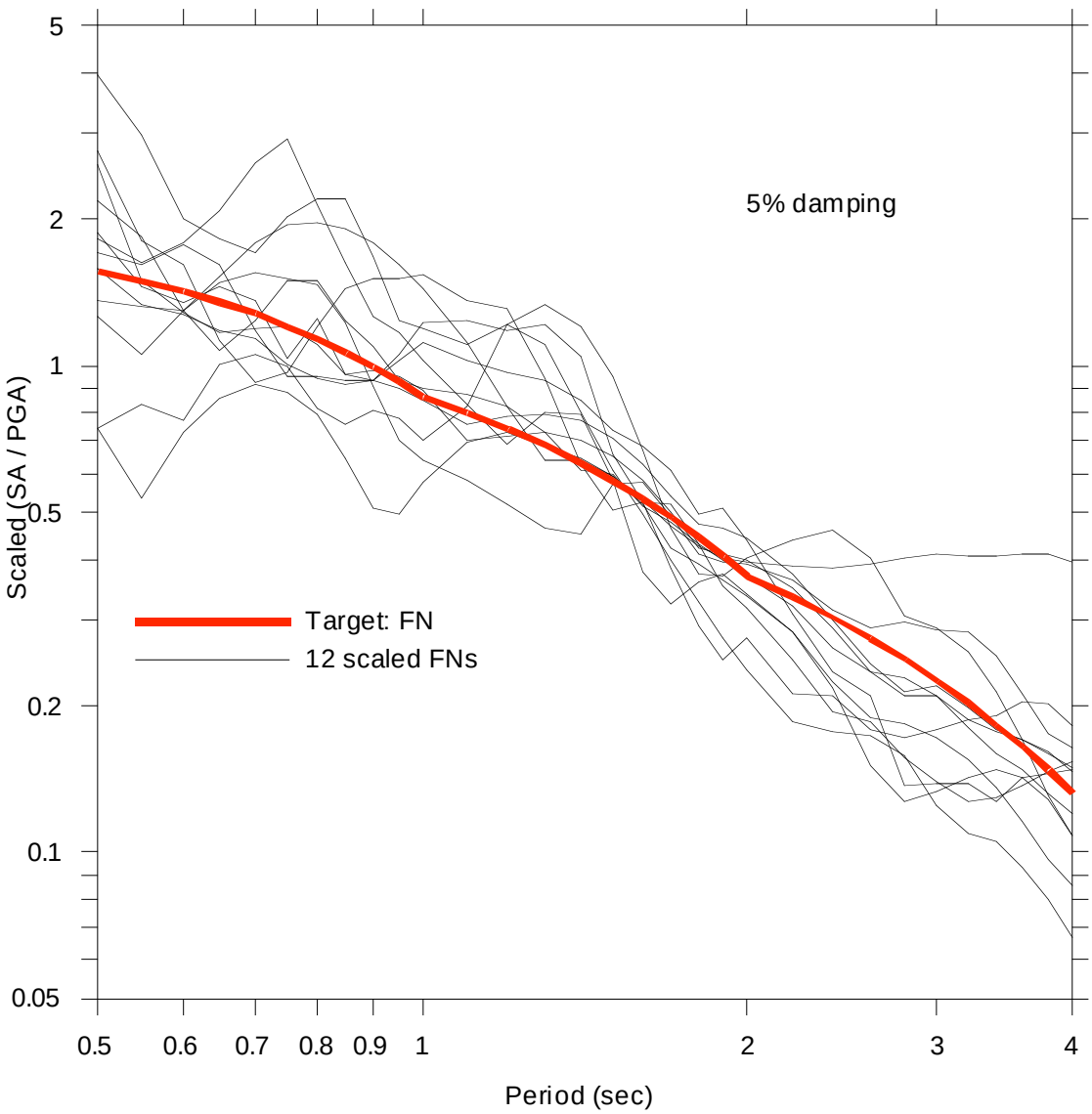


Figure 1 Comparison of response spectral shapes of fault-normal components of 12 records with target median spectral shape for M-R-S bin M ≥ 6.9, R= 0-20 km, rock -- period range 0.5 to 4.0 seconds.

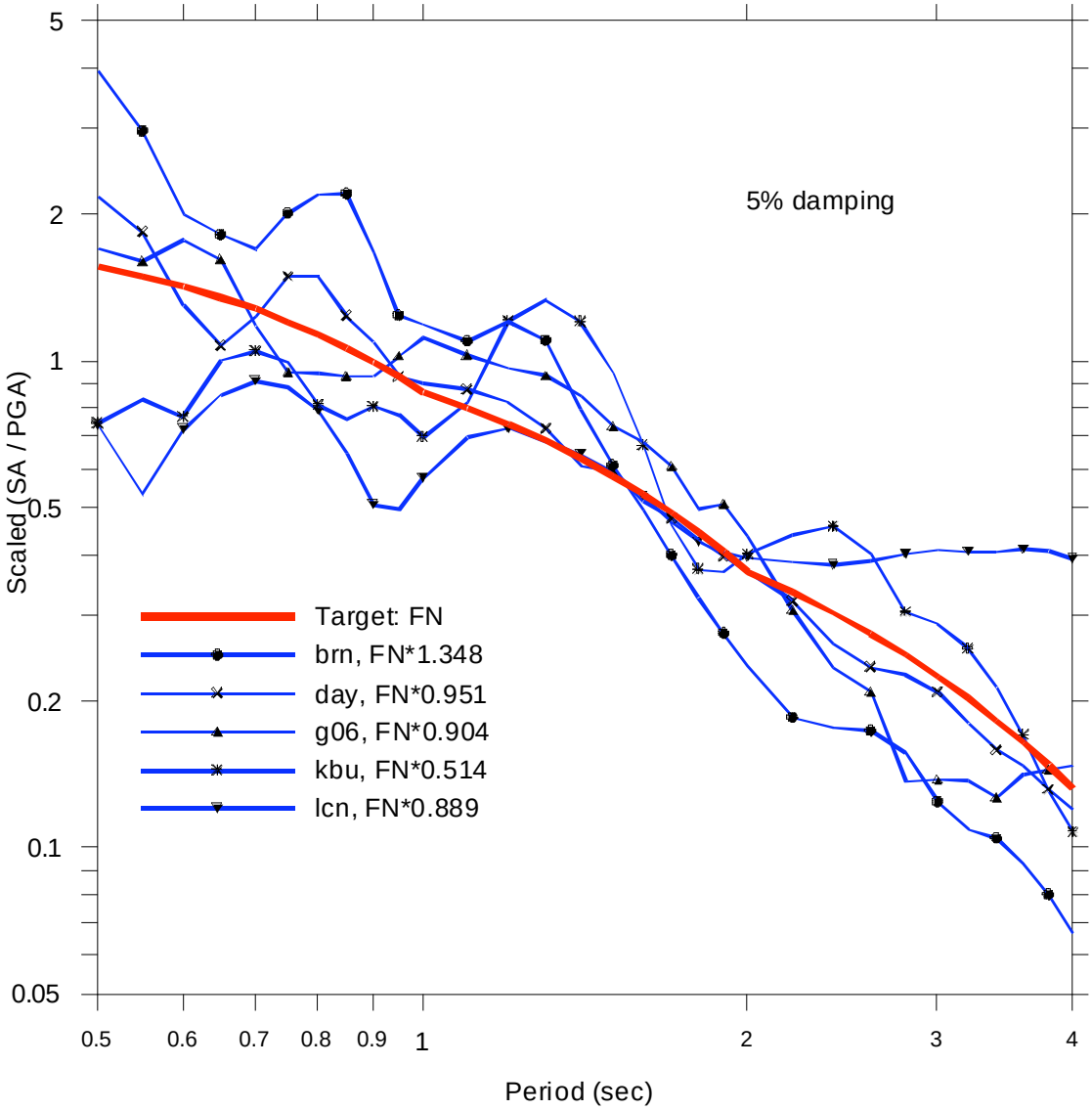


Figure 2 Comparison of response spectral shapes of fault-normal components of 5 selected records with target median spectral shape for M-R-S bin M ≥ 6.9, R= 0-20 km, rock -- period range 0.5 to 4.0 seconds.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Parameterization of Non-Stationary Acceleration Time History*—**1G00**		
Start/End Dates	12/1/01 – 6/30/04	Budget/ Funding Source	$142,839 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**Bazzurro (AIR Worldwide),** Luco (AIR Worldwide), Sjoberg (AIR Worldwide), Cornell (Stanford Univ.)		

1. Project goals and objectives

This project consists of the primary task (1G00) and three addendum tasks (denoted here as AT1, AT2, and AT3). The goals and objectives of each of these tasks are …

1G00: To investigate whether "non-stationary" characteristics of seismograms, in addition to more conventional ground motion intensity measures (e.g., spectral values), may improve the accuracy in the prediction of structural seismic performance.

AT1: To provide the quantitative technical basis to establish the threshold limits beyond which ground motion record scaling introduces bias in the nonlinear response of structures.

AT2: To provide the tools necessary for validation of ground motion simulation methods, addressing the issue of nonlinear structural response.

AT3: To provide a technical basis for assumptions made in the "Advanced Seismic Assessment Guidelines" study (PEER Lifelines 507 Project supervised by Prof. C.A. Cornell) regarding (i) whether the ultimate capacity of a structure damaged by an earthquake mainshock can be accurately estimated by applying a Nonlinear Static Pushover technique to mimic the effect of the mainshock, followed by a SDOF-based Nonlinear Dynamic Analysis technique to estimate its residual capacity to withstand aftershocks, and (ii) the distribution of the structure's residual roof drift angle after a mainshock excitation that results in a given peak roof drift angle.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The results of the first three tasks (1G00, AT1, AT2) provide guidance in selecting, scaling, and simulating earthquake ground motion recordings for nonlinear dynamic analysis during vulnerability-mitigating design and/or damage evaluation of structures. The results of the fourth task (AT3) were used to update the "Advanced Seismic Assessment Guidelines" for existing structures that are common in the PG&E building inventory. Predicting the post-earthquake functionality of such structures is a crucial step in evaluating the likelihood that the PG&E power distribution network will not be able to provide power to customers. The Guidelines are also applicable to a more general class of structures that are not limited to those owned by PG&E.

3. Brief description of the accomplishments of the project

1G00: The use of the Empirical Mode Decomposition algorithm (developed by Norden E. Huang) is explored in search of ground motion record characteristics that induce severe structural responses, but it is found that the damageability of a record can only be measured in relation to a particular vibration period and specific strength. (This is evidenced by the low correlation between the nonlinear responses to structures of differing strengths, as illustrated in Figure 1). Hence, using record characteristics that do not account for the period and strength of the structure (e.g., characteristics of the velocity pulse, duration) are not likely to be "good" predictors of its response. In contrast, the inelastic displacement of an elastic-perfectly-plastic SDOF system with similar period and strength as the MDOF structure of interest, and, more innovatively, the first "significant" peak displacement of the elastic oscillator with the same fundamental period as the MDOF structure appear to be promising candidate predictors.

AT1: Dependent on the period and strength of the structure, as well as on the nature of the ground motion recordings (e.g., near- versus far-field), it is discovered that scaling recordings by factors greater or less than unity can result in, respectively, significant positive and negative biases in (median) nonlinear structural response relative to un-scaled recordings (as demonstrated in Figure 2). This is found to be true for both "intra-bin" scaling (i.e., same magnitude and distance for scaled and un-scaled recordings) and "inter-bin" scaling, as well as for SDOF and MDOF structures.

AT2: The differences between the median and dispersion of nonlinear structural response to recorded earthquake ground motions (from Northridge) versus those simulated by 7 different seismologists for the same earthquake and site conditions as the real recordings are compared. So seismologists can also validate other simulation methods, an SDOF nonlinear structural analysis code and, in a spreadsheet, nonlinear structural responses for all of the records in the Next Generation Attenuation (NGA) database are provided.

AT3: A nonlinear-static-pushover-based procedure for estimating the (median) residual capacity against aftershocks of a mainshock-damaged structure is developed that is consistent with the results of back-to-back (mainshock-aftershock) nonlinear dynamic analyses. From the dynamic analyses it is observed that the residual capacity is not much different than the intact capacity before the mainshock, particularly if the post-mainshock residual drift is small.

4. Describe any instances where you are aware that your results have been used in industry

Some aspects of the "Advanced Seismic Assessment Guidelines" (revised for AT3) have been applied to the analysis of a 8-story building located in San Jose, CA, by two local engineering companies. PG&E intends to adopt the guidelines for assessing the functionality of their structures after future earthquakes.

5. Methodology employed

In very general terms, all four of the tasks involve numerous nonlinear dynamic analyses of SDOF and MDOF structures of various fundamental periods of vibration and strengths under un-scaled (1G00, AT1, AT2), amplitude scaled (1G00, AT1, AT3), and response-spectrum-matched (1G00) earthquake records. The spectrum-matched records employed in Task 1G00 make it possible to focus on characteristics beyond the elastic response spectrum that influence the nonlinear structural responses. For Task AT3, back-to-back nonlinear dynamic analyses to iteratively scaled earthquake records are performed.

6. Other related work conducted within and/or outside PEER

"Correlation of Damage of Steel Moment-Resisting Frames to a Vector-valued Ground Motion Parameter Set that includes Energy Demands: Collaborative Research with the University of Texas at Austin, and AIR Worldwide" (Funded by USGS NEHRP External Research Program, 2003).

7. Recommendations for the future work: what do you think should be done next?

1G00: The spectrum-matched earthquake records used in this task were created via only one of several available approaches. It is possible that the observed bias in nonlinear structural response introduced by these records (relative to un-scaled records) is particular to the spectrum-matching approach; hence, other approaches should be considered.

AT1: For practical applications, it is important to understand whether the scaling-induced bias in nonlinear structural response observed in this task can be reduced, e.g., by only scaling earthquake records that have an elastic spectral shape similar to the target.

AT2: Further research into the reasons behind the observed differences between recorded and simulated ground motions is warranted. The dataset used here was limited to 20 stations and one earthquake.

AT3: Further studies of the effect of residual drift and damage on residual capacity (both median and dispersion) are important for generalizing the conclusions reached in this task to, e.g., other building types.

8. <u>Author(s), Title, and Date</u> for the final report for this project

1G00: Bazzurro, P. & Luco, N. "Parameterization of Non-Stationary Acceleration Time Histories" (Dec., 2003)

AT1: Luco, N. & Bazzurro, P. "Effects of Ground Motion Scaling on Nonlinear Structural Response" (Sept., 2004)

AT2: Sjoberg, B., Bazzurro, P., & Luco, N. "Post-Elastic Response of Structures to Synthetic Ground Motions" (Aug., 2004)

AT3: a) Bazzurro, P., Cornell, C.A., Menun, C., Luco, N., & Motahari, M. "Advanced Seismic Assessment Guidelines" (Aug., 2004)

b) Luco, N., Bazzurro, P., & Cornell, C.A. "Dynamic versus Static Computation of the Residual Capacity of a Mainshock-Damaged Building to Withstand and Aftershock" (Aug., 2004)

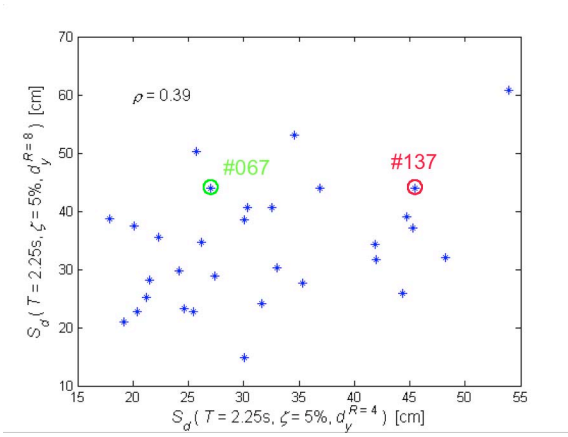


Figure 1. Example of the low correlation between the nonlinear drift responses of structures (SDOF oscillators) with the same fundamental period, but with different strengths. The two earthquake records identified (#067 and #137) both result in relatively large inelastic spectral displacements for oscillator with a strength reduction factor (*R*) of 8, but only #137 induces a relatively large response when *R*=4.

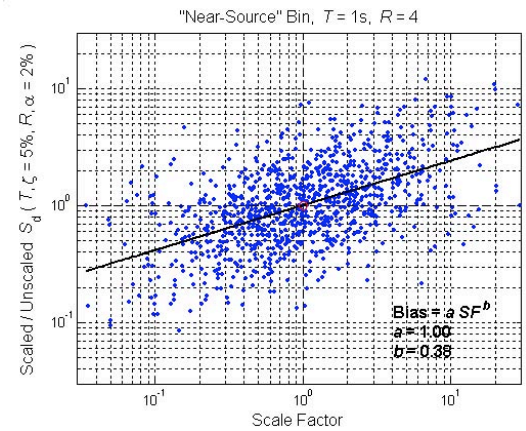


Figure 2. Example of the bias in nonlinear structural response induced by scaling (in amplitude only) earthquake records, as compared to un-scaled records. The records are scaled to match the elastic spectral acceleration of the un-scaled at the fundamental period of the structure of interest (in this case *T*=1 second).

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Surface Fault Rupture Design Models: Statewide Mapping Products*—**1J03**		
Start/End Dates	2/1/02 – 6/30/04	Budget/ Funding Source	$50,000 / Caltrans
Project Leader (boldface) and Other Team Members	**Wills (CDMG)**		

1. Project goals and objectives

The overall goal of the 1J project series is the development of improved design-oriented conditional probability models needed for estimating fault rupture hazard within either a deterministic or probabilistic framework, and implementing them both in spreadsheet form and as trial fault rupture hazard maps. The model is structured to yield rupture hazard as a function of earthquake parameters, distance from mapped fault, and footprint area of a facility. The model was developed in close coordination with technical experts in the field, and periodically reviewed by additional experts representing the user community.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

Surface fault rupture can be highly damaging to extended infrastructure systems as evidenced by bridge and pipeline damage in the recent Turkey and Taiwan earthquakes. This project developed improved design-oriented models and maps for estimating surface fault rupture hazard. This tool will provide lifeline organizations with the information needed to better site and/or design important facilities near faults.

3. Brief description of the accomplishments of the project

For this project we utilized a database of fault rupture and displacement developed under project 1J01 to develop a model for calculating the probability of fault displacement. We assembled advisory panels to direct the work and suggest both the form of the analysis and the use of the resulting program. We have used the model to calculate the probability of fault displacement for example locations and prepare maps showing fault displacement hazard.

4. Describe any instances where you are aware that your results have been used in industry

None at this time. As part of this project we have developed example analyses for "real world" problems, but use in industry probably won't occur until the final report is completed.

5. Methodology employed

We have developed empirical equations relating the amount of surface displacement to earthquake magnitude and distance from fault, considering how the fault trace was mapped prior to the earthquake and the complexity of the fault trace. This can be incorporated with the probabilities of earthquakes of different magnitudes from a probabilistic seismic hazard analysis and the probability that an earthquake will rupture the ground surface, from global statistics, to calculate the displacement hazard given distance from a fault and information about that fault.

6. Other related work conducted within and/or outside PEER

Project 1J01 and 1J02, by the U.S. Geological Survey in Golden, CO and Menlo Park, CA, were coordinated with this project and the three effectively functioned as one project.

7. Recommendations for the future work: what do you think should be done next?

The analysis developed in this project could be extended by developing similar equations for thrust fault earthquakes. We were not able to obtain data for the ChiChi, Taiwan earthquake in satisfactory form to use in this project, and data for other thrust fault earthquakes was not available.

8. <u>Author(s), Title, and Date</u> for the final report for this project

Not yet completed. 2 interim reports have been published:

Mark Petersen, Tianqing Cao, Tim Dawson, Arthur Frankel, Chris Wills, and David Schwartz: Mapping Fault Rupture Hazard for Strike-Slip Earthquakes, 13th World Conference on Earthquake Engineering, Vancouver, B.C., Canada

Mark Petersen, Tianqing Cao, Tim Dawson, Arthur Frankel, Chris Wills, and David Schwartz: Mapping Fault Rupture Hazard for Strike-Slip Earthquakes, American Society of Civil Engineers, GeoTrans 2004 Conference, Universal City, California

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Next Generation Attenuation (NGA) Models, WUS Shallow Crustal Earthquake*—**1L01**		
Start/End Dates	8/1/02 – 6/30/04	Budget/ Funding Source	$352,630 / Caltrans
Project Leader (boldface) and Other Team Members	**Power (Geomatrix)**		

1. Project goals and objectives

The overall goal of the project is to develop Next Generation Attenuation (NGA) relationships for shallow crustal earthquakes in the western United States. These attenuation relationships will have a substantially better scientific basis than current relationships because they are developed through the efforts of five selected attenuation relationship developer teams working in a highly interactive process with other researchers who are: (a) developing an expanded and improved data base of strong ground motion recordings and supporting information on the causative earthquakes, the source-to-site travel path characteristics, and the site and structure conditions at ground motion recording stations; (b) conducting research to provide improved understanding of the effects of various parameters and effects on ground motions that are used to constrain attenuation models; and (c) developing improved statistical methods used to develop attenuation relationships including uncertainty quantification.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The assessment of the damage that earthquakes can cause to electrical systems and other lifelines depends significantly on how well the vibratory ground motions can be predicted as a function of the seismic environment characteristics, including earthquake magnitude and other earthquake source characteristics, source-to-site-distance and other travel path characteristics, and the stiffness and depth of the geologic media in which lifelines are founded. This project greatly improves the reliability and the quantification of uncertainty associated with ground motion predictions, thus allowing more reliable assessments of damage to, and design of, lifelines.

3. Brief description of the accomplishments of the project

The project accomplishments to date are summarized as follows.

(1) The PEER data base of ground motion recordings and supporting information, which is vital for developing attenuation relationships, has been substantially improved through the addition of a large number of recordings, evaluation of the characteristics of recordings (e.g. better understanding of the usable period range for response spectra of the recordings), and research and quality assurance that has resulted in more accurate and increased information about the earthquake source, path, and recording station parameters. The additions of records to the PEER data base is shown in Figure 1.

(2) Selected research and synthesis of current and previous research by PEER, PEER-LL, U.S. Geological Survey, Southern California Earthquake Center, and others, has been conducted to develop increased understanding of the various earthquake source, travel path, and site factors affecting earthquake ground motions and thus provide better constraints on empirically-based attenuation relationships. The research synthesis includes findings from the following projects:

(a) rock motion simulations; (b) basin response simulations; (c) site response simulations; (d) attenuation at moderate distances; (e) effects of rupture directivity on ground motions; (e) and synthesis of empirical studies on site response.

(3) Six two-day NGA workshops have been held in 2003 and 2004 following a two-day kickoff meeting on October 2002. These workshops, each attended by approximately 40 to 45 researchers and stakeholders in the NGA project, have facilitated review of interim results for the project. Presentations from the workshops have been placed on the PEER web site. In addition to the workshops, a number of less formal meetings of NGA working groups and of the NGA developers have been held for project review and interaction. The working groups have been an integral part of the project for review of selected research and data base findings. Six working groups, each consisting of five to thirteen scientists and engineers involved in various project activities have been active: #1Strong Ground Motion Data Processing; #2 Validation of Ground Motion Database; #3 Validation of 1D Rock Motion simulations; #4 Source and Path Effects; #5 Site Classification and Site Effects; and #6 Statistical Modeling of Data.

(4) Preliminary results for effects modeled in NGA relationships were presented by the five NGA attenuation developer teams at Workshop #6 in July 2004. Examples of analysis of effects of soil type and soil depth on ground motions are shown in Figures 2 and3. Results are scheduled to be finalized during October and presented at a final workshop for this phase in November 2004. In addition to preparation of comprehensive project reports covering the new attenuation relationships, the new data base, and the supporting research, it is planned that the new attenuation relationships will be presented at special sessions at conferences and published together in a special issue of a widely read professional journal.

4. Describe any instances where you are aware that your results have been used in industry

The final project results are not yet available. When available later this year, extensive use of the new attenuation relationships is anticipated in engineering practice, including in the development of future ground motion maps for California, the United States, and in national building codes, as well as for site-specific ground motion definition. The data base developed for the project will be a major resource to the entire engineering and seismological community as a source of well documented strong motion records and supporting information. Reports of supporting research for the NGA project will similarly be used to advance the practice of ground motion definition for new construction and retrofit projects.

5. Methodology employed

The methodology developed and its implementation is summarized in items (1) and (3) above.

6. Other related work conducted within and/or outside PEER

The NGA project is unique in providing a focused, coordinated, and highly interactive effort involving participation of five selected expert attenuation relationship developer teams, development of an improved and expanded data base of ground motion recordings and supporting data required for attenuation relationship development, conduct and synthesis of supporting research on the processes of earthquake generation, seismic wave propagation, and site response to provide better physical constraints on attenuation relationships, development of better statistical methods for attenuation relationship development, and integration of all project

elements through a series of workshops and meetings of working groups and attenuation relationship developers.

7. Recommendations for the future work: what do you think should be done next?

The present project is limited to development of attenuation relationships for horizontal elastic response spectral acceleration and horizontal PGA, PGV, and PGD of ground motions for shallow crustal earthquakes in the western U.S. Future phases of attenuation relationships development may be conducted for: (1) vertical ground motions; (2) other ground motion parameters found to be important in determining earthquake damage to structures (e.g. inelastic response spectral accelerations); and (3) western U.S. subduction zone earthquakes. The present project is also limited to the use of ground motion recordings from actual earthquakes in the statistical analyses for attenuation relationship development. Simulated earthquake recordings, although used in the present project to guide the modeling of effects in attenuation relationship development, and not used as data in developing attenuation relationships. Future phases may consider incorporating simulated recorded data directly along with the actual data for conditions that are not well represented in or well constrained by the existing recorded data (e.g. recordings from large earthquake magnitudes at close distances).

8. Author(s), Title, and Date for the final report for this project

The final report will be submitted later in 2004. Final reports will be submitted by each attenuation relationship development team. In addition, the series of a final reports will (a)compare attenuation relationships from all of the development teams; (b) document the data base of ground motion recordings and supporting information developed for the project; (c)document and synthesize research conducted in support of NGA relationship development.

Figure 1
Magnitude – Distance Distribution of NGA Data Base

Previous Data

New EQ Data

- Kobe
- Kocaeli
- ChiChi
- Duzce
- Hector Mine
- Denali
- Moderate magnitude earthquake aftershocks

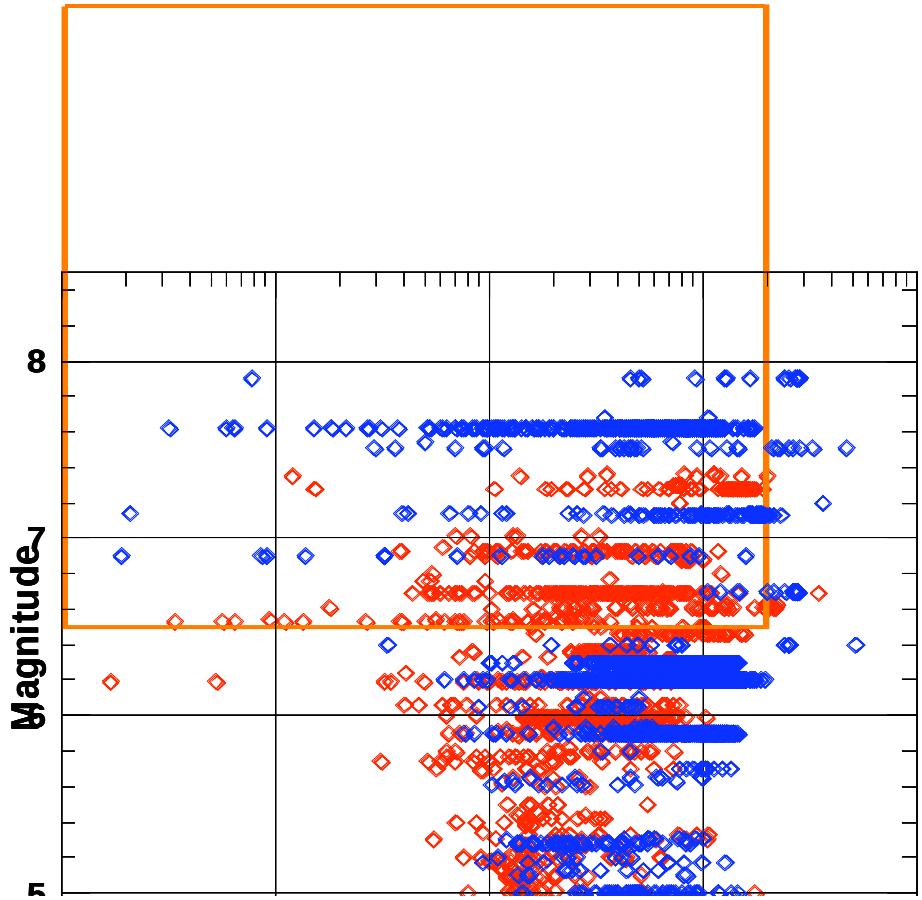


Figure 2
Effects of NEHRP Soil Type on 3-Sec Spectral Acceleration

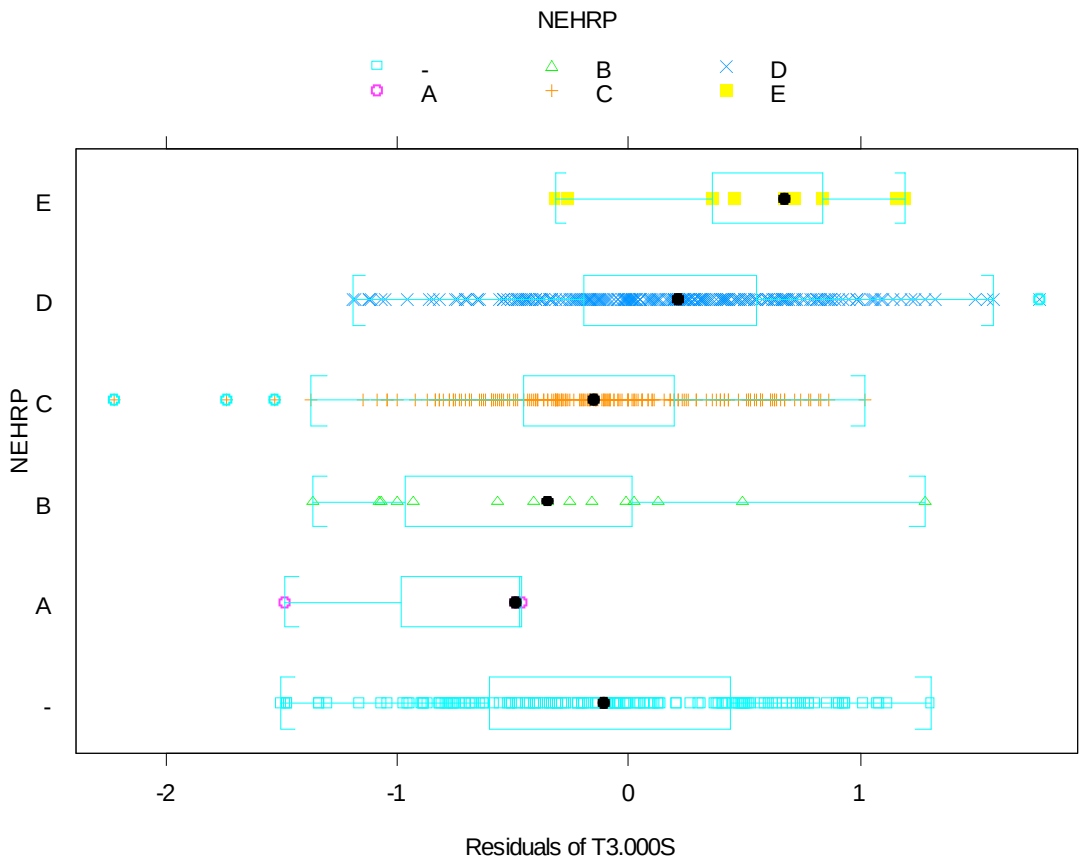
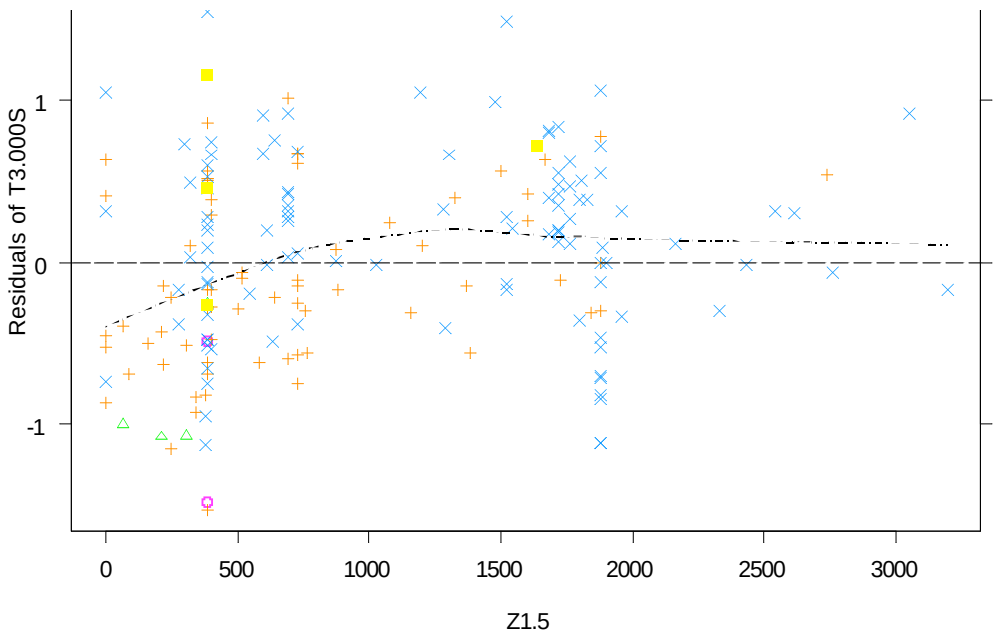


Figure 3
Effects of Depth to Bedrock on 3-Sec Spectral



Depth to Bedrock (taken as depth to rock with V_s = 1.5 km/sec)

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*NGA Data Sets*—**1L02**		
Start/End Dates	11/1/02 – 12/31/03	Budget/ Funding Source	$215,722/ PG&E-CEC
Project Leader (boldface) and Other Team Members	**Walter Silva (PEA)**		

1. Project goals and objectives

The project goal is to update the existing PEER strong motion dataset for use in developing the next generation of empirical attenuation relations for the PEER-NGA project. This project involves first updating and adding metadata (e.g. earthquake source, wave propagation path and recording and site parameters). Second, new earthquake/site metadata will be added. In addition, comparison of PEER strong motion dataset time histories and spectra were made to corresponding USGS and CGS values.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

Attenuation relationships are the backbone of modern earthquake hazard assessment. These relationships are used in all earthquake hazard assessment ranging from the U.S. national and California seismic hazards maps, (the latter produced jointly by the USGS and CGS), to site-specific assessments, both deterministic and probabilistic, used for specific facilities ranging from bridges to dams to power plants and other electrical systems. Hazard assessment results are used to establish design strategies and details of the build environment and to predict their performance.

3. Brief description of the accomplishments of the project

The PEER strong motion data set currently consists of over 10700 time histories (acceleration velocity, displacement) (Figure 1) and response spectra (Figure 2) from 175 earthquakes (magnitude **M** 4.37 to 7.9) at 1580 recording sites. All data were put into a common format for ease of use. A catalog and various spreadsheets provides the supporting metadata including V_s 30, fault mechanism (strike, dip, rake) and many other parameters.

4. Describe any instances where you are aware that your results have been used in industry

The database is currently being used in the PEER-NGA project to produce the next generation of attenuation relations for the western U.S.

5. Methodology employed

The methodology employed was to augment the PEER data set with strong motion recordings that were readily available from data providers (e.g. USGS, CGS, USC) on the www or other electronic media. Also, metadata (e.g. source, path and site information) were requested and received from leading attenuation modelers, seismologists and engineers. An extensive literature and web search for ground motion data and metadata was also performed.

6. Other related work conducted within and/or outside PEER

Substantial amounts of strong motion data and metadata collected during this project were provided by other organizations and individuals (e.g. PE&A, USGS, CGS).

7. Recommendations for the future work: what do you think should be done next?

Continue to expand and update the PEER strong motion data set with additional earthquakes and metadata.

8. <u>Author(s), Title, and Date</u> for the final report for this project

Not completed.

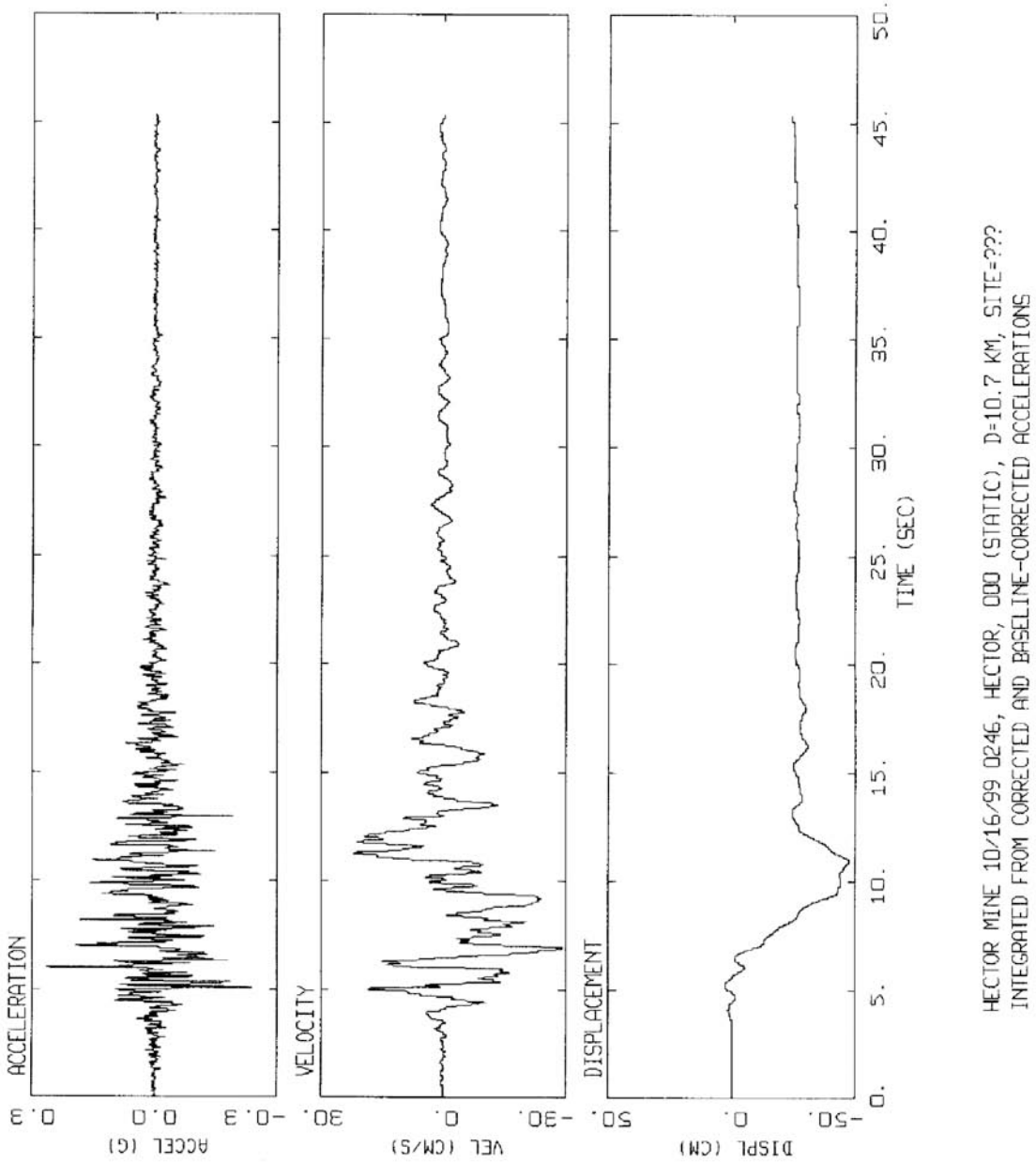


Figure 1. Acceleration, velocity and displacement time histories from the 1999 Hector Mine, CA earthquake at the closest station. The time history was processed at PE&A to retain static displacement offsets.

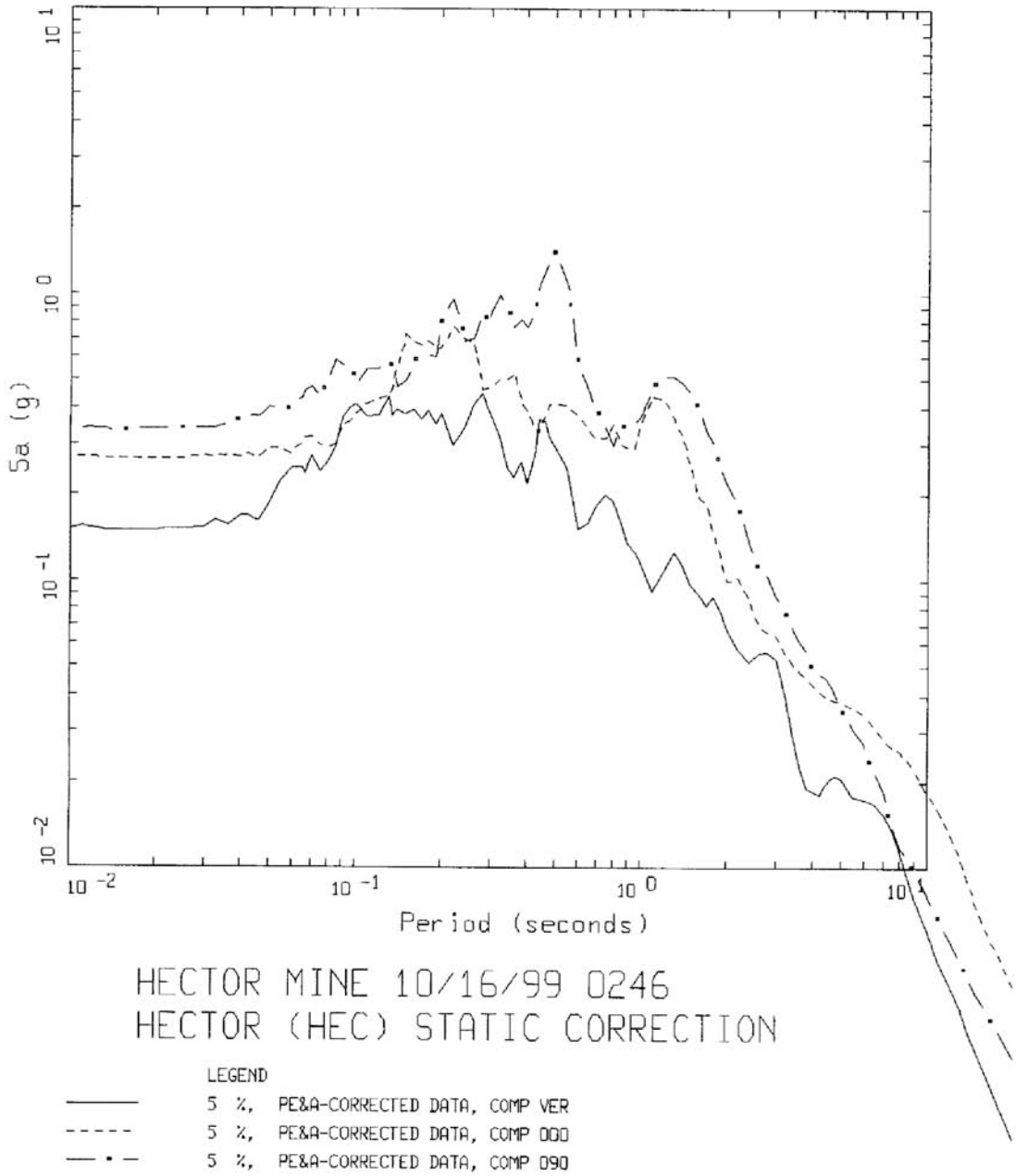


Figure 2. 5% damped response spectra at Hector. The Comp 000 spectrum is from the acceleration time history of Figure 1.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*D. Boore participation with NGA modeling*—**1L03**		
Start/End Dates	3/1/03 – 6/30/04	Budget/ Funding Source	$50,000 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**Boore (USGS)**		

1. Project goals and objectives
Derive new ground-motion prediction equations

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.
From project chief

3. Brief description of the accomplishments of the project
Attended all but one meeting and spent considerable time with the strong-motion database, checking entries and preparing "notes" on various database subjects. See accompanying spreadsheet.

4. Describe any instances where you are aware that your results have been used in industry
Not used yet

5. Methodology employed
various

6. Other related work conducted within and/or outside PEER
See my web site (http://quake.usgs.gov/~boore) for papers, software, and data related to the work.

7. Recommendations for the future work: what do you think should be done next?
Continue to derive the equations

8. Author(s), Title, and Date for the final report for this project
David M. Boore, Geophysicist, 27 July 2004

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*NGA: Site Condition Metadata from Geology*—**1L05**		
Start/End Dates	4/1/03 – 6/30/04	Budget/ Funding Source	$59,359 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**Wills (CDC-CGS)**		

1. Project goals and objectives
Provide geology-based estimates of shear-wave velocity at all California strong-motion recording sites in the PEER-NGA database.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.
The PEER Next Generation Attenuation Equation project and developers of attenuation codes need to consider site conditions in seismic hazard analysis. To accommodate this need, CGS is contributing to PEER's database of site conditions information for all strong motion stations that have recorded earthquake ground motion.

3. Brief description of the accomplishments of the project
To expand the database of strong ground motion data and metadata , CGS has added preliminary estimates of the average shear-wave velocity to 30 m each of approximately 1200 sites based on existing GIS data. These estimates have then been refined from the preliminary statewide site conditions map based on existing data from measured shear-wave velocity profiles and newly measured profiles, principally in areas where existing profile data is sparse or lacking. Based on the available site conditions information, CGS has estimated of the average shear wave velocity to 30 m for each site, including the basis for the estimate and uncertainty.

4. Describe any instances where you are aware that your results have been used in industry
Velocity estimates based on this technique are the basis of the "Preliminary site conditions map of California" which is used in estimating earthquake ground shaking for emergency response through "ShakeMap"s and is used in estimating future potential ground shaking used in setting earthquake insurance rates in California though the California Earthquake Authority.

5. Methodology employed
For this project CGS compares the locations of measurements of shear-wave velocity with geologic maps to develop correlations between Vs and geologic units. The summary statistics can then be applied to earthquake strong-motion recording stations on those or similar geologic units.

6. Other related work conducted within and/or outside PEER
This project is intended to provide background data to the PEER NGA project.

7. Recommendations for the future work: what do you think should be done next?
Future work should focus on providing velocity estimates for specific sites where the generalized approach does not provide a sufficiently accurate estimate, mainly sites where the geologic conditions change in the upper 30 m.

8. <u>Author(s), Title, and Date</u> for the final report for this project
Not complete at this time.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Ground Motion Models for Fling step*—**1L06**		
Start/End Dates	5/1/03 – 6/30/04	Budget/ Funding Source	$64,603 / PG&E
Project Leader (boldface) and Other Team Members	**Graves (URS Corporation)**		

1. Project goals and objectives

The objective of this project is to develop a parametric description of the fling step behavior expected for dip-slip faulting using numerical simulations of scenario earthquakes. The earthquake magnitude range is Mw 6.5-7.9. Our goal is to use these numerical results along with existing recorded ground motions to help guide and develop a model of fling step behavior that can be used for engineering purposes, specifically in the NGA program.

Another component of this project will support the participation of Robert Graves in the NGA program. The analysis and characterization of fling effects form a component of the NGA program in Working Group 1 (task 2). This work will entail the coordination of a panel of experts to provide input and guidance on the characterization of fling effects. We will solicit input from these experts on two key questions: 1) Are the characteristics of fling effects fundamentally different than the characteristics of more general ground shaking (e.g. different distance dependence)? 2) Do fling effects behave in a systematic manner that can be adequately represented using a regression model? The input from these experts will be documented and a summary report describing our recommendations will be provide to NGA.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The results of this project will be directly incorporated in the NGA program. The goal of NGA is to develop the Next Generation of Ground Motion Attenuation relations. It is expected that these ground motion models will be used extensively in engineering practice in the years to come.

3. Brief description of the accomplishments of the project

Using a combination of empirical analysis and numerical simulations, we have developed a preliminary model of fling step behavior expected very close to large earthquakes. The fling model is parameterized by start time, final residual displacement, and pulse period. These parameters are constrained by modeling the ground motion records from recent large earthquakes, including Chi-chi (Taiwan), Izmit (Turkey), and Landers.

4. Describe any instances where you are aware that your results have been used in industry

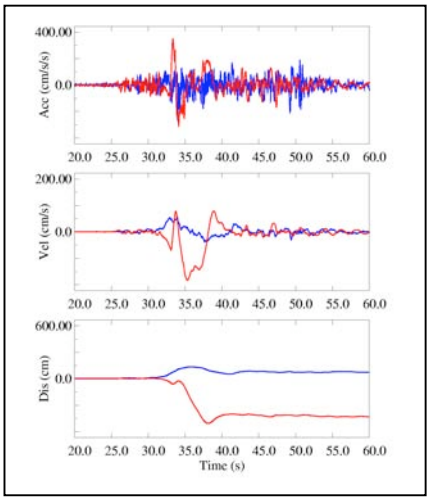
The results of this project will be directly incorporated in the NGA program. The goal of NGA is to develop the Next Generation of Ground Motion Attenuation relations. It is expected that these ground motion models will be used extensively in engineering practice in the years to come.

5. Methodology employed

This project employs a combination of empirical data analysis and numerical simulation techniques to develop the fling ground motion model. The numerical simulations consist of a theoretically rigorous representation of heterogeneous fault rupture within a plane-layered visco-elastic velocity structure. Full waveform ground motions in the frequency range 0 – 2 Hz (including residual displacement) are computed. From the suite of empirical and simulated ground motion time histories, fling parameters including pulse start time, pulse period and residual displacement amplitude are measured. These parameters are used to develop a regression model to be used for estimating expected fling behavior.

The deployment in recent years of broadband, high dynamic range, digital seismometers has resulted in a wealth of strong ground motion data. The nature of the modern instrumentation has allowed recovery, in several instances, of ground motion records covering a continuous frequency range from several tens of Hertz down to zero frequency. These records provide an unprecedented opportunity to examine not only the dynamic ground shaking characteristics, but also the growth and temporal evolution of static ground displacements. These static displacements represent the effects of tectonic deformation associated with the fault rupture. Recent earthquakes generating such recordings include the 1992 Landers, 1999 Izmit, and 1999 Chi-Chi events.

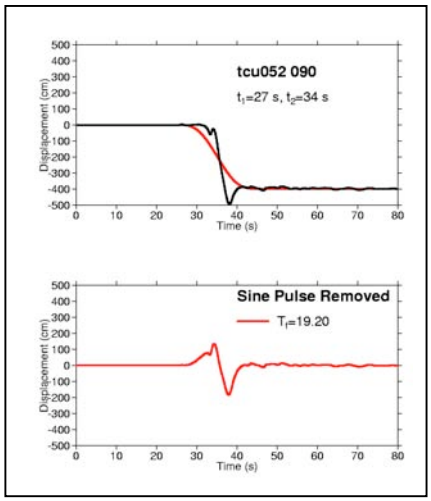
Figure 1 shows an example of the significance of fling effects. These two records are obtained on opposite sides (foot- / hanging-wall) of the fault during the Chi-Chi earthquake. Both sites are within 2 km of the fault rupture and they are directly across the fault from one another.



The blue traces are from the footwall site and the red traces are from the hanging wall. At longer periods (velocity and displacement) the hanging wall motions are much larger than the footwall. This is due to fling effects (growth of residual displacement). However, this can have a significant effect on PGV as well. These effects are accurately reproduced with the numerical simulations.

From a theoretical standpoint, one may expect the frequency and distance dependence of the static deformation field to exhibit somewhat different characteristics than the dynamic ground shaking. This is because the static field is generated from the near- and intermediate-field terms, while the dynamic motions are also controlled by the far-field terms. However, the contribution of the near- and intermediate-field terms to the dynamic motions may also be important in the near-fault region. Unfortunately, the currently available set of recorded motions is not sufficient to adequately parameterize these effects. Thus, we propose to use numerical simulations to augment the existing recorded motions.

The tabulated fling parameters from the dip slip faulting simulations will be combined with those from the strike slip simulations into a database that will then be used to develop the fling model. Norm Abrahamson will be responsible for the development of the fling model. The model will be built using regressions on the tabulated parameters. We expect the model will explicitly include dependencies on earthquake magnitude and closest distance; however, we will also test the sensitivity of the model to other parameters such as hypocenter location and slip distribution to quantify the expected uncertainty in the estimates of the model parameters.



The fling pulse is modeled using the double integral of a single cycle of a sine function. The parameters controlling the shape of the pulse are start time (t_1), final residual displacement (D), and pulse period (T_f). The start time can be estimated from the theoretical S-wave arrival time and the final displacement can be directly measured (or inferred). We estimate the pulse period using numerical simulation of fault rupture. Following this procedure, we have developed a fling pulse for the TCU052 record shown in Figure 1. The original displacement record is plotted against the fling pulse displacement in Figure 2. Shown at the bottom of Figure 2 is the result of removing the fling pulse from the recorded displacement.

6. Other related work conducted within and/or outside PEER

Previously, we have calculated a suite of numerical simulations to investigate the fling step behavior for strike slip faulting. That study examined a suite of rupture scenarios and a suite of rupture magnitudes. This project will augment that study be extending the analysis to dip slip faulting. We will incorporate the strike slip results with the dip slip results in our final fling model.

7. Recommendations for the future work: what do you think should be done next?

The preliminary fling pulse model developed here needs further testing against both recorded and simulated data. In particular, the pulse period is not well constrained by current information. It is most certainly related to the rupture propagation speed along the fault and the fault slip rise time. More sophisticated numerical experiments utilizing dynamic rupture simulations would probably help to better understand the relationship between the faulting parameters and the fling pulse period.

8. <u>Author(s), Title, and Date</u> for the final report for this project

Robert W. Graves and Norm Abrahamson "Ground Motion Models for Fling Step", 2004

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Statistical Methods for Attenuation Modeling*—**1L07a**		
Start/End Dates	10/1/03 – 6/30/04	Budget/ Funding Source	$56,470 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**Youngs (Geomatrix)**		

1. Project goals and objectives

The primary objective of the project was to develop statistical methods to be used to address the issues of data truncation and data uncertainty in developing ground motion attenuation models from the empirical PEER NGA ground motion data base.

A separate task funded under the same project ID (1L07a) provided additional information on recording site conditions as part of the development of the PEER NGA strong motion data base.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The benefit of the primary results of the project is improved statistical estimates of strong ground motions based on the analysis of empirical strong motion data. The benefit of the separate task is improvements in the PEER NGA strong motion data base. Both tasks lead towards the goal of improving the prediction of strong ground motion amplitudes.

3. Brief description of the accomplishments of the project

To date, the statistical methods task has identified techniques to deal with data truncation and data uncertainty and implemented initial versions of these algorithms in R. Demonstrations of these techniques have been presented at project workshops.

The data base improvement task involved a review of information on recording stations contained in the PEER NGA data set, including information on the station structure and information on the geologic conditions at the station sites. The data reviewed included the classification of the recording station structure type using the Geomatrix structure classification system; and classifications and parameters for the geologic conditions at the recording station sites, including classification according to different systems (Geomatrix, NEHRP, Campbell-Bozorgnia, and surface geology) and average shear wave velocity to depth of 30 meters (V_{S30}). The data were reviewed yo identify missing and incorrect entries, and conflicts between preferred assignments for data set classifications and parameters and assignments provided by different contributors to the data set. Because several data sets were identified that had not been incorporated into the station data base, a significant effort was made to update the station structure classification and geological classifications using the additional data sets. Several of the larger data sets that were incorporated into the data base included soil boring data from U.S. Geological Survey Open-File Reports and the ROSRINE project for California stations, and structural classifications and geological classifications for Taiwan stations from station site plans and geological maps of Taiwan.

4. Describe any instances where you are aware that your results have been used in industry

None to date.

5. Methodology employed

A verity of statistical methods will be adapted from the statistical literature for application to the NGA empirical ground motion assessments. These will likely be implemented in the statistical language R or possibly FORTRAN.

6. Other related work conducted within and/or outside PEER

N/A.

7. Recommendations for the future work: what do you think should be done next?
N/A.

8. Author(s), Title, and Date for the final report for this project
The statistical methods will be described in a report by:
Robert Youngs, Brian Chiou, Norm Abrahamson, and David Brillinger
Statistical Methods for Improved Estimation of Strong Ground Motion Using Empirical Data
June 2005

No report is being prepared for the data base task.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*1-D Rock Motion Simulations*—**1L08**		
Start/End Dates	12/1/03 6/30/04	Budget/ Funding Source	$80,000 / PG&E-CEC
Project Leader (boldface) and Other Team Members	**Walter Silva (PEA)**		

1. Project goals and objectives

Develop a data set of simulated strong ground motions for a suite of strike slip and reverse slip earthquakes at about 150 site locations. Part of the project included validating the simulation methodology with six recent earthquakes for recordings at about 100 sites.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

Simulated motions were developed to provide guidance in developing empirical attenuation relations for the PEER NGA project.

3. Brief description of the accomplishments of the project

Over 300,000 motions were simulated for magnitudes ranging from **M** 6.5 to **M** 7.8 at various azimuths and rupture distances (out to about 200 km).

4. Describe any instances where you are aware that your results have been used in industry

Results are to be used in the PEER NGA project by the developers of attenuation relations.

5. Methodology employed

The stochastic finite fault methodology developed by Pacific Engineering was used. Examples of the validation results are shown in Figure 1 for mean residual over all sites. Figure 2 shows mean residual (at five seconds) verses a directivity parameter for all sites within a 20 km rupture distance.

6. Other related work conducted within and/or outside PEER

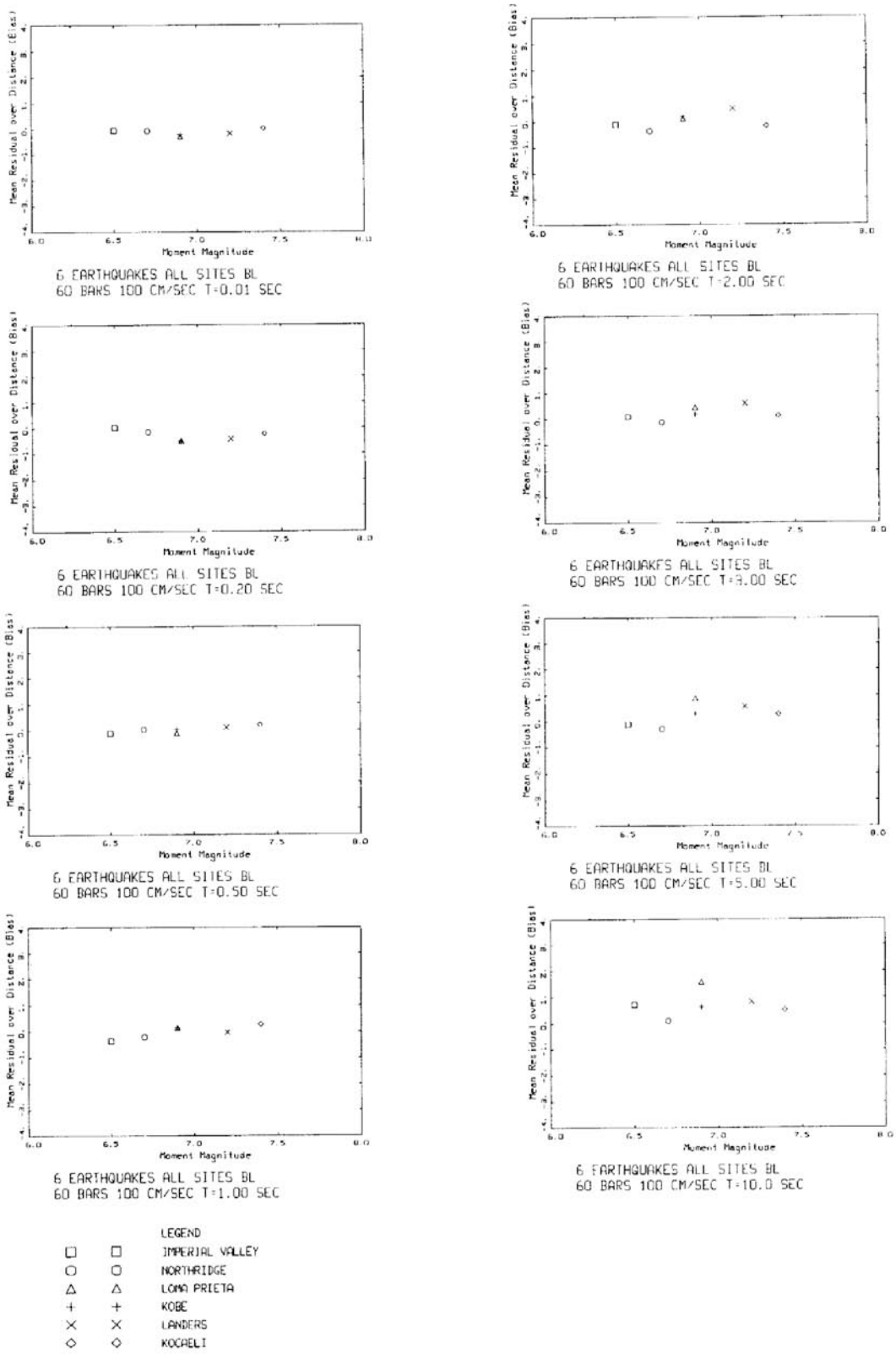
Two other modeling teams with distinct simulation methodologies simulated the same suit of earthquakes and site locations.

7. Recommendations for the future work: what do you think should be done next?

More realistic crustal parameters should be used so direct comparisons to motions from California attenuation relations can be made at absolute levels.

8. <u>Author(s), Title, and Date</u> for the final report for this project

Report is pending.


Mean Residual over Distance (Bias)
Moment Magnitude
6 EARTHQUAKES ALL SITES BL
60 BARS 100 CM/SEC T=0.01 SEC
6 EARTHQUAKES ALL SITES BL
60 BARS 100 CM/SEC T=0.20 SEC
6 EARTHQUAKES ALL SITES BL
60 BARS 100 CM/SEC T=0.50 SEC
6 EARTHQUAKES ALL SITES BL
60 BARS 100 CM/SEC T=1.00 SEC
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60 BARS 100 CM/SEC T=5.00 SEC
6 EARTHQUAKES ALL SITES BL
60 BARS 100 CM/SEC T=10.0 SEC
LEGEND
IMPERIAL VALLEY
NORTHRIDGE
LOMA PRIETA
KOBE
LANDERS
KOCAELI

Figure 1.

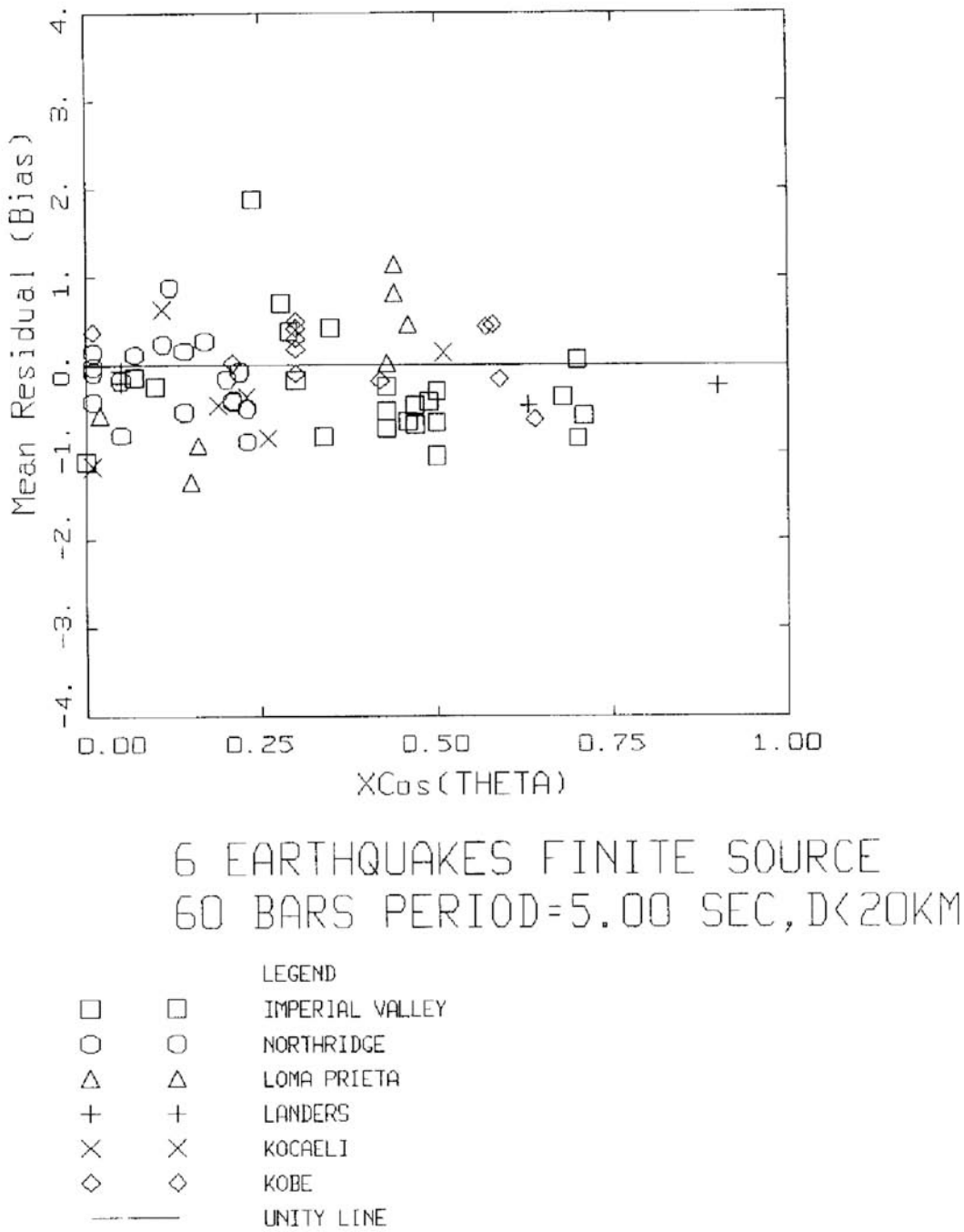

Mean Residual (Bias)
4.
3.
2.
1.
0.
-1.
-2.
-3.
-4.
0.00
0.25
0.50
0.75
1.00
XCos(THETA)
6 EARTHQUAKES FINITE SOURCE
60 BARS PERIOD=5.00 SEC, D<20KM
LEGEND
IMPERIAL VALLEY
NORTHRIDGE
LOMA PRIETA
LANDERS
KOCAELI
KOBE
UNITY LINE

Figure 2.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Checking and Augmentation of NGA Database*—**1L09**		
Start/End Dates	5/1/03 – 6/30/04	Budget/ Funding Source	$54,498 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**Collins,** Graves, Somerville, Thio, Willis (URS Corporation)		

1. Project goals and objectives

Review the NGA empirical database including earthquake source parameters, station distance and directivity parameters, orientation of recorded components, and station locations and other items as may be deemed pertinent. Add to the database depth to Vs isosurfaces; basin outlines at the ground surface; other basin parameters that more fully describe the geometric relation of source, basin, and site; and a flag indicating shallow vs deep asperities of fault models. Calculate residuals of 3D basin simulations with respect to the Abrahamson and Silva (1997) model. Add data from USGS processed data to the database including PGA and sampling interval from Volume 1 files and PGA, PGV, PGD, and filter information from Volume 2 files. Create summary tables of simulations results from the three modeling groups.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

This projects supports the development of NGA attenuation relations which will be used widely in engineering practice to develop seismic design criteria

3. Brief description of the accomplishments of the project

We have reviewed the magnitudes and source parameters of major earthquakes in the database and documented references used. Finite fault models have been checked in detail for 13 earthquakes including four earthquakes with multiple segments (Landers, Kocaeli, Hector Mine (Fig 1), and Denali). Fault models and source parameters for an additional six earthquakes have been reviewed by literature search. Results have been documented by updating Excel spreadsheets created by the original researchers and providing notes with references.

The formula used for calculation of closest distances has been checked. Component orientations entered in the database were checked against those in the COSMOS database and any discrepancies noted on the appropriate Excel spreadsheets. We have added basin depth information to the “flat file” that had been created by Brian Chiou to summarize a number of tables developed by Pacific Engineering and Analysis (PEA).

The “flat file” was updated with data from 333 three-component Volume 1 time histories representing 40 earthquakes and 354 three-component Volume 2 time histories representing 41 earthquakes.

A table of results of simulations done by the three modeling groups (Pacific Engineering and Analysis, University of Nevada Reno and URS Corporation) was created.

For all work, reports were written and suggestions for additional tasks that need to be addressed were made.

4. Describe any instances where you are aware that your results have been used in industry

When completed, the NGA ground motion models will be used widely in industry.

5. Methodology employed

See Section 3.

6. Other related work conducted within and/or outside PEER

This work relates to the development of a database of empirical records and one of simulation results that will be used by the Developers in preparing a new ground motion attenuation model.

7. Recommendations for the future work: what do you think should be done next?

As these databases have great value, not only within the NGA project, but also for the earthquake engineering and seismological community, quality checks on both the empirical and synthetic databases should continue. In addition, the empirical database should be kept up to date by adding new data as it is available.

8. <u>Author(s), Title, and Date</u> for the final report for this project

Somerville, Paul, Nancy F. Collins, Robert Graves, Hong Kie Thio. "NGA Data Base Review, Final Report," April 12, 2004.

Somerville, Paul and Nancy F. Collins. "Add USGS Data to NGA Database, Final Report," April 16, 2004.

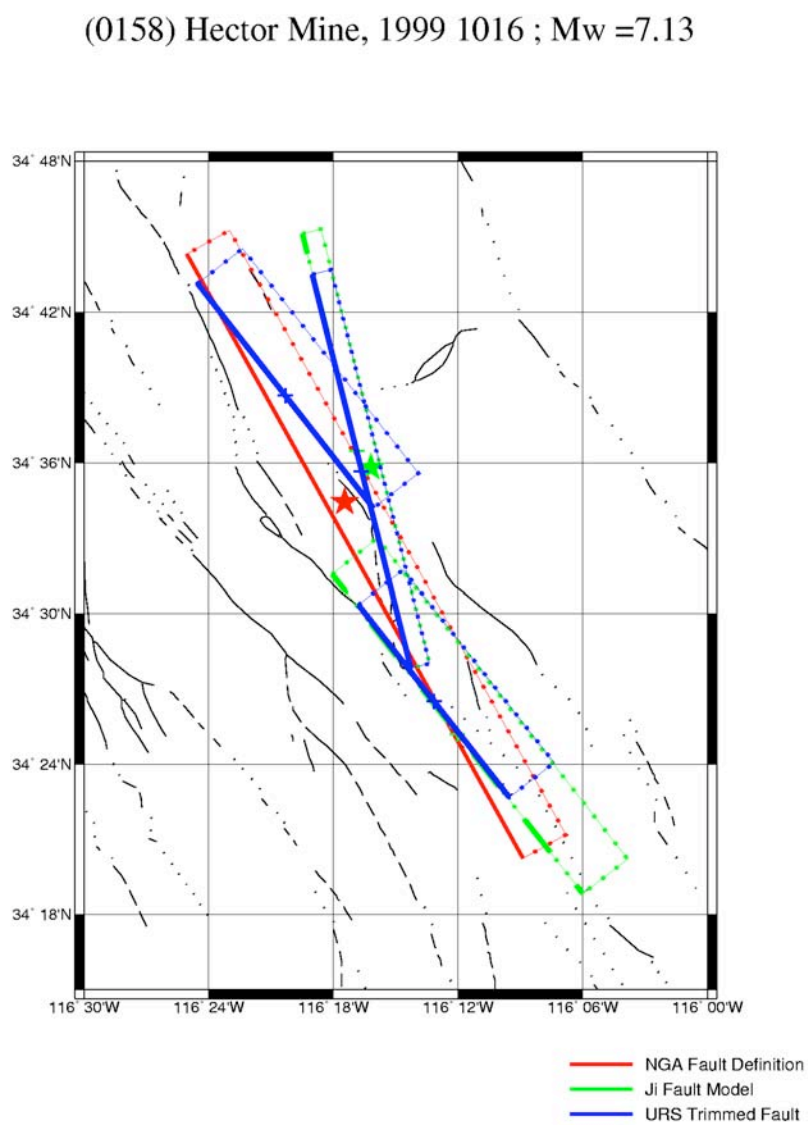


Figure 1. Map of Hector Mine fault projection showing the original NGA fault definition, the preferred model chosen (Ji Model), and the trimmed Ji model as entered into the revised database.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Supplemental USGS Work for NGA Project*—**1L10**		
Start/End Dates	11/18/03 – 6/30/04	Budget/ Funding Source	$36,761 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**P. Spudich,** J. Boatwright, W. Mooney, C. Stephens, T. Brocher, R. Catchings, W. Savage		

1. Project goals and objectives

A. Development of improved functional forms for directivity, based on isochrone theory, that can be used by NGA attenuation relation developers in their new attenuation models.
B. Depths and uncertainties to 1.5 and 2.5 km/s S-wave velocities for all stations within the Bay Area and northern California that contribute strong motion recordings to the PEER/NGA database.
C. Processed accelerograms for 56 USGS 3-component accelerograms.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

This project contributes directly to the strong-motion data (C.) and meta-data (B.) in the PEER/NGA database, and to the development of physically-appropriate attenuation relations (A.) for the regressions that form the heart of NGA.

3. Brief description of the accomplishments of the project

A. Task A used isochrone theory to develop period-independent functional forms for directivity that have a basis in physics and can be easily used or generalized for nonplanar fault geometries. Several possible functional forms were developed, each of which has a wider range of applicability than previous forms.
B. Task B determined P-wave velocity structures for 6 refraction lines in the Bay Area. These P-wave velocity structures obtained from refraction studies were used to calibrate and revise the Brocher/Jachens/Wentworth Bay Area 3D velocity model. This revised model was used to estimate the depth to the 1.5 and 2.5 km/s S-wave velocities beneath the strong motion stations.
C. Task C vetted and processed 56 accelerograms, which has added important data to the PEER database.

4. Describe any instances where you are aware that your results have been used in industry

None yet.

5. Methodology employed

A. Task A used isochrone theory, a method based on ray theory, that yields simple analytical expressions.
B. Task B determined P-wave velocity structures for the 6 refraction lines in the Bay Area by standard analysis techniques. The P-wave velocity structures obtained from these refraction studies were systematically different from the Brocher/Jachens/Wentworth Bay Area 3D velocity model. Depths of isovelocity surfaces in the 3D model were revised to correct the systematic differences from the refraction results.
C. Task C vetted and processed the 56 accelerograms using standard USGS processing procedures.

6. Other related work conducted within and/or outside PEER

A similar 3D-velocity structure of the Los Angeles region has been developed for the Southern California Earthquake Center.

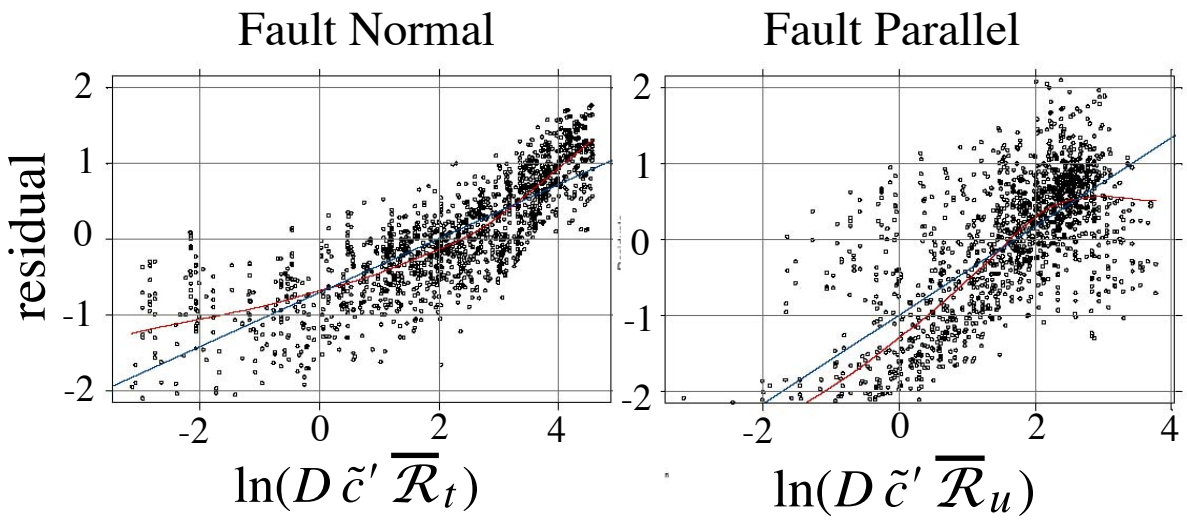
7. Recommendations for the future work: what do you think should be done next?

It would be possible to use isochrone theory to develop period-dependent functional forms for directivity.

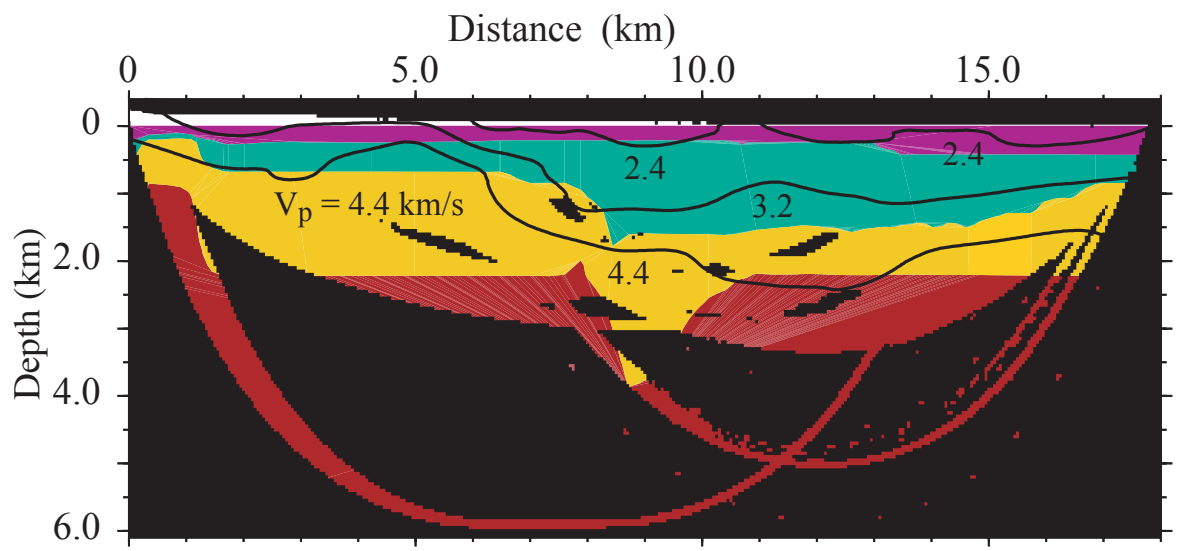
8. Author(s), Title, and Date for the final report for this project

Spudich, P., Chiou, S.J., Graves, R., Collins, N., and Somerville, P., A formulation of directivity for earthquake sources using isochrone theory, U.S. Geological Survey Open-File Report 2004-1268, 54 pp., http://pubs.usgs.gov/of/2004/1268/

Boatwright, J., Blair, L., Catchings, R., Goldman, M., Perosi, F., and Steedman, C., Using twelve years of USGS refraction lines to calibrate the Brocher and others 3D Velocity model of the Bay Area, Geological Survey Open-File Report 2004-1282, 33 pp., http://pubs.usgs.gov/of/2004/1282/



Correlation of isochrone directivity parameter with 3-s SA residual for fault-normal and fault-parallel components of motion for synthetic test strike-slip event. Residual is ln(numerically generated SA for test event) - ln(best-fitting nondirective model).



Comparison of a slice through the Brocher et al. (1997) 3D velocity model (solid colors) with Catchings et al. (2004) model (black contours) derived from a linear seismic refraction profile 1025 through Los Gatos, CA. Solid black areas are regions where the Catchings model is undefined. Purple/teal, teal/yellow, and yellow/maroon interfaces are the 2.4, 3.2, and 4.4 km/s contours in the Brocher model. In general, Catchings' velocity contours are shallower than Brocher's.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*SMA Site Characterization in Taiwan-SASW*—**2A02c**		
Start/End Dates	7/1/02 – 5/31/04	Budget/ Funding Source	$108,092 / Caltrans
Project Leader (boldface) and Other Team Members	**Stokoe/Rathje (UT at Austin)**		

1. Project goals and objectives

Apply the Spectral-Analysis-of-Surface-Waves (**SASW**) Method to determine the shear wave velocity profiles of selected strong-motion recording (SMR) sites in Imperial Valley and Los Angeles, CA and use the results to determine classification of these sites in terms of the shear wave velocity in the top 30 m ($V_{s,30}$) and the upper portion of the V_s profiles to evaluate of their liquefaction potential.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The SASW method can be used in siting facilities for electric systems, because $V_{s,30}$ obtained from the SASW method is used by engineers in estimating the earthquake site response and the upper portion of the V_s profiles can be used in liquefaction evaluations.

3. Brief description of the accomplishments of the project

In total, 42 shear wave velocity profiles (26 from Univ. of Texas at Austin and 16 from National Cheng Kung University) of the SMR sites in Taiwan were determined. Also, the site classification of each site was determined.

4. Describe any instances where you are aware that your results have been used in industry

The shear wave velocity profile reduced from the SASW method can be applied to determine earthquake site response/classification, liquefaction evaluations, landfill/soil compaction control, and pavement quality evaluation.

5. Methodology employed

Spectral-Analysis-of-Surface-Waves (**SASW**) Method is a non-intrusive seismic method of profiling geotechnical sites.

6. Other related work conducted within and/or outside PEER

Outside PEER: SASW testing in the Seattle, Washington area, at several landfills in the San Francisco area, and at the Yucca Mountain, Nevada, test site.

7. Recommendations for the future work: what do you think should be done next?

Perform SASW testing with a source which can generate more energy to explore deeper soil profiles at some sites which already have deeper V_s data obtained from other intrusive methods to demonstrate the accuracy of the SASW method for future deeper profiling.

8. Author(s), Title, and Date for the final report for this project

Authors: K.H. Stokoe, II, Yin-Cheng Lin, Brent L. Rosenblad, Farn-Yuh Menq, and Ellen M. Rathje.
Title: SMA Site Characterization in Taiwan-SASW
Date: August 31, 2004

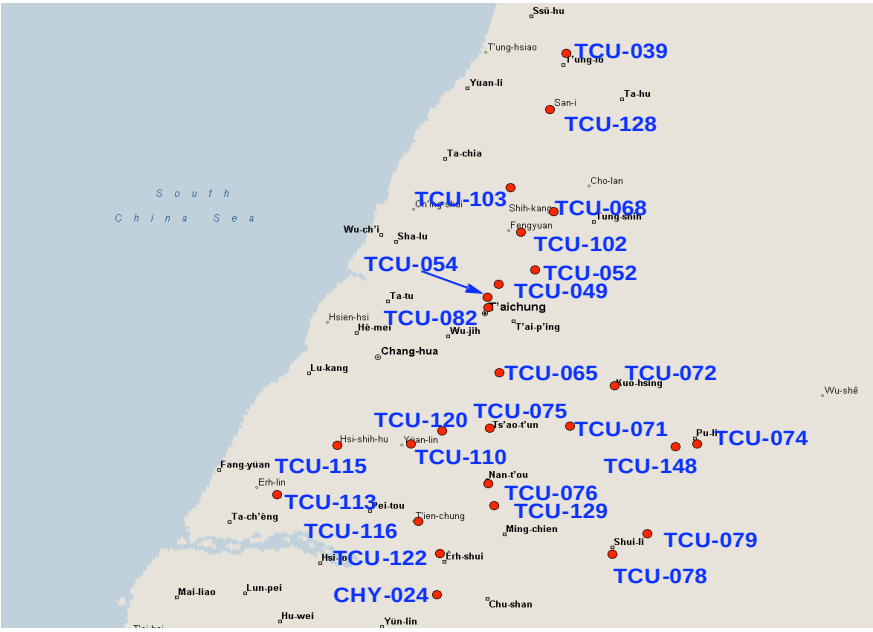


Figure 1. Map of Approximate Locations of 26 SMR Stations in Taiwan where SASW Seismic Tests were Performed by the University of Texas at Austin

Table 1. $V_{S,30}$ Values from 26 Sites and Site Classifications26 SMR Stations in Taiwan where SASW Seismic Tests were Performed by the Univ. of Texas at Austin

No.	Site Name	Station No.	$V_{s,30}$ (fps)	Site Classification
1	Lin - Chong Elementary School	CHY-024	1400	C
2	Ton - Lo Elementary School	TCU-039	1810	C
3	Cheou - Shio Elementary School	TCU-049	1490	C
4	Wu - Fon Elementary School	TCU-065	800	D
5	Si - Kon Elementary School	TCU-068	1660	C
6	Suan - Don Elementary School	TCU-071	1930	C
7	Kuo- Sing Elementary School	TCU-072	1350	C
8	Nan - Kon Elementary School	TCU-074	1370	C
9	Chiou - Tun Elementary School	TCU-075	1480	C
10	Nan - To Elementary School	TCU-076	1750	C
11	Shai - Li Elementary School	TCU-078	1540	C
12	Tor - Se Elementary School	TCU-079	1390	C
13	Fon - Ton High School	TCU-102	1770	C
14	Nai - Pu Elementary School	TCU-103	2060	C
15	Yuan - Lin Elementary School	TCU-110	700	D
16	Sin - Hua Elementary School	TCU-113	780	D
17	Si - Hu Elementary School	TCU-115	750	D
18	Ten - Chong High School	TCU-116	1250	C
19	Ton - Ang Elementary School	TCU-120	1360	C
20	A - Sua Elementary School	TCU-122	1560	C
21	Cheng - Jung Elementary School	TCU-128	1720	C
22	Sin - Jai Elementary School	TCU-129	2180	C
23	Kung - Chung Elementary School	TCU-052	1290	C
24	Sin - San Elementary School	TCU-054	1600	C
25	Tai - Chung Weather Station	TCU-082	1310	C
26	Chi - Nan University	TCU-148	1390	C

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Workshop on Uncertainties in Nonlinear Soil Properties and impact on modeling response*—**2B01/2B02**		
Start/End Dates	6/01 – 6/30/04	Budget/ Funding Source	$135,000 / Caltrans
Project Leader (boldface) and Other Team Members	**D.G. Anderson (CH2M HILL), K.H. Stokoe, II (University of Texas at Austin), M. Vucetic (University of California at Los Angeles)**		

1. Project goals and objectives

Evaluate the shear modulus and material damping properties of intact soil samples at small to large shearing strains and from low to high confining pressures.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The overall benefit from this testing program is to provide additional high quality laboratory test data that can be used to validate existing and develop new soil models which can be used to estimate ground response during seismic events. Additional specific benefits are listed below:

- *The results of these laboratory tests can be used in completing the characterization of sites where in situ shear wave velocities have been collected and where site response calculations are planned as part of a post-Northridge earthquake ground response study; and*
- *Direct comparisons of shear modulus and material damping properties can be made for a limited number of companion specimens tested with DSDSS and RC/TS testing equipment.*

3. Brief description of the accomplishments of the project

Enter text here.

The results of this testing program consist of 15 sets of dual specimen direct simple shear (DSDSS) test results and 25 sets of combined resonant column/torsional shear (RC/TS) test results. Each set of tests includes shear modulus and material damping as a function of shearing strain level. Combined RC/TS results also show effects of confining pressure and testing frequency on modulus and damping.

4. Describe any instances where you are aware that your results have been used in industry

Enter text here.

It is unclear whether these results have been put into use by industry. However, they have been used by Dr. Cliff Roblee, formerly of Caltrans, and by Professor Ken Stokoe, University of Texas, to develop alternate soil models. These models have been presented during an NSF workshop. Participants at the workshop may have used the proposed models in some of their ground response studies.

5. Methodology employed

Tests were conducted using state of the art laboratory testing equipment developed at the University of Texas by Professor Ken Stokoe and his colleagues, and at the University of California at Los Angeles by Professor Vucetic and his Colleagues.

6. Other related work conducted within and/or outside PEER

This work was conducted within the overall framework of the ROSRINE project. The ROSRINE project involves the evaluation of site response. Others providing support for the ROSRINE project (outside PEER) have included the National Science Foundation, the Electric Power Research Institute, the United States

Geological Survey, the Californian Geological Survey, the Nuclear Power Engineering Corporation (Japan), and the Kajima Corporation of Japan.

7. Recommendations for the future work: what do you think should be done next?

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Specific recommendations for additional testing were made in the report prepared from this project. These recommendations include the need for a comprehensive evaluation of all ROSRINE information, additional laboratory testing to investigate effects of soil disturbance and uncertainties associated with boundary conditions imposed by current testing methods, in situ testing methods that allowed stiffness and damping to be determined at high shearing strain levels, and further evaluation of the effects of uncertainties on site response.

8. Author(s), Title, and Date for the final report for this project

Donald G. Anderson
Laboratory Testing of Nonlinear Soil Properties: I & II
December 2003

Kentaro Tabata and Mladen Vucetic
Results of Cyclic Simple Shear Tests on Fifteen Soils Conducted for PEARL Project and Other Research Purposes
November 2002

Kenneth H. Stokoe, Won Kyoung Choi, Farn-Yuh Menq, and Celestino Valle
Linear and Nonlinear Dynamic Properties Determined by Combined Resonant Column and Torsional Shear Tests
March 2003

The second and third reports listed above are included as appendices to the report prepared by Don Anderson. Vucetic and Stokoe have also published these as UCLA and UT-Austin reports.

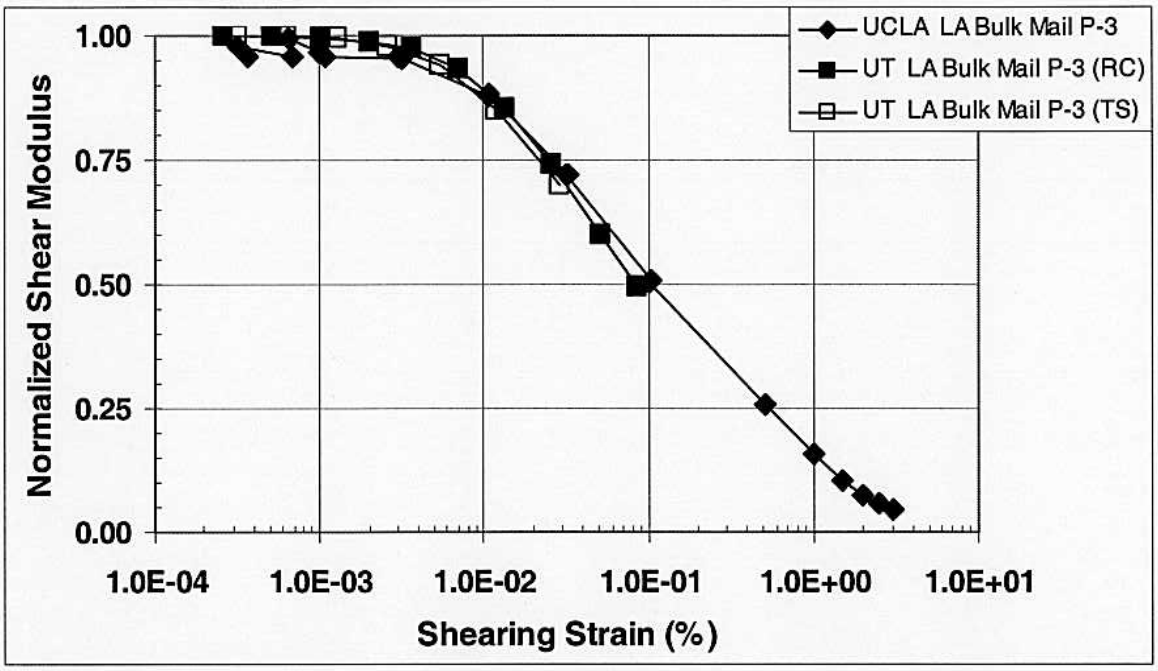


Fig. 3-14 Normalized Shear Modulus Ratio Comparisons (LA Bulk Mail P-3)

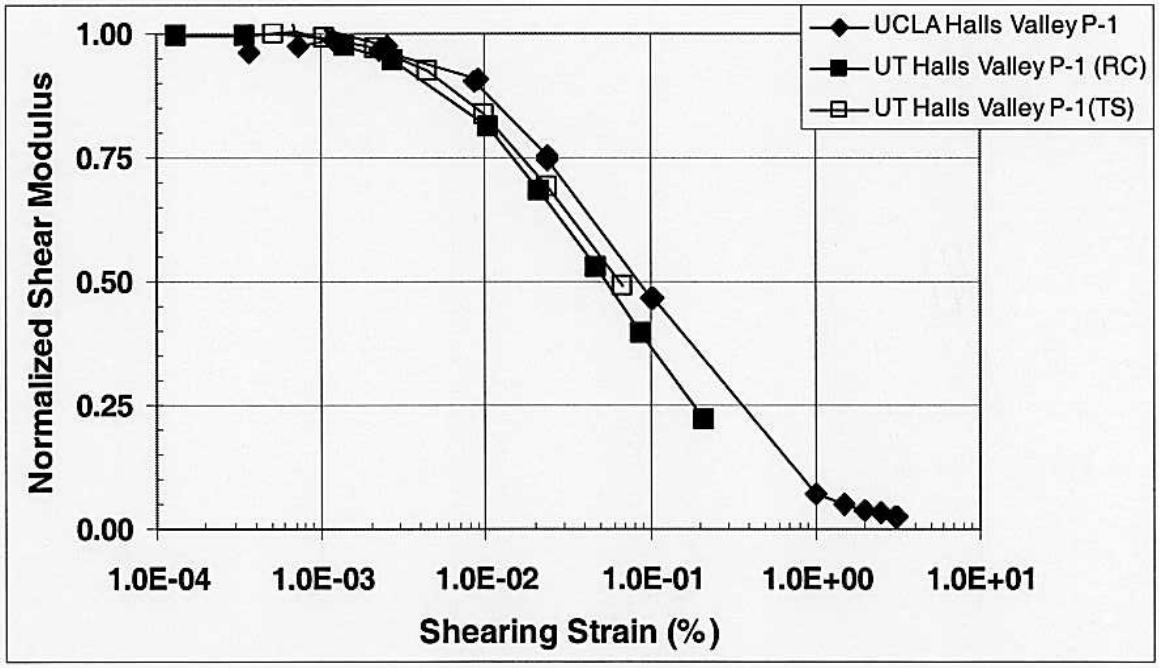


Fig. 3-15 Normalized Shear Modulus Ratio Comparisons (Halls Valley P-1)

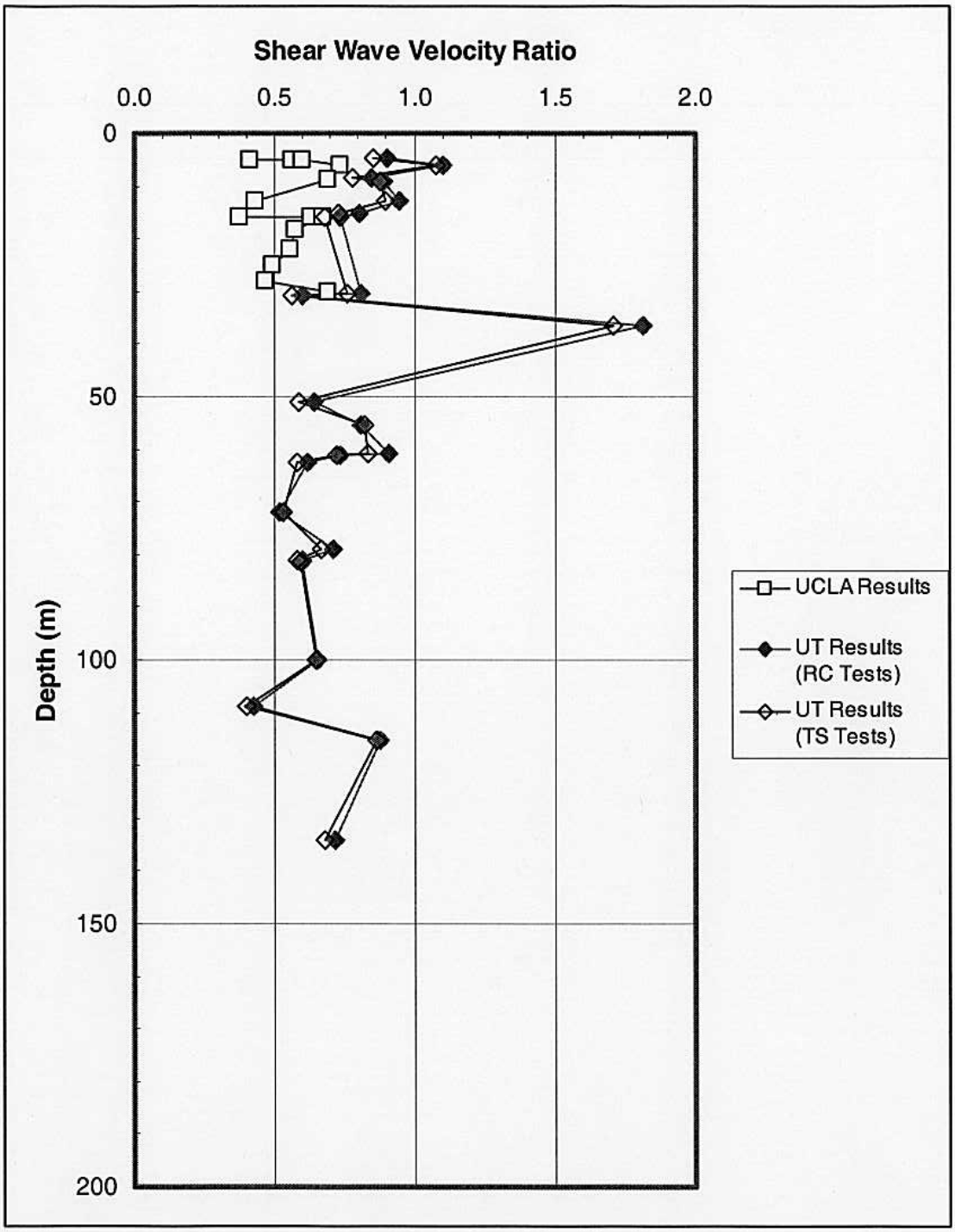


Fig. 3-1 **Comparison of In Situ and UT and UCLA Laboratory Measurements in terms of Velocity Ratio**

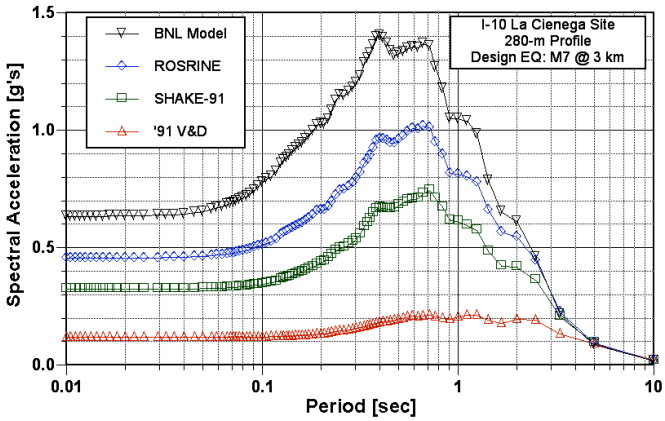
Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Workshop on Uncertainties in Nonlinear Soil Properties and Iimpact on Modeling Response* -- **Project 2B03**		
Start/End Dates	6/1/00 – 4/30/04	Budget/ Funding Source	$30,000 / Caltrans
Project Leader (boldface) and Other Team Members	**Riemer (UCB);** committee included E. Rathje, D. Anderson, C. Roblee		

1. Project goals and objectives

This project provided supplemental funding for an NSF Workshop focusing on identification of key sources of uncertainty surrounding the non-linear dynamic properties of soils, and evaluating the role of this uncertainty in the context of other factors in performing Site Response Analysis (SRA).

It is well established that uncertainties exist in nonlinear soil property determination. These uncertainties result from a number of sources, including inherent variations in nonlinear soil properties, soil sample disturbance, equipment testing effects, and in situ stress state/stress history. There are also a variety of soil models in use for predicting site effects, which can lead to substantial variation in predicted motions in some cases (see figure, after Silva).



The primary goals of the project were:

- Evaluation of the levels of uncertainty and bias in nonlinear soil property determination, and the types of testing and modeling that best address this issue.
- A better understanding of the current and future needs for soil modeling, and how these needs are related to the prediction of ground response and soil-structure interaction.
- A consensus between the *Testers* and *Modelers* on the types of development that should occur in each of their respective areas, through improved communication.
- Guidance to funding agencies on areas of research that are likely to achieve the most progress in the overall area of soil response and soil-structure interaction modeling.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

High levels of uncertainty in the likely ground motions at the site of any major component of a Lifeline system will necessarily lead to either very conservative (and expensive) design or retrofit of the structure,

or the assumption of considerable risk. Reduction of this uncertainty is complicated by the fact that there are multiple sources contributing, including the inherent variability of the seismic activity, bias and scatter in the evaluation of soil properties, and simplifications in the modeling and analysis used to predict site response. This Workshop brings together experts to begin untangling these various sources, evaluate their relative importance, and propose avenues of research that can best identify and reduce the most important sources of the uncertainty. As the research is performed, and the dominant sources of the uncertainty are better characterized, the ground motions will be predicted with greater confidence, and thus the costs of developing or retrofitting key Lifelines facilities can be reduced.

3. Brief description of the accomplishments of the project

The Workshop itself was held on March 18 and 19, 2004, at the PEER Center in Richmond, and was attended by some 44 participants from around the world, include three from overseas. All participants were required to write "opinion papers" laying out their perspectives on key questions in the field of site response analysis, and were selected based on the relevance of their research or experience in practice, with care taken to provide a balance among experimentalists, constitutive modelers, code developers and practicing engineers.

The products of the Workshop include:

- opinion papers and plenary papers of the individual participants,
- plenary presentations made by the invited speakers on the first day,
- reports made by the eight breakout session groups on the second day,
- summary report synthesizing the discussions and conclusions reached.

These materials will all be available on the project web site (most are already there):
http://peer.berkeley.edu/lifelines/Workshop304/index.html

4. Describe any instances where you are aware that your results have been used in industry

As the Workshop was primarily concerned with identifying key issues for quantifying sources of uncertainty and key areas for further research, there are not yet specific cases in practice that have been impacted. However, the inclusion of practicing engineers in the Workshop formed an important "reality check" on the ideas proposed by researchers at the workshop, while also establishing a direct path by which future developments can be incorporated by these individuals in industry.

5. Methodology employed

The organizing committee for the Workshop was active through frequent teleconference calls to identify appropriate speakers and other Workshop participants, develop and revise the agenda to best meet the goals of the Workshop, and prepare the participants through solicitation and posting of preliminary materials on the Project web site.

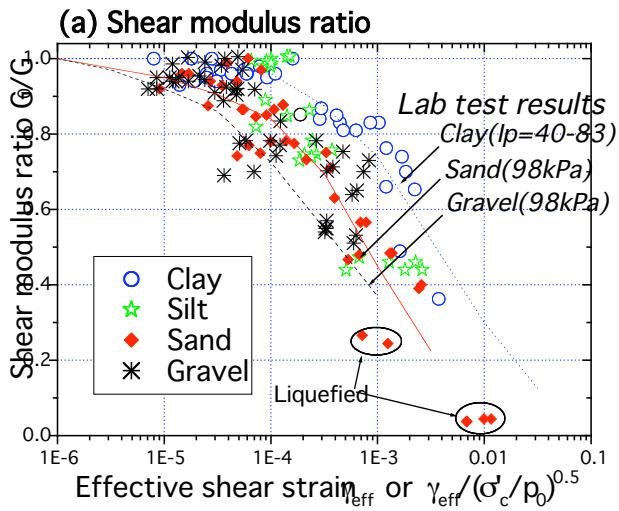
The first day focused on plenary sessions, with 11 invited presentations covering specific issues within the field of site response analysis. These presentations provided the group with a common background on the current issues from different perspectives, and stimulated excellent plenary discussions on the relative importance of various factors in contributing to accurate site response analysis. The second day was organized around eight "break out" sessions, in which smaller groups of participants met to work out responses to specific questions, including prioritization of future research to most effectively improve

response analysis. The conclusions of each group were summarized individually by the members, and are provided in the Workshop documentation.

6. Other related work conducted within and/or outside PEER

PEER Lifelines Project 2B01/02 involved extensive testing of high quality soil samples obtained as part of the ROSRINE program in Southern California. As such, it provided direct comparisons of dynamic properties as determined through Resonant Column, Torsional Shear, and Double Specimen Direct Simple Shear testing methods. While this provided some measure of the variability in properties associated with different methods, the current Workshop establishes a framework for evaluating the importance of these variabilities, particularly in comparison with other sources of uncertainty.

Outside of PEER, there is a strong interest in many of the same issues surrounding uncertainty in soil response analysis, particularly in seismically active regions of the world. This emphasizes the importance of developing international consensus on issues such as benchmark cases for validation of models and codes, and including international researchers to participate in database development.



(*Kokusho, 2004*)

7. Recommendations for future work: what do you think should be done next?

One of the primary goals of the program was the identification and prioritization of both short term and longer term research needs. Some of the most pressing needs identified included: quantification of the uncertainty in site response from all sources; characterization of soil response at larger strains (especially for non-linear models and pore pressure softening); rigorous benchmark testing of available non-linear models; calibration of available models with high quality array data and centrifuge data; field methods of measuring stiffness and damping over wide strain ranges, to tie together lab testing with Vs methods; development of a public database of high quality data for calibration of constitutive models; and the need to augment available data on a broader range of soils (eg. silts, gravels and other commonly encountered materials).

8. <u>Author(s), Title, and Date</u> for the final report for this project

The final report is not yet completed, but is anticipated in November 2004. The title will be:

International Workshop on uncertainties in nonlinear soil properties and their impact on modeling response

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Application of SASW to US SMA Sites*—**2C01**		
Start/End Dates	6/1/01 – 5/31/03	Budget/ Funding Source	$125,000 / Caltrans
Project Leader (boldface) and Other Team Members	**Stokoe (UT at Austin)**		

1. Project goals and objectives

Apply the Spectral-Analysis-of-Surface-Waves (**SASW**) Method to determine the shear wave velocity profiles of selected strong-motion recording (SMR) sites in Imperial Valley and Los Angeles, CA and use the results to determine classification of these sites in terms of the shear wave velocity in the top 30 m ($V_{s,30}$) and the upper portion of the V_s profiles to evaluate of their liquefaction potential.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The SASW method can be used in siting facilities for electric systems, because $V_{s,30}$ obtained from the SASW method is used by engineers in estimating the earthquake site response and the upper portion of the V_s profiles can be used in liquefaction evaluations.

3. Brief description of the accomplishments of the project

In total, 30 shear wave velocity profiles in the Imperial Valley area and 19 shear wave velocity profiles in the Los Angeles area were determined. The site classification for each site was determined and was used in ground motion studies.

4. Describe any instances where you are aware that your results have been used in industry

The shear wave velocity profile reduced from the SASW method can be applied to determine earthquake site response/classification, liquefaction evaluations, landfill/soil compaction control, and pavement quality evaluation.

5. Methodology employed

Spectral-Analysis-of-Surface-Waves (**SASW**) Method is a non-intrusive seismic method of profiling geotechnical sites.

6. Other related work conducted within and/or outside PEER

Outside PEER: SASW testing in the Seattle, Washington area, at several landfills in the San Francisco area, and at the Yucca Mountain, Nevada, test site.

7. Recommendations for the future work: what do you think should be done next?

Perform SASW testing with a source which can generate more energy to explore deeper soil profiles at some sites which already have deeper V_s data obtained from other intrusive methods to demonstrate the accuracy of the SASW method for future deeper profiling.

8. Author(s), Title, and Date for the final report for this project

Authors: K.H. Stokoe, II and Yin-Cheng Lin
Title: Application of SASW to US SMA Sites

Date: August 31, 2004

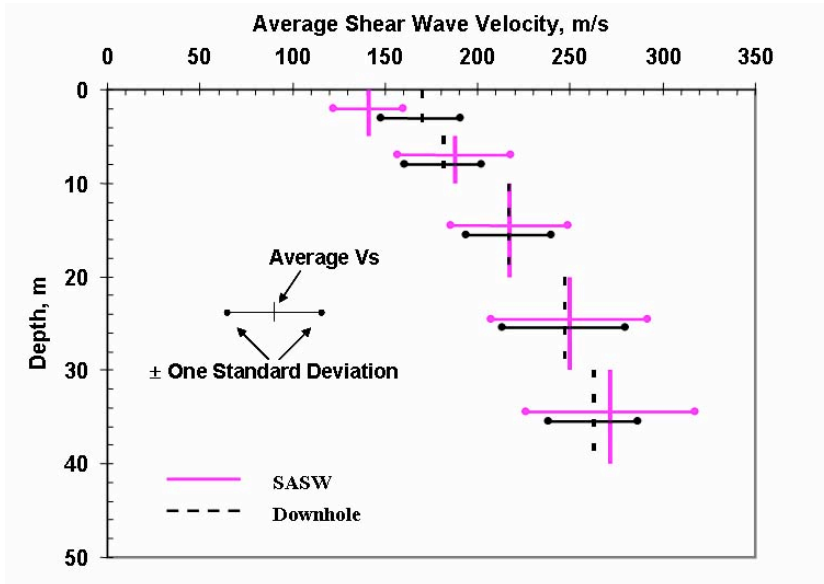


Figure 1. Comparison of Average V_s Values from SASW and Downhole Seismic Tests at 19 Common SMR Sites in Imperial Valley, California

Table 1. Comparison of $V_{S,30}$ Values and Site Classifications from 19 Common Sites where SASW and Downhole Seismic Tests were Performed; Imperial Valley, CA.

No.	Site Name	$V_{S,30}$, m/s ($V_{S,100}$, ft/s)		Classification	
		Downhole	SASW	Downhole	SASW
1	Bond's Corner	223(743)	236(780)	D	D
2	Brawley Airport	209(696)	188(620)	D	D
3	Calexico Fire Station	231(769)	197(650)	D	D
4	Calipatria Fire Station	203(676)	224(740)	D	D
5	El Centro Array # 2	189(629)	179(590)	D	E
6	El Centro Array # 3	164(546)	173(570)	E	E
7	El Centro Array # 4	207(690)	215(710)	D	D
8	El Centro Array # 5	208(692)	194(640)	D	D
9	El Centro Array # 6	202(672)	200(660)	D	D
10	El Centro Array # 7	212(706)	194(640)	D	D
11	El Centro Array # 8	208(692)	203(670)	D	D
12	El Centro Array # 9	213(710)	206(680)	D	D
13	El Centro Array # 10	204(680)	203(670)	D	D
14	El Centro Array # 11	198(660)	203(670)	D	D
15	El Centro Array # 12	209(696)	197(650)	D	D
16	El Centro Array # 13	251(835)	270(890)	D	D
17	El Centro Differential Array	220(666)	191(630)	D	D
18	Holtville Post Office	201(670)	209(690)	D	D
19	Westmorland Fire Station	195(650)	203(670)	D	D

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Design Guidelines for Site Response Analysis for Vertical Ground Motion*—**2F01**		
Start/End Dates	05/01/00–11/30/01	Budget/ Funding Source	$65,026 / Caltrans
Project Leader (boldface) and Other Team Members	**Walter Silva (PEA)**		

1. Project goals and objectives
Develop engineering model for developing site-specific vertical design ground motions.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.
Bridge structures have vulnerabilities to vertical motions. Currently no generally accepted procedure is available to characterize vertical site-specific design motions.

3. Brief description of the accomplishments of the project
Using vertical array (surface and at-depth recordings) data for about 15 earthquakes at 10 vertical arrays, simulated surface motions have been compared to recorded motions. Results have suggested that at low frequency vertical motions are dominated by inclined shear-waves (SV) while high frequency motions are dominated by vertically propagating compression waves.

4. Describe any instances where you are aware that your results have been used in industry
Results of this project (among others) were used to develop design ground motions for the high level nuclear waste repository at Yucca Mtn, Nevada.

5. Methodology employed
Model recorded motions at the surface using at-depth motions as input. Both inclined and vertically incident P and S waves were used.

6. Other related work conducted within and/or outside PEER
Several researchers have analyzed vertical array data but a generally accepted approach to model vertical motions for engineering design has not yet been developed.

7. Recommendations for the future work: what do you think should be done next?
Project not yet completed.

8. <u>Author(s), Title, and Date</u> for the final report for this project
Project not yet completed.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Calibration Sites for Validation of Non-Linear Geotechnical Models*—**2G01**		
Start/End Dates	5/1/00 – 9/30/03	Budget/ Funding Source	$81,952 / Caltrans
Project Leader (boldface) and Other Team Members	**Stewart (UCLA)**, M. Bora Baturay (UCLA), Annie O. Kwok (UCLA)		

1. Project goals and objectives

The objective of this project was to investigate the degree to which 1D ground response modeling can improve predictions of response spectral acceleration (S_a) relative to the use of attenuation relations. The potential "improvement" takes two forms: (1) removal of bias that might otherwise be present for a particular site condition, and (2) reduction of standard deviation. In two separate studies, those improvements were investigated first for the case of site-specific ground response analysis, and second for the use of site factors derived from 1D analyses by Silva and co-workers.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The results of this project give Earthquake Engineers the opportunity to improve their predictions of ground motion intensity measures (IMs). The effect on IMs, and hence on electrical subsystem and lifelines, is greatest for soft clay sites, where predicted ground motions for rare events (e.g., 10% probability of exceedance in 50 years) would be reduced as a result of smaller standard deviations on IM when site-specific analyses are performed.

3. Brief description of the accomplishments of the project

The benefits of 1D site-specific analysis was evaluated by comparing S_a from recordings to predictions derived using ground response analysis procedures as well as attenuation relationships with and without amplification factors. The results were compiled for 134 motions from 68 sites, and prediction residuals are interpreted to assess the models' relative bias and dispersion. We found that ground response analyses are unbiased for $T \leq 1$ s, but underestimate longer period S_a in deep basins. For soft soils (e.g., Holocene lacustrine-marine geology = Hlm), ground response analyses produce relatively low dispersion for $T < 1$ s relative to other site categories, as shown in Figure 1. This dispersion reduction is not observed for other models such as site factors or attenuation relationships. These results indicate that ground response analyses are beneficial for S_a predictions at soft soil sites, but generally provide no identifiable benefit for stiff soil or rock site conditions.

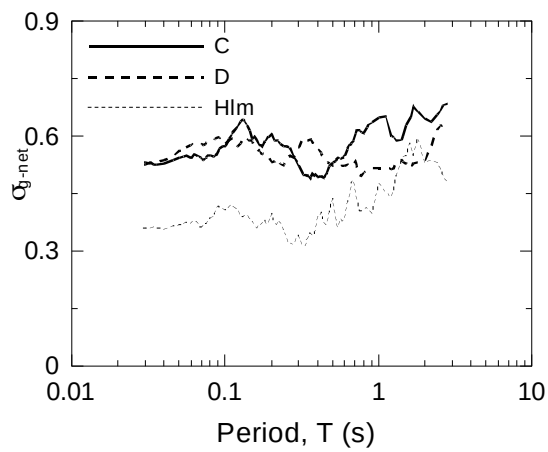


Fig. 1. Standard deviation term for use with results of 1D site specific ground response analyses

The calibration work for the Silva site factors model found that this model consistently under-predicted short-period spectral accelerations and over-predicted long period spectral accelerations. This is illustrated in Figure 2 by the positive residuals at short periods and the negative residuals at long periods. Based on these findings, it is recommended that empirical site factors, when available, generally be used in lieu of theoretical site factors.

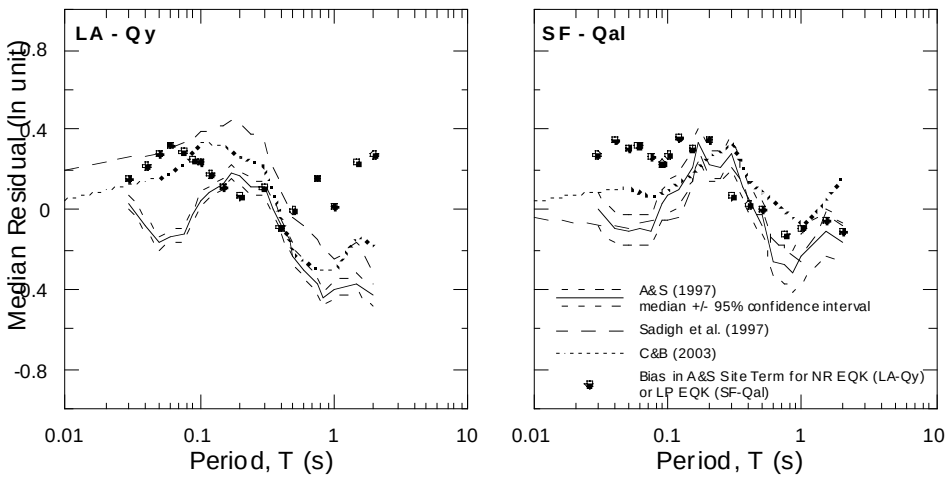


Fig. 2. Median and standard deviation of residuals of Silva 1D site factors model when applied with various attenuation models. Results shown for Quaternary alluvium site categories

4. Describe any instances where you are aware that your results have been used in industry

Results of the project on 1D site specific analysis were distributed among Caltrans design engineers by Cliff Roblee in an internal memo. Those results, along with the results on 1D amplification factors, have been the subject of discussions at NGA meetings.

5. Methodology employed

This evaluation of benefits of 1D site-specific analyses was performed by comparing S_a from recordings to predictions derived using ground response analysis procedures as well as attenuation relationships with and without amplification factors.

The validation of the 1D site factors was carried out by comparing response spectral accelerations predicted by the model to those recorded during earthquakes in the respective regions. The model predictions are prepared using a procedure that mimics how the model would be applied in engineering practice: ground motion estimates for a reference (rock) site condition are generated using three well-known empirical attenuation relationships, and the rock spectra are modified using the theoretical site factors.

6. Other related work conducted within and/or outside PEER

PEER Core program work developed empirical site factors used in the present studies.

7. Recommendations for the future work: what do you think should be done next?

PEER Lifelines Project 2G02 will investigate the use of nonlinear ground response procedures for estimation of site effects.

8. <u>Author(s), Title, and Date</u> for the final report for this project

Stewart, J. P. and Baturay, M.B. (2003). "Uncertainty and bias in ground motion estimates from ground response analyses," *Rpt. No. PEER-2003/02*, Pacific Earthquake Engineering Research Center, Univ. of California, Berkeley, June.

Stewart, J.P. and Kwok, A.O. (2004). "Application of theoretical 1D amplification factors for evaluation of seismic site effects," Report to Pacific Earthquake Engineering Research Center.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Benchmarking of Nonlinear Geotechnical Ground Response Analysis Procedures*—**2G02**		
Start/End Dates	7/1/04 – 6/30/06	Budget/ Funding Source	$253,317 / Caltrans
Project Leader (boldface) and Other Team Members	**Stewart (UCLA)**		

1. Project goals and objectives

This project consists of a benchmarking study of nonlinear ground response analysis procedures. The project has two principal objectives:

1. Identify the conditions for which nonlinear geotechnical modeling should be performed in lieu of more approximate equivalent-linear modeling.
2. Provide clear guidelines for the use of several nonlinear geotechnical models, with particular emphasis on the selection of input parameters. By following the guidelines for input parameter selection, users of the nonlinear codes should be able to obtain stable and unbiased median estimates of site amplification as well as reasonable levels of variability when model parameters and input motions are simultaneously varied over their distributions.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The results of this project will give Earthquake Engineers the opportunity to improve their predictions of ground motion intensity measures (IMs). The effect on IMs, and hence on electrical subsystem and lifelines, is expected to be greatest for soft clay sites, where predicted ground motions for rare events (e.g., 10% probability of exceedance in 50 years) would be reduced as a result of smaller standard deviations on IM when site-specific nonlinear geotechnical analyses are performed.

3. Brief description of the accomplishments of the project

None to report – project was approved only recently, and project funds are not yet in place.

4. Describe any instances where you are aware that your results have been used in industry

Not applicable.

5. Methodology employed

The project involves a broad array of researchers and practitioners working collaboratively. These individuals are divided into three groups. One group consists of the Management team (PI Stewart, graduate student Annie Kwok, Tom Shantz, and Yousef Bozorgnia). The second group is referred to as the "developers," and consists of researchers that have developed nonlinear ground response analysis codes. The third group is referred to as the "advisory panel," and consists of engineers and researchers who have significant experience with ground response analyses. By engaging the advisory panel throughout the duration of the project, we hope to solicit recommendations to help guide the project to ensure that it will produce useful results.

The developers and advisory panel members are listed below.

Code	Developer	Advisory Panel
DEEPSOIL	Hashash, Y	Chang, Susan
D-MOD_2	Matasovic, N.	Idriss, I.M.
TESS	Pyke, R.	Kramer, Steven
SUMDES	Wang, Z.L.	Makdisi, Faiz
OPENSEES	Yang, Z.	Martin, Geoff
		Mehia, Lelio
		Silva, Walter
		Sun, Joseph

A meeting of all participants is scheduled for September 21, 2004. At this meeting, the project team will finalize project objectives and scope. This scope is tentatively envisioned to include a sequence of benchmarking efforts. This sequence of tasks is conceived at present to include the following (modifications are possible based on feedback from developers and advisory panel members):

1. Model parameter selection protocols: Identify all parameters used in each nonlinear constitutive model that is being considered in the study. All model parameters should be identified as "fixed" or "free" parameters. Identify the values to be used for fixed parameters. For free parameters, use existing laboratory test data to develop 'baskets,' or rule-based procedures, for the selection of best estimate values and distributions of the parameters for various generic soil types (i.e., unsaturated clean sands and fines-dominated soils with various plasticities).
2. Model verification – very small strain (visco-elastic) conditions: Verify the accuracy of the wave propagation component of the models by solving problems involving fixed soil parameters and simple site layering.
3. Model verification – small to moderate strain conditions: Verify the nonlinear analyses using ground motions recorded in vertical arrays without liquefaction. The strains spanned by this data set are expected to vary from small to moderate.
4. Model verification – large strain conditions: Verify the nonlinear analyses using available centrifuge test data.
5. Parametric uncertainty studies – various strain ranges:
    a. For vertical array sites, randomize the appropriate parameters of the nonlinear soil models to represent appropriate (and pre-selected) ranges of shear wave velocity (V_s) profiles, modulus reduction curves (G/G_{max}), and soil damping curves (β). Input motions will consist of recorded downhole motions (producing small to moderate strains) and synthetic waveforms (producing large strains). Evaluate the parametric variability of the results to identify the input parameters to which the results are most sensitive.
    b. For vertical array sites, fix the parameters of the nonlinear soil model that control V_s, G/G_{max}, and β, and select an appropriate range for other model parameters, such as a viscous damping term. The parametric variability of the results will be evaluated.
6. Parametric studies involving selected codes: Perform analyses targeted at identifying the benefits of nonlinear ground response analyses relative to equivalent linear.

6. Other related work conducted within and/or outside PEER

Many supporting studies have been performed in which the nonlinear codes were developed. Preliminary benchmarking studies have been performed in PEER Lifelines.

7. Recommendations for the future work: what do you think should be done next?

Not applicable.

8. Author(s), Title, and Date for the final report for this project

Not applicable.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Benchmarking of Nonlinear Geotechnical Ground Response Analysis Procedures*—**2G02**		
Start/End Dates	7/1/04 – 6/30/06	Budget/ Funding Source	$253,317 / Caltrans
Project Leader (boldface) and Other Team Members	**Stewart (UCLA)**		

1. Project goals and objectives

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3. Brief description of the accomplishments of the project

None to report – project was approved only recently, and project funds are not yet in place.

4. Describe any instances where you are aware that your results have been used in industry

Not applicable.

5. Methodology employed

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6. Parametric studies involving selected codes: Perform analyses targeted at identifying the benefits of nonlinear ground response analyses relative to equivalent linear.

6. Other related work conducted within and/or outside PEER

Many supporting studies have been performed in which the nonlinear codes were developed. Preliminary benchmarking studies have been performed in PEER Lifelines.

7. Recommendations for the future work: what do you think should be done next?

Not applicable.

8. Author(s), Title, and Date for the final report for this project

Not applicable.

Predictions will be required both for the bedrock underlying Treasure island and for the Yerba Buena Island rock outcrop. Results will be presented and discussed in the final workshop, which will include students and practitioners.

6. Other related work conducted within and/or outside PEER

Results of the first qualification round were used by Dr Paolo Bazzurro et al. in PEER-funded project 1G00
Title: "Parameterization of Non-stationary Acceleration Time History" (Task 2 of the Addendum).
Participants: Paolo Bazzurro, Nicolas Luco, and Brian Sjoberg

7. Recommendations for the future work: what do you think should be done next?

The current study will result in a very well-constrained prediction of ground motions on bedrock and outcropping rock for the Treasure Island site. Treasure Island was selected because it has a deep soft soil profile which will be driven into the non-linear response range by strong motion, and because this 88-m deep soil deposit and the underlying bedrock have been instrumented with accelerometers to a depth of 120 m. The next obvious step is to organize a second prediction exercise in which the bedrock and outcrop motions will be used to predict the response of this deposit to the scenario earthquakes.

8. <u>Author(s), Title, and Date</u> for the final report for this project

I. Beresnev, J. Boatwright, B. Chiou, P.de Alba, D. Dreger, A. Gusev, L. Hutchings, W. Silva , P. Somerville and Y. Zeng "Uncertainty in Strong-Motion Earthquake Predictions: A Case Study," January 2005

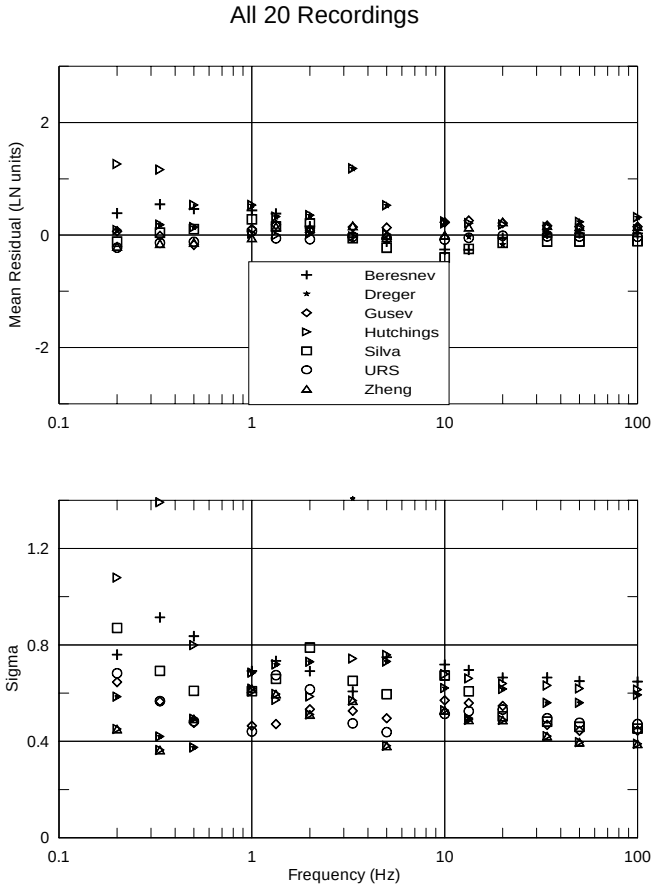


Figure 1. Model bias and modeling variability based on the 20 Northridge recordings (average horizontal spectral acceleration). A positive model bias reflects underprediction, negative reflects overprediction.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Workshop on Ground Motions for Treasure Island National Geotechnical Experimental Site*—**2K01**		
Start/End Dates	9/01/01 – 6/30/04	Budget/ Funding Source	$30,000 / Caltrans
Project Leader (boldface) and Other Team Members	**Pedro de Alba (U of New Hampshire)**		

1. Project goals and objectives

The basic objective of this project is to develop unbiased estimates of variability about the median (aleatory variability, randomness) and variability of the median (epistemic variability, uncertainty) for selected state-of-the-art strong-ground-motion prediction methods, by applying them to records of past earthquakes, and then to use these methods in a forward prediction of bedrock motion for a well-documented site (Treasure Island) in the San Francisco Bay Area.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The results of this project are confidently expected to result in a better estimates of predicted risk for engineered facilities.

2. Brief description of the accomplishments of the project

To date, six predictors from the US and abroad have completed two rounds of calibration (regression) exercises designed to both evaluate the different models' ability to predict recorded motions as well as to develop model parameter values and their expected ranges.

4. Describe any instances where you are aware that your results have been used in industry

None to date

5. Methodology employed

As mentioned above, potential predictors were required to complete two rounds of qualification exercises. In the first round, to provide a basis for a preliminary qualification of participants, they were requested to apply their models to the closest twenty sites which recorded the 1994 M 6.7 Northridge earthquake. The project selection committee evaluated variability and bias for each model (e.g. Figure 1) Six predictors, five from the US and one from Russia, successfully completed the first exercise.

A second round was then requested of the participants, to better calibrate their models against earthquakes which closely resembled the scenario earthquakes of the final forward prediction. In this case, model predictions were required for six earthquakes: Imperial Valley,1979; Loma Prieta, 1989; Landers, 1992; Northridge, 1994; Kobe, 1995; and Kocaeli 1999. Predictions were required for a total of 197 stations. The results of this second round are currently being evaluated by the selection committee.

For the third and final round, two scenario earthquakes will be used:
a) A moment magnitude 7.1 event on the Hayward Fault. For this event, two scenarios will be required: a) initiation of rupture in the vicinity of Berkeley and b) initiation of rupture in the vicinity of Fremont, close to the end of the southern segment of the fault. The latter scenario should introduce significant directivity effects into the exercise. In both cases, the rupture will be assumed to extend through both segments of the fault, about 87 km.
b) A moment magnitude 7.9 event on the San Andreas Fault, assuming a rupture of the four northern segments of the fault along a 475-km length, from just north of Santa Cruz in the south to Petrolia, 330 km north of San Francisco. In this case, predictors would be asked to assume at least two nucleation points: a) in the vicinity of San Francisco, and b) near Cape Mendocino.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*COSMOS-GEOINFO Standards for Archiving & Dissemination of Geotechnical Data*—**2L01**		
Start/End Dates	5/15/01 – 11/15/01	Budget/ Funding Source	$45,208 / PG&E
Project Leader (boldface) and Other Team Members	**Stepp (COSMOS)**		

1. Project goals and objectives

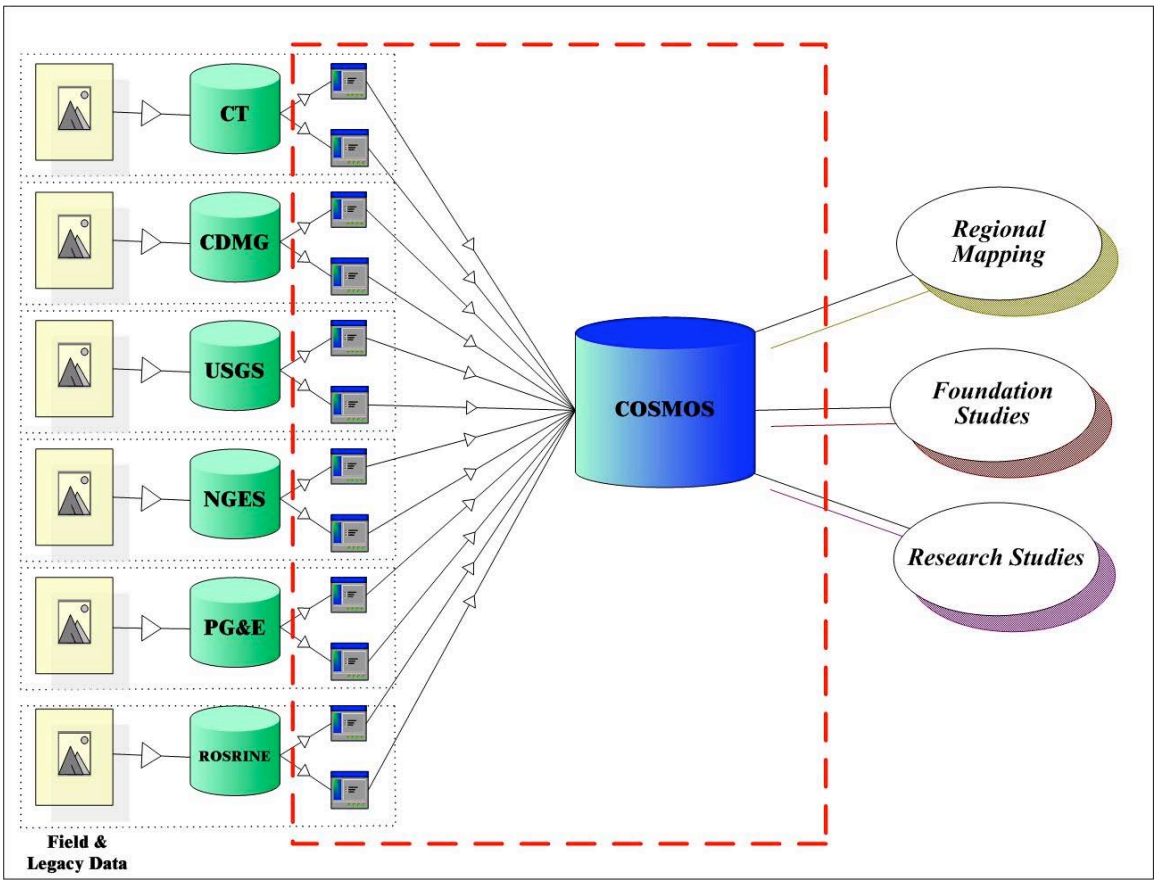
Assess state of technology, identify technology development requirements, and develop consensus recommendations for classifying, archiving, and web dissemination of geotechnical data.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

This work is relevant to PEER Lifelines research and to the sponsors' ongoing management of geotechnical hazards. It focused on integration of distributed geotechnical databases and on developing architecture for data archiving and web dissemination of multiple, linked geotechnical databases.

3. Brief description of the accomplishments of the project

The Project organized and held a workshop to assess state of technology, identify technology development requirements, and develop consensus recommendations and a work plan for the development of web-based system for archiving, and web dissemination of geotechnical data. The workshop developed the concept of a central hub that would function as a virtual geotechnical data center through which data providers share data and disseminate their own data. The most important conclusion of the workshop based on the invited papers and discussions, was that the development of a virtual geotechnical data center for web dissemination of linked geotechnical databases can be largely accomplished by modifying existing technologies. The workshop defined the primary needs for a development project as: 1) define the functional requirements for design of the virtual center, 2) define necessary data formats, data dictionaries, indexes, and exchange standards, and 3) define and link the organizational components of the overall system. The principal consensus recommendation for future development was that, initially, a pilot implementation of a virtual geotechnical data center should be developed. The pilot system should involve several large data providers including California Department of Transportation (Caltrans), Pacific Gas and Electric Company (PG&E), California Geological Survey (CGS), and the U. S. Geological Survey (USGS). Building on this pilot system, the links can be expanded to include other data providers and the general user community. A specific action plan for developing the pilot virtual system was developed. The overall concept and essential components of the proposed Geotechnical Virtual Data Center (GVDC) are shown in the figure below.



Elements of an extensible web-based virtual geotechnical database center (GVDC)

4. Describe any instances where you are aware that your results have been used in industry

The results of this project consist of a workshop proceeding, which included an action plan for the development of a Pilot GVDC. The work plan is being implemented by PEER LL Project 2L02.

5. Methodology employed

The methodology consisted of planning and holding a workshop: identification of participants, identification of subject content, identification of appropriate discussion topics and structure, compilation of the findings and recommendations of the workshop, and publication of the workshop proceedings.

6. Other related work conducted within and/or outside PEER

This work is relevant to PEER Lifelines geotechnical research. It is focused on developing an optimal system for data archiving, transfer and dissemination of geotechnical data that is capable of serving the needs of both researchers and practitioners.

7. Recommendations for the future work: what do you think should be done next?

This project developed a plan for developing a Pilot GVDC, which includes four main tasks: 1) definition of geotechnical data user scenarios for a GVDC that links the CDMG, CalTrans, PG&E, and USGS

geotechnical databases, 2) development of a data dictionary standard for the pilot system which can be expanded to a larger system linking multiple geotechnical databases, 3) integration of these results to implement the pilot system, and 4) plan and implement a workshop that is structured to obtain geotechnical community consensus and deliver a workshop proceedings that will serve as an expanded implementation plan for development of GVDC that is capable of linking a large number of geotechnical databases.

8. Author(s), Title, and Date for the final report for this project

Jennifer N. Swift and J. Carl Stepp, 2002. "Development of Archiving and Web Dissemination of Gotechnical Data", in Proceedings SMIP02 Seminar on Utilization of Strong-Motion Data, Las Angeles, CA, California Strong-Motion Instrumentation Program, Sacramento, CA.

J. C. Stepp, J. Swift, C. Roblee, L Turner, C. Real, W. U. Savage, and C. M. Johnson, editors (2001). Proceedings, Workshop on Archiving and Web Dissemination of Geotechnical Data, COSMOS Publication CP-2001/03, Richmond, CA.

J. Carl Stepp, and J. Swift, 2001. "COSMOS Workshop on Archiving and Web Dissemination of Geotechnical Data", COSMOS Newsletter, Issue No. 5, August.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Archiving & Web Dissemination of Geotechnical Data*—**2L02/2L02a**		
Start/End Dates	5/23/02 – 3/31/04	Budget/ Funding Source	$206,906 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**Stepp (COSMOS)**		

1. Project goals and objectives

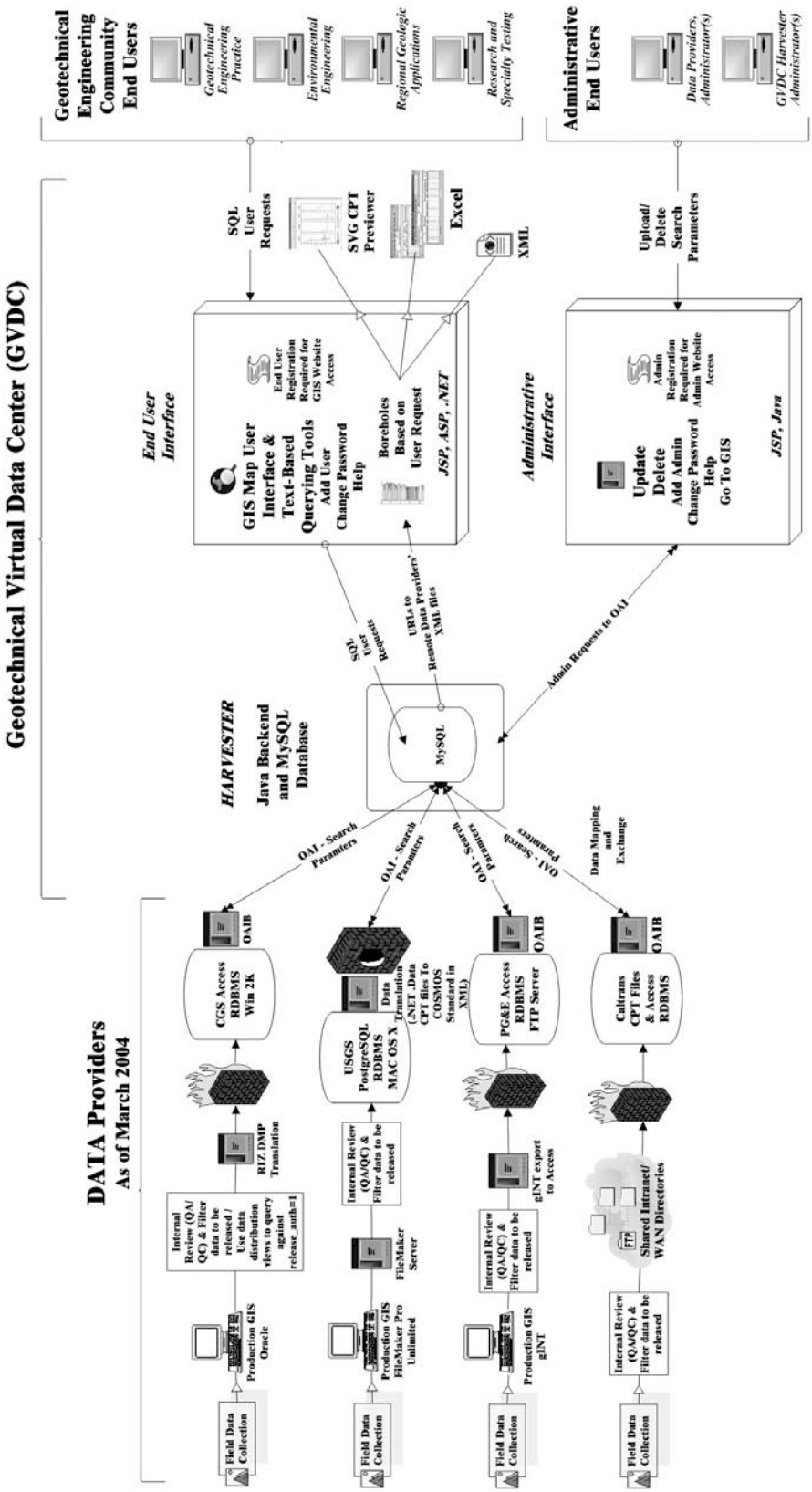
Develop a Pilot Geotechnical Virtual Data Center (GVDC) for archiving and web dissemination of geotechnical data and plan and conduct a workshop to review and obtain input and consensus of the geotechnical community.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

This project designed and developed a Pilot GVDC for web dissemination of geotechnical data. The project created a forum that brought together active geotechnical database archiving activities and established communication and coordination among them. The project combined the efforts of the participating organizations by sharing the technological knowledge necessary to implement exchange geotechnical and related information over the internet with each other and with the public, including the earthquake engineering community, government agencies, researchers, and industry. Participants retain all rights to use any and all products or their derivatives including computer programs, algorithms or other tools developed throughout the project for educational purposes, and that these products will be made available to any interested parties at no cost, subject to the following conditions: 1) interested parties may have a copy of compiled products or source code from any types of programming developed during the project, the source code may be used and modified, but if used and modified, the interested parties agree to pass along the same rights to the interested parties' version; 2) if interested parties use and/or modify source code, credit must be given to the originator of the code.

3. Brief description of the accomplishments of the project

This project accomplished the development of a Pilot Geotechnical Virtual Data Center system that links databases of Caltrans, the California Geological Survey, PG&E, and the U. S. Geological Survey. The system uses the Extensible Markup Language (XML) and the data dictionary developed for the project (COSMOS-XML) for data exchange. Elements of the GVDC system are shown in the following figure.



Detailed overview of GVDC system architecture

4. Describe any instances where you are aware that your results have been used in industry

The project final report is in preparation. Notwithstanding, the GVDC-XML (Extensible Markup Language) data exchange protocol developed for the Pilot System has been adopted by Caltrans, CGS, PG&E, and USGS, and the University of Missouri at Rolla Natural Hazards Mitigation Institute is adopting the GVDC-XML for the purpose of developing a "sister site" that will serve the mid-America Region. The Federal Highway Administration (FHWA) and representatives of departments of transportation (DOTs) from a number of states participated in the Project Workshop, which was held on June 21 – 23. Following the presentation and discussion of the GVDC at the workshop the FHWA has expressed interest in adopting the GVDC-XML as an element of the Geotechnical Assets Management System that the Agency is developing. COSMOS has drafted a scope of work and discussions are in progress with a number of organizations, NEESinc, NGS, POSC, FHWA, to initiate a project to develop an international consensus geotechnical data exchange standard (See Section 7).

5. Methodology employed

This scope of the project includes four main tasks: 1) define geotechnical data user scenarios for a Pilot GVDC system that links the CGS, CalTrans, PG&E, and USGS geotechnical databases, 2) develop a data dictionary standard for the pilot system that is expansible to a GVDC system that links many geotechnical databases, 3) integrate these results to implement the Pilot GVDC system, and 4) plan and implement a workshop structured to obtain geotechnical community consensus and deliver a workshop proceedings that will serve as an expanded implementation plan for development of a GVDC system that will serve the needs of the broad geotechnical community. A Work Group (WG) was established to implement each of these tasks. WG leaders were identified: Loren Turner, Caltrans, for WG-1; Jean Benoit, UNH, for WG-2; Jennifer Swift, USC, for WG-3; and Carl Stepp, Project PI, for WG-4. WGs 1-3 included about ten persons each and were constituted of persons representing the four data providers, other data centers, Petrotechnical Open Standards Consortium (POSC) and COSMOS Strong-Motion VDC, PEER and SCEC, and private sector companies. The WGs met together to initiate the project and interim project meetings were held to coordinate the work, track progress, and plan the remaining efforts to complete the project scope of work. The workshop included participation by the broad community of geotechnical data developers, groups engaged in geotechnical database development, and geotechnical data users.

6. Other related work conducted within and/or outside PEER

NEESinc - Developing a system for exchange of geotechnical data within the NEESinc
Association of Geotechnical and Geoenvironmental Specialists (AGS) – Maintains the AGS geotechnical data exchange protocol, http://www.ags.org.uk/.
Open GIS Consortium, Inc. – Maintains the OGC data exchange protocol, http://www.gis.com/.
POSC – Serves the Petrochemical Industry using the XML data exchange protocol, http://www.posc.org
USC – Research under the leadership of J. P. Bardet, bardet@rccg01.usc.edu

7. Recommendations for the future work: what do you think should be done next?

The following tasks, all of which were recommended by the Project Workshop held on June 21-23, 2004, should be completed in order to implement the Pilot GVDC for the broadest benefit to the geotechnical engineering community.

1. Development a General Data Exchange Dictionary Standard that has broad international consensus. The standard could be developed by merging the GVDC-XML and the AGSML (Association of Geotechnical and Geoenvironmental Specialists) data dictionaries.
2. Migrate to the Open GIS Consortium (Open GIS Consortium, Inc.) standard, which has the potential advantage that it would open access to geotechnical data to a significantly larger user community.
3. Complete the steps required to release GVDC-XML schema to version 1.0.
   - Declare the schema to be normative.

- Establish a working group to oversee version developments.
- Develop "User Guidelines" for Data Providers.
- Provide for documentation.
- Develop training materials and hold training classes for GVDC data providers and their user base.

4. Develop a geotechnical velocity log previewer.
5. Expand the Data Dictionary to include additional geotechnical and related data types.

8. Author(s), Title, and Date for the final report for this project

Jennifer Swift, Loren Turner, Jean Benoit, Dan Ponti, Charles Real, John Bobbitt, Carl Stepp, and Clifford Roblee, "A Pilot Geotechnical Virtual Data Center", September, 2004.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Examining Site Response issues for NGA*—**2M01**		
Start/End Dates	8/1/03 – 6/30/04	Budget/ Funding Source	$59,570 / Caltrans
Project Leader (boldface) and Other Team Members	**Wang (Geomatrix)**		

1. Project goals and objectives

The issues to be examined in the study: 1) Comparison of RASCAL against SHAKE (both equivalent-linear soil models); 2) Comparison of SHAKE against non-linear codes (SUMDES and D-MOD2); 3) selection of typical dynamic properties and profiles for the analyses; 4) selection of typical ground motion sets;

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

This project will support the Next Generation Attenuation (NGA) project (lifeline) in resolving the modeling issues that will be used to develop the site amplification functions needed by NGA attenuation relationship developers in their regression analyses of empirical ground motion data.

3. Brief description of the accomplishments of the project

1. Typical sites, geophysical measurements, dynamic soil properties were reviewed and selected; 2. Two sets of earthquake records (30 records for each of two magnitudes) were selected, spectral matched and used in the study;
3. RASCAL and SHAKE results were compared for two magnitudes and three soil profiles in terms of amplification functions and surface response spectra; 4. Two non-linear codes (SUMDES and D-MOD2) were revised (SUMDES) and evaluated (D-MOD2); 5. Non-linear results were computed using the two codes for selected records and compared with SHAKE results for two earthquake magnitudes and two soil profiles.

4. Describe any instances where you are aware that your results have been used in industry

Results from this project have not been used in industry so far. We have not published this project results.

5. Methodology employed

RASCAL uses random vibration theory, SHAKE uses frequency domain solutions, non-linear codes use time domain integration. Equivalent linear model is used in RASCAL and SHAKE. Bounding Surface Plasticity model is used in SUMDES. Modified hyperbolic model is used in D-MOD2. Results are compared at average levels from multi-input motions (30 records for each of two earthquake magnitudes).

6. Other related work conducted within and/or outside PEER

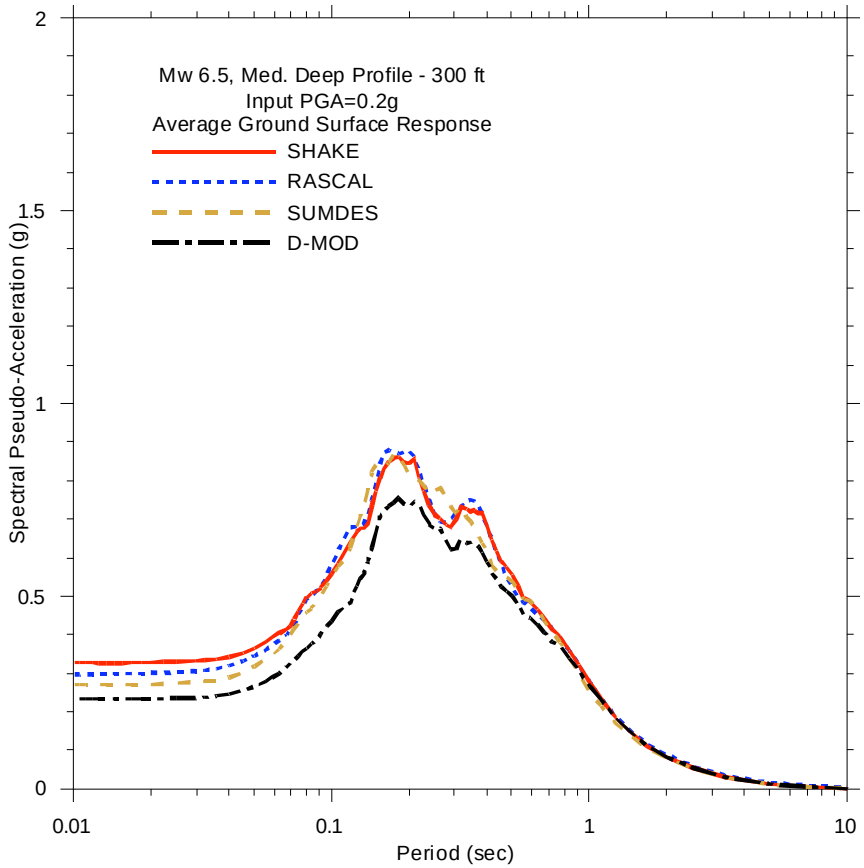
In Geomatrix, non-linear (as well as equivalent linear) response and deformation (including liquefaction) analyses are used in our project work. A number of projects have been performed using the nonlinear constitutive model (Wang et al., 1990) that is implemented in the SUMDES code, and a two dimensional program FLAC.

7. Recommendations for the future work: what do you think should be done next?

More detailed and critical evaluation should be done to identify the cases where the non-linear approach is more appropriate than the conventional equivalent linear approach. In addition, rational and practical non-linear codes should be identified and recommended to the industry.

8. Author(s), Title, and Date for the final report for this project

Final report has not been completed.


Mw 6.5, Med. Deep Profile - 300 ft
Input PGA=0.2g
Average Ground Surface Response
SHAKE
RASCAL
SUMDES
D-MOD
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Period (sec)
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0.5
1
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2
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1
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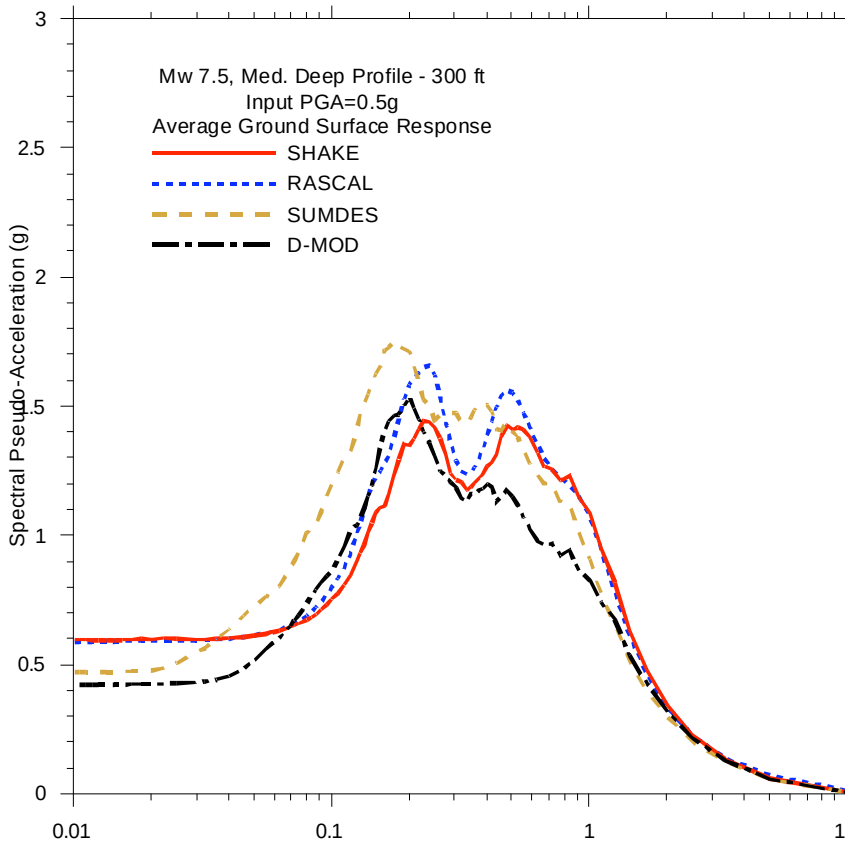
Mw 7.5, Med. Deep Profile - 300 ft
Input PGA=0.5g
Average Ground Surface Response
SHAKE
RASCAL
SUMDES
D-MOD
Spectral Pseudo-Acceleration (g)
0
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3
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1
1

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Liquefaction Site Characterization in Taiwan*—**3A02**		
Start/End Dates	9/1/01 – 6/30/03	Budget/ Funding Source	$78,217 / Caltrans
Project Leader (boldface) and Other Team Members	**Stewart (UCLA),** Daniel Chu (UCLA), Emily Gugliemo (UCLA)		

1. Project goals and objectives

The principal objective of this research was to develop case histories for a liquefaction triggering database from the Chi Chi Taiwan earthquake. A second objective was to document soil conditions at sites where interesting liquefaction effects occurred, such as lateral spreading or soil bearing failures beneath building foundations.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

Well documented field case histories form the basis of contemporary procedures for analysis of liquefaction triggering and liquefaction effects. The Lifeline Program has for several years sought to develop improved probabilistic models for liquefaction triggering and liquefaction-induced ground deformations, and data such as that generated in this project is vital to the development of such models.

3. Brief description of the accomplishments of the project

We performed large site investigation programs in Nantou and Wufeng, Taiwan. We documented the results of those investigation programs, as well as other complimentary programs conducted in Nantou, Wufeng, and Yuanlin by others. Results are presented at: http://peer.berkeley.edu/lifelines/research_projects/3A02.

The seismic performance of the investigated sites include non-ground failure building and free-field sites, building sites with partial foundation bearing failures, free-field lateral spread sites, and free-field level ground sites with sediment boils. The web site presents field and laboratory investigation protocols for the sites, results of cone penetration testing (some with pore pressure and shear wave velocity measurements), and results of rotary wash borings with standard penetration testing (including energy measurements). An example of the type of data collected is presented in Figure 1.

4. Describe any instances where you are aware that your results have been used in industry

None to report.

5. Methodology employed

Sites were selected for field exploration if there was high quality field reconnaissance data available. Among sites with such data, emphasis was given to building settlement sites, lateral spread sites, and non-ground failure sites. In each of these cases, there are significant needs for high quality case histories to support the development of semi-empirical or empirical models for liquefaction triggering or effects.

Most borings were limited to depths of 10-30 m. Drilling equipment consisted of a tripod-supported rotary wash rig. A typical rig setup over a hole is shown to the right. For SPT sampling, the percentage of the total theoretical energy delivered to the split-spoon sampler, or energy ratio, was controlled by following procedures in ASTM D6066-98 and ASTM D1586. We measured the actual delivered energy for each blow of the safety hammer using a rod section instrumented with accelerometers and strain gages.

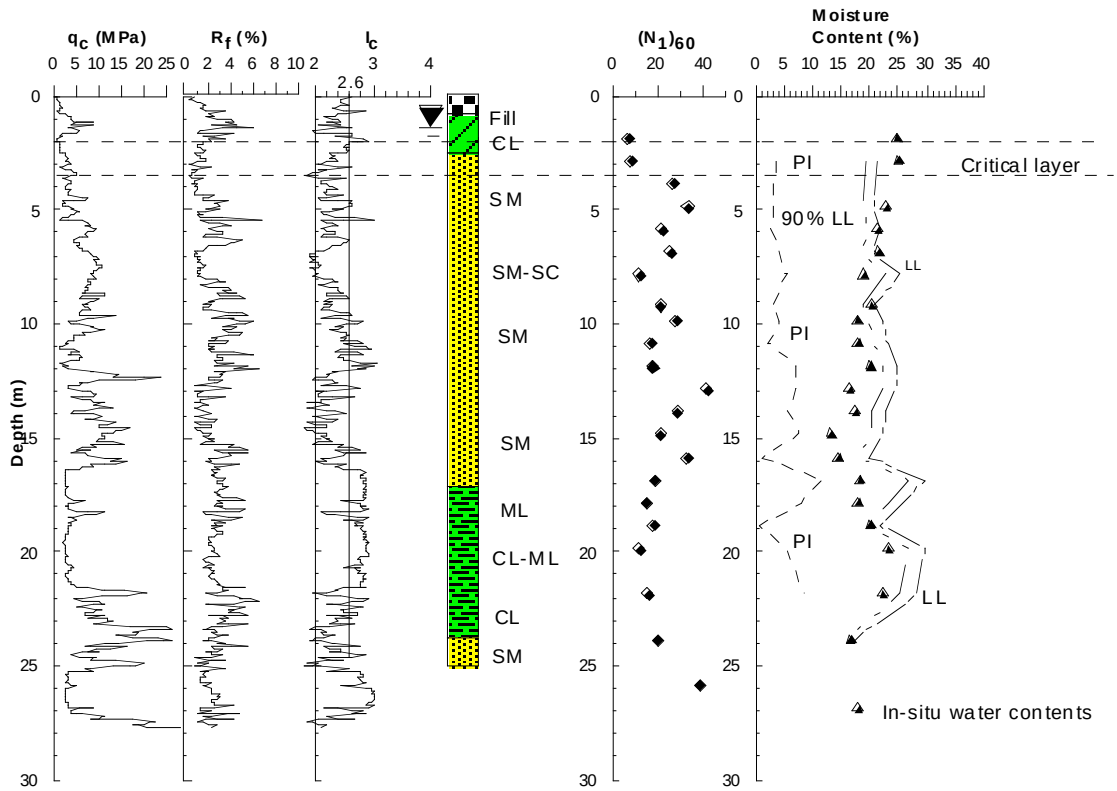


Fig. 1. Subsurface data for example site that experienced liquefaction (Wufeng Site C).

All retrieved soil specimens from the split spoon sampler were subjected to a full suite of laboratory index tests per ASTM standards including sieve, hydrometer, liquid limit, plastic limit, density and water content. In addition, in-situ vane shear tests (ASTM D 2573) were performed at selected locations and depths to estimate the undrained shear strengths of clayey soils. A limited number of monotonic and cyclic triaxial tests have also been performed.

Cone penetration tests (CPT's) were performed using standard procedures. A piezocone was used that provided U_2-type pore pressure measurements. Downhole seismic velocity profiling was performed at selected sites using a cone instrumented with one geophone.

6. Other related work conducted within and/or outside PEER

Similar work has been performed in Turkey by Jonathan Bray (UCB) and Les Youd (BYU). Similar work was performed in Taiwan by NCREE. The results of that study are included on the web page for this project.

7. Recommendations for the future work: what do you think should be done next?

Site reconnaissance and investigation programs should be continued after future major earthquakes.

8. Author(s), Title, and Date for the final report for this project

Stewart, J.P., Chu, D.B. and Gugliemo, E. (2003). "Documentation of Soil Conditions at Liquefaction Sites from 1999 Chi Chi (Taiwan) Earthquake," Report to Pacific Earthquake Engineering Research Center.

Final Project Summary— PEER Lifelines Program

Project Title—**ID Number**	*Probabilistic Liquefaction Assessment by Shear Wave velocity*—**3D03**		
Start/End Dates	4/1/01 – 6/30/04	Budget/ Funding Source	$47,450 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**Kayen (USGS/UCB)**		

INTRODUCTION

Shear wave velocity (V_s) offers engineers a tool to assess liquefaction triggering of soil that is lower cost and provides more physically meaningful measurements than penetration methods. Development of the shear wave velocity liquefaction method has been hampered by a paucity of published velocity profiles; particularly in deeper soil deposits (>10m) and deposits subjected to high cyclic stress ratios (CSR > 0.3). To remedy the scarcity of data, we set out to assemble a global V_s dataset by acquiring new data at over 300 sites in Japan, Taiwan, China, and the United States (US). These data are merged with the exiting catalog of published velocity data. To acquire new field data, we use the continuous swept-sine wave spectral analysis of surface waves test (SASW). This test has proven to be extremely reliable at rapidly gathering high signal-to-noise dispersion data sufficient to invert 20-40 meter V_s profiles at liquefaction sites. This new dataset represents the majority of the worlds documented sites of liquefaction occurrence since instrumental recording.

To correlate the global shear wave velocity data set with likelihood of initiation of seismic-soil liquefaction, we utilize high-order probabilistic tools (Bayesian updating) and structural reliability techniques. A limit-state function for liquefaction triggering is modeled and evaluated based on the means, distributions and uncertainties of each model-variable. Each case history is sub-divided into 'quality'-ranking categories based on the conjugate-uncertainties of CSR and V_{s1}. A cut-off threshold of the coefficient of variation is used filter-out poorly constrained sites. A Bayesian updating procedure is used to estimate coefficients for the limit-state function that minimize model error. The probability of liquefaction is then calculated using first- and second-order reliability methods (FORM and SORM). The intended outcome of this effort is a new evaluation of the V_s-liquefaction-triggering boundary in light of a global data set and modern limit-state probabilistic tools.

NEW DATA COLLECTION

Our project sought to elevate the V_s liquefaction-catalog to a level par with the penetration-based methods by conducting new investigations at sites previously documented using conventional tests. The catalogs developed for SPT and CPT correlations served as initial 'road maps' for new site investigation, and subsequent on-site access to local knowledge, observations, data-sets, and domestic publications allows us to fine-tune and expand our data collection efforts, particularly in the identification of non-liquefaction sites. At first step, we identified Asia and the United States liquefaction-investigation sites documenting conventional exploration and missing shear wave velocity logs. Recent well-documented historic events, spanning in time from the disastrous 1948 Fukui City earthquake up to the most recent 2003 Miyagi earthquake, were the principal targets of our field investigation. To efficiently re-evaluate these documented sites without drilling apparatus we are using the Spectral Analysis of Surface Waves (SASW) method to rapidly and non-invasively evaluate the shear wave velocity characteristics of soil. Surface wave methods are particularly useful for rapid, lightweight, high-resolution surveys of liquefaction sites where characterization of the near surface (typically <15m) are needed, and work well in difficult materials such as gravely deposits and stiff soils. Between 2001 and 2004, we visited and profiled at 315 liquefaction and no-liquefaction evaluation sites Asia and the US using surface wave techniques (Figure 1). Nearly all of well-documented liquefaction sites in East Asia, originally evaluated only by conventional penetration apparatus, have been re-tested in our study using surface wave methods.

BAYESIAN UPDATING for PROBABILISTIC ASSESSMENT of LIQUEFACTION

Bayesian updating is a rigorous probabilistic framework within which we experiment to identify a model that best describes the bounding frontier between regions of high- and low-likelihood of liquefaction occurrence. The curves in this bounding region express our degree-of-belief that initial triggering of liquefaction has, or will, occur. The model for seismic soil liquefaction is formulated in a traditional manner that limit-state models are formulated for single-component structural reliability problems: That is, capacity minus load. An example of one of the limit-state models we are testing is presentedas:

$$g_{Vs1}=V_{s1}(1+\square_1 FC)+\square\square_2 FC-\square_3 \ln(CSR)-\square_4 \ln(M_w)-\square_5 \ln(\square' v)+\square\square_6+\square;$$

where V_{s1} is effective stress normalized shear wave velocity; □FC is fines content (est. from other tests); CSR is earthquake-induced cyclic stress ratio; M_w is moment magnitude; □'v is effective stress; $□_6$ is the standard normal variate for an unbiased model, and □□is the model error term. We formulate a limit state model with positive-capacity and negative-load terms and solve, through iterative Bayesian updating, for the best-fit model parameters,□□□'s, that minimize the model error term, □□. The generalized model is a limit-state expression of strengths minus stresses. When the model tips into negative terrain, we have some degree-of belief that failure has, or will, occur. The Bayesian updating process used to solve for the model parameter, □'s, and model error term, □□ involves selecting the critical liquefaction evaluation layer from the shear wave velocity logs and then computing the appropriate statistics for each model parameter. For our data set, critical layers are selected from adjacent SPT or CPT logs using the NCEER-workshop guidelines . Each variable in the limit-state function (CSR, V_{s1}, etc.) is assessed for their distribution statistics.

Bayesian updating involves forming an experimental likelihood function, selecting a non-informative prior distribution, calculating a normalizing constant, and then calculating a best estimate of the posterior statistics. Starting with a non-informative prior distribution allows for the computation of an unbiased posterior distribution. The experimental process of Bayesian updating is a search for the optimal likelihood function that minimizes model error. The equal probability contours for V_{s1} are presented in Figure 2 for approximately 60% of the dataset processed to date. These preliminary contours are generated by a mean value-first order-second moment (MVFOSM) estimation of the failure surface, and will be assessed for quality using higher order first- and second-order reliability methods (FORM and SORM) and Monte Carlo simulations.

SUMMARY

This project presents our efforts to expand the worldwide data set of shear wave velocity at liquefaction evaluation sites, and processi these data within a Bayesian framework for probabilistic assessment of seismic-triggering of liquefaction. Since 2001, we have investigated approximately 300 Asia and US liquefaction evaluation sites using SASW. The elements of our investigation are (1) cataloging locations of all documented liquefaction and non-liquefaction sites, (2) identifying critical layers and their textural characteristics; (3) re-evaluating sites by active-source and passive-signal surface wave methods; and, (4), applying Bayesian udating and structural reliability methods to assess the likelihood of liquefaction occurrence. The objective of this project is a formal re-evaluation of the liquefaction resistance assessment methodology by shear wave velocity in light of a new global data set and higher order probabilistic data processing.

ACKNOWLEDGEMENTS
Components of this work were supported through funding by the Pacific Earthquake Engineering Research Center (PEER) Lifelines Program 3D03. We thank PEER for their support and guidance during this project.

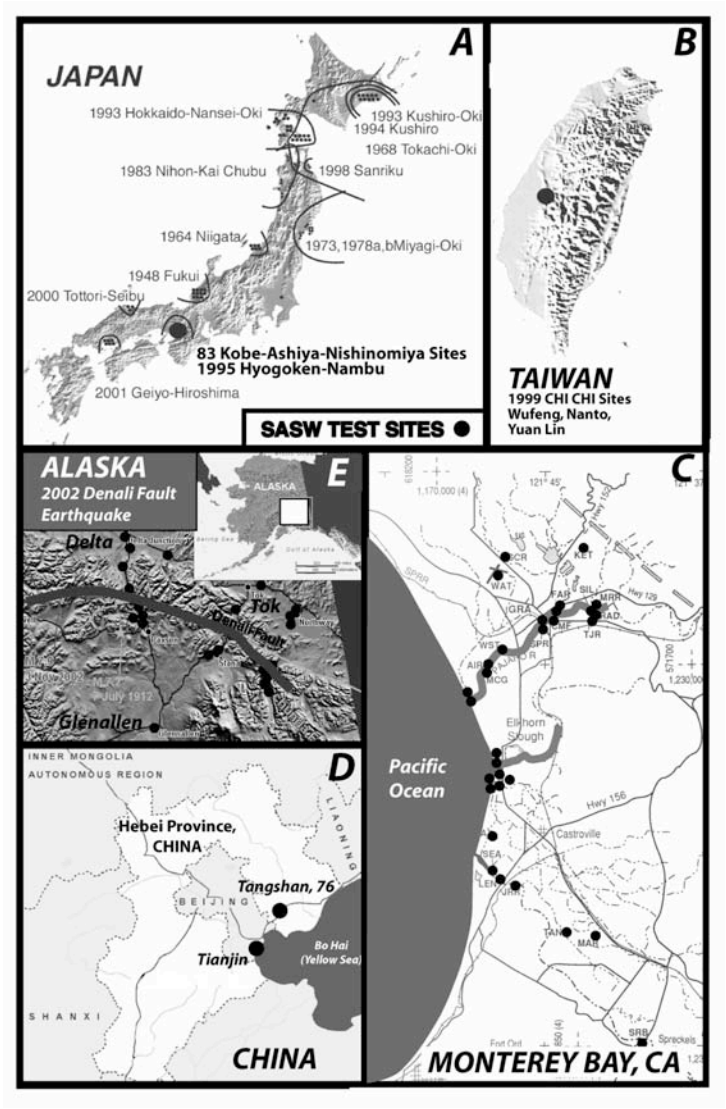


Figure 1. New shear wave velocity profiles at liquefaction evaluation sites (clockwise from top-left): (A) 168 - Japanese test sites (83 in Kobe area) collected in 2001-2; (B) 14 - Chi Chi, Taiwan, earthquake sites collected in 2001, and new sites collected in Nov. 2003; (C) 36 - Moss Landing, Pajaro, Salinas River sites and inner Bay Area sites (not shown) collected 2001-2003; (D) 26 Tangshan and Tianjin, China sites collected in October 2003; (E) 26 - Denali Fault earthquake sites, central Alaska and 22 - 1964 Alaska earthquake (not shown).

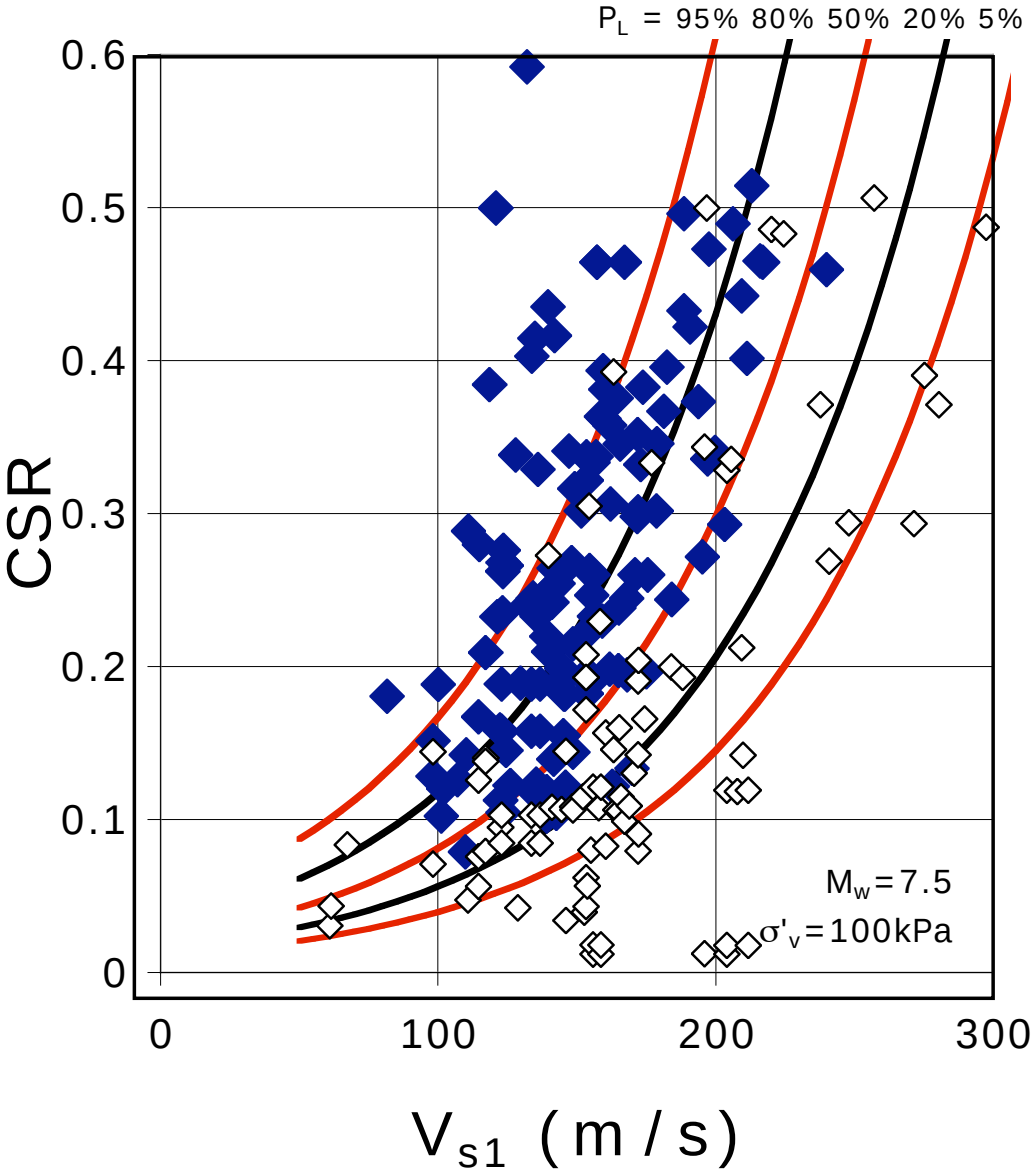


Figure 2. Preliminary probabilistic liquefaction triggering contours for ~60% of the global V_{s1} data set processed to date. P_L is the probability (degree-of-belief) that liquefaction has occurred.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*CPT Testing of Deposits in Imperial Valley*—**3D04**		
Start/End Dates	5/1/03 – 3/31/04	Budget/ Funding Source	$6,361 / Caltrans
Project Leader (boldface) and Other Team Members	**Stewart (UCLA),** Robb E.S. Moss (Fugro)		

1. Project goals and objectives

This project consisted of retesting of liquefaction and non-liquefaction field case histories in the Imperial Valley with the cone penetration test (CPT). The River Park and Heber Road sites were originally tested using a mechanical cone following the 1979 Imperial Valley Earthquake by Les Youd and co-workders. These two sites are rich in information because they have experienced several earthquakes in recent history, have been subjected to moderate levels of strong ground shaking, the liquefiable soils have appreciable fines content, and the sites contain a number of non-liquefied data points. The retesting was necessary because friction measurements from a modern electric cone are required to fully utilize these important case histories within liquefaction triggering databases.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The data strengthens the database upon which probabilistic liquefaction triggering models are based. Such triggering models are important for incorporating ground failure phenomena into performance based design procedures.

3. Brief description of the accomplishments of the project

The electric cone data at the Heber Road and River Park sites is summarized in Figure 1. These important sites can now be incorporated into liquefaction case history databases and used in back-analysis of liquefaction triggering. The data points are overlaid on the world-wide liquefaction case history inventory in Figure 2.

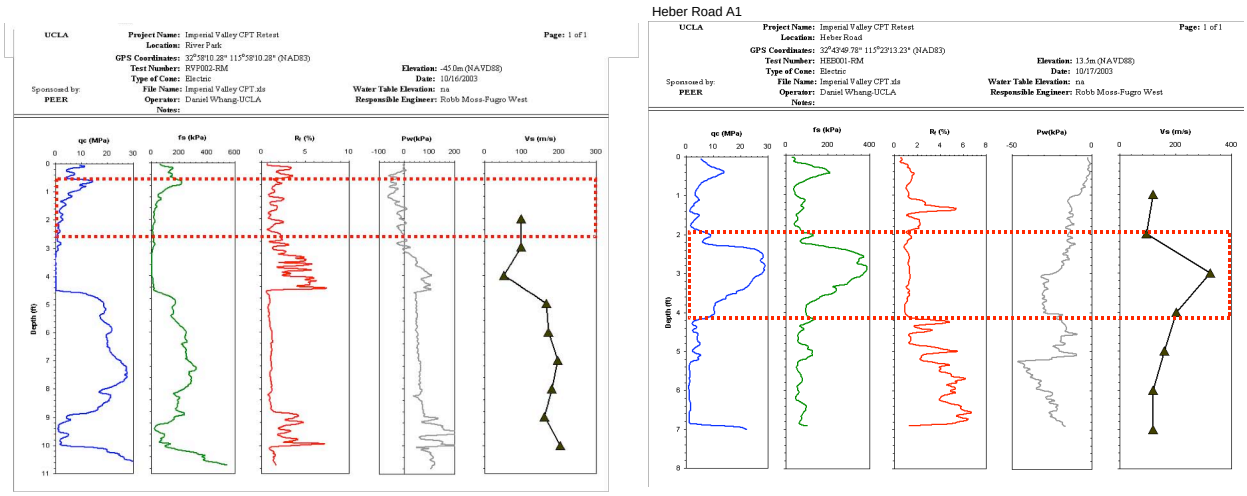


Fig. 1. Example CPT data from River park (left) and Heber Road (right) showing critical layers for liquefaction triggering

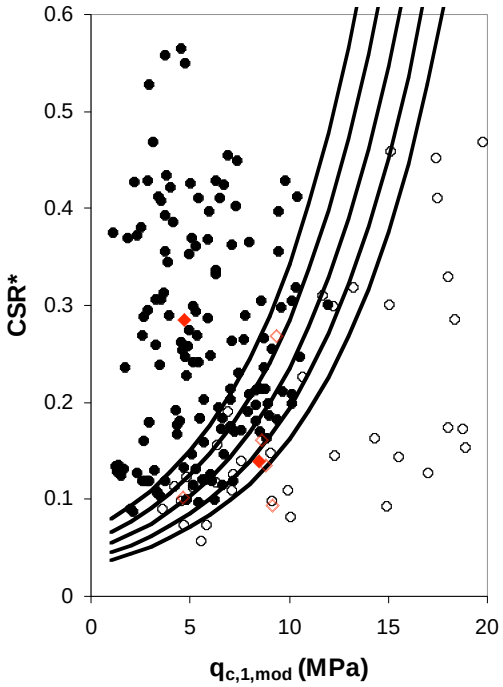


Fig. 2. New liquefaction/non-liquefaction case histories, corrected for friction ratio, shown with probabilistic liquefaction triggering curves and worldwide database developed by Moss & Seed (2004). Filled symbols are liquefaction data points and hollow symbols are non-liquefaction data points.

4. Describe any instances where you are aware that your results have been used in industry

None to report.

5. Methodology employed

Standard CPT testing procedures

6. Other related work conducted within and/or outside PEER

Liquefaction case history documentation and analysis by Bray and co-workers using Turkey data and Stewart and co-workers using Taiwan data.

7. Recommendations for the future work: what do you think should be done next?

Site reconnaissance and investigation programs should be continued after future major earthquakes.

8. <u>Author(s), Title, and Date</u> for the final report for this project

Moss, R.E.S., Collins, B.D., Whang, D.H., and Stewart, J.P. (2004). "Retesting of Liquefaction and Non-Liquefaction Case Histories in the Imperial Valley using CPT," Report to Pacific Engineering Research Center.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Inertial & Kinematic Load Combinations on Pile Foundations in Liquefying and Laterally Spreading Ground*—**3F03**		
Start/End Dates	4/1/04 – 6/30/04	Budget/ Funding Source	$250,000 / Caltrans
Project Leader (boldface) and Other Team Members	**Boulanger (UCD)**		

1. Project goals and objectives

The objective of this project is to establish guidelines for inertial and kinematic load combinations to be used in simplified pushover analyses of pile foundations in liquefied and laterally spreading ground.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The proposed project, combined with an expected follow-on project, will contribute to simplified design procedures for estimating loads on foundations due to lateral spreading.

3. Brief description of the accomplishments of the project

We completed the back-analyses of the inertial and kinematic load combinations that acted on the pile foundations in the dynamic centrifuge tests by Chang et al. (2003, as archived at the UC Davis Center for Geotechnical Modeling). A draft report describing the back-analysis procedures and findings has been written, but still needs to be reviewed and edited. This draft report formed the basis for the following paper:

> Chang, D., Boulanger, R. W., Kutter, B. L, and Brandenberg, S. J. (2005). "Experimental observations of inertial and lateral spreading loads on pile groups during earthquakes." GeoFrontiers Conference, Austin, Texas, Geotechnical Special Publication, ASCE, accepted.

Dynamic time-history analyses of the centrifuge tests by Chang et al. using OpenSees are in progress. Efforts to date have involved calibration of the soil material models, calibration of the soil-spring models, mesh generation, and initial dynamic analyses to evaluate numerical stability issues. The constitutive model by Yang and Elgamal has had some recent revisions which have required that we re-evaluate our material parameter selections and adjust our numerical solution schemes. We also experimented with the new coupled-flow elements that have been implemented in OpenSees, but have returned to the fully-undrained elements for the first round of analyses.

4. Describe any instances where you are aware that your results have been used in industry

None at this time.

5. Methodology employed

This project involves performing dynamic time-history analyses of published centrifuge experimental data to validate the numerical approach, and then using that numerical approach to perform parametric studies for the derivation of more general design guidelines. The numerical approach involves two-dimensional modeling of the soil profile with the foundation's structural components (piles, pile cap) connected to the soil mesh through soil spring elements, thereby allowing relative displacements between the soil profile and the piles (3D effects).

6. Other related work conducted within and/or outside PEER

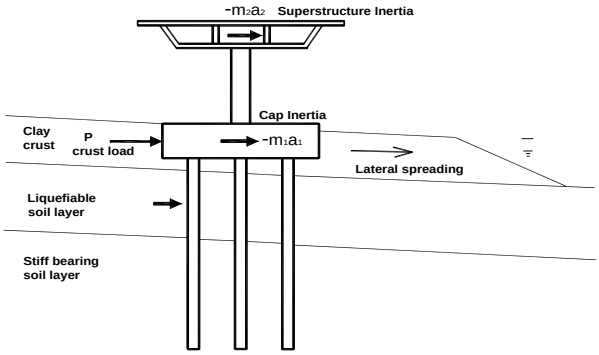
This project will utilize results from the US/Japan Centrifuge-Shaketable comparison project (3F02), and has strong synergy with the PEER Bridges and Transportation Systems thrust area's demonstration of the PEER methodology for a representative bridge configuration subject to liquefaction and lateral spreading. In addition, results from 3G02 (Improved estimates of lateral deformation) will also contribute to the proposed guidelines for design of pile foundations in laterally spreading ground.

7. Recommendations for the future work: what do you think should be done next?

The most serious limitation of emerging design methodologies for pile foundations in laterally spreading ground is the absence of experimental data to evaluate the mechanisms by which pile foundations may restrain lateral deformations of abutments. This coupling of deformations between the pile foundation and surrounding ground has been shown to have a major effect on design decisions for representative bridges (NCHRP 472). Consequently, a proposed amendment to this project was submitted that would directly address this issue of validating design methodologies for this "pile pinning" effect.

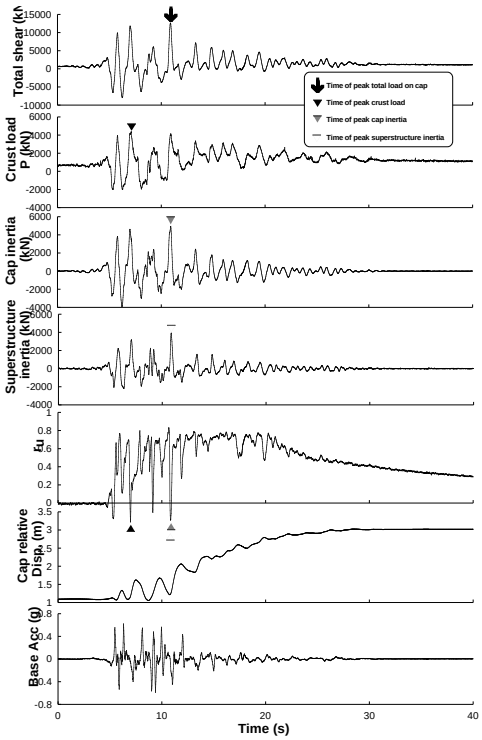
8. Author(s), Title, and Date for the final report for this project

The final report for the amended project would be submitted by May 30, 2006.

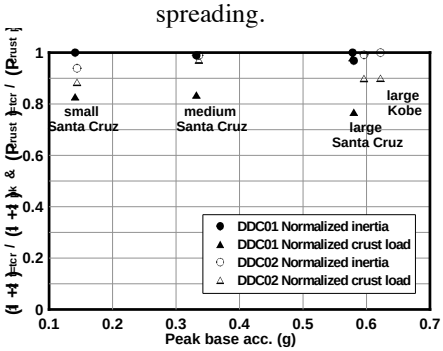


(a) Schematic of lateral spreading & inertial loads

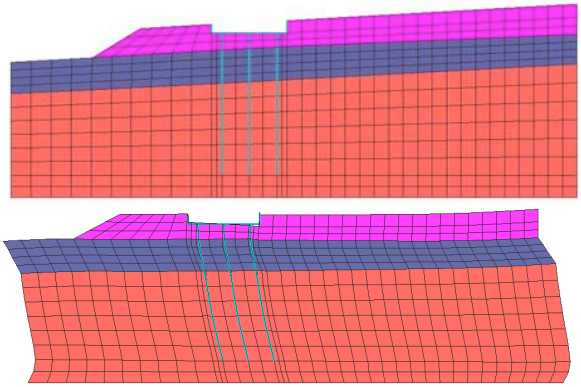
(b) Centrifuge pile group with passive bulge & lateral spreading.



(c) Back-calculated loads a on pile group during centrifuge testing.



(d) Inertial & lateral spreading load combinations at critical loading cycle during shaking (Chang et al. 2005)



(e) Initial and deformed FE mesh of the soil profile and pile group from photo (b) during large Kobe motion (superstructure omitted for this example).

Final Project Summary— PEER Lifelines Program

Project Title—**ID Number**	*Pilot Application of Regional Liquefaction Ground Deformation Models*—**3G01**		
Start/End Dates	7/1/01 – 6/30/04	Budget/ Funding Source	$103,999 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**Knudsen, K.L. (CGS),** Rosinski, A. (CGS), Wiegers, M. (CGS), Real, C. (CGS), Wu, J. (UC Berkeley), Seed, R.B. (UC Berkeley)		

1. Project goals and objectives

The goals of this project include:

(1) To identify the most appropriate and best available methods of developing regional hazard maps showing liquefaction-induced surface deformation.

(2) To develop a detailed, GIS-based, three-dimensional depiction of subsurface geology for a part of the Santa Clara Valley.

(3) If feasible, to produce liquefaction *deformation* hazard maps for both vertical and lateral movements for a part of the Santa Clara Valley.

(4) Based on the results of our work, examine the feasibility of developing regional maps of liquefaction-induced deformation hazard with existing technology and knowledge.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

CDMG's Seismic Hazard Mapping Program is interested in the possibility of using deformation-based models as the basis for its zones of required investigation. Additionally, ground deformation due to liquefaction-induced lateral spreading and settlement are earthquake hazards that adversely impact the performance of lifelines such as utility pipelines and highway roadways/bridges. New methods for the reliable prediction of the location and extent of such deformation would immediately be applied by those organizations interested in increasing lifeline-network reliability after major earthquakes.

3. Brief description of the accomplishments of the project

To date, we have presented the working results of our project at 3 conferences and published papers in the related proceedings volumes:

1) Geo-Trans 2004 in Los Angeles during the summer of 2004

2) The 11th International Conference on Soil Dynamics & Earthquake Engineering in Berkeley during January of 2004, and

3) the Technical Council on Lifeline Earthquake Engineering in Long Beach in August of 2003.

We are presently finalizing the final report and have produced a variety of liquefaction hazard maps of part of the Santa Clara Valley using a variety of approaches. Our report describes the data needs, uncertainties, and relative merits of the different approaches.

Lastly, two graduate students have been partially supported by this project: Dr. Jiaer Wu at UC Berkeley recently completed his phd, and Anne Rosinski at San Jose State University is nearing completion of her MS degree in the geology department.

4. Describe any instances where you are aware that your results have been used in industry

Since the project is just being wrapped up the results are not yet being used in industry. However, we (California Geological Survey, Seismic Hazard Mapping Program) are beginning to reevaluate the way we produce maps of liquefaction hazards using the results of this study. We also are discussing a project with CALTRANS in which the results of this project would be applied in helping CALTRANS identify their most at-risk bridges.

5. Methodology employed

The two main methods applied in developing regional maps of potential liquefaction induced ground surface displacement are: (1) estimation of lateral spread displacements using empirical methods developed by Youd and colleagues, and Bardet and colleagues; and (2) estimation of horizontal and vertical displacement using the concept of limiting strain. Data needed for these analyses include. geotechnical, geologic, seismologic and topographic. The analyses have been done utilizing geographic information systems (GIS) and an extensive electronic database of geotechnical borings. A significant part of this project is researching alternative methods of characterizing the area's geology for the purposes of assessing liquefaction hazard. The dynamic depositional processes and variability in sediment properties has caused us to investigate and develop new methods of relating three-dimensional geologic and geotechnical information to two-dimensional hazard maps.

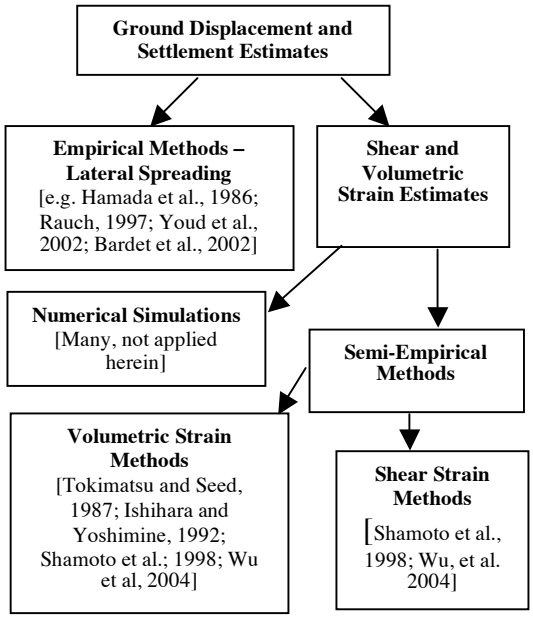


Fig 1. Methods of predicting liquefaction-induced deformation

An example of a sample map product is attached at the end of this document

6. Other related work conducted within and/or outside PEER

We are making use of several recent PEER studies that were conducted to improve the ability to assess liquefaction on a site specific basis and applying these methods to our regional hazard assessment. Additional, realted projects inlcude: (1) The CDMG SHMP is synthesizing vast subsurface data sets for key urbanized regions (LA and Bay Areas) as part of its effort to develop maps of liquefaction zones of required investigation for these regions (as mandated under the 1990 Seismic Hazards Act). These maps identify microzones within which liquefaction may occur, but do not predict either the likelihood of liquefaction nor the extent of deformation.

(2) Scientists and engineers at the U.S. Geological Survey are developing new methods of estimating deformation based on Cone Penetrometer (CPT) data. They are acquiring new data with a CPT rig in order to have sufficient data for making hazard maps. Our proposed approach is based on the use of existing geotechnical data.

(3) Scientists at William Lettis & Associates, CDMG and USGS are developing 1:24,000-scale original maps of Quaternary deposits and derivative liquefaction susceptibility maps for the core San Francisco Bay area. Production of these maps includes very little evaluation of subsurface data.

We are familiar with all of these efforts and directly involved in two of them (1 and 3). Additionally, we have strong ties with other scientists and engineers working on liquefaction-related issues.

7. Recommendations for the future work: what do you think should be done next?
We will continue exploring application of the methods developed during this project to hazard mapping. In particular, we are exploring integrating these methods into the mapping performed by the CGS Seismic Hazrds Mapping Program. We also plan to use these methods to assist CALTRANS in prioritizing structures for more detailed investigations and mitigation. Related research that would improve our ability to produce regional maps of hazard would include incorporating topographic parameters in predictions of shear and volumetric strain induced by liquefaction. To date, the most current relationships to predict strain assume a ground surface that has little to no slope and do not account for proximity to a free face.

8. <u>Author(s), Title, and Date</u> for the final report for this project
K. L. Knudsen[1], A. Rosinski[1], J. Wu[2], R. B. Seed[3], M.O. Wiegers[1], C.R. Real[4]
[1] California Geological Survey, San Francisco, CA, [2] URS Corporation, Oakland, CA
[3] Dept. of Civil and Environmental Engineering, Univ. of California at Berkeley
[4] California Geological Survey, Sacramento, CA

Tentative title: Assessment, development, and application of methods to produce regional maps of liquefaction-induced deformation
Date: September 2004

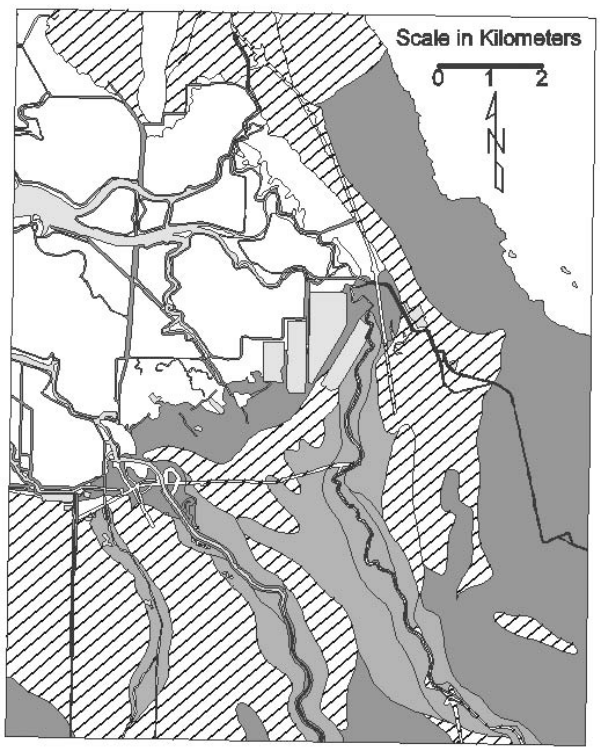


Fig. 2. Liquefaction-induced ground settlement (ft), Milpitas 7.5-minute Quadrangle, California (settlement calculated using Wu et al., 2003 method)

- 0 – 0.20 ft (Qf, af, Qhc, Qhff, Qhl)
- 0.21 - 0.40 ft (Qhfy, Qhly, Qhty)
- 0.41 - 0.60 ft (alf, Qhfe, Qhf)
- 0.61 - 0.80 ft (ac)
- NOT EVALUATED

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Analytical Models for Electrical Equipment Connected by Rigid Buses* — **401**		
Start/End Dates	5/1/02 – 6/30/04	Budget/ Funding Source	$82,121/ PG&E/CEC
Project Leader (boldface) and Other Team Members	**Der Kiureghian (UCB)**		

1. Project goals and objectives

This project aimed at developing analytical models and methods for assessing the seismic response of electrical substation equipment connected by assemblies of rigid bus (RB) and flexible strap connectors (FSC) or slider connectors (SC). Also developed is a method to estimate the reliability of electrical substation systems subjected to stochastic earthquake loading.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The project resulted in mechanical models and dynamic analysis methods of equipment items connected by RB-FSC's or RB-SC's. The model and analysis approach allow accurate prediction of the behavior of connected equipment items by properly accounting for the nonlinear behavior of the connectors and the interaction effect between equipment items. This study also introduced a new S-shaped FSC, called *S*-FSC, which has enhanced flexibility and is highly effective in reducing the adverse effect of dynamic interaction between the connected equipment items. Through extensive parametric investigations, simple design guidelines are suggested for reducing the hazardous effect of the seismic interaction in practice. In order to assess and improve the seismic reliability of electrical substation systems, a new method is developed for computing bounds on the reliability of general systems by use of Linear Programming (LP). These results will help identify and reduce the seismic vulnerability of electrical substation equipment and systems.

3. Brief description of the accomplishments of the project

Considering the plethora of equipment types and configurations in a substation, and the dearth of available information about their characteristics, simple modeling of equipment items is essential. In this study an electrical substation equipment item is idealized as a single-degree-of-freedom (SDOF) oscillator by use of a displacement shape function. In order to examine the accuracy of the SDOF idealization for interaction studies, a connected system consisting of a disconnect switch and a bus support is examined in great detail. The response ratios predicted by the SDOF models are compared with those obtained by 3D finite-element dynamic analysis. Based on these results, recommendations are made on the best choice of the shape functions for the SDOF idealization.

The hysteretic behavior of rigid bus connectors is described by differential-equation-type models for use in nonlinear time history and random vibration analyses of the interconnected electrical substation equipment. For the existing designs of FSC's, a generalized Bouc-Wen model is developed that is capable of describing the highly asymmetric hysteresis behavior. This model is appropriate for use in conjunction with nonlinear random vibration analysis by the equivalent linearization method (ELM). For SC, a bi-linear model in the form of a differential equation is adopted. The hysteretic behavior of the *S*-FSC is modeled by the original Bouc-Wen model. These theoretical models are fitted to available experimental results conducted at UC San Diego and finite element predictions, and then are used to conduct a comprehensive parametric study of the interaction effect.

Analysis methods are developed for estimating the seismic response of equipment items connected by nonlinear rigid bus conductors. The analysis methods use the SDOF models for equipment items and the differential-equation-type hysteresis models for the rigid bus connectors. For deterministic time-history analysis, the adaptive Runge-Kutta-Fehlberg algorithm is used. For stochastic dynamic analysis, the ELM is used. For each connector hysteretic model, closed-form expressions are derived for the coefficients of the equivalent linear system in terms of the second moments of the response. Numerical simulations verify the accuracy of the proposed models and methods as demonstrated in Figure 1.

Employing nonlinear random vibration analysis with the developed models and methods, the effect of interaction in the connected equipment system is investigated through extensive parametric studies. For each connector, parametric charts of the amplification in the response of the higher-frequency equipment item relative to its stand-alone configuration are developed, which describe the influences of important system parameters over wide ranges of values. The performances of the various connectors under identical conditions are then compared in terms of the amplification in the response of the higher-frequency equipment item. Based on this parametric investigation, simple design guidelines are suggested for reducing the adverse effect of the seismic interaction in practice. The design guidelines utilize the parametric charts and an interpolation/extrapolation formula for easy estimate of the interaction effect in practice.

In order to assess and improve the seismic reliability of electrical substation systems, a method is developed for computing bounds on the reliability of general systems by use of LP. The usefulness of the methodology for assessing the seismic reliability of complex electrical substation systems is demonstrated by applications to three transmission-line-substation examples. It is also shown that the proposed LP formulation provides a convenient framework for a systematic identification of critical components and cut sets of the system. Numerical examples with the two-transmission-line substation system demonstrate the proposed methodology.

In order to obtain narrow bounds on the reliability of an electrical substation system under stochastic loading, the new concept of "joint first-passage probability of a vector process" is introduced and new formulations for Gaussian vector processes are derived. The accuracy of the proposed formulas is verified by comparing analytical predictions with Monte Carlo simulation results. By synthesis of the analytical models and methods developed in the study, a general methodology for estimating the reliability of an electrical substation system subjected to a stochastic ground excitation is proposed. The methodology is demonstrated for an example electrical substation system. Figure 2 shows the marginal and system fragility curves of the example system.

4. Describe any instances where you are aware that your results have been used in industry

PG&E has funded the manufacturing and testing of prototypes of the *S*-FSC. The tests have verified the advantages of this FSC as predicted by our analytical models. We hope that this improved design will be used in practice in the near future.

5. Methodology employed

We used and developed differential-equation type models for describing the hysteresis behavior of the connectors. For deterministic dynamic analysis, the adaptive Runge-Kutta-Fehlberg algorithm was used. For nonlinear random vibration analysis by use of ELM, closed-form coefficients were derived for each connector. The LP bounds methodology is newly developed to estimate the reliability of electrical substation systems subjected to earthquake loadings. To obtain narrow bounds on the reliability of an electrical substation system under stochastic loading, the joint first-passage probability of a vector process is introduced and new formulations for Gaussian vector processes are derived. Design charts and interpolation formulas are developed for easy assessment of the interaction effect in practice.

6. Other related work conducted within and/or outside PEER

Experimental work parallel to this study was conducted at UC San Diego by Professor A. Filiatrault. Comparisons between the experimental results and analytical predictions based the model developed are presented in this study.

7. Recommendations for the future work: what do you think should be done next?

In order to improve the applicability of the proposed methods in practice and to improve their efficiency and accuracy, the following topics are recommended for future research.

- Develop a method for assessing the reliability of large systems by use of the LP bounds methodology. The idea of employing "super-components" to reduce the size of the LP problem should be explored. Specifically, it is desirable to develop a method for the optimal selection of "super-components," which achieves the objective of problem size reduction, while minimizing the information loss.
- Develop a rigorous and practical decision framework for optimal upgrading of systems relative to specified performance and safety criteria and load hazard. This problem may take the form of a mixed integer-linear programming algorithm that aims at identifying the most effective and economical scheme for strengthening the components of a system to enhance its reliability, subject to prescribed constraints. Such an algorithm may also be used for developing optimal inspection and maintenance strategies for an electrical substation system.
- It would be highly desirable and instructive to apply the methods developed in this research to a real-world electrical substation system. Such an application would highlight the power and usefulness of these newly developed or extended methods, as well as identify shortcomings and areas needing further development. Furthermore, the system analysis methods developed in this research are applicable to any system, and applications to other lifelines may produce fruitful results. In particular, consideration may be given to applying these techniques to an entire power transmission network, or a subset of such a network, consisting of generation nodes, transmission lines, substations, and consumption nodes.

8. <u>Author(s), Title, and Date</u> for the final report for this project

Junho Song, Armen Der Kiureghian and Jerome L. Sackman, "Seismic Response and Reliability of Electrical Substation Equipment and Systems," *will be published soon*.

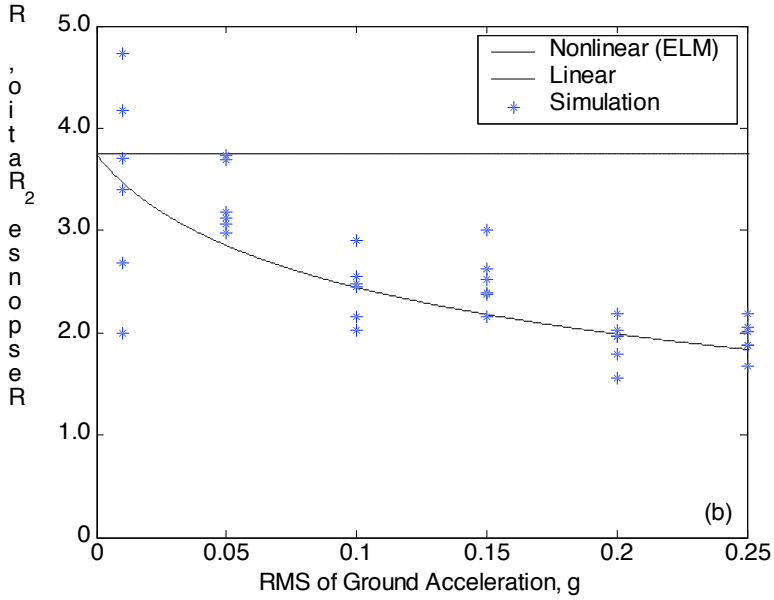


Figure 1. Response ratios for higher-frequency equipment item connected by *S*-FSC

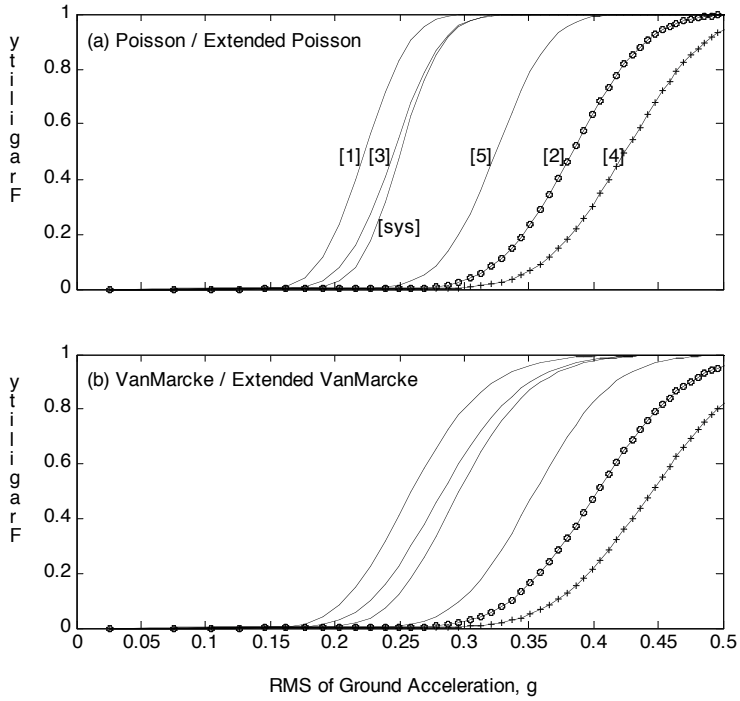


Figure 2. Equipment and system fragility estimates by (a) extended Poisson approximation; (b) extended VanMarcke approximation

Final Project Summary — PEER Lifelines Program

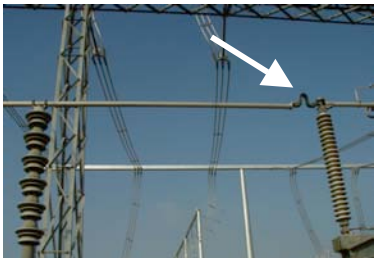
Project Title—**ID Number**	*Substation Equip. Interaction-Experimental Models of Rigid Bus Connectors*—**402**		
Start/End Dates	4/1/02 – 3/31/03	Budget/ Funding Source	$100,000 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**Filiatrault (UCSD)**		

1. Project goals and objectives

The main objective of this project is to experimentally investigate the interaction between components of substation equipment connected by re-designed (or improved) rigid bus connectors through quasi-static and shake table testing. The purpose was to generate data that would provide guidance in the design of conductor assemblies with the improved connectors.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

Earthquakes in recent years have demonstrated that electrical substations display a certain level of vulnerability to seismic loading. Because substation equipment items were designed in the 1950s and 1960s, consequences from seismic events were not always taken into consideration. Certain equipment components were designed solely to supply electricity and have shown to perform poorly in seismic events. In response to these vulnerabilities, in recent years, the IEEE 693 standard was developed to address the performance of substation equipment under seismic loading. However, this standard does not address the influence of interconnection on the equipment performance. Due to the complexity of the connectors, the seismic response of interconnected system may become complicated and unpredictable. Currently, according to the IEEE 693 standard, the equipments are qualified in a "stand-alone" condition. One type of connection that is particularly complicated is the rigid bus connection (see Figure). Typically, rigid buses utilize relatively flexible end connectors that account for thermal expansion. Depending on the flexibility and damping characteristics of these connectors, some of the seismic energy may be absorbed in the connectors before being transferred to the equipment components. Connectors in current systems, however, have shown not to provide a sufficient amount of flexibility nor dissipate a large amount of energy, thereby transferring forces to the equipment, resulting in damage. In 1999 as part of the Task 2C project of the PEER-PG&E program, several types of rigid bus connectors currently installed in electrical substations underwent quasi-static and shake table testing. Three types of flexible strap connectors, which dissipate energy through yielding of and friction between flexible straps, were tested. Additionally, a second type of connector, the bus slider connector, was tested. This bus slider dissipates energy through friction and exhibits a higher damping capacity. While the results of these tests showed a relatively good energy dissipation capacity, these connectors were relatively stiff and could transmit significant forces to the equipment. Consequently, these results led to the realization that connectors with lower stiffness should be examined as possible replacements for the current connectors. This project is the continuation of the investigation on substation equipment interaction performed in Task 2C of the PEER-PG&E program. Two new specimens were recently fabricated to improve the connector performance through lower stiffness and higher damping capabilities.



3. Brief description of the accomplishments of the project

Based on the results of the quasi-static tests performed on the improved rigid bus connectors, the following main conclusions can be drawn:

- The new S-shape Flexible Strapped Connector (S-FSC) specimen tested exhibited large and stable hysteresis loops with good energy dissipation capabilities.
- The equivalent damping ratios of all FSC specimens increase with displacement amplitude, indicating higher dissipation capacity at large inelastic displacements.

- The new S-FSC specimen exhibited higher damping than all the original FSC specimens.
- Both the old and new bus sliders exhibited a behavior that is typical of a Coulomb-type friction system coupled with an elastic restoring force mechanism.
- The improved bus slider had a lower post-slip stiffness about half of that of the original bus slider.

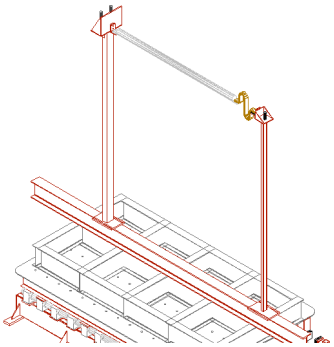
Based on the results of the shake table tests performed on five different pairs of generic equipment connected by three different types of rigid bus connectors, the following main conclusions can be drawn:

- The natural frequencies measured on the generic equipment specimens interconnected by the bus assemblies were always between the natural frequencies obtained for the uncoupled equipment specimens.
- The natural frequencies measured on the generic equipment specimens interconnected by the SEFCOR connector were nearly the same as the frequencies obtained from the uncoupled equipment specimens.
- The bus slider specimen exhibited the highest damping capabilities of the three specimens.
- The new bus slider specimen performed well except when subjected to the high amplitude Tabas record, when the plunger extended to the point where the stoppers hit the inside of the tube, and high impact forces were transmitted to the equipment items. More stroke may be needed to prevent this impact phenomenon.
- The response of the equipment items connected with the SEFCOR connector was similar to the response with the S-FSC specimen. The size of the loops from the SEFCOR specimen is believed to be great enough such that the connector will not become taut under severe ground motions.
- Among the three connectors investigated, the new bus slider consistently reduced the response at the top of both equipment specimens.

4. Describe any instances where you are aware that your results have been used in industry

The results generated in this study are being considered by the IEEE-693 Committee for future editions of their standard.

5. Methodology employed



In the first part of the project, quasi-static tests performed on improved S-shaped Flexible Strap Connectors (S-FSC) and on an improved bus slider connector. These tests were performed in the longitudinal direction of the connectors under a prescribed displacement history. The main objective of these tests was to obtain the mechanical properties of each specimen and compare them with the mechanical properties of the connectors tested previously in the Task 2C study. In the second part of the project, shake table tests were performed on five pairs of generic substation equipment connected with the three different rigid bus assemblies considered in this study (see Figure). Simulated horizontal ground motions were applied in the longitudinal direction of the bus assemblies by the uniaxial earthquake simulation facility at UC-San Diego. The variables considered in the tests were: the dynamic characteristics of the generic equipment, the types of rigid bus assemblies, the simulated ground motions, and the intensities of the simulated ground motions.

6. Other related work conducted within and/or outside PEER

This project was conducted in close collaboration with an analytical project on the same topic conducted at the University at California, Berkeley.

7. Recommendations for the future work: what do you think should be done next?

Enter text here.

8. Author(s), Title, and Date for the final report for this project

Filiatrault, A., and Stearns, C., Electrical Substation Equipment Interaction–Experimental Rigid Conductor Studies, March 2004.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Substation Equip. Interaction - Experimental Models of Flexible Bus Connectors*—**403**		
Start/End Dates	7/1/00 – 12/31/02	Budget/ Funding Source	$160,000/ PG&E/CEC
Project Leader (boldface) and Other Team Members	**Filiatrault (UCSD)**		

1. Project goals and objectives

This project has two main objectives: 1) to investigate experimentally the dynamic interaction between components of electrical substation equipment interconnected by flexible (cable) conductors and 2) to observe experimentally the flexural response of flexible conductors and to determine their moment-curvature relationships under axial tension.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

In response to the vulnerabilities exhibited by substation equipment in recent earthquakes, utilities, manufacturers, and others closely related with the industry have developed new seismic qualification procedures that are described in the IEEE 693 standard. These procedures, however, only qualitatively address the interaction between equipment connected by conductors by recommending that equipment connections be designed and installed to minimize interaction forces. This lack of specificity in the standard is due to the wide variety and complex behavior of equipment used in substations, manufacturer and utility-specific design characteristics of both the equipment and their support structures, and practical considerations of the qualification procedure. For these reasons, electrical equipment items are, in general, seismically qualified in a “stand-alone” condition (i.e. without connection to the adjacent equipment). Analytical studies have suggested that bending properties of flexible conductors might affect the behavior of short jumpers and some “long” conductors. Limited dynamic interaction experiments involving equipment models interconnected by flexible conductors have been performed to evaluate the importance of this dynamic interaction effect. The results generated in this project shed further light on this issue by characterizing the seismic response of substation equipment interconnected by flexible conductors.

3. Brief description of the accomplishments of the project

Based on the results of the shake table tests performed in this study on five different pairs of generic equipment connected by three different types of flexible connector assemblies, the following conclusions can be drawn:

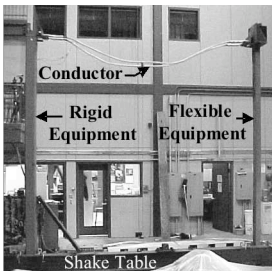
- For large slackness, the fundamental frequencies of the equipment items were not affected significantly by the presence of the flexible conductor assemblies.
- The presence of the conductor assemblies increased significantly the damping ratios of interconnected equipment.
- No damage to any of the three flexible conductors was observed during all the seismic tests conducted.
- For all slackness values, the dynamic response of the most flexible equipment is not affected very much by any of the three flexible conductors tested.
- At large slackness, the dynamic response of the most rigid equipment is generally reduced by the presence of the conductor assemblies.
- At large slackness, the forces generated at the top of the interconnected equipment are small. In most cases, the force at the top of the most flexible equipment is larger than the force at the top of the stiffer equipment.
- At small slackness, the dynamic response of the rigid equipment can be significantly increased once the conductor assemblies become tight and act as tension-only springs. This amplification of the dynamic response increases with the intensity of the ground motion.
- At small slackness, the forces generated at the top of the interconnected equipment are an order of magnitude higher that that measured at 5 and 10% slackness. For this slackness, the forces at the top of both interconnected equipment specimens are similar.

The results obtained from the quasi-static bending tests performed on two different full-scale flexible conductors (cables) indicate that the global force-displacement behavior of both conductors is linear-elastic with negligible hysteretic response. For most combinations of axial tension and lateral conductor displacement, the flexural stiffness exhibited by both conductors is very small, and tends toward the minimum possible flexural stiffness, corresponding to the situation where all the strands are slipping past each other, and are unable able to transfer any shear force. Only for very large axial tension values (more than 4.5 kN or 100με that the flexural stiffness of the conductors approach the maximum possible flexural stiffness, corresponding to the situation where all the strands are able to transfer longitudinal shear forces over one another, and the conductor section acts as a solid cross-section. It is unlikely that such high axial tension values can be mobilized during the seismic response of interconnected substation electrical equipment.

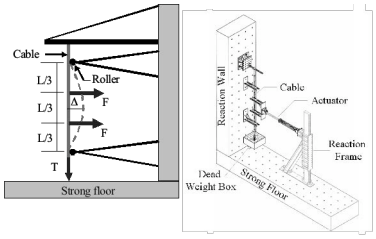
4. Describe any instances where you are aware that your results have been used in industry

The results generated in this study are being considered by IEEE-693 Committee for future editions of their standard.

5. Methodology employed



In the first part of the study, shake table tests of five pairs of generic substation equipment interconnected by three different flexible conductors with three different levels slackness were performed to evaluate the influence of different conductor assemblies on the structural dynamic response of interconnected substation equipment components. Simulated horizontal ground motions were applied in the longitudinal direction of the bus assemblies by a uniaxial shake table. In the second part of the project quasi-static bending tests performed on two different full-scale flexible conductors (cables). These tests were performed in transverse direction of the conductor assemblies under prescribed axial tension and displacement time history. The main objectives of these quasi-static tests were to observe the flexural response of flexible conductors and to determine their moment-curvature relationships under various axial tension values.



6. Other related work conducted within and/or outside PEER

This project was conducted in close collaboration with an analytical project on the same topic conducted at the University at California, Berkeley.

7. Recommendations for the future work: what do you think should be done next?

The experimental study conducted herein represents only a first step in fully understanding the seismic interaction between interconnected substation equipment. Future research is needed to expand the experimental studies to multi-span equipment/conductor layouts and multi-axis ground motion input. Furthermore, simplified analysis tools need to be developed in order to consider interaction effect at the design stage of interconnected substation equipment.

8. <u>Author(s), Title, and Date</u> for the final report for this project

Filiatrault, A., and Stearns, C., Electrical Substation Equipment Interaction–Experimental Flexible Conductor Studies, February 2003.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Substation Equipment Interaction -- Analytical Modles of Flexible Bus Connectors*—**403b**		
Start/End Dates	7/1/00 – 12/31/02	Budget/ Funding Source	$100,000/ PG&E/CEC
Project Leader (boldface) and Other Team Members	**Der Kiureghian (UCB)**		

1. Project goals and objectives

This project aimed at developing a better understanding of the mechanical behavior of conductor cables (flexible bus) and the dynamic response of equipment items connected by such conductors. In particular, the effect of interaction between equipment items were to be quantified and the necessary conductor slack to reduce this adverse effect was to be determined, while accounting for the stochastic nature of ground motions.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The results of the project have provided an improved understanding of the mechanical behavior of conductor cables, which are formed by helically wrapped aluminum wires. The model properly accounts for the effect of wire slippage under friction forces. This model has been implemented in a finite element code for dynamic analysis of cable-connected equipment items, accounting for material and geometric nonlinearities. This novel model and analysis approach allows accurate prediction of the behavior of substation equipment items connected by flexible bus and subjected to earthquake loading. Furthermore, design rules are provided to determine the required conductor slack in order to reduce the adverse effect of interaction on the equipment items to a manageable level. These results will help reduce the seismic vulnerability of electrical substation equipment connected by flexible bus conductors.

3. Brief description of the accomplishments of the project

A theoretical model is developed to describe the nonlinear moment-curvature relationship of conductor cables composed of helically wrapped aluminum wires. The model accounts for the friction and slippage that occurs between wires in neighboring layers when the cable is bent. A first-order differential condition for slippage of wires is derived by noting that a wire slips if the unbalanced tension force in a differential element of the wire, which is caused by bending, exceeds the maximum friction force on the wire that can be generated. The wire remains in a stick state if the unbalanced tension force is less than the maximum friction force that can be generated. In each cross section of the cable, two regions are identified: a region of stick and a region of slip. In the stick region, the continuity of axial strain in each wire along with the Bernoulli-Euler-Navier kinematic beam assumption are used to determine the axial force in the wire. In the slip region, the condition for the slippage of wires is used to determine the axial force in each wire. The resultant moment of the cable is nonlinearly related to the curvature of the cable; this nonlinear relationship also depends on the axial strain (or axial force) in the cable. Accordingly, the bending stiffness of the cable nonlinearly varies between two extreme limits. These correspond to the extreme cases of fully slipping and fully stuck wires. The difference between the two stiffnesses can be as large as two orders of magnitude. Figure 1 shows the moment-curvature relations for a specific conductor cable for two values of the friction coefficient and selected values of the cable tension force.

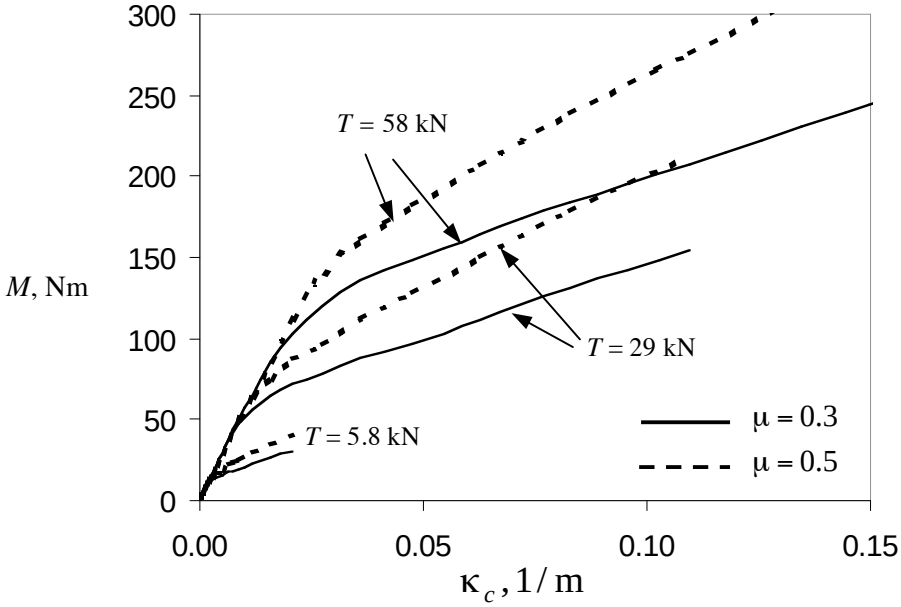


Figure 1. Moment-curvature relations of Jessamine conductor cable for two values of friction coefficient and selected cable tension force

A finite element model for the cable is developed by using a geometrically exact rod model and fitting the nonlinear moment-curvature-tension relationship of the cable with a bilinear elasto-plastic constitutive model. Kinematic hardening is assumed to represent the nonlinear bending behavior of the cable. Comparisons are made between predictions by the finite element model and tests conducted by other investigators under static and dynamic conditions.

The finite element model developed is used to investigate the effect of dynamic interaction between two idealized equipment items connected by a conductor cable and subjected to ground motion. It is shown that the dynamic cable force can be significantly larger than the cable force under static equilibrium conditions. Furthermore, it is shown that the equipment response in the connected system can be strongly amplified relative to the response of the stand-alone equipment, particularly for the equipment item having the higher frequency. A simple predictive formula to estimate the amplification of equipment response due to the interaction effect is developed, and a practical design rule for selecting the cable slackness to limit the interaction effect in the cable-connected system is derived.

Figure 2 shows the effect of interaction on the higher-frequency equipment item in a pair of equipment items connected by the Trillium conductor cable. The effect is shown as an amplification factor in the response of the equipment, relative to its stand-alone response, as a function of an interaction parameter that depends on the conductor slack. Results for five ground motions are shown. It can be seen that the amplification in the equipment response as a result of the interaction effect can be very significant.

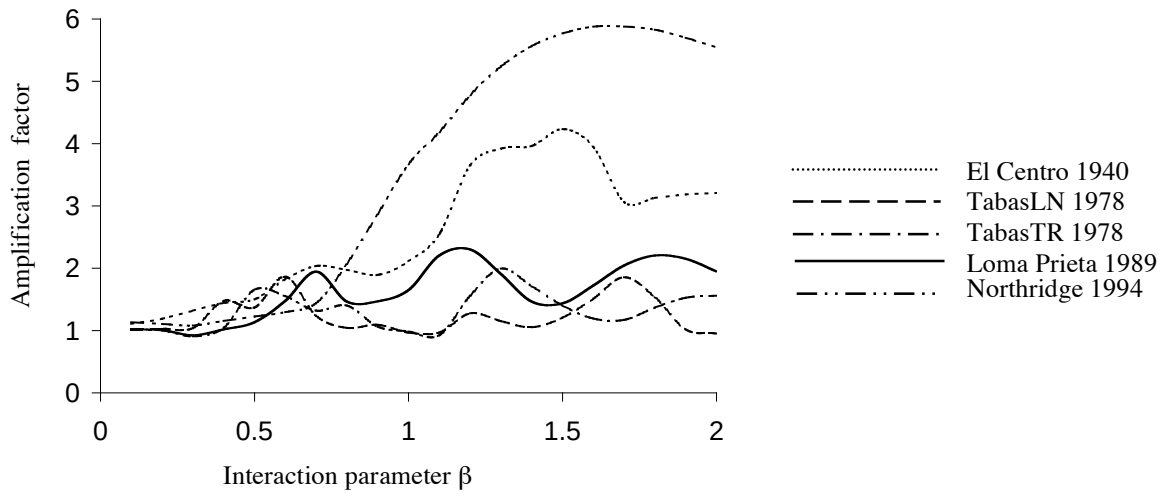


Figure 2. Effect of interaction in higher-frequency equipment item for selected ground motions.

4. Describe any instances where you are aware that your results have been used in industry

We are not aware that our results have been used by the industry at this time. However, we are aware that power company engineers have shown strong interest in our results.

5. Methodology employed

We used continuum mechanics to develop the model for the bending behavior of the conductor cable. This model was then implemented in an existing finite element code (FEAP by R. L. Taylor) by use of an exact rod element that accounts for large displacements and rotations. A time integration method was then selected, which is capable of dynamic analysis with material and geometric nonlinearities. The finite element code was used to simulate the response for a large number of example cable-connected equipment systems. Comparisons were made with experimental data. Finally, the numerical simulations were used as virtual data to fit a statistical model to predict the interaction effect as a function of system characteristics and the cable slack. This model was used to derive a design rule for the required slack in order for the amplification factor to remain below a specified threshold.

6. Other related work conducted within and/or outside PEER

Experimental work parallel to this study was conducted at UC San Diego by Professor A. Filiatrault. Comparisons between the experimental results and analytical predictions based the model developed are presented in this study.

7. Recommendations for the future work: what do you think should be done next?

The model developed for the conductor cable assumes motions in a vertical plane. This is adequate for analysis of seismic interaction between two connected equipment items, since the interaction then primarily happens in the plane of the conductor. It would be beneficial to extend the model to 3 dimensions. Such a model would be necessary to investigate the dynamic response of transmission lines and other cable structures under wind, ice and earthquake loading, or their combinations.

Our investigations also showed that further experiments under well controlled environment are needed to better understand the hysteretic behavior of the helically wrapped conductor cable under bending and axial force, so as to provide a basis for the validation and calibration of analytical models. Experiments to determine the interlayer friction coefficient between the wires in conductor cables is also needed.

8. Author(s), Title, and Date for the final report for this project

Kee-Jeung Hong, Armen Der Kiureghian and Jerome L. Sackman, “Dynamic Interaction in Cable-Connected Equipment,” Spring 2003.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Improvements to Modeling Substation Equipment*—**404**		
Start/End Dates	7/15/01 3/31/04	Budget/ Funding Source	$130,000/ PG&E/CEC
Project Leader (boldface) and Other Team Members	**Pardoen (UC Irvine)**		

1. Project goals and objectives

Utilities use different types of substation equipment that have dynamic characteristics that are not well known for many classes of equipment. Manufacturer differences in design, method of structural support, physical dimensions, voltage class differences as well as differences at the component level are just some of the features that introduce variations of dynamic behavior. Although utilities have been specifying that equipment be seismically qualified by analysis for many years, there is uncertainty in the dynamic properties and methods of modeling used in these analyses. This project improves the methods used for modeling electric substation equipment through a combination of experimental and analytical studies of bushings and transformers.

The experimental program consisted of testing substation equipment in laboratory (UCI, UCSD) and in-situ, field conditions (BPA, SDGE) using force-calibrated hammer and shake table excitation techniques. The analytical program consisted of developing linear structural models based upon the experimentally-acquired data that can be integrated with existing finite element models as well as conducting parametric studies for bushing response under various support conditions observed in the field.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The research improves the modeling of bushings under dynamic loads. Specifically the research has determined the fundamental vibration characteristics for a wide range of bushings and, through its shake table tests, has identified a potential isolation retrofit that can substantially mitigate the destructive effects of earthquakes on most bushings.

3. Brief description of the accomplishments of the project

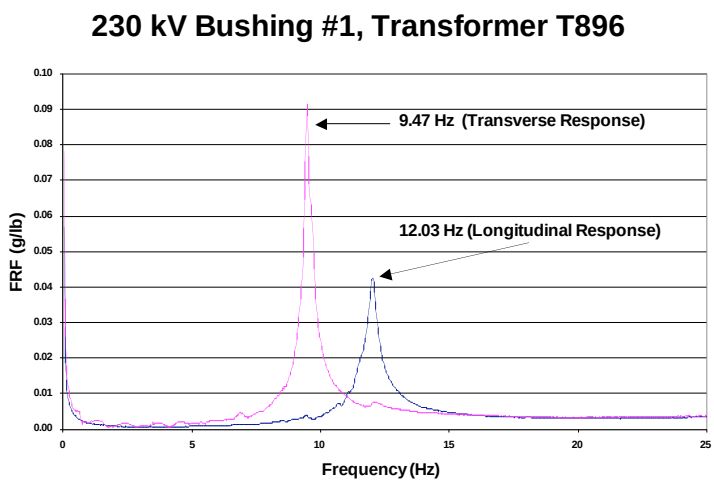
From the tests of more than 35 bushings, most in the transverse and longitudinal directions, it was determined that (a) almost all bushings could be characterized as a SDOF, lightly damped (< 1%) system, (b) bushing orientation and mounting location on the transformer had a significant natural frequency effect. UCI shake table tests of a wire-rope isolator confirmed that the damping characteristics could be significantly increased (< 1% to > 15%). The response of three transformers tested were found to be SDOF systems for frequencies < 35 Hz.

4. Describe any instances where you are aware that your results have been used in industry

Enidine (a former and/or current PEER BIP member) wants to market its wire-rope isolators as a retrofit to transformer-mounted bushings in seismically vulnerable areas.

5. Methodology employed

The experimental approach required a combination of laboratory and field-testing of substation equipment. The laboratory tests used both force-calibrated hammer and shake table excitations whereas the field-testing was confined to force-calibrated hammer and sledgehammer excitation. The experimental work was purposely divided into laboratory and field studies so that the vibration characteristics of the substation equipment can be investigated from two different perspectives. The laboratory test component provided more in-depth, iterative investigations using approximate support conditions whereas field-testing provided the correct support conditions for the substation equipment. Although the field tests at the BPA and SDGE sites did not permit in-depth investigations, the fundamental vibration characteristics of a transformer and more than 35 bushings of different sizes, orientations, and support configurations that were tested significantly adds to the database of such components.



The vibration characteristics of the 35+ bushings were interpreted using commercially available software (ME'Scope) in order to define the frequency, mode shape and damping characteristics of the equipment. Since the bushing's response due to the impact excitation was characterized as linear, ME'Scope determined the modal properties of the multiple degree-of-freedom, lumped parameter modal models from the experimentally-derived frequency response functions. The photo above denotes the force-calibrated excitation technique on a typical bushing at BPA whereas the graph depicts the longitudinal and transverse response for a 230 kV bushing on Transformer T896. It is significant to note that the response of these bushings (a) can be characterized as SDOF systems with low (< 1%) damping and (b) is dependent upon bushing orientation and location on the transformer.

These modal models can be integrated with standard finite elements to model structural response modifications due to mass or stiffness changes resulting from support structures. The linear analytic studies recommend methods for modeling equipment and major components. The significance of the experimentally-derived, modal model serves at least four purposes. First, the analytical models for bushings were found to be relatively simple compared to those that would have been derived from standard finite element techniques. Secondly, the effects of boundary conditions can be easily assessed by posing 'what if' questions to the ME'Scope Structural Dynamics Modification (SDM) software. Thirdly, the lumped parameter model of the substation equipment should be easily integrated with more elaborate finite element models of the support structure. Lastly, the modal models for the response of the bushings due to low- and moderate-level shake table excitation should provide some guidance regarding the appropriateness of assuming a linear analytical model.

Lastly, an MCEER-PEER cooperative effort to determine the vibration mitigation effects of bushings mounted with a variety of elastomeric pads and wire-rope isolators was conducted on the UCI shake table. The results were extremely encouraging. The Enidine wire-rope isolators were particularly effective in increasing the bushing's damping from < 1% to > 15%.

6. Other related work conducted within and/or outside PEER

An MCEER-PEER joint venture investigated the mitigation effects of bushings mounted with elastomeric pads and wire-rope isolators.

7. Recommendations for the future work: what do you think should be done next?

More experimental vibration tests of disconnect switches using experimental modal analysis techniques to supplement the work conducted at UCB. More shake table experimentation of bushings with wire-rope isolators should be conducted.

8. Author(s), Title, and Date for the final report for this project

Pardoen, G.C., Hamilton, C.H., "Improved Modeling of Electrical Substation Equipment for Seismic Loads", November 1, 2004.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Seismic Qualification Requirements for Transformer Bushings*—**406**		
Start/End Dates	10/1/01 – 9/30/03	Budget/ Funding Source	$120,000 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**Filiatrault (UCSD)**		

1. Project goals and objectives

This research task investigates the factors that most greatly influence the dynamic response of high voltage bushings as well as attempts to quantify the ground motion amplification for various high voltage transformers. Numerical models of four different high voltage transformers were developed and used for modal and dynamic time-history analyses. In addition, system identification and seismic shake table tests were performed on a full-scale 525 kV transformer-mock bushing system, as shown in Fig. 1. A numerical model of the test configuration was created to predict the seismic test results through dynamic time-history analyses.

Figure 1.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The IEEE-693 standard, which provides seismic design recommendations for substation equipment, states that bushings with voltage ratings exceeding 161kV must be seismically qualified by shake table testing. Since placing a full-scale transformer-bushing system on a shake table is not economically feasible on a routine basis, bushing qualification tests are generally performed by placing the bushing on a rigid frame in lieu of the transformer body itself. Although the transformer body is assumed to be fairly rigid, it is acknowledged that the supporting structure of the bushing, consisting of the turret and transformer tank, amplifies the ground acceleration. For this purpose, the IEEE-693 standard assumes that the motion at the base of the bushing is equal to the ground motion multiplied by a factor of 2. Shake table testing of porcelain bushings on a rigid base using the IEEE-693 seismic qualification procedure has demonstrated a generally good performance of these components. This good experimental performance is contrary to the failure of bushings observed in the field following past earthquakes. It is believed that the actual seismic vulnerability of porcelain bushings might be caused by the flexibility of transformer tanks and of bushing attachments, which amplify their dynamic response. To clarify this issue, this study investigated numerically the dynamic response of porcelain bushings mounted on transformer tanks.

3. Brief description of the accomplishments of the project

The numerical experimental results obtained in this study have provided several insights into the seismic response of high voltage transformer-bushing systems. The main conclusions that can be drawn from this study are summarized below:

- The flexibility of the top plate of the transformer tank greatly reduces significantly the fundamental frequency of a bushing compared to that of the same bushing rigidly mounted.
- The top plate flexibility of the transformer tank provides the largest influence on the amplification between the ground and the base of the bushing.
- In a given direction, the ground motion amplification occurs at two predominant frequencies: the fundamental frequency of the transformer tank and the fundamental frequency of the bushing.
- The lower fundamental frequency transverse direction of the transformer tank consistently results in larger ground motion amplifications than the higher frequency longitudinal direction.
- The ground motion amplification factor of 2.0 specified in the IEEE-693 standard may not be conservative for transformer-bushing systems for which the bushing fundamental frequency is tuned to the fundamental frequency of the transformer tank.

- Bracing members attached near the turret of the bushing effectively reduce the ground motion amplification as well as improve the overall bushing response.

4. Describe any instances where you are aware that your results have been used in industry

The results generated in this study are being considered by the IEEE-693 Committee for future editions of their standard.

5. Methodology employed

In the numerical study, linear dynamic time-history analyses on three-dimensional finite element models of four different high voltage transformers were performed using the commercially available structural analysis software SAP 2000 (Computers and Structures 2003). The finite element mesh for each of these 4 models is shown in Fig. 2. The analyses were performed in each principal direction of the transformers under 20 different historical strong ground motion time-histories scaled to the 2% damped high required level response spectrum specified in the seismic qualification procedure of the IEEE-693 standard.

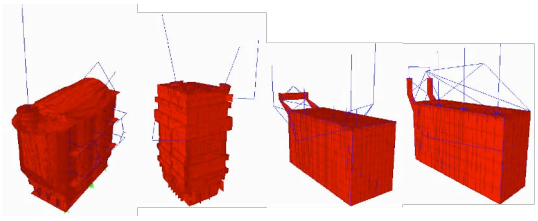


Figure 2.

The ground motion amplification was then quantified in two different ways. First, a frequency dependent spectral amplification was computed by taking the ratio of the 2% damped absolute acceleration response spectrum of the horizontal acceleration time-history obtained at the base of the bushing to that of the horizontal ground acceleration. Second, for three of the four transformer-bushing systems, the ground motion amplification was also computed by taking the ratio of the maximum bending moment obtained at the base of the bushing mounted on the transformer to that of the same bushing rigidly mounted.

The numerical study was complemented by system identification and seismic shake table tests on a full-scale 525 kV transformer-mock bushing system.

6. Other related work conducted within and/or outside PEER

Complementary experimental and numerical studies on bushing-transformer systems have been carried out by researchers from the Multidisciplinary Center for Earthquake Engineering Research (MCEER).

7. Recommendations for the future work: what do you think should be done next?

Further numerical and experimental studies on the influence of various transformer tank top plates may have on the dynamic response of transformer-bushing systems should be conducted. Isolation systems to decouple the fundamental frequency of bushing from that of transformer tank should be investigated.

8. <u>Author(s), Title, and Date</u> for the final report for this project

Matt, H. and Filiatrault, A. “Seismic Qualification Requirements for Transformer Bushings,” April 2004.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Input Motions for Earthquake Simulator Testing of Electric Substation Equipment*—**408**		
Start/End Dates	5/1/00 – 9/30/01	Budget/ Funding Source	$40,000/ PG&E/CEC
Project Leader (boldface) and Other Team Members	**Anderson (UNR)**		

1. Project goals and objectives

Improving the specifications for input motions for earthquake simulator testing of electric substation equipment.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

(1). The spectral matching method we developed provides a useful technique to scale historical earthquake records for use in engineering testing or designing. **(2).** Our results by examine ground motion response spectra from recent large earthquakes indicate the shape of the seismic response spectra show strong magnitude dependence. That dependence is useful for some earthquake resistant design situations. The IEEE-693 spectrum is exceeded by the average spectra at long periods for sites in the softest category, as a result of soil amplification. However, the magnitude dependence of the spectrum will cause the low frequencies to be amplified relative to the high frequencies for larger earthquakes. The result is that it will be no surprise to see the low frequency part of the spectrum exceeding the IEEE spectrum for all site categories in a significantly larger magnitude earthquake.

3. Brief description of the accomplishments of the project

In this project, we have accomplished two major tasks. **(1).** we have developed a method to calculate accelerograms that match a testing or designing target spectrum for appropriate earthquake magnitude, distance, and site conditions. Adjustments are made to acceleration-time history records by computing the response spectra and determining the amount of adjustment needed in different period ranges to nearly match the target spectrum. Fourier spectra are then computed. The Fourier amplitude spectra are adjusted while the Fourier phase spectra are preserved. The inverse Fourier transform is used to re-compute acceleration-time histories. If necessary, the procedure can be iterated to achieve reasonably optimal spectral matching. **(2).** we have examined ground motion response spectra from the recent large earthquakes in California, Japan, Turkey and Taiwan. We have studied the distance, site, and magnitude effect on the shape of the response spectra and compared these response spectra with the standard response spectra specified by the IEEE 693-1997 for high seismic performance level. We found the shape of the response spectra show strong magnitude and site dependency, but weak distance dependency. A larger earthquake generates much more long-period seismic energy than a smaller earthquake. An average soft soil site shows higher amplification of the long-period seismic signal than a rock or stiff soil site. Thus, the normalized spectra from a large earthquake recorded on a soft soil site have the highest likelihood of exceeding IEEE 693-1997 at long periods. By comparing acceleration response spectra with the response spectrum given in IEEE 693-1997 for high seismic performance level, we found the stations that exceed the absolute level of IEEE 693-1997 response spectrum are generally located: 1) very close to the fault rupture trace; 2) near the edge of a fault in a location that experienced a strong directivity effect; 3) on the hanging wall adjacent to the primary fault trace; or 4) at a site that experiences large site amplification. In the low frequency range, the excedance is usually associated with a larger magnitude earthquake at soft soil sites at near source distance (D<50 km). For larger earthquakes, exceedance at low frequencies may become more common.

4. Describe any instances where you are aware that your results have been used in industry

Spectral match method is been used.

5. Methodology employed

We have used Fast Fourier Transforms (FFT), inverse FFT and standard spectral analysis methods.

6. Other related work conducted within and/or outside PEER

We have also studied nonlinear site response effect on response spectra, explored the effects from distance, magnitude and site response on response spectra and compare them with building codes.

7. Recommendations for the future work: what do you think should be done next?

Analysis the results we have obtained as well as other related work and develop recommendations to future IEEE standards.

8. Author(s), Title, and Date for the final report for this project

Title of the final report: Input Motions for Earthquake Simulator Testing of Electric Substation Equipment (408), by Feng Su, Yuehua, John G. Anderson, August, 2002.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Input Motions for Earthquake Simulator Testing of Electric Substation Equipment*—**408**		
Start/End Dates	5/1/00 – 6/30/04	Budget/ Funding Source	$90,720 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**Fenves (UCB)**		

1. Project goals and objectives

The main objective of the study was to develop a set of earthquake ground strong motion time histories suitable for seismic qualification testing of electrical substation equipment in accordance with the IEEE 693-1997 standard. Although the study's objective deals with shake table testing of a particular class of equipment, many of the issues investigated are equally relevant to the dynamic testing of other types of equipment and components. This study was motivated by a desire to introduce a standard set of input motions in three orthogonal directions, and thus achieve more consistency in earthquake simulator testing. The project is focused on developing an input strong motion based on a record of actual earthquake with a time-domain spectral matching procedure, so the spectrum-compatible strong motion time history would preserve the non-stationary behavior of the real record. Figure 1 shows the elastic response spectra of the proposed strong motion time history (TestQke4IEEE) for qualification testing of electrical equipment closely matching the IEEE 693 required response spectra.

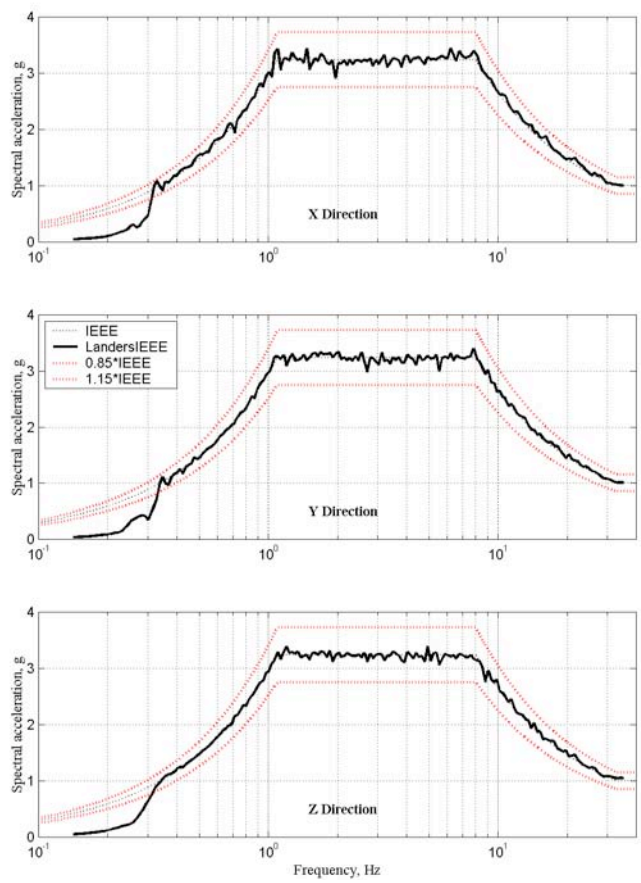


Fig. 1 IEEE-compatible Landers (TestQke4IEEE) at 2% damping (1/24 octave resolution).

A selection of 35 three-component historic records from 18 earthquakes was analyzed and the records were cross-compared based on use several parameters. From the analysis the best candidate for the input strong motion was selected and modified by adding non-stationary wavelets to the signal. The resulting strong motion time history

preserves the non-stationary behavior of the real earthquake record while its response spectra envelope the IEEE target response spectra in a broad range of natural frequencies as required by the standard. The resulting strong motion time history is intended for use by testing facilities, and will be considered for inclusion in a future revision to IEEE 693.

Additional requirements on the input motion generation and the IEEE seismic qualification procedure are recommended. The requirements are proposed for inclusion in the new version of the IEEE 693 standard.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The project deliverables benefit the industry by providing newly developed requirements and a strong motion time history for seismic qualification testing of electrical equipment in accordance with IEEE 693.

3. Brief description of the accomplishments of the project

The main objective of the study was achieved and a three-component set of earthquake ground motion time histories suitable for seismic qualification of electrical substation equipment in accordance with the IEEE 693-1997 standard (IEEE, 1998) was developed. The strong motion time histories in three principal directions of testing are available for download from the Westcoast Subcommittee's web site:
http://www.westcoastsubcommittee.com/ieee693/qualified.php.

Along with the set of strong motion time histories, the study provides specifications for spectral matching procedure and extended requirements on the IEEE-compatible time history. The recommendations on requirements for test response spectrum (TRS) are also provided. The specifications and requirements are summarized in 'Specification for Input Motion Used in Earthquake Simulator Testing Under IEEE 693' in Appendix C of the project's report and is available on the PEER's web-site:
http://peer.berkeley.edu/lifelines/Task408_411/Task408.html.

Matlab (The MathWorks, 2001) codes developed in the study form another set of the study's deliverables. The set consists of implementations of the filtering procedure and of the high cycle counting procedure in single degree of freedom system response. The codes are available at the Westcoast Subcommittee's web site provided above.

4. Describe any instances where you are aware that your results have been used in industry

The test strong motion time history (TestQke4IEEE) was used during a companion experimental study on seismic qualification of a 500-kV disconnect switch: Shakhzod M. Takhirov, Gregory L. Fenves, Eric Fujisaki. 'Seismic Qualification and Fragility Testing of Line Break 550 kV Disconnect Switches'. The newly developed requirements on the time history testing procedure have been included in the current draft version of the IEEE 693 document.

5. Methodology employed

The scope of the work was achieved by means of a comprehensive theoretical study and some experimental study on an earthquake simulator performance with no specimen attached.

6. Other related work conducted within and/or outside PEER

Shakhzod M. Takhirov, Gregory L. Fenves, Eric Fujisaki. 'Seismic Qualification and Fragility Testing of Line Break 550 kV Disconnect Switches'.

7. Recommendations for the future work: what do you think should be done next?

8. <u>Author(s), Title, and Date</u> for the final report for this project

Shakhzod M. Takhirov, Gregory L. Fenves, Eric Fujisaki, Don Clyde. 'Ground Motions for Earthquake Simulator Qualification of Electrical Substation Equipment'. 06/30/2004.

Final Project Summary— PEER Lifelines Program

Project Title—**ID Number**	*Equipment Overturning*—**409**		
Start/End Dates	5/1/00 – 9/30/01	Budget/ Funding Source	$65,000 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**Makris (UCB)**		

1. Project goals and objectives

This study concentrates on the rocking response of rigid equipment, such as electrical equipment in substation, supported on a foundation base when subjected to earthquake ground motions.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The study shows that for specific equipment/base configurations the high-strength restrainers used by PG&E are sufficient to engage the foundation base in rocking motion for a wide family of recorded earthquake motions. It was shown that the minimum strength capacity of the restrainer needed to avoid fracture is closely related to peak ground acceleration and that only the Cape Mendocino record is capable of fracturing the high-strength restrainers.

3. Brief description of the accomplishments of the project

It was found that the strength capacity of the restrainer should be as high the weight of equipment as to engage the base foundation in rocking motion. The study reveals that for earthquakes with long distinguishable pulses, the margin between exceeding the serviceability level of uplift and achieving overturning is minimal. Nevertheless, none of the strong motions used in this study is capable of overturning the freestanding configurations examined. Two

4. Describe any instances where you are aware that your results have been used in industry

The results of this study are directly applicable for utilities such as PG&E.

5. Methodology employed

In the event that the strength of the restrainers is sufficiently large and the ground acceleration is sufficiently strong, the equipment will engage its foundation in rocking motion. On the other hand, if the restrainers are too fragile they will fracture and eventually the equipment will rock atop its foundation base. Accordingly, equipment anchored to a base foundation exhibits two distinct rocking capacities: (a) the equipment engages the base foundation in rocking motion and (b) the restrainers fracture and the equipment subsequently rocks as a freestanding block atop its foundation base. The aim of this study is to compare these two capacities for practical values of the foundation footprint and the restrainer strength. The study examines intensity levels of ground shaking that will exceed serviceability levels (6 in. uplift at edge), and intensity levels that will result in overturning.

6. Other related work conducted within and/or outside PEER

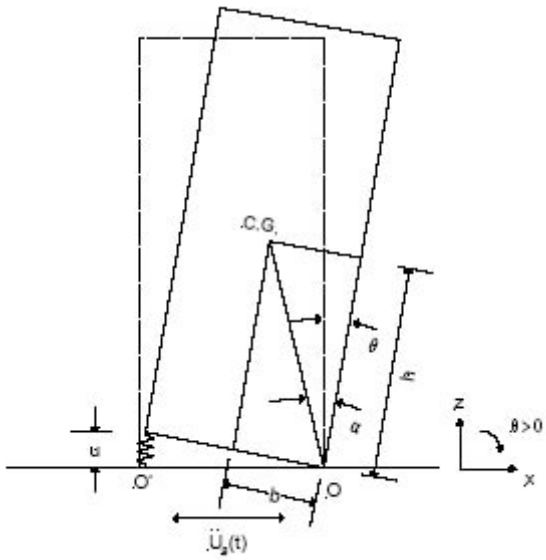
A previous related work by the same PI was conducted in 1999: PEER Report 1999/06, "Rocking Response and Overturning of Anchored Equipment under Seismic Excitations **by** N. Makris and J. Zhang

7. Recommendations for the future work: what do you think should be done next?

8. <u>Author(s), Title, and Date</u> for the final report for this project

N. Makris and C. Black, "Rocking Response of Equipment Anchored to a Base Foundation**,"** PEER Report 2001/14, 2001.

Figure 1.1. Overturned electrical equipment at Sylmar Converter Station damaged during the 1971 San Fernando earthquake (top), and a detail showing the failed back-left restrainer (bottom). Photos taken from the Steinbrugge collection, NISEE, University of California, Berkeley.



Schematic of an anchored block in rocking motion.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Feasibility for Large-Scale Testing of Electrical Equipment*—**410**		
Start/End Dates	5/1/00 – 12/31/01	Budget/ Funding Source	$49,655 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**Nigbor (USC)**		

1. Project goals and objectives

The objective of this project was to quantitatively compare available methods for large-scale seismic fragility testing of electrical substation components: shake tables, NETi, and mine blasts.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

Results of this project will allow more informed specification of large-scale seismic testing methods by researchers studying electric system vulnerability and risk.

3. Brief description of the accomplishments of the project

Real and simulated data from generic and specific seismic testing facilities were assembled and then analyzed uniformly to allow quantitative comparison of the strengths and weaknesses of each method. Unique to this study was the assessment of the NETI facility and large mine blasts for seismic fragility testing.

4. Describe any instances where you are aware that your results have been used in industry

Preliminary results were used by Kajima Corporation to develop large-scale seismic testing for shallow pile foundations for nuclear waste storage in Japan.

5. Methodology employed

A suite of ground motion time histories from various testing methods were passed through standardized linear and nonlinear dynamic analyses, including

6. Other related work conducted within and/or outside PEER

The PI has been using mine blasts to study fragility of nuclear power plant structures in collaboration with researchers in Japan.

7. Recommendations for the future work: what do you think should be done next?

Results of this study are and will be used to select appropriate methods for large-scale seismic testing. No further work is needed on this evaluation study.

8. <u>Author(s), Title, and Date</u> for the final report for this project

Robert L. Nigbor and Elena Kallinikidou, EVALUATION OF LARGE SCALE SEISMIC TESTING METHODS FOR ELECTRICAL SUBSTATION SYSTEMS PEER Lifelines Project 410, Draft submitted May 22, 2002, final report October 12, 2004.

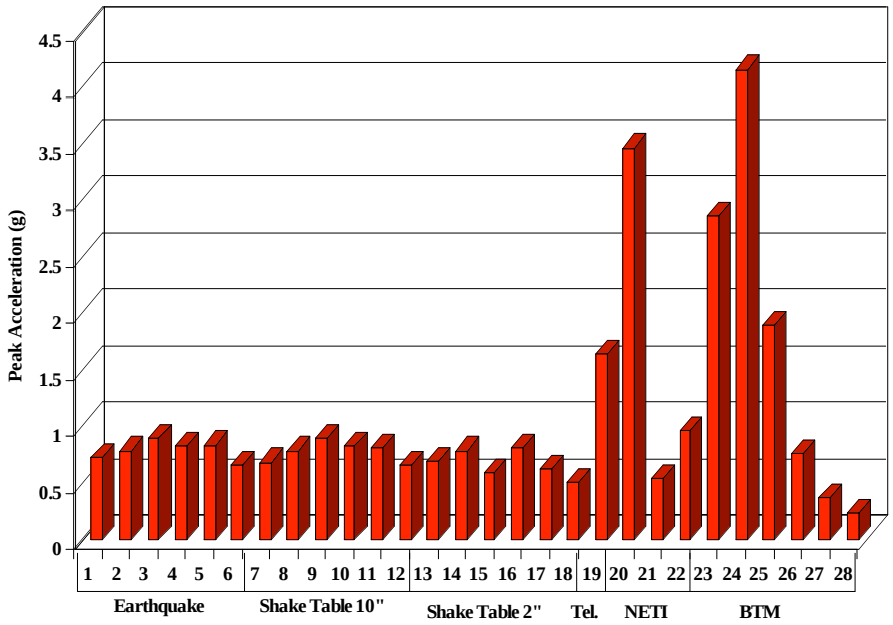


Figure 3-7 Peak acceleration values for the record ensemble

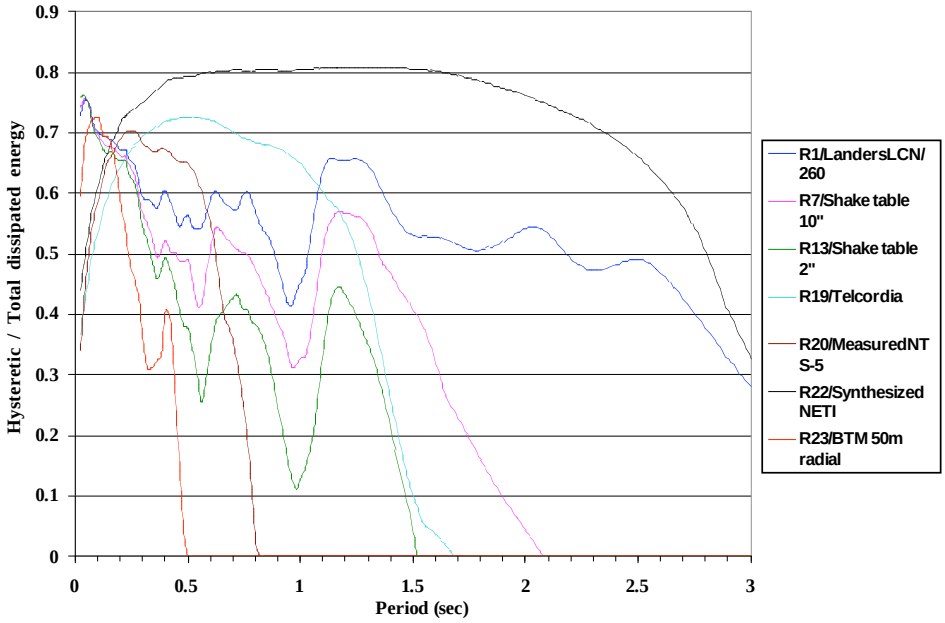


Figure 3-28 Ratio of the hysteretic energy over total dissipated energy at the end of the excitation for a selective group of records.

Final Project Summary— PEER Lifelines Program

Project Title—**ID Number**	*Seismic Qualification and Fragility Testing of 500 kV Disconnect Switches*—**411**		
Start/End Dates	8/1/02 – 6/30/04	Budget/ Funding Source	$210,012 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**Fenves (UCB)**		

1. Project goals and objectives

The objective of the study is to conduct seismic qualification and fragility testing of a single pole of 550-kV porcelain disconnect switch shown in Fig.1. Due clearance limitations above the shaking table the switch with the main blade in open position could not be tested in a typical field installation; therefore, several switch configurations were developed for testing. The 550-kV disconnect switch is tested in three configurations: mounted on typical 14 ft tall supports, mounted on a short 4-in spacer to simulate flexibility of the top plates of the supports, and rigidly fixed to the earthquake simulation platform. In the two latter configurations the switch is tested with the main blade in open and closed positions, and these configurations are used for seismic qualification testing of the open-blade switch (shown in Fig. 2) and in the experimental study for amplification factor estimation.

Fig. 1 550-kV switch in the closed position mounted on supports

Fig. 2 550-kV switch in the open position mounted without the tall supports.

Tri-axial tests of a single pole of the porcelain disconnect switch mounted on elevated supports are conducted by means of IEEE-compatible time history to determine its dynamic properties and to qualify the switch to the high Performance Level. A feasibility of seismic qualification testing of tall electrical equipment with supports removed by introduction of an amplification factor due to the supports is also studied experimentally. Tri-axial time history tests of a single pole of porcelain disconnect switch mounted without the tall supports on the simulator platform is conducted to determine the dynamic properties of the pole and to evaluate its seismic response. A seismic qualification test for the switch in open blade position on the earthquake simulator platform (mounted without the tall supports) by means of use the amplification factor is performed.

In addition, the main objective of the study includes static and dynamic testing of switch components (the tall supporting legs and the insulator posts) and a study of feasibility to replace the blade with an equivalent shorter

blade or a concentrated mass for seismic qualification testing of tall electrical equipment that cannot accommodate clearance above the table. The component testing also includes static cantilever tests on insulator posts to determine failure modes and equivalent cantilever loads in failure for the ceramic insulators used in the switch.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The seismic qualification testing of the 550-kV disconnect switch assessed its vulnerability and demonstrated its adequate performance during strong earthquakes.

3. Brief description of the accomplishments of the project

The disconnect switch preserved its major functions up to the highest levels of PL testing conducted in this project, without any major damage. Some anomalies occurred during the test were insignificant and minor. The restoration work did not involve any installation of new parts: the parts impacted out from their original positions were simply repositioned back in place. Therefore, the disconnect switch complied with seismic qualification criteria for PL testing, up to the level conducted in the project. Although the TRS achieved in the test program technically does not satisfy the new recommended specification for IEEE 693 (developed in a companion theoretical study: Task408) for qualification to the High Seismic PL, the deficiencies in the TRS are limited to frequency ranges not close to the important modal frequencies of the equipment. Although the TRS came close to satisfying the new recommended input motion specifications for IEEE 693, the rigid insulator post in the PL test was loaded to a level 37% beyond the rated cantilever strength assigned to this model of insulator by the manufacturer. Fracture of the porcelain insulator post did not occur during the PL test because the actual strength of the installed insulator exceeded the rated cantilever strength by over 40%. This outcome highlights the conservatism associated with insulator cantilever strength ratings.

The disconnect switch mounted on 4-in spacer with main blade in the open position and grounding blade in closed position preserved its major functions after the 1.17g target pga testing without major damage. Therefore, the disconnect switch complies with IEEE 693 criteria for PL seismic qualification testing at the Moderate Seismic Qualification Level, using the new recommended input motion specifications for IEEE 693 (developed in the companion theoretical study: Task408). In order to qualify the switch to the High Seismic Qualification Level, allowable stresses in critical elements are reviewed. Demand to capacity ratios for porcelain insulators were found to exceed allowable values by about 60%, assuming that a 1.83 amplification factor is used.

4. Describe any instances where you are aware that your results have been used in industry

Since the disconnect switch tested represents a very common design of the 500-kV switch used by utilities, the results of qualification testing are very important for assessing the vulnerability of a electrical power transmission system during strong earthquakes.

5. Methodology employed

The seismic qualification testing and associated experimental study of the 550-kV switch was conducted by means of earthquake simulator. The experimental study on the switch components was consisted of low-level pull-back, free-vibration, and cantilever strength tests. The latter testing was conducted for porcelain posts only.

6. Other related work conducted within and/or outside PEER

The qualification testing used a strong motion time history for the IEEE 693 that was developed in a companion theoretical study entitled ‘Ground Motions for Earthquake Simulator Qualification of Electrical Substation Equipment’ by Shakhzod M. Takhirov, Gregory L. Fenves, Eric Fujisaki, Don Clyde.

7. Recommendations for the future work: what do you think should be done next?

Both numerical and experimental studies should be conducted to develop a reliable procedure for estimation of the amplification factor. Such procedures or guidelines are needed in order to streamline the qualification procedure, particularly for large equipment that cannot be practically tested on their supports, and also for equipment that may be supported on several different types of support structures. In addition, the consideration of alternative methods of testing, possibly using substitute support structures which are intended to provide the same equipment response as a full-scale structure, would be valuable.

Further material studies on porcelain insulator acceptance criteria are needed. IEEE 693 acceptance criteria for qualification require a factor of safety of 2.0 and 1.0 against the "ultimate strength" of the insulator, respectively for the RRS and PL. The current practice of most utilities, manufacturers or consulting engineers is to use the rated cantilever strength as the ultimate strength of the insulator. As highlighted in the tests conducted in this project, the rated cantilever strengths of insulators are frequently set at levels representing a guaranteed minimum breaking strength. Alternative definitions of ultimate strength should be explored for use when designing for extreme events such as a large earthquake.

Differences between the stiffness of porcelain insulators in tension and compression should be investigated further. Investigations should include further tests on multiple-section insulators, porcelain material studies and tests, and collaboration with insulator manufacturers. The differences observed in this project may be significant enough to influence the outcome of qualification tests.

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8. Author(s), Title, and Date for the final report for this project

Shakhzod M. Takhirov, Gregory L. Fenves, Eric Fujisaki. 'Seismic Qualification and Fragility Testing of Line Break 550 kV Disconnect Switches' 08/20/2004.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Database of Seismic Parameters of Equipment in Substations*—**413**		
Start/End Dates	3/1/03 – 3/31/04	Budget/ Funding Source	$35,250 / PG&E
Project Leader (boldface) and Other Team Members	**Ostrom (D. Ostrom Consulting)**		

1. Project goals and objectives

Electrical substations consist of many pieces of equipment that are vulnerable to earthquakes. Vulnerability depends on a variety of parameters including equipment type, voltage, manufacturer, seismic design criteria, installation and anchorage, foundations and soil conditions, and connection to other equipment. In order to be able to make accurate and standardized estimates of potential losses in earthquakes and to set priorities for equipment upgrades and replacements, an accurate database of the relevant seismic-performance parameters of substation equipment is needed. In this project, a comprehensive procedure for compiling seismic performance parameters of critical electrical components was developed and documented. The experience gained in assessing seismic vulnerability of substation equipment in previous PEER Lifelines Program research was incorporated.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

Development of a comprehensive procedure for compiling seismic performance data of electric substation equipment that is tied to a network-based earthquake loss estimation methodology will enable accurate and standardized estimates of potential losses to electrical systems in earthquakes and set priorities for equipment upgrades and replacements.

3. Brief description of the accomplishments of the project

Documentation of substation equipment performance data base.
Documentation of substation equipment installation and connectivity data base.
Creation of hypothetical electrical system and its equipment data documentation
Sample simulation run and data results of a hypothetical electrical system to a single earthquake scenario

4. Describe any instances where you are aware that your results have been used in industry

No System Earthquake Risk Assessment (SERA) of the nature that is contained in this work has been done on an electrical system since this project was completed. This work is that documentation and extension of previous work that was done at Southern California Edison in the 1990s.

5. Methodology employed

Document

6. Other related work conducted within and/or outside PEER

This work is an extension and documentation of the SERAs that were done on SCE in 1990 and 1998 and EBMUD in 1993.

7. Recommendations for the future work: what do you think should be done next?

Develop more complete equipment performance data and improve the loading metrics on which the electrical system performance is based.

Develop system performance metrics
Develop Return-to-service algorithms
Combine MCEER system “return to service” work with PEER “system performance” work and conduct full SERA on hypothetical system.

8. <u>Author(s), Title, and Date</u> for the final report for this project

Author: Dennis K. Ostrom
Title: Database of Seismic Parameters of Equipment in Substations
Date: June 30, 2004

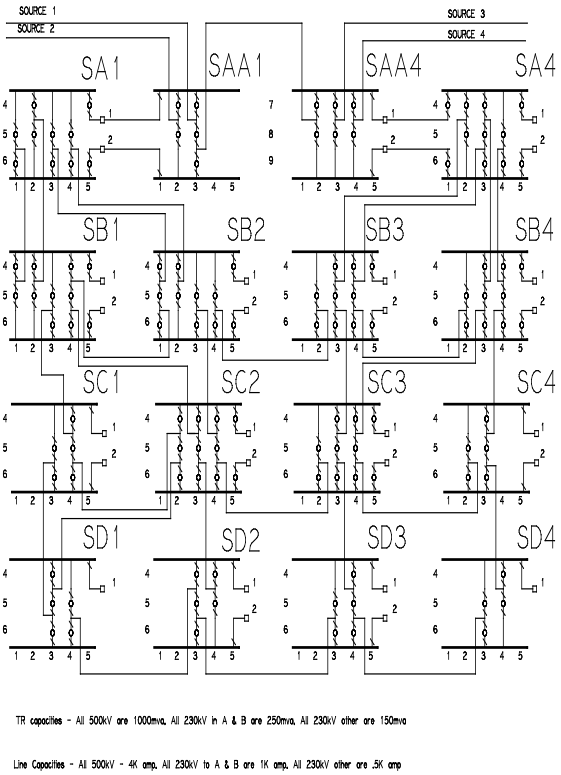


Figure 4-1 – Hypothetical System Single Line Drawing.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Development of Improved Methodology for Buildings w/ Rigid Walls & Flexible Diaphragms*—**504**		
Start/End Dates	5/1/00 – 1/31/03	Budget/ Funding Source	$129,991 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**Anderson (USC)**		

1. Project goals and objectives

The goals of this research are to develop improved practical analysis procedures for evaluating the seismic performance of low rise buildings with rigid walls and flexible diaphragms and to use these procedures to evaluate current seismic design provisions. Representative of this type of building system are one story buildings with concrete tilt-up walls and low rise buildings with reinforced masonry walls.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

Analysis and modeling techniques have been developed for commercial computer programs that can be used by engineering offices to better design new buildings and to better evaluate the seismic performance of existing buildings and indicate areas of structural weakness. Areas where modifications to current building lateral force requirements could be made to improve building performance are identified.

3. Brief description of the accomplishments of the project

Comparison of the recorded response at all instrument locations shows good correlation with the time history response calculated using the computer models and the idealizations discussed. In general, the responses of all three buildings were either less than or near the minimum lateral force requirements of the Uniform Building Code ’97. therefore, the behavior was primarily linear elastic with on some limited cracking of the concrete. This was verified by site visits to the three buildings. However, using acceleration records of near fault earthquakes indicate force values that far exceed minimum code requirements and suggest significant inelastic behavior. It was also noted that the criteria currently used by building codes to classify diaphragms as rigid or flexible contains considerable uncertainty. Significant differences were observed between the use of static or dynamic loading.

Connection details used prior to the San Fernando earthquake (1971) are referred to as “old” connections whereas connection details used in the late 1970’s and beyond are referred to as “new” connections. The results of this study confirm that the “old” connections are not adequate for the stronger earthquake ground motions. The “new” connections offer a significant improvement, particularly when used in combination with a strengthened diaphragm that remains elastic. When “new” connections are used with existing diaphragms having dense nailing, ductility demands in the connection and diaphragm are not excessive. Sparse nailing of the diaphragm results in performance that is not adequate.

4. Describe any instances where you are aware that your results have been used in industry
None identified to date.

5. Methodology employed
In order to evaluate the accuracy of the analytical models, three instrumented buildings (one tilt-up and two masonry) were selected for detailed study. Detailed three dimensional finite element models were developed for use with the SAP2000 and ETABS computer programs. Following verification of the models for the recorded earthquake motions the effect of stronger, pulse-type ground motions was evaluated. For the tilt-up building, available nonlinear elements were used to evaluate the push-over behavior and the nonlinear seismic response. Within the limitations of the experimental data base, the effect of vertical accelerations on the long span roof of the tilt-up was estimated.

6. Other related work conducted within and/or outside PEER
Tokoro, K. A. T. (2002), "Seismic Performance of Two Instrumented Masonry Buildings," Thesis presented to the University of Southern California in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering

7. Recommendations for the future work: what do you think should be done next?
Only a limited amount of full scale testing has been conducted on building components including the critical floor and roof diaphragms and the connections of these elements to the rigid walls. Connections have not been tested under the multiaxial loading experienced in the actual building. A detailed consideration of the performance of tilt-up walls without pilasters was beyond the scope of this investigation. This construction procedure which is representative of current practice need to be investigated. Results of this study have shown that inelastic behavior of the various elements of the building are very important for building performance. These aspects need to be investigated more thoroughly when test data becomes available.

8. <u>Author(s), Title, and Date</u> for the final report for this project
Tokoro, K. A. T., Anderson, J. C., and Bertero, V.V. (2004), "Seismic Performance of Masonry Buildings and Design Implications," PEER Report 2004/01.

Anderson, J. C. and Bertero, V.V. (2004), "Seismic Performance of an Instrumented Tilt-up Wall Building," PEER Report 2004/04, In Review.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	Methods to Estimate Displacements of PG&E Structures - **505**		
Start/End Dates	5/1/00 – 8/30/01	Budget/ Funding Source	$65,000 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**MacRae, Gregory A.** (PI), and Tagawa, Hiroyuki – Graduate Student, (UW)		

1. Project goals and objectives

The objectives of this applied research are to answer the following questions:

- What are the advantages, disadvantages and relative reliability of the CM and CSM methods for design?
- What modifications are required to the CM and CSM approaches to allow them to accurately predict the response of structures of different periods to near-fault shaking?
- How should PG&E structures be designed using the findings above?

2. Benefits of the results of this project

The following technologies were developed to mitigate the seismic vulnerability of PG&E mill-type structures:

- An assessment method for estimation displacements of structures located in the near-fault region resulted.
- A methodology for PG&E mill-type structures resulted.
- An alternative to the inadequate *m*-factor method in FEMA-356 was developed.

3. Brief description of the accomplishments of the project

The accomplishments of the project are as follows:

1) For short period structures, such as PG&E mill type structures, with fundamental periods less than about 0.8s, it was shown that directivity effects from NF shaking did not increase the demands above that found for FF shaking.

2) When comparing the Coefficient Method (FEMA 356) CM and the Capacity Spectra Method (ATC-40) CSM methods it was shown that:

(a) The CM is relatively simple to use, but it does not consider the influence of different types of damping or hysteretic loop shape easily, and results may be sensitive to the definition of yield displacement. The CSM is less sensitive to the definition of yield displacement and can take damping effects into account easily. However iteration is required to estimate the likely structural displacements, the method may require use of very long period response values which have dubious accuracy, three empirical relationships have to be assumed or calibrated, and an understanding of the structure's hysteretic shape is required to estimate the demand.

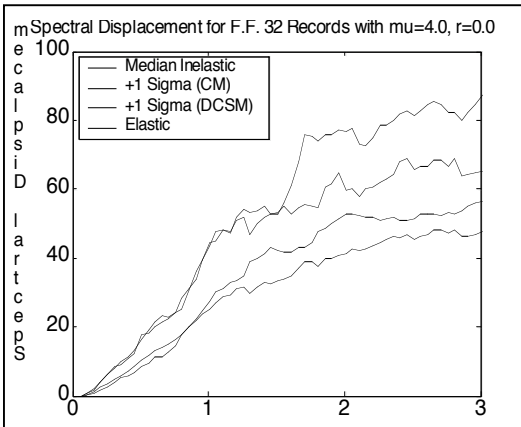


Figure 1. The Capacity Spectra Method (CSM) and the Coefficient Method (CM) have been calibrated to obtain the same median inelastic displacement. The scatter for a series of records, indicated by +1 Sigma, is different for the two methods.

(b) Both the CM and CSM can be calibrated to estimate the exact response. For the CM a bilinear approximation of lateral force reduction factor, *R*, vs. fundamental period, *T*, for a specific ductility is reasonable. The CSM effective damping, ζ_{eff}, for a specific ductility, μ, as well as the spectral reduction, *SR*, for a specific damping, ζ, are dependent on period, *T*.

(c) When both the CM and CSM are well calibrated, the scatter in displacement, σ, for oscillators with an effective (secant) period, T_{eff}, less than about 3.0s is similar. For structures with T_{eff} greater than about 3.0s, the CSM has more scatter as shown in Figure 1.

(d) When the CSM was calibrated according to ATC-40, ATC-40 significantly overestimated the average effective damping at periods greater than about 0.2s. ATC-40 non-conservatively estimated the median inelastic response over the majority of the period range from 0-3s and its estimation was as low as 60% of the median displacement for some periods. The CM calibrated according to FEMA356 conservatively estimated the median displacement over most of the period range. For some periods, FEMA356 estimated displacements more than 30% greater than the actual median displacements.

3) Oscillators with demands estimated by the CM, and with fundamental periods less than about 0.8s, were not affected significantly by near-fault shaking effects. For longer period oscillators, oscillator strengths may need to be increased by more than 60% to account for inelastic shaking effects from NF sites in the region of positive directivity compared to that for shaking from FF or NF near-epicenter sites for the same target displacement ductility as shown in Figure 2. NF shaking did not cause significant trends in the displacement demands of oscillators evaluated by the CSM method. Modifications to the existing FEMA356 CM nonlinear static procedure (NSP) C_1 factor, accounting for NF shaking effects when appropriate, was developed for structures with fundamental periods in the range of 0-3s.

4) For design of PG&E structures, it was determined in conjunction with PG&E/PEER that the FEMA356 CM Linear Dynamic Procedure (LDP) should be used to evaluate the demands of PG&E mill-type structures. The estimation of inelastic response should be made using the C_1 factor from the FEMA356 Nonlinear Static Procedure (NSP). While the C_1 factor may be modified for NF shaking effects, this is only required for structures with periods greater than 0.8s. NF shaking effects therefore do not need to be considered on the inelastic response of the majority of PG&E mill-type structures since their fundamental periods are less than 0.8s. The difference between member and system ductility demands is not considered in the FEMA356 LDP often resulting in non-conservative demand estimates. A method to show how it can easily be accounted for in assessment and in design is provided. A design procedure and example for assessing NF shaking inelastic displacement demands on a mill type structure using the CM was provided.

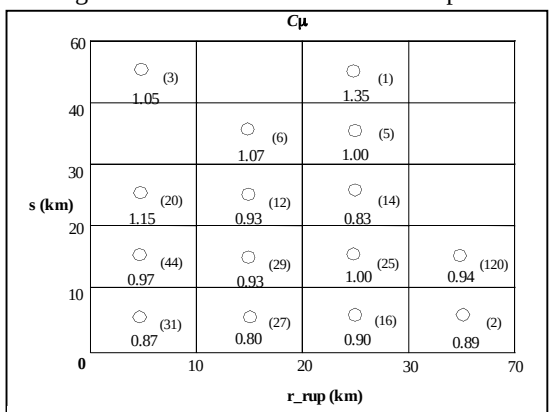


Figure 2. Average ratio of inelastic to elastic displacement demands for long period oscillators from a number of records in blocks s (km) in the fault direction and r_{rup} (km) from the fault surface with a ductility of 4.

4. Describe any instances where you are aware that your results have been used in industry

Results of this project, and an previous project, have been used by PG&E and their consultants to assess the seismic vulnerability of their mill-type structures.

5. Methodology employed

Dynamic inelastic time-history analyses of single-degree-of-freedom (SDOF) bilinear oscillators were undertaken to determine the ability of the Coefficient Method (FEMA273/FEMA356) and the Capacity Spectrum Method (ATC-40) to predict the total displacement demands of simple structures. Both the Coefficient Method (CM) and the Capacity Spectrum Method (CSM) were calibrated to obtain the exact inelastic response displacements for near-fault (NF) and far-fault (FF) shaking.

6. Other related work conducted within and/or outside PEER

Other related, but different types of studies, on displacement prediction methods for structures were carried out by Chopra and Goel, and more recently by Bill Iwan, ATC-55 and ATC-58 projects. Roeder and MacRae also conducted an earlier PG&E-PEER project on some related issues.

7. Recommendations for the future work

1. To obtain better procedures and calibration for near fault shaking effects, more records with known locations and orientations relative to the fault and epicenter, and on different soil conditions, are required. Studies should also be carried out using structures with different shaped hysteresis loops.
2. Methods have been developed to assess the near-fault (NF) demands at different locations relative to the epicenter and fault. However, in general location of the epicenter of the next earthquake on the fault is not known. Appropriate statistical procedures are required to account for the probable location of the site relative to the epicenter in a performance-based assessment/design context.

8. Author(s), Title, and Date for the final report for this project

MacRae, G. A. and Tagawa H. “Methods to Estimate Displacements of PG&E Structures”, Final Report to PEER, August, 2002.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Application of Simplified Model to Assess Structural Behavior of Mill Type Bldg*—**506**		
Start/End Dates	3/19/01 – 8/31/01	Budget/ Funding Source	$10,000 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**Nazir (ABS/EQE Intn'l)**		

1. Project goals and objectives

In this study wall out of plane anchorage forces in certain type of sub-station buildings were examined.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The results of this project can benefit seismic design of certain type of electrical substation buildings.

3. Brief description of the accomplishments of the project

It was found that the wall out of plane stiffness, diaphragm stiffness, and relative stiffness of two diaphragms have significant effects on the wall out of plane anchorage. Recommendations were presented on a proposed deign equation.

4. Describe any instances where you are aware that your results have been used in industry

This study is based on PG&E substation "K" located in San Francisco, which represents a typical substation building structure built in 1920s. Thus, the results of this study are directly applicable to utilities.

5. Methodology employed

Two separate analyses were performed: (a) SAP2000 three dimensional dynamic model; and (b) simplified multi-degree-of-freedom spring model. Variations in the following parameter were made to cover various different conditions: wall to diaphragms connection, wall out of plane stiffness; wall foundation rocking; diaphragm stiffness; and diaphragm relative stiffness.

6. Other related work conducted within and/or outside PEER

7. Recommendations for the future work: what do you think should be done next?

8. <u>Author(s), Title, and Date</u> for the final report for this project

Nazir, "A Simplified Analysis Method for Wall Out of Plane Anchorage Forces".

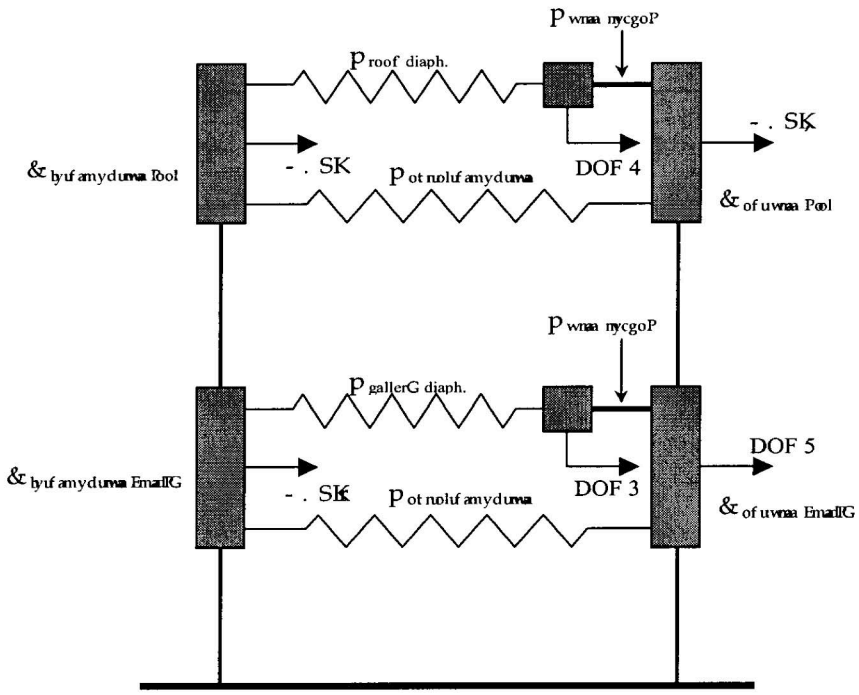


Figure 2-1. Simplified spring model.

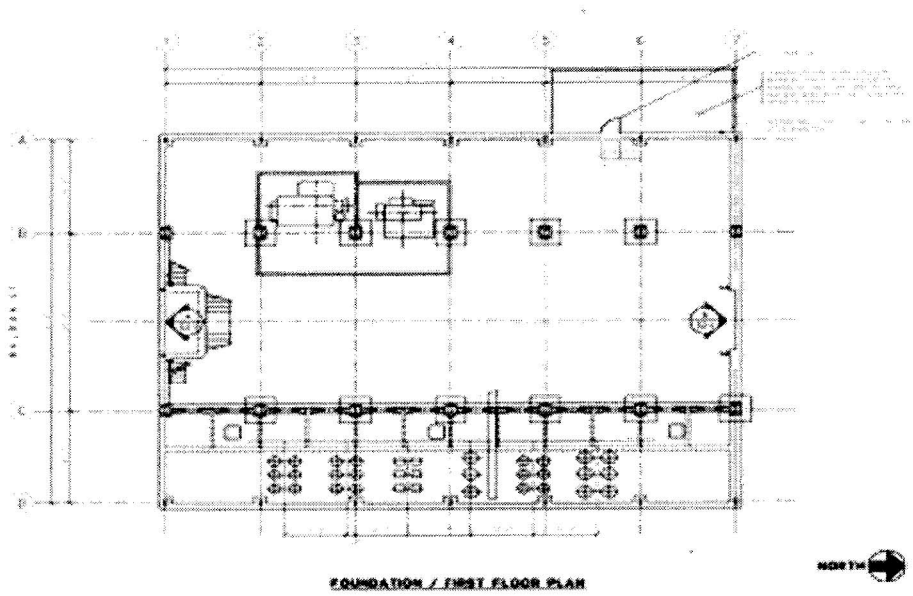


Figure 3-1: First Floor Plan

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Advanced Seismic Assessment Guidelines*—**507**		
Start/End Dates	1/1/01 – 12/31/03	Budget/ Funding Source	$266,301 / PG&E/CEC
Project Leaders (boldface) and Other Team Members	**C. A. Cornell. and P. Bazzurro,** C. Menun, M. Motahari, G. L. Yeo, (Stanford); N. Luco AIR		

1. Project goals and objectives

The objective of this project was to develop a practical professional tool to estimate "tagging fragility curves" which could be used by PG&E to assess the likelihood that a specific building their electrical distribution system would be closed to occupancy (i.e., tagged "yellow" or "red") and hence rendered inoperable after being exposed to a given level of earthquake ground motion.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The tool will aid in a proposed probabilistic system assessment of the seismic vulnerability of PG&E production and distribution network. By-products have been (1) an explicit way to evaluate a damaged structure after an earthquake to help judge whether it poses a life threat, and (2) a tool to help assess whether a building should be up-graded prior to an earthquake.

3. Brief description of the accomplishments of the project

The project developed a procedure based on the standard NSP (Nonlinear Static Procedure) professional tool, but extended to include application to the post-earthquake damaged structure. This procedure leads the way to the desired fragility curves. The method was put into a draft guideline in the first year of the project. In subsequent years the method was tested by two engineering firms and the procedure was further studied by the investigators to improve the analysis scheme. The final report reflects the results of all these efforts. The following papers were prepared for the 13th World Conference on Earthquake Engineering: (1) Bazzurro, P., Cornell, C.A., Menun, C. And Motahari, M., "Guidelines for Seismic Assessment of Damaged Buildings"; (2) Yeo, G.L. and Cornell, C.A., "Building Tagging Criteria Based on Aftershock PSHA"; and (3) Luco, N. , Bazzurro, P., and Cornell, C. A., "Dynamic Versus Static Computation Of the Residual Capacity of a Mainshock-Damaged Building to Withstand an Aftershock".

4. Describe any instances where you are aware that your results have been used in industry

The procedure has been used on three PG&E structures which were used as tests of the methodology. These cases studies were conducted by Rutherford and Chekene and by Degenkolb and Associates. In addition another application is currently under way for PG&E by Drs. J. Mafei and R. Hamburger.

5. Methodology employed

The NSP is applied to the intact structure to assess the likely damage state as a function of ground motion (IM) level. For each of several such damage states (as indexed by roof drift), another NSP analysis is applied as shown in the first figure below. It is this damaged structure that is the potential life-safety threat and whose status dictates closure or not. The damaged-structure static pushovers are transformed by D. Vamvatsikos' SPO2IDA tool into (median) Incremental Dynamic Analyses (IDAs), as illustrated by the left side of the second figure. These produce estimates of the collapse capacity of the damaged structure. Based on this capacity to resist aftershocks the "tagging-state" is determined by one or more "tagging rules" developed by the project. The original intact structure (right side of the second figure) is assessed to determine the (median) ground motion amplitude necessary to put it into the each of these damage states. To this median are "added" estimates of the "dispersion" – both aleatory and epistemic. The former is provided by SPO2IDA and the latter by tables develop through interviews with three practicing engineers.

6. Other related work conducted within and/or outside PEER

The efforts of this project led to the sponsorship by the NSF portion of the PEER Center in 2003-2004 of a project on the roll of aftershock assessment in the larger PEER PBEE context. This project will lead to a PhD thesis by Mr. Gee Liek Yeo. Also Prof. Stojadinovic with student Kevin Mackey has been studying aftershock capacity of bridges.

7. Recommendations for the future work: what do you think should be done next?

At the implementation end it is suggested that there be a workshop and other follow up to disseminate to professionals the new procedures proposed in the guidelines. At the research end there is need to understand still better the connection between earthquake damage in a mainshock and its effect on the capacity of the structure to withstand aftershocks without collapse and life loss. These studies should involve (1) nonlinear dynamic analyses of the type initiated in this project (varying levels of mainshock damage followed by aftershock collapse capacity assessment via IDAs); (2) further study of the role of residual displacement to aid in rapid post-quake evaluation of building safety; and (3) improvement in practical nonlinear static procedures to mimic the damage and residual capacity

8. <u>Author(s), Title, and Date</u> for the final report for this project

Paolo Bazzurro, C. Allin Cornell, Charles Menun, Maziar Motahari, and Nicolas Luco, "Advanced Seismic Assessment Guidelines", July, 2004. (To be submitted for publication as a PEER report.)

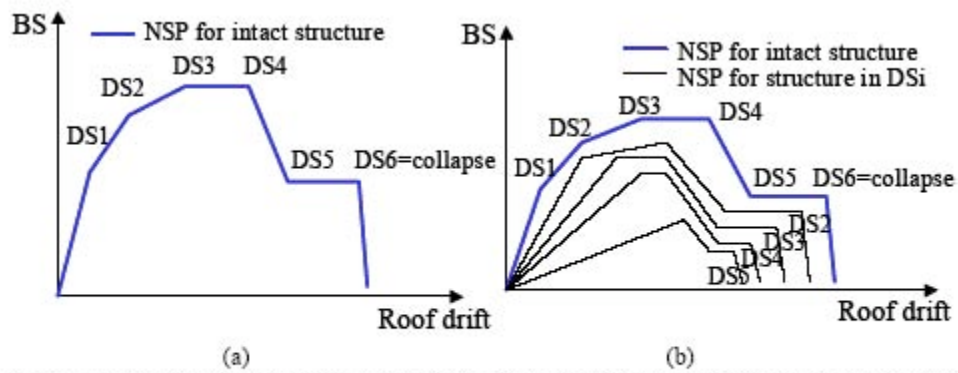


Figure 1: (a) NSP curve for the example building in its, intact, pre-earthquake condition. (b) NSP curves for the building in the pre-earthquake intact condition and in the four most relevant of all the post-earthquake damage states. For simplicity, all the curves for the damaged building have had the residual offset removed.

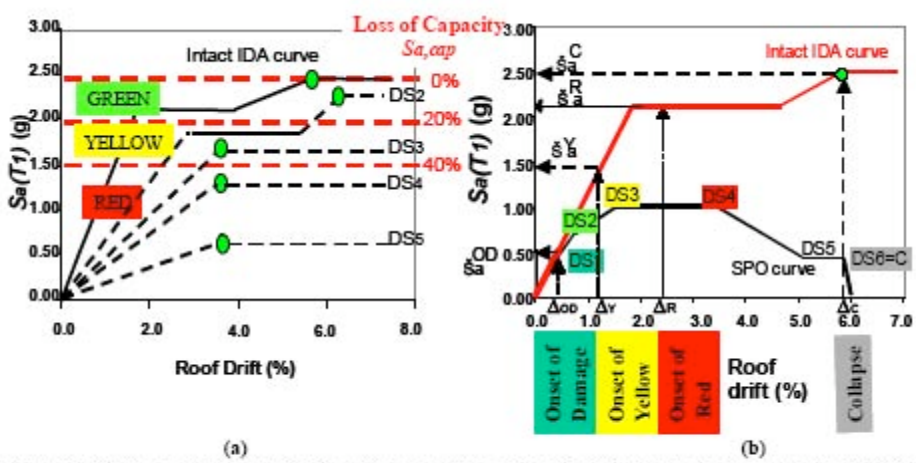


Figure 8: (a) Onset of yellow and red tagging according to the criteria in Figure 4 for a structure with P_0 less or equal to about $2x10^{-4}$. (b) Median estimates of the mainshock $S_a(T_1)$ that takes the intact structure to the onset of OD, Y, R, and C. Note that, in general, the onset of a limit state may not occur exactly at the roof drift of any

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Test Applications of Advanced Seismic Assessment Guidelines*—**508**		
Start/End Dates	7/1/02 – 6/30/04	Budget/ Funding Source	$79,138 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**Maffei (Rutherford & Chekene)**		

1. Project goals and objectives

Advanced seismic assessment guidelines were developed by Stanford University (C. Allin Cornell, Paolo Bazzurro, Charles Menun, Maziar Motahari) as part of the PEER Lifelines Program, Building Vulnerability Studies (Project Task Number 507). Predicting the post-earthquake functionality of utility structures is a crucial step in evaluating the likelihood of the electric distribution network being able to provide gas and electricity to its customers. The final product of the guidelines is a set of fragility curves for structural limit states directly related to post-earthquake building occupancy status, namely green, yellow, or red tagging.

This project is for a practicing Structural Engineer to apply these guidelines to utility type buildings.
The objectives are to:

1. Identify potential difficulties that Structural Engineers would encounter in using the procedure described in the advanced seismic assessment guidelines.
2. Recommend possible revisions to the procedure to address any identified difficulties.
3. Identify and make recommendations on other issues related to assessing the seismic reliability of utility structures and systems.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The project is a key step in investigating the practical application and potential of performance based seismic assessment methods. As such, the project can lead to the wider application of seismic and structural engineering procedures that use state of the art techniques.

In the application to fragility curves for buildings of utility systems, the project can lead to a better understanding of the seismic vulnerability of lifeline systems, and a better understanding of the most effective ways to reduce seismic vulnerability.

3. Brief description of the accomplishments of the project

Detailed assessment and understanding of two example buildings, leading to

- Better knowledge of characteristics of steel moment frame behavior.
- Improved understanding of reliability based structural engineering and effects of vulnerability and uncertainty.
- Better knowledge of mill building concrete wall behavior
- Understanding of the effects of various modeling assumptions for concrete and steel buildings, including pushover load pattern, foundation flexibility, inclusion of gravity frames, assumed concrete stiffness and strength properties.

4. Describe any instances where you are aware that your results have been used in industry

Recommendations used by PG&E, with Rutherford & Chekene and Simpson Gumpertz and Heger on the evaluation of an 8-story building.

5. Methodology employed

Structural analyses using Nonlinear Static Procedures and Incremental Dynamic Analyses. Evaluation of damaged structures, proposal of tagging criteria, and creation of fragility curves.

6. Other related work conducted within and/or outside PEER

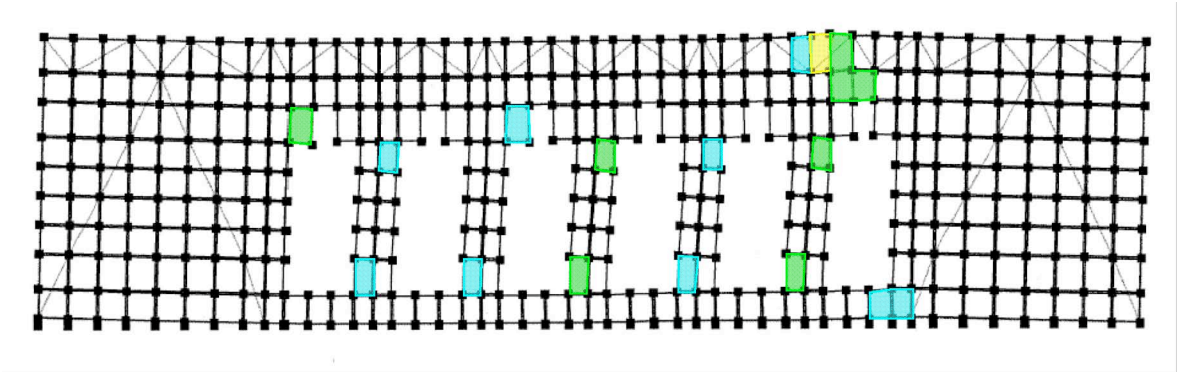
Being integrally related to task 507 project, this project takes advantage of developments in two other projects being carried out by professor C. Allin Cornell. The first is investigating Incremental Dynamic Analysis, global ductility, and approximate techniques for NL dynamic analysis. The second is focused on intensity measures and near source motions. The project has made use of the PEER project on nonstructural damage to gypsum wall board partitions being carried out under Professor Restrepo at UCSD. The project has been coordinated with the Task 509 project.

7. Recommendations for the future work: what do you think should be done next?

1. Evaluation of modeling methods for steel and concrete buildings.
2. Applicability of analysis techniques for high-rise buildings.
3. Possible techniques for deriving fragility curves using less detailed analysis.
4. Building-specific tagging criteria.

8. Author(s), Title, and Date for the final report for this project

Maffei, Nakayama, Mohr, Holmes
Test Applications of Advanced Seismic Assessment Procedures
Expected completion in August 2004



DEFLECTED SHAPE SHOWING USAGE RATIOS

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Limit state group = all deformation states

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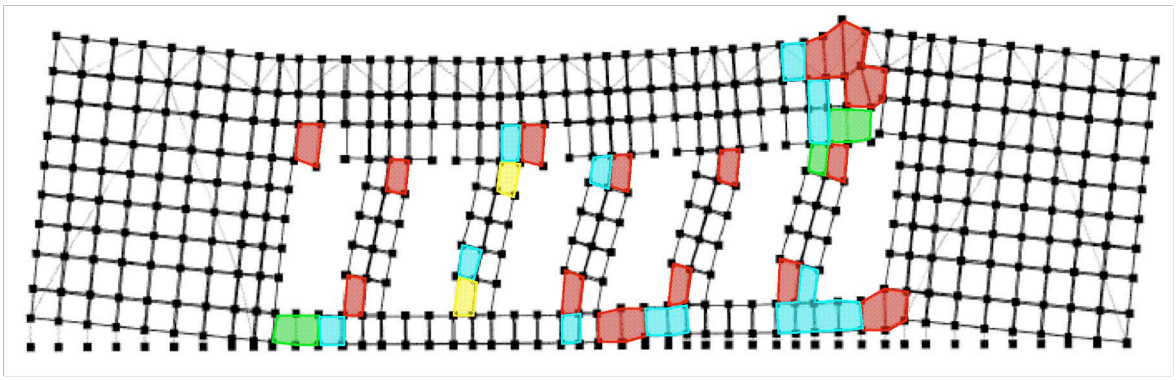

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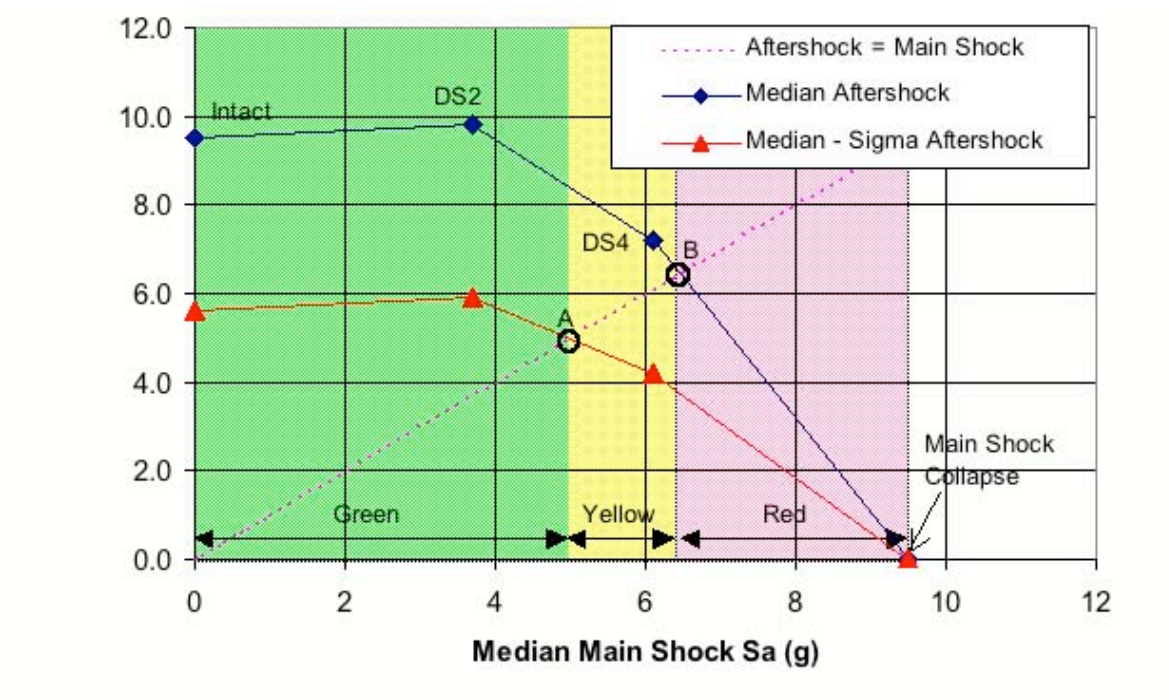
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Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Evaluation and Application of Concrete Tilt-up Assessment Methodologies*—**509**		
Start/End Dates	4/1/03 – 6/30/04	Budget/ Funding Source	$68,130 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**Malley (Degenkolb Engineers)**		

1. Project goals and objectives

Task 1

The goal of Task 1 is to provide input to existing codes (e.g. International Building Code) and guidelines (e.g. FEMA 356) that will improve the seismic design and assessment methodologies of concrete tilt-up and other low-rise, rigid-wall, flexible diaphragm buildings. The input will be based on research findings and results of previous (PEER) research projects on concrete tilt-up buildings. These research projects are: 1) *Seismic Response of Tilt-up Buildings* by John F. Hall; 2) *Modeling and Evaluation of Tilt-up and Steel Reinforced Concrete Buildings* by John W. Wallace; 3) *Stiffness of Timber Diaphragms and Strength of Timber Connections* by Gerard C. Pardoen; and 4) *Improved Methodology for Evaluating the Seismic Resistance of Low Rise Buildings with Flexible Diaphragms* by Jim Anderson.

Task 2

As practicing structural engineers, we will apply the building assessment methodology developed in PEER Task 507, *Advanced Seismic Assessment Guidelines* by C. Allin Cornell, Paolo Bazzurro, Charles Menun, Maziar Motahari, to a concrete tilt-up building in the Pacific Gas & Electric (PG&E) building inventory. The selected building is the PG&E Fremont Materials Distribution Center that Degenkolb Engineers has previously designed seismic upgrades for.

The objectives are to: 1) identify potential difficulties that Structural Engineers would encounter in using the procedure described in the *Advanced Seismic Assessment Guidelines*; 2) recommend possible revisions to the procedure to address any identified difficulties; and 3) identify and make recommendations on other issues related to assessing the seismic reliability of utility structures and systems.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

Predicting the post-earthquake functionality of utility structures is a crucial step in evaluating the likelihood that the PG&E power distribution network will not be able to provide power to customers. The final product of the guidelines is a set of fragility curves for structural limit states directly related to post-earthquake building occupancy status; namely green, yellow, or red tags.

The project is a key step in investigating the practical application and potential of performance-based seismic assessment methods. As such, the project will lead to the wider application of seismic and structural engineering procedures that use these state-of-the-art techniques.

3. Brief description of the accomplishments of the project

Task 1

Each of the four reports was reviewed and summarized. The data from the reports was evaluated to test the validity of design procedures and see what changes, if any, could be made to current design methodologies. Each report raised questions regarding assumptions and procedures in the research process, and the questions are presented for the authors. The reports also illuminated ideas for further research in the area of tilt-up building construction. From the four reports evaluated, some suggestions are presented for changes in design. However, no major changes to the current codes and guidelines were recommended due to this review.

Task 2

A 2D Static Pushover Analysis was performed on the roof diaphragm of the selected building for the intact structure. The analysis confirmed that a plywood roof diaphragm could be modeled using truss elements and that the results obtained would be comparable to those predicted using FEMA 356. Further application of the guidelines yielded Incremental Dynamic Analyses curves, the residual dynamic capacity and the occupancy status of the structure in each damage state, and a set of fragility curves. The authors confirmed the successful application of the guidelines. At the same time, difficulties associated with using the Guidelines and possible clarifications were identified.

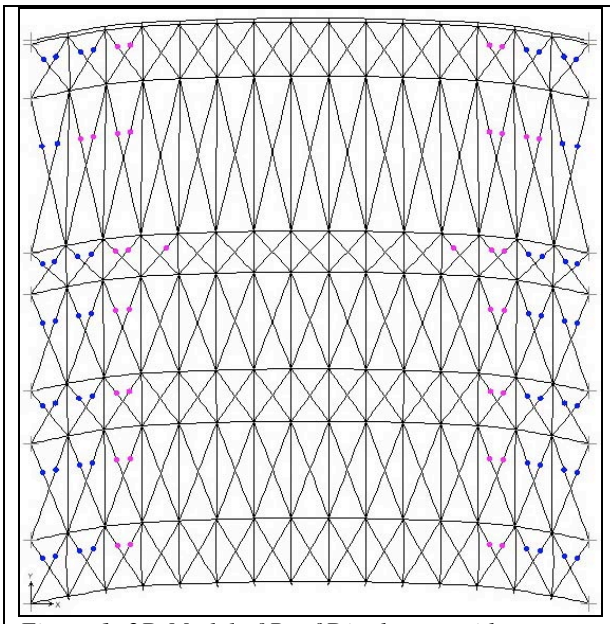


Figure 1: 2D Model of Roof Diaphragm with Diaphragm Represented by Axial Elements with Nonlinear Hinges

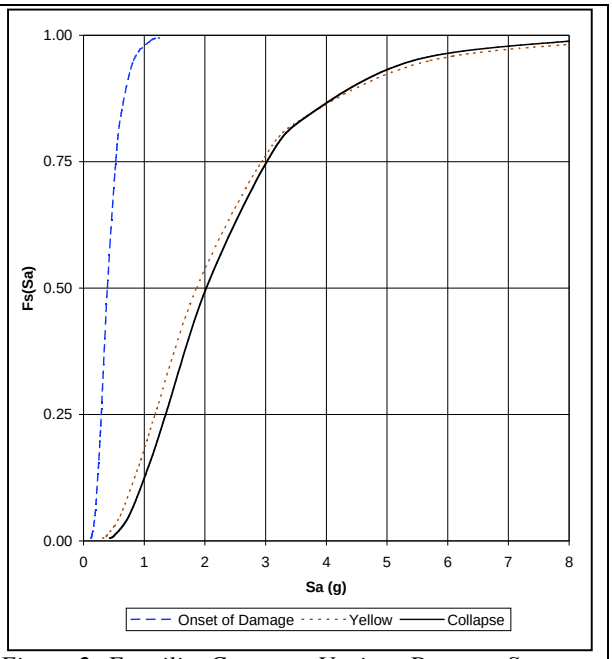


Figure 2: Fragility Curves at Various Damage States

4. Describe any instances where you are aware that your results have been used in industry

None to date.

5. Methodology employed

The Nonlinear Static Procedure (NSP) is performed on the structure using SAP 2000, commercially available software frequently used by practicing structural engineers.

Incremental Dynamic Analysis (IDA) is performed using the SPO2IDA spreadsheet tool developed by Vamvatsikos and Cornell.

6. Other related work conducted within and/or outside PEER

Within PEER, this project is integrally related to Task 507, the development of the Advanced Seismic Assessment Guidelines. Task 508 is similar to Task 2 of this project in its investigation of the use of the guidelines, in which a steel moment frame building was studied. This project applies the guidelines to a different type of construction, a concrete tilt-up building with a flexible diaphragm.

The reports reviewed in Task 1 were PEER projects concerned with experimental and analytical studies of concrete tilt-up buildings. This project seeks to summarize these studies and to make further recommendations for research as well as practice.

Outside PEER, two other related documents include: 1) *Guidelines for Seismic Evaluation and Rehabilitation of Tilt-up Buildings and other Rigid Wall/Flexible Diaphragm Structures* by the Structural Engineers Association of Northern California; and 2) *FEMA 356, Prestandard and Commentary for the Seismic Rehabilitation of Buildings*. These documents have not fully incorporated all of the findings from the previous PEER studies. Also, the application of the guidelines offers an advanced tool for the post-earthquake assessment of tilt-up buildings that has never been used in practice.

7. Recommendations for the future work: what do you think should be done next?

Research recommendations for tilt-up building construction include further research suggestions for the authors of the reports reviewed, and research not specific to any of the reports. Suggestions for research for the authors of the reports range from studying the anchorage forces along the short side of the building versus the long side, rerunning analysis done in the reports using the current building code, FEMA 356 values, or updated data, and more laboratory testing of tilt-up building components. Suggestions for other areas of research include instrumentation of more tilt-up buildings, studies of connection improvement in existing tilt-ups, better period estimation, additional and better documentation of damage in tilt-ups, investigating the strength of connections in cross grain ledger bending, and estimating the amplification of forces at pilasters.

Additional application of the Advanced Seismic Assessment Guidelines by practicing structural engineers is also recommended. This would provide additional input to the authors with regards to the ease or difficulties of using the guidelines.

8. Author(s), Title, and Date for the final report for this project

Tim Graf and Jim Malley, Evaluation and Application of Concrete Tilt-Up Assessment Methodologies, May 27, 2004
Jack Hsueh and Jim Malley, Application of Advanced Seismic Assessment Guidelines, August 15, 2004

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Development of Improved Methodology for Buildings w/ Rigid Walls & Flexible Diaphragms*—**504**		
Start/End Dates	5/1/00 – 1/31/03	Budget/ Funding Source	$129,991 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**Anderson (USC)**		

1. Project goals and objectives

The goals of this research are to develop improved practical analysis procedures for evaluating the seismic performance of low rise buildings with rigid walls and flexible diaphragms and to use these procedures to evaluate current seismic design provisions. Representative of this type of building system are one story buildings with concrete tilt-up walls and low rise buildings with reinforced masonry walls.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

Analysis and modeling techniques have been developed for commercial computer programs that can be used by engineering offices to better design new buildings and to better evaluate the seismic performance of existing buildings and indicate areas of structural weakness. Areas where modifications to current building lateral force requirements could be made to improve building performance are identified.

3. Brief description of the accomplishments of the project

Comparison of the recorded response at all instrument locations shows good correlation with the time history response calculated using the computer models and the idealizations discussed. In general, the responses of all three buildings were either less than or near the minimum lateral force requirements of the Uniform Building Code ’97. therefore, the behavior was primarily linear elastic with on some limited cracking of the concrete. This was verified by site visits to the three buildings. However, using acceleration records of near fault earthquakes indicate force values that far exceed minimum code requirements and suggest significant inelastic behavior. It was also noted that the criteria currently used by building codes to classify diaphragms as rigid or flexible contains considerable uncertainty. Significant differences were observed between the use of static or dynamic loading.

Connection details used prior to the San Fernando earthquake (1971) are referred to as “old” connections whereas connection details used in the late 1970’s and beyond are referred to as “new” connections. The results of this study confirm that the “old” connections are not adequate for the stronger earthquake ground motions. The “new” connections offer a significant improvement, particularly when used in combination with a strengthened diaphragm that remains elastic. When “new” connections are used with existing diaphragms having dense nailing, ductility demands in the connection and diaphragm are not excessive. Sparse nailing of the diaphragm results in performance that is not adequate.

4. Describe any instances where you are aware that your results have been used in industry
None identified to date.

5. Methodology employed
In order to evaluate the accuracy of the analytical models, three instrumented buildings (one tilt-up and two masonry) were selected for detailed study. Detailed three dimensional finite element models were developed for use with the SAP2000 and ETABS computer programs. Following verification of the models for the recorded earthquake motions the effect of stronger, pulse-type ground motions was evaluated. For the tilt-up building, available nonlinear elements were used to evaluate the push-over behavior and the nonlinear seismic response. Within the limitations of the experimental data base, the effect of vertical accelerations on the long span roof of the tilt-up was estimated.

6. Other related work conducted within and/or outside PEER
Tokoro, K. A. T. (2002), "Seismic Performance of Two Instrumented Masonry Buildings," Thesis presented to the University of Southern California in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering

7. Recommendations for the future work: what do you think should be done next?
Only a limited amount of full scale testing has been conducted on building components including the critical floor and roof diaphragms and the connections of these elements to the rigid walls. Connections have not been tested under the multiaxial loading experienced in the actual building. A detailed consideration of the performance of tilt-up walls without pilasters was beyond the scope of this investigation. This construction procedure which is representative of current practice need to be investigated. Results of this study have shown that inelastic behavior of the various elements of the building are very important for building performance. These aspects need to be investigated more thoroughly when test data becomes available.

8. <u>Author(s), Title, and Date</u> for the final report for this project
Tokoro, K. A. T., Anderson, J. C., and Bertero, V.V. (2004), "Seismic Performance of Masonry Buildings and Design Implications," PEER Report 2004/01.

Anderson, J. C. and Bertero, V.V. (2004), "Seismic Performance of an Instrumented Tilt-up Wall Building," PEER Report 2004/04, In Review.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	Methods to Estimate Displacements of PG&E Structures - **505**		
Start/End Dates	5/1/00 – 8/30/01	Budget/ Funding Source	$65,000 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**MacRae, Gregory A.** (PI), and Tagawa, Hiroyuki – Graduate Student, (UW)		

1. Project goals and objectives

The objectives of this applied research are to answer the following questions:

- What are the advantages, disadvantages and relative reliability of the CM and CSM methods for design?
- What modifications are required to the CM and CSM approaches to allow them to accurately predict the response of structures of different periods to near-fault shaking?
- How should PG&E structures be designed using the findings above?

2. Benefits of the results of this project

The following technologies were developed to mitigate the seismic vulnerability of PG&E mill-type structures:

- An assessment method for estimation displacements of structures located in the near-fault region resulted.
- A methodology for PG&E mill-type structures resulted.
- An alternative to the inadequate *m*-factor method in FEMA-356 was developed.

3. Brief description of the accomplishments of the project

The accomplishments of the project are as follows:

1) For short period structures, such as PG&E mill type structures, with fundamental periods less than about 0.8s, it was shown that directivity effects from NF shaking did not increase the demands above that found for FF shaking.

2) When comparing the Coefficient Method (FEMA 356) CM and the Capacity Spectra Method (ATC-40) CSM methods it was shown that:

(a) The CM is relatively simple to use, but it does not consider the influence of different types of damping or hysteretic loop shape easily, and results may be sensitive to the definition of yield displacement. The CSM is less sensitive to the definition of yield displacement and can take damping effects into account easily. However iteration is required to estimate the likely structural displacements, the method may require use of very long period response values which have dubious accuracy, three empirical relationships have to be assumed or calibrated, and an understanding of the structure's hysteretic shape is required to estimate the demand.

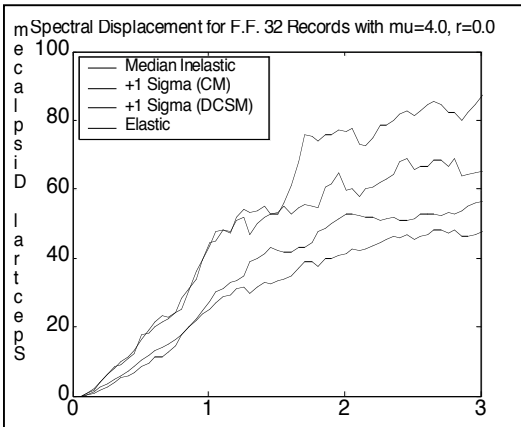


Figure 1. The Capacity Spectra Method (CSM) and the Coefficient Method (CM) have been calibrated to obtain the same median inelastic displacement. The scatter for a series of records, indicated by +1 Sigma, is different for the two methods.

(b) Both the CM and CSM can be calibrated to estimate the exact response. For the CM a bilinear approximation of lateral force reduction factor, *R*, vs. fundamental period, *T*, for a specific ductility is reasonable. The CSM effective damping, ζ_{eff}, for a specific ductility, μ, as well as the spectral reduction, *SR*, for a specific damping, ζ, are dependent on period, *T*.

(c) When both the CM and CSM are well calibrated, the scatter in displacement, σ, for oscillators with an effective (secant) period, T_{eff}, less than about 3.0s is similar. For structures with T_{eff} greater than about 3.0s, the CSM has more scatter as shown in Figure 1.

(d) When the CSM was calibrated according to ATC-40, ATC-40 significantly overestimated the average effective damping at periods greater than about 0.2s. ATC-40 non-conservatively estimated the median inelastic response over the majority of the period range from 0-3s and its estimation was as low as 60% of the median displacement for some periods. The CM calibrated according to FEMA356 conservatively estimated the median displacement over most of the period range. For some periods, FEMA356 estimated displacements more than 30% greater than the actual median displacements.

3) Oscillators with demands estimated by the CM, and with fundamental periods less than about 0.8s, were not affected significantly by near-fault shaking effects. For longer period oscillators, oscillator strengths may need to be increased by more than 60% to account for inelastic shaking effects from NF sites in the region of positive directivity compared to that for shaking from FF or NF near-epicenter sites for the same target displacement ductility as shown in Figure 2. NF shaking did not cause significant trends in the displacement demands of oscillators evaluated by the CSM method. Modifications to the existing FEMA356 CM nonlinear static procedure (NSP) C_1 factor, accounting for NF shaking effects when appropriate, was developed for structures with fundamental periods in the range of 0-3s.

4) For design of PG&E structures, it was determined in conjunction with PG&E/PEER that the FEMA356 CM Linear Dynamic Procedure (LDP) should be used to evaluate the demands of PG&E mill-type structures. The estimation of inelastic response should be made using the C_1 factor from the FEMA356 Nonlinear Static Procedure (NSP). While the C_1 factor may be modified for NF shaking effects, this is only required for structures with periods greater than 0.8s. NF shaking effects therefore do not need to be considered on the inelastic response of the majority of PG&E mill-type structures since their fundamental periods are less than 0.8s. The difference between member and system ductility demands is not considered in the FEMA356 LDP often resulting in non-conservative demand estimates. A method to show how it can easily be accounted for in assessment and in design is provided. A design procedure and example for assessing NF shaking inelastic displacement demands on a mill type structure using the CM was provided.

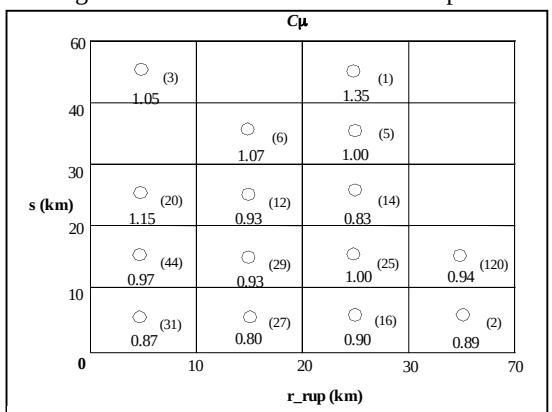


Figure 2. Average ratio of inelastic to elastic displacement demands for long period oscillators from a number of records in blocks s (km) in the fault direction and r_{rup} (km) from the fault surface with a ductility of 4.

4. Describe any instances where you are aware that your results have been used in industry

Results of this project, and an previous project, have been used by PG&E and their consultants to assess the seismic vulnerability of their mill-type structures.

5. Methodology employed

Dynamic inelastic time-history analyses of single-degree-of-freedom (SDOF) bilinear oscillators were undertaken to determine the ability of the Coefficient Method (FEMA273/FEMA356) and the Capacity Spectrum Method (ATC-40) to predict the total displacement demands of simple structures. Both the Coefficient Method (CM) and the Capacity Spectrum Method (CSM) were calibrated to obtain the exact inelastic response displacements for near-fault (NF) and far-fault (FF) shaking.

6. Other related work conducted within and/or outside PEER

Other related, but different types of studies, on displacement prediction methods for structures were carried out by Chopra and Goel, and more recently by Bill Iwan, ATC-55 and ATC-58 projects. Roeder and MacRae also conducted an earlier PG&E-PEER project on some related issues.

7. Recommendations for the future work

1. To obtain better procedures and calibration for near fault shaking effects, more records with known locations and orientations relative to the fault and epicenter, and on different soil conditions, are required. Studies should also be carried out using structures with different shaped hysteresis loops.
2. Methods have been developed to assess the near-fault (NF) demands at different locations relative to the epicenter and fault. However, in general location of the epicenter of the next earthquake on the fault is not known. Appropriate statistical procedures are required to account for the probable location of the site relative to the epicenter in a performance-based assessment/design context.

8. Author(s), Title, and Date for the final report for this project

MacRae, G. A. and Tagawa H. “Methods to Estimate Displacements of PG&E Structures”, Final Report to PEER, August, 2002.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Application of Simplified Model to Assess Structural Behavior of Mill Type Bldg*—**506**		
Start/End Dates	3/19/01 – 8/31/01	Budget/ Funding Source	$10,000 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**Nazir (ABS/EQE Intn'l)**		

1. Project goals and objectives

In this study wall out of plane anchorage forces in certain type of sub-station buildings were examined.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The results of this project can benefit seismic design of certain type of electrical substation buildings.

3. Brief description of the accomplishments of the project

It was found that the wall out of plane stiffness, diaphragm stiffness, and relative stiffness of two diaphragms have significant effects on the wall out of plane anchorage. Recommendations were presented on a proposed deign equation.

4. Describe any instances where you are aware that your results have been used in industry

This study is based on PG&E substation "K" located in San Francisco, which represents a typical substation building structure built in 1920s. Thus, the results of this study are directly applicable to utilities.

5. Methodology employed

Two separate analyses were performed: (a) SAP2000 three dimensional dynamic model; and (b) simplified multi-degree-of-freedom spring model. Variations in the following parameter were made to cover various different conditions: wall to diaphragms connection, wall out of plane stiffness; wall foundation rocking; diaphragm stiffness; and diaphragm relative stiffness.

6. Other related work conducted within and/or outside PEER

7. Recommendations for the future work: what do you think should be done next?

8. <u>Author(s), Title, and Date</u> for the final report for this project

Nazir, "A Simplified Analysis Method for Wall Out of Plane Anchorage Forces".

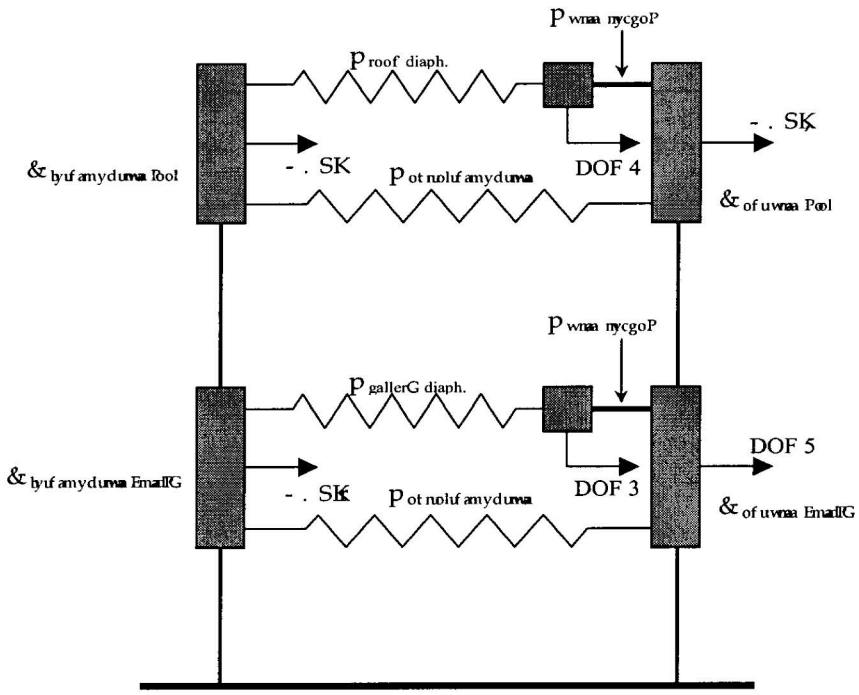


Figure 2-1. Simplified spring model.

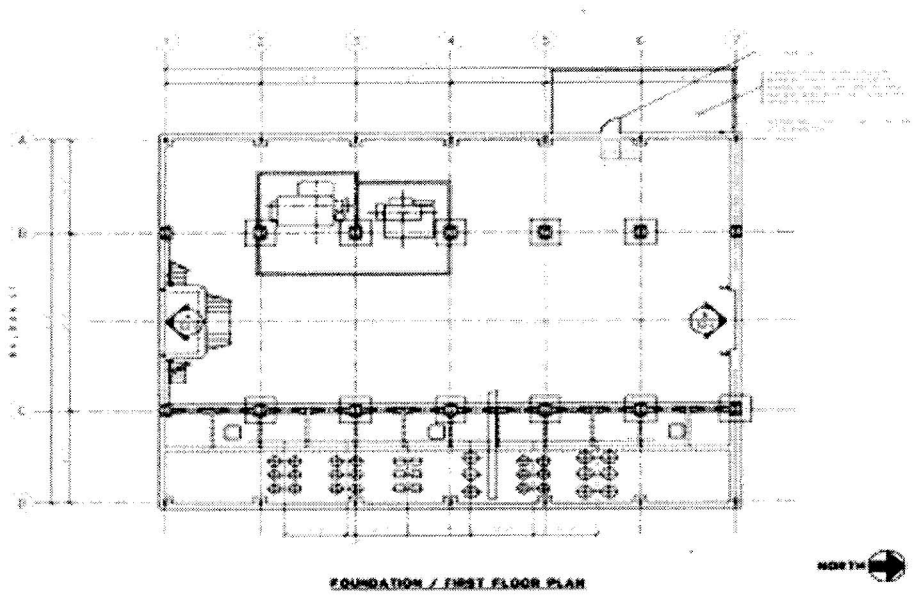


Figure 3-1: First Floor Plan

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Advanced Seismic Assessment Guidelines*—**507**		
Start/End Dates	1/1/01 – 12/31/03	Budget/ Funding Source	$266,301 / PG&E/CEC
Project Leaders (boldface) and Other Team Members	**C. A. Cornell. and P. Bazzurro,** C. Menun, M. Motahari, G. L. Yeo, (Stanford); N. Luco AIR		

1. Project goals and objectives

The objective of this project was to develop a practical professional tool to estimate "tagging fragility curves" which could be used by PG&E to assess the likelihood that a specific building their electrical distribution system would be closed to occupancy (i.e., tagged "yellow" or "red") and hence rendered inoperable after being exposed to a given level of earthquake ground motion.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The tool will aid in a proposed probabilistic system assessment of the seismic vulnerability of PG&E production and distribution network. By-products have been (1) an explicit way to evaluate a damaged structure after an earthquake to help judge whether it poses a life threat, and (2) a tool to help assess whether a building should be up-graded prior to an earthquake.

3. Brief description of the accomplishments of the project

The project developed a procedure based on the standard NSP (Nonlinear Static Procedure) professional tool, but extended to include application to the post-earthquake damaged structure. This procedure leads the way to the desired fragility curves. The method was put into a draft guideline in the first year of the project. In subsequent years the method was tested by two engineering firms and the procedure was further studied by the investigators to improve the analysis scheme. The final report reflects the results of all these efforts. The following papers were prepared for the 13th World Conference on Earthquake Engineering: (1) Bazzurro, P., Cornell, C.A., Menun, C. And Motahari, M., "Guidelines for Seismic Assessment of Damaged Buildings"; (2) Yeo, G.L. and Cornell, C.A., "Building Tagging Criteria Based on Aftershock PSHA"; and (3) Luco, N. , Bazzurro, P., and Cornell, C. A., "Dynamic Versus Static Computation Of the Residual Capacity of a Mainshock-Damaged Building to Withstand an Aftershock".

4. Describe any instances where you are aware that your results have been used in industry

The procedure has been used on three PG&E structures which were used as tests of the methodology. These cases studies were conducted by Rutherford and Chekene and by Degenkolb and Associates. In addition another application is currently under way for PG&E by Drs. J. Mafei and R. Hamburger.

5. Methodology employed

The NSP is applied to the intact structure to assess the likely damage state as a function of ground motion (IM) level. For each of several such damage states (as indexed by roof drift), another NSP analysis is applied as shown in the first figure below. It is this damaged structure that is the potential life-safety threat and whose status dictates closure or not. The damaged-structure static pushovers are transformed by D. Vamvatsikos' SPO2IDA tool into (median) Incremental Dynamic Analyses (IDAs), as illustrated by the left side of the second figure. These produce estimates of the collapse capacity of the damaged structure. Based on this capacity to resist aftershocks the "tagging-state" is determined by one or more "tagging rules" developed by the project. The original intact structure (right side of the second figure) is assessed to determine the (median) ground motion amplitude necessary to put it into the each of these damage states. To this median are "added" estimates of the "dispersion" – both aleatory and epistemic. The former is provided by SPO2IDA and the latter by tables develop through interviews with three practicing engineers.

6. Other related work conducted within and/or outside PEER

The efforts of this project led to the sponsorship by the NSF portion of the PEER Center in 2003-2004 of a project on the roll of aftershock assessment in the larger PEER PBEE context. This project will lead to a PhD thesis by Mr. Gee Liek Yeo. Also Prof. Stojadinovic with student Kevin Mackey has been studying aftershock capacity of bridges.

7. Recommendations for the future work: what do you think should be done next?

At the implementation end it is suggested that there be a workshop and other follow up to disseminate to professionals the new procedures proposed in the guidelines. At the research end there is need to understand still better the connection between earthquake damage in a mainshock and its effect on the capacity of the structure to withstand aftershocks without collapse and life loss. These studies should involve (1) nonlinear dynamic analyses of the type initiated in this project (varying levels of mainshock damage followed by aftershock collapse capacity assessment via IDAs); (2) further study of the role of residual displacement to aid in rapid post-quake evaluation of building safety; and (3) improvement in practical nonlinear static procedures to mimic the damage and residual capacity

8. <u>Author(s), Title, and Date</u> for the final report for this project

Paolo Bazzurro, C. Allin Cornell, Charles Menun, Maziar Motahari, and Nicolas Luco, "Advanced Seismic Assessment Guidelines", July, 2004. (To be submitted for publication as a PEER report.)

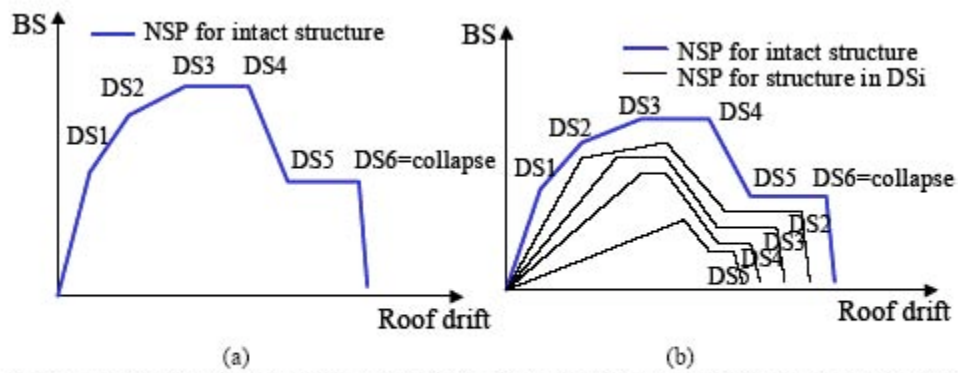


Figure 1: (a) NSP curve for the example building in its, intact, pre-earthquake condition. (b) NSP curves for the building in the pre-earthquake intact condition and in the four most relevant of all the post-earthquake damage states. For simplicity, all the curves for the damaged building have had the residual offset removed.

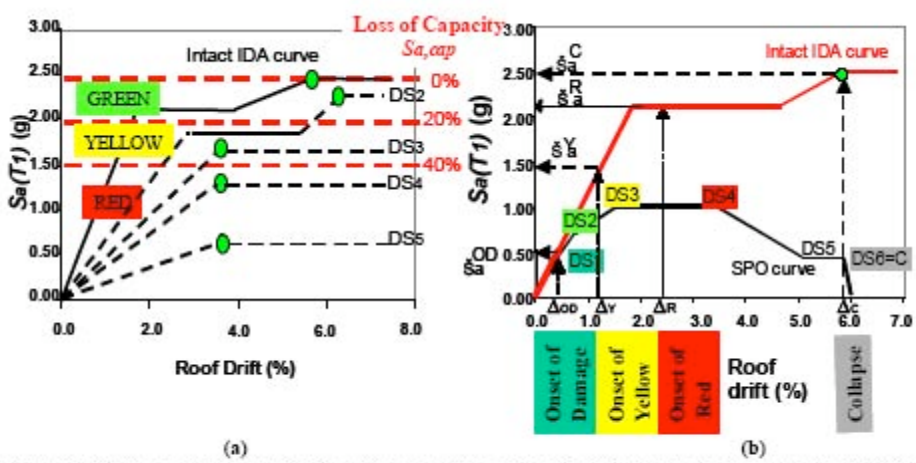


Figure 8: (a) Onset of yellow and red tagging according to the criteria in Figure 4 for a structure with P_0 less or equal to about $2x10^{-4}$. (b) Median estimates of the mainshock $S_a(T_1)$ that takes the intact structure to the onset of OD, Y, R, and C. Note that, in general, the onset of a limit state may not occur exactly at the roof drift of any

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Test Applications of Advanced Seismic Assessment Guidelines*—**508**		
Start/End Dates	7/1/02 – 6/30/04	Budget/ Funding Source	$79,138 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**Maffei (Rutherford & Chekene)**		

1. Project goals and objectives

Advanced seismic assessment guidelines were developed by Stanford University (C. Allin Cornell, Paolo Bazzurro, Charles Menun, Maziar Motahari) as part of the PEER Lifelines Program, Building Vulnerability Studies (Project Task Number 507). Predicting the post-earthquake functionality of utility structures is a crucial step in evaluating the likelihood of the electric distribution network being able to provide gas and electricity to its customers. The final product of the guidelines is a set of fragility curves for structural limit states directly related to post-earthquake building occupancy status, namely green, yellow, or red tagging.

This project is for a practicing Structural Engineer to apply these guidelines to utility type buildings.
The objectives are to:

1. Identify potential difficulties that Structural Engineers would encounter in using the procedure described in the advanced seismic assessment guidelines.
2. Recommend possible revisions to the procedure to address any identified difficulties.
3. Identify and make recommendations on other issues related to assessing the seismic reliability of utility structures and systems.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The project is a key step in investigating the practical application and potential of performance based seismic assessment methods. As such, the project can lead to the wider application of seismic and structural engineering procedures that use state of the art techniques.

In the application to fragility curves for buildings of utility systems, the project can lead to a better understanding of the seismic vulnerability of lifeline systems, and a better understanding of the most effective ways to reduce seismic vulnerability.

3. Brief description of the accomplishments of the project

Detailed assessment and understanding of two example buildings, leading to

- Better knowledge of characteristics of steel moment frame behavior.
- Improved understanding of reliability based structural engineering and effects of vulnerability and uncertainty.
- Better knowledge of mill building concrete wall behavior
- Understanding of the effects of various modeling assumptions for concrete and steel buildings, including pushover load pattern, foundation flexibility, inclusion of gravity frames, assumed concrete stiffness and strength properties.

4. Describe any instances where you are aware that your results have been used in industry

Recommendations used by PG&E, with Rutherford & Chekene and Simpson Gumpertz and Heger on the evaluation of an 8-story building.

5. Methodology employed

Structural analyses using Nonlinear Static Procedures and Incremental Dynamic Analyses. Evaluation of damaged structures, proposal of tagging criteria, and creation of fragility curves.

6. Other related work conducted within and/or outside PEER

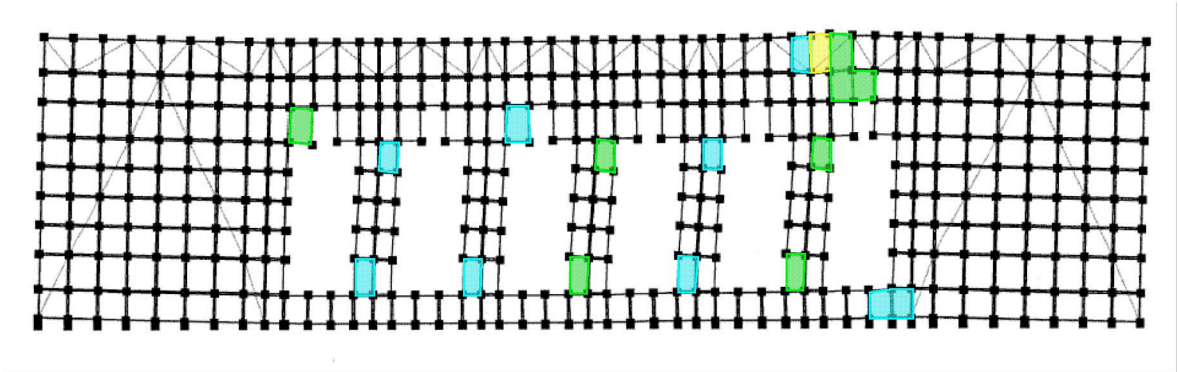
Being integrally related to task 507 project, this project takes advantage of developments in two other projects being carried out by professor C. Allin Cornell. The first is investigating Incremental Dynamic Analysis, global ductility, and approximate techniques for NL dynamic analysis. The second is focused on intensity measures and near source motions. The project has made use of the PEER project on nonstructural damage to gypsum wall board partitions being carried out under Professor Restrepo at UCSD. The project has been coordinated with the Task 509 project.

7. Recommendations for the future work: what do you think should be done next?

1. Evaluation of modeling methods for steel and concrete buildings.
2. Applicability of analysis techniques for high-rise buildings.
3. Possible techniques for deriving fragility curves using less detailed analysis.
4. Building-specific tagging criteria.

8. Author(s), Title, and Date for the final report for this project

Maffei, Nakayama, Mohr, Holmes
Test Applications of Advanced Seismic Assessment Procedures
Expected completion in August 2004

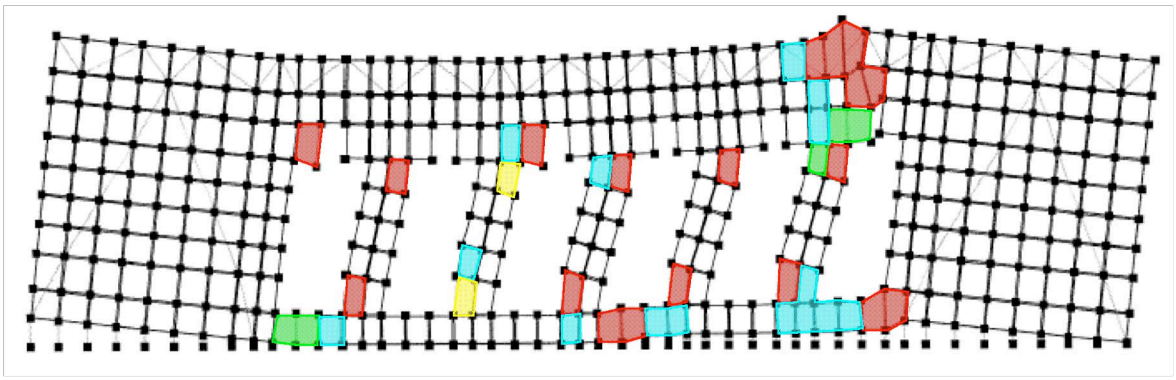


DEFLECTED SHAPE SHOWING USAGE RATIOS

Reference Drift = 0.004958

Limit state group = all deformation states

Minimum usage ratio for each color : 0.0 | 0.5 | 1 | 1.5 | 2



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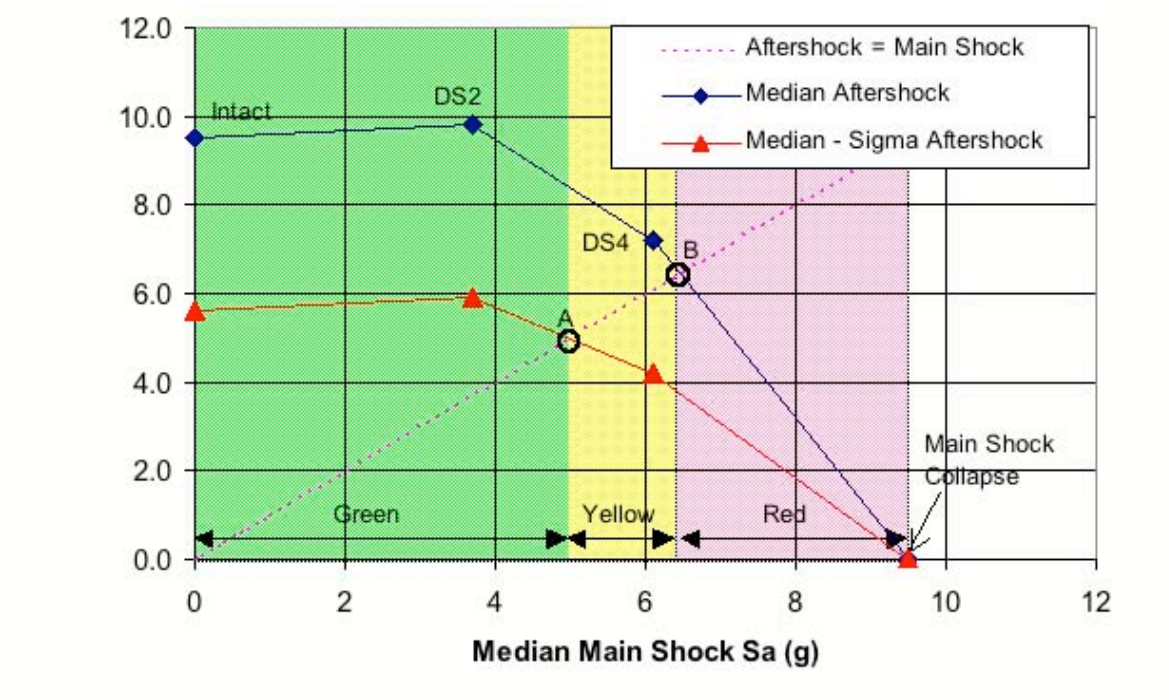
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Main Shock
Collapse
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Yellow
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Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Evaluation and Application of Concrete Tilt-up Assessment Methodologies*—**509**		
Start/End Dates	4/1/03 – 6/30/04	Budget/ Funding Source	$68,130 / PG&E/CEC
Project Leader (boldface) and Other Team Members	**Malley (Degenkolb Engineers)**		

1. Project goals and objectives

Task 1

The goal of Task 1 is to provide input to existing codes (e.g. International Building Code) and guidelines (e.g. FEMA 356) that will improve the seismic design and assessment methodologies of concrete tilt-up and other low-rise, rigid-wall, flexible diaphragm buildings. The input will be based on research findings and results of previous (PEER) research projects on concrete tilt-up buildings. These research projects are: 1) *Seismic Response of Tilt-up Buildings* by John F. Hall; 2) *Modeling and Evaluation of Tilt-up and Steel Reinforced Concrete Buildings* by John W. Wallace; 3) *Stiffness of Timber Diaphragms and Strength of Timber Connections* by Gerard C. Pardoen; and 4) *Improved Methodology for Evaluating the Seismic Resistance of Low Rise Buildings with Flexible Diaphragms* by Jim Anderson.

Task 2

As practicing structural engineers, we will apply the building assessment methodology developed in PEER Task 507, *Advanced Seismic Assessment Guidelines* by C. Allin Cornell, Paolo Bazzurro, Charles Menun, Maziar Motahari, to a concrete tilt-up building in the Pacific Gas & Electric (PG&E) building inventory. The selected building is the PG&E Fremont Materials Distribution Center that Degenkolb Engineers has previously designed seismic upgrades for.

The objectives are to: 1) identify potential difficulties that Structural Engineers would encounter in using the procedure described in the *Advanced Seismic Assessment Guidelines*; 2) recommend possible revisions to the procedure to address any identified difficulties; and 3) identify and make recommendations on other issues related to assessing the seismic reliability of utility structures and systems.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

Predicting the post-earthquake functionality of utility structures is a crucial step in evaluating the likelihood that the PG&E power distribution network will not be able to provide power to customers. The final product of the guidelines is a set of fragility curves for structural limit states directly related to post-earthquake building occupancy status; namely green, yellow, or red tags.

The project is a key step in investigating the practical application and potential of performance-based seismic assessment methods. As such, the project will lead to the wider application of seismic and structural engineering procedures that use these state-of-the-art techniques.

3. Brief description of the accomplishments of the project

Task 1

Each of the four reports was reviewed and summarized. The data from the reports was evaluated to test the validity of design procedures and see what changes, if any, could be made to current design methodologies. Each report raised questions regarding assumptions and procedures in the research process, and the questions are presented for the authors. The reports also illuminated ideas for further research in the area of tilt-up building construction. From the four reports evaluated, some suggestions are presented for changes in design. However, no major changes to the current codes and guidelines were recommended due to this review.

Task 2

A 2D Static Pushover Analysis was performed on the roof diaphragm of the selected building for the intact structure. The analysis confirmed that a plywood roof diaphragm could be modeled using truss elements and that the results obtained would be comparable to those predicted using FEMA 356. Further application of the guidelines yielded Incremental Dynamic Analyses curves, the residual dynamic capacity and the occupancy status of the structure in each damage state, and a set of fragility curves. The authors confirmed the successful application of the guidelines. At the same time, difficulties associated with using the Guidelines and possible clarifications were identified.

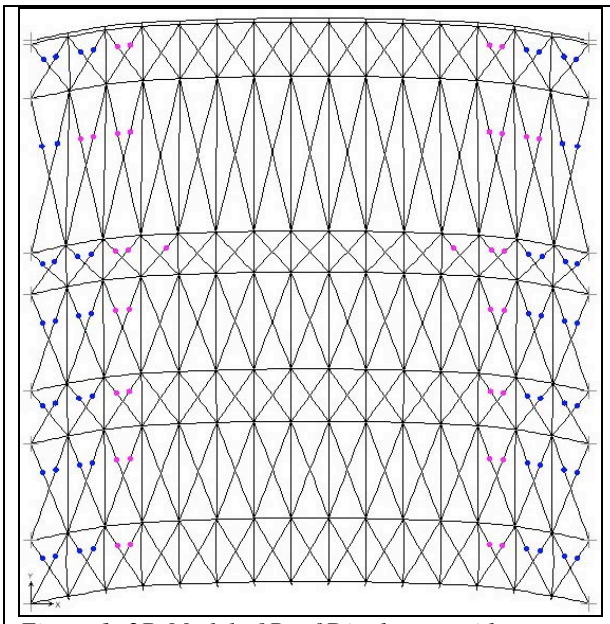


Figure 1: 2D Model of Roof Diaphragm with Diaphragm Represented by Axial Elements with Nonlinear Hinges

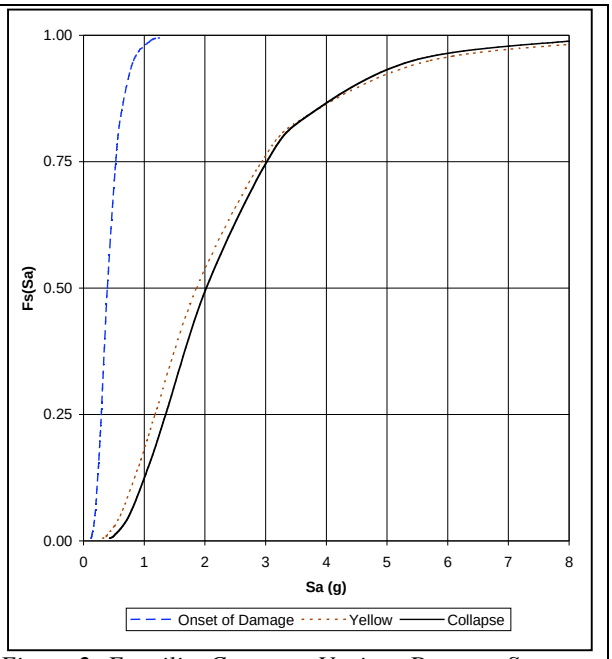


Figure 2: Fragility Curves at Various Damage States

4. Describe any instances where you are aware that your results have been used in industry

None to date.

5. Methodology employed

The Nonlinear Static Procedure (NSP) is performed on the structure using SAP 2000, commercially available software frequently used by practicing structural engineers.

Incremental Dynamic Analysis (IDA) is performed using the SPO2IDA spreadsheet tool developed by Vamvatsikos and Cornell.

6. Other related work conducted within and/or outside PEER

Within PEER, this project is integrally related to Task 507, the development of the Advanced Seismic Assessment Guidelines. Task 508 is similar to Task 2 of this project in its investigation of the use of the guidelines, in which a steel moment frame building was studied. This project applies the guidelines to a different type of construction, a concrete tilt-up building with a flexible diaphragm.

The reports reviewed in Task 1 were PEER projects concerned with experimental and analytical studies of concrete tilt-up buildings. This project seeks to summarize these studies and to make further recommendations for research as well as practice.

Outside PEER, two other related documents include: 1) *Guidelines for Seismic Evaluation and Rehabilitation of Tilt-up Buildings and other Rigid Wall/Flexible Diaphragm Structures* by the Structural Engineers Association of Northern California; and 2) *FEMA 356, Prestandard and Commentary for the Seismic Rehabilitation of Buildings*. These documents have not fully incorporated all of the findings from the previous PEER studies. Also, the application of the guidelines offers an advanced tool for the post-earthquake assessment of tilt-up buildings that has never been used in practice.

7. Recommendations for the future work: what do you think should be done next?

Research recommendations for tilt-up building construction include further research suggestions for the authors of the reports reviewed, and research not specific to any of the reports. Suggestions for research for the authors of the reports range from studying the anchorage forces along the short side of the building versus the long side, rerunning analysis done in the reports using the current building code, FEMA 356 values, or updated data, and more laboratory testing of tilt-up building components. Suggestions for other areas of research include instrumentation of more tilt-up buildings, studies of connection improvement in existing tilt-ups, better period estimation, additional and better documentation of damage in tilt-ups, investigating the strength of connections in cross grain ledger bending, and estimating the amplification of forces at pilasters.

Additional application of the Advanced Seismic Assessment Guidelines by practicing structural engineers is also recommended. This would provide additional input to the authors with regards to the ease or difficulties of using the guidelines.

8. Author(s), Title, and Date for the final report for this project

Tim Graf and Jim Malley, Evaluation and Application of Concrete Tilt-Up Assessment Methodologies, May 27, 2004
Jack Hsueh and Jim Malley, Application of Advanced Seismic Assessment Guidelines, August 15, 2004

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Scoping Study for Unified Lifeline Risk/Reliability Models*—**601**		
Start/End Dates	10/1/00 – 6/31/01	Budget/ Funding Source	$64,996 / PG&E
Project Leader (boldface) and Other Team Members	**S.D. Werner (SSEC),** D.K. Ostrom, and C.E. Taylor (NHMI)		

1. Project goals and objectives

The objective of this project was to develop a program plan for a future PEER research program that will initially develop and demonstrate a modular, technically sound, and practical unified risk/reliability platform to: (a) evaluate seismic risks to as-built lifeline systems with no seismic improvements; (b) evaluate seismic risks to modified lifeline systems with physical and/or operational seismic improvements now included; and (c) provide results from the evaluations that can guide decision makers as they assess and then select seismic improvement strategies that limit risks to their system to acceptable levels. This initial research program will focus on the need for unification and commonalities of modeling methods for electric power and highway transportation systems. During future PEER research, this can be extended to other lifelines as well.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The research defined by this program plan will lead to a unified seismic risk/reliability platform that will: (a) be initially developed as separate but parallel packages for electric power and highway transportation systems (using procedures/models from current practice and research) during the first two years of this program; (b) be further developed into a more sophisticated platform (with improved procedures and models from new research) during the remaining years of this program; (c) focus on system performance rather than merely component performance; (d) be developed not as a decision-making tool, but instead as a decision-guidance toll that provides useful results for lifeline-system decision makers (Figure 1 illustrates the role of this platform in one possible seismic risk reduction decision-making process.); (e) accommodate a wide range of decision-making approaches and contexts; and (f) be applied in a demonstration application to an actual electric-power and highway-transportation system in California.

3. Brief description of the accomplishments of the project

The unified risk/reliability modeling platform that will be developed under the research program defined by this program plan will contain the six main steps shown in Figure 2 and summarized below:

- ***Step 1. Initialization.*** Step 1 enables the user to define the type of seismic risk evaluation to be made, depending on his/her decision-making needs.

- ***Step 2. Inventory of Facilities.*** Under Step 2, an input database is prepared to define configurations, linkages, physical and operational characteristics, and soil conditions for the lifeline system and its components.

- ***Step 3. Evaluation of Seismic Hazards.*** Under Step 3, existing earthquake source models are used to define individual or multiple scenario earthquake events to be used in the system risk analysis. Then, existing seismic hazard models are adapted into a system model that can accommodate multiple random events, in order to estimate site-specific hazards from earthquake ground shaking, liquefaction, landslide, and surface fault rupture.

- ***Step 4. Evaluation of Component Performance.*** Step 4 enables the user to evaluate the seismic performance of each component in the system due to each of the hazards identified in Step 3 for each earthquake event. In this, the component's damage state, repair costs, and post-earthquake functionality (downtime) are estimated.
- ***Step 5. Evaluation of System Performance.*** Under Step 5, each component's functionality at various post-earthquake times is input into a model of the lifeline-system that evaluates its ability to function satisfactorily after an earthquake. As a minimum, this should include: (a) simple performance algorithms or expert opinion of system operators to assess post-earthquake performance of an electric power system; (b) traffic flow models to estimate post-earthquake traffic flows in a roadway system; and (c) return-to-service models.

- ***Step 6. Summary of Results.*** Step 6 enables the user to summarize and display the results from the previous steps, in order to communicate important technical results to decision makers.

4. Describe any instances where you are aware that your results have been used in industry

Prior versions of the platform that will be further developed under this research program have had the following industry uses: (a) a similar platform was used in 1999-2004 to evaluate costs and risks for various combinations of seismic upgrades for the Port of Oakland's entire system of berths; (b) the REDARS platform for evaluating seismic risks to roadway systems is now being used by the California Department of Transportation (Caltrans) to enable them to assess the utility of this platform in their future seismic risk reduction programs; and (c) the SERA platform was used in 1990 and 1998 to assess seismic risks to the Southern California Edison's electric power system, and was also used in 1993 to estimate seismic risks to the East Bay Municipal Utility District's water system.

5. Methodology employed

The following methodology was used to develop the program plan that was the end result of this project:

- ***Strawman Program Plan.*** The project investigators used their experience and knowledge of current practice and existing research to develop an initial strawman version of the program plan.

- ***Open-Ended Interviews and Mini-Workshops.*** The project investigators conducted open-ended interviews and mini-workshops with staff from electric power utilities (Southern California Edison, Los Angeles CA; Pacific Gas & Electric Company, San Francisco CA; San Diego Gas & Electric Company, San Diego CA; and Los Angeles Dept. of Water & Power, Los Angeles CA) and Caltrans offices statewide (District 7 Office, Los Angeles CA; District 4 Office, Oakland CA; and maintenance, engineering, and operations staff from Caltrans' Sacramento CA offices). These interviews/mini-workshops solicited feedback regarding: (a) anticipated value of a unified risk/reliability program to their seismic-risk-reduction activities; (b) future uses of such a program; (c) how the program should be developed to optimize its usefulness; and (d) engineering/planning elements of the program for which improvement through future research is most needed. The project investigators also held meetings/mini-workshops with members of the academic and consulting engineering communities, to obtain their feedback regarding relevant research/engineering practices that could be factored in the program planning.

- ***Review of Current Practice and Research.*** The project investigators conducted an independent review of current related practice and research, as well as experience from past earthquakes, in order to identify relevant research issues that should be addressed under the program plan for this unified risk/reliability platform.

- ***Updated Program Plan Development.*** The project investigators used the results of the above tasks to update the original strawman program plan. This updated plan was then reviewed by members of the PEER Lifelines Program's Joint Management Committee. Recommendations from this review were used to further modify the updated program plan, and develop the final version of the plan.

6. Other related work conducted within and/or outside PEER

Development of REDARS software for seismic risk analysis of roadway systems is being sponsored by the Federal Highway Administration, through the Multidisciplinary Center for Earthquake Engineering Research. PEER has just completed a one-year effort entitled "Database of Seismic Parameters for Equipment in Substations" that provides a systematic way (needed data and format) to gather substation/system physical data for an electrical utility system -- which is a necessary early step in conducting a detailed seismic risk analysis for such a system.

7. Recommendations for the future work: what do you think should be done next?

The research from this program plan should be carried out under the PEER Lifelines Program. Consistent parameters/metrics for determining the seismic performance of a lifeline system and for characterizing the seismic performance of the components that comprise the system should be developed.

8. <u>Author(s), Title, and Date</u> for the final report for this project

Two companion reports coauthored by S.D. Werner, D.K.Ostrom, and C.E. Taylor and published in October 2002 were developed under this project: (a) *Program Plan: Planning of Unified Lifeline Risk/Reliability Platform for Seismic Risk Decision Making;* and (b) *Process for Development of Program Plan: Planning of Unified Lifeline Risk/Reliability Platform for Seismic Risk Decision Making*.

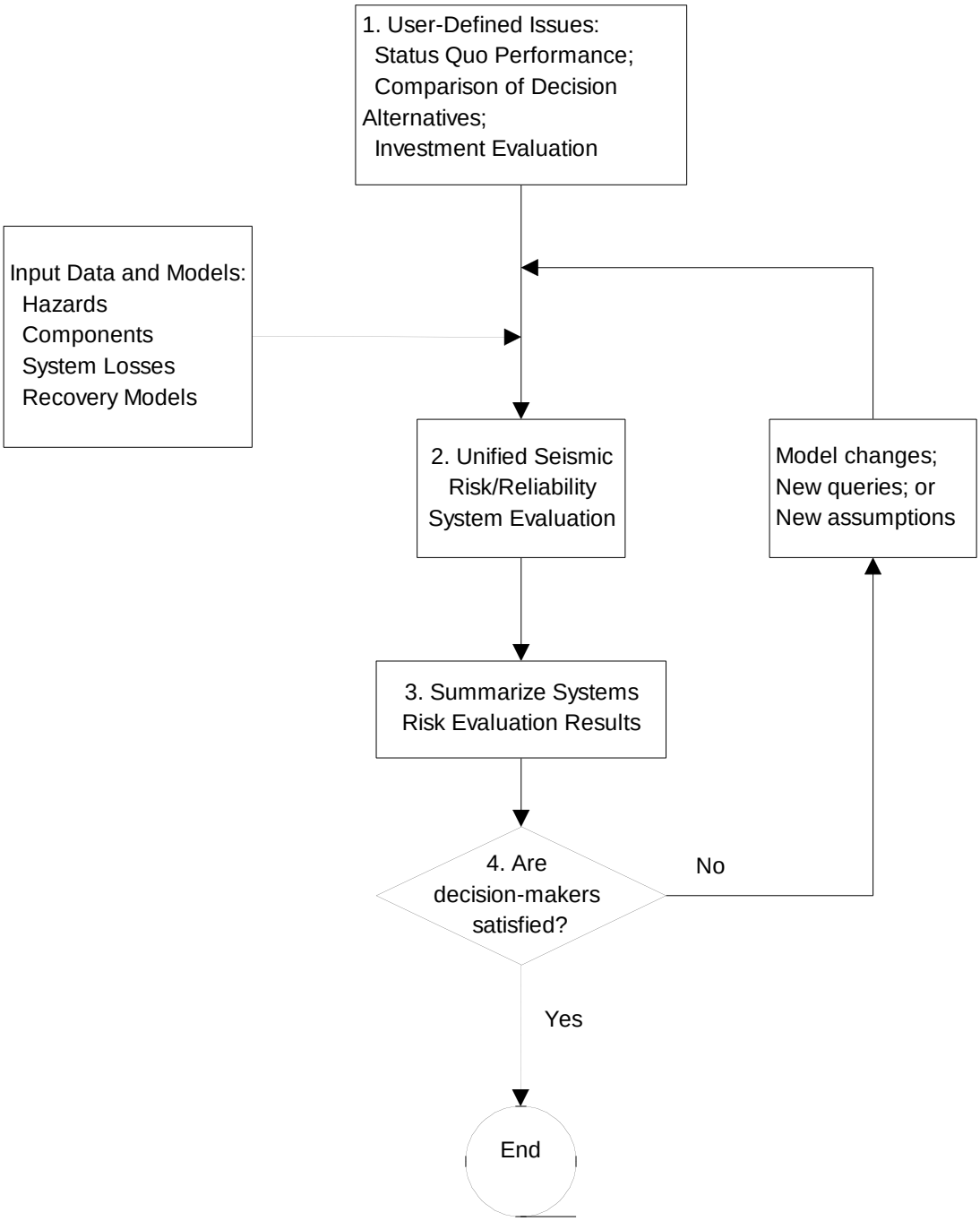


Figure 1. Role of Unified Seismic Risk/Reliability Evaluation in Seismic Risk Decision-Making for Lifelines.

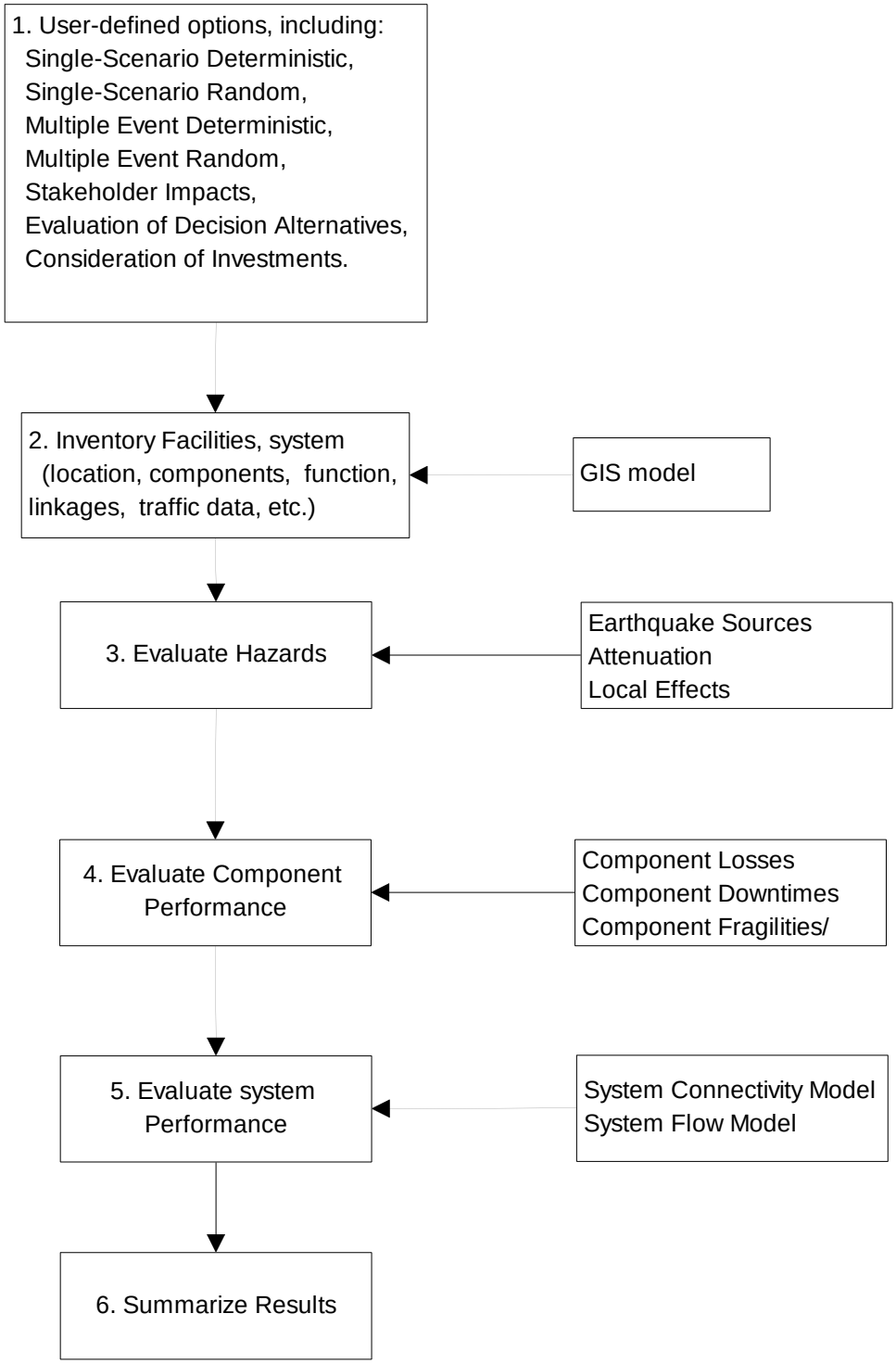


Figure 2. Basic Common Steps in a Seismic Risk/Reliability Evaluation for Lifeline Networks.

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Earthquake Risk Decision-Making in Lifeline Organizations*—**604**		
Start/End Dates	6/1/01 – 4/30/02	Budget/ Funding Source	$173,972 / FEMA
Project Leader (boldface) and Other Team Members	**Seaver,** Robershotte, and Baker **(Battelle – Pacific Northwest Division)**		

1. Project goals and objectives

In areas with earthquake potential, preparing for and responding to earthquakes is a significant responsibility of lifeline organizations. The decisions made by these organizations about how to manage and mitigate the risk of earthquakes are vital to both the organizations and the communities they serve. The overall purpose of this research is to improve the understanding of how lifeline organizations make decisions about earthquake risk, identify critical issues and areas for potential improvement, and transfer general recommendations about decision-making to a broad range of lifeline organizations. This report describes the initial pilot phase of the research. The purpose of the pilot effort is to test data collection and analysis methods and to provide the participating organizations, the Pacific Gas & Electric Company (PG&E) and California Department of Transportation (Caltrans), with preliminary analysis on earthquake risk decision-making in their organizations.

This pilot study is primarily descriptive. It is an attempt to better describe and characterize earthquake risk mitigation decisions. It focuses on earthquake risk mitigation decisions in the lifeline organizations that are leaders in this area, and on the methods for studying these decisions. The pilot study is intended to identify key research issues and develop and assess the research methods to provide the basis for designing and conducting subsequent phases of research not to come to final conclusions.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

External events drove the earthquake risk decision-making programs in both organizations. In general, most decisions were made either explicitly or implicitly in regard to political considerations and influences. For both organizations, the decision-makers did not generally get involved in the details of the issues. No specific tradeoff analysis or cost-benefit approaches were deemed necessary or relevant. It was clear that general organizational objectives and goals included a strong safety culture and responsibility towards the public. Generally, a broad set of mitigation options were considered and a salience bias was clearly in evidence. Relevant criteria were generally considered. Both organizations learned and improved their prioritization decision methodologies as time went on. In general, most of the criteria were explicit. For the two organizations, tradeoffs were difficult to assess in any meaningful way and uncertainties associated with technical information were generally not directly communicated to the decision-makers.

Beyond protecting the public safety and insuring continuity of service one measure of success of the earthquake risk decision-making program for PG&E is if the costs are allowable and can be passed on in the rate base. For Caltrans, success beyond safety is achieved by pleasing the communities served and acceptance by the elected officials. Overall, by these measures, both organizations' programs are clearly successes. The major difference found in this study between the two organizations was the involvement and influence of many more organizations and stakeholders in Caltrans decisions.

3. Brief description of the accomplishments of the project

Earthquake risk decision challenges differ only in a matter of degree from other non-earthquake related complex business decisions. The same decision elements are present but they are usually more daunting in earthquake risk decisions. Often, too little mitigation action is taken prior to major earthquakes and then decision-makers may tend to overspend on mitigation efforts after the earthquake. Cost benefit analysis as part of a comprehensive decision analysis to maximize expected utility would be a logical approach and the preferred way to address earthquake risk mitigation decisions. However, this has not been done in the past.

Earthquake risk management actions are most successful soon after actual earthquakes. Determining and communicating additional benefits from the mitigation efforts can help justify a program/project, particularly with some stakeholders. Organizations should focus as much as possible on the lifeline "systems" rather than the individual components. Also, R&D efforts are important and significantly contribute to successful earthquake risk decisions. Since retrofitted bridges and buildings look and function the same as before mitigation efforts, it is

difficult for the public to see the benefits. Thus, the public needs to be educated and frequently reminded of the value of such programs/projects. Probabilistic rather than deterministic analysis of earthquake hazards produces more complete and accurate results and is an effective part of performance-based earthquake engineering.

An organizational champion for earthquake risk management is critical as is the organizational culture to nurture that champion. Peer reviews of earthquake risk programs are essential. In addition, the lifeline organization should participate in cross-organizational technical groups to share up-to-date information and experiences. A core group of professionals within the organization should be identified as the technical lead for earthquake risk. Lifeline organizations should make full use of external organizations to support earthquake risk management programs/projects and develop close working relationships with Federal agencies heavily involved in the program/project. Communications with external parties need to be carefully managed and external advisory groups should be used to enhance credibility and technical accuracy.

It is important to note that key earthquake engineering champions and staffs in both organizations should be appreciated and commended for their extraordinary performance over many years and against great odds. To develop, champion and sustain the earthquake mitigation efforts in both companies was not without problems but was no small feat. PG&E and Caltrans have proven they are indeed leaders in their field with much to teach both lifeline and other organizations.

4. Describe any instances where you are aware that your results have been used in industry

Results not available yet.

5. Methodology employed

The methodological approach developed for the pilot study was the product of several workshops involving the project team, the participating representatives from the sponsoring organizations, and a panel of academic experts. The pilot study approach focused on specific past earthquake risk decisions in PG&E and Caltrans. These decisions were selected to cover a wide range of earthquake risk mitigation decisions. A decision analysis framework was used to identify key characteristics of these decisions that should be described and analyzed. In-depth interviews with program and project participants were conducted to obtain the information about the decisions. For each organization three decisions were studied. The PG&E decisions were: the establishment of the earthquake risk management program; the retrofit of the San Francisco Headquarters building; and the retrofit of the Lake Almanor and Butt Valley dams. The Caltrans decisions were: the establishment of the bridge seismic retrofit program; the retrofit prioritization program; and the replacement and retrofit of the Carquinez Bridge.

6. Other related work conducted within and/or outside PEER

None.

7. Recommendations for the future work: what do you think should be done next?

PEER should pursue a deductive theory driven approach to Phase II. The many significant questions that arose after examining the pilot phase interview data beg to be more fully answered in Phase II and include: How should earthquake risk mitigation decisions be made in lifeline organizations and how do these concepts translate to organizations confronting different environmental contexts? What is acceptable risk? What is meant by performance based decision-making? How can earthquake risk champions encourage decision-makers to seriously assess earthquake risks in the absence of a major quake? How important is it that top-level decision-makers understand risk probabilities and uncertainty issues and how can engineers better communicate with these decision-makers? How are alternatives generated and evaluated and what can be done to position organizations to be able to more effectively respond to a salient earthquake event? A comprehensive theoretical approach appears to offer the best method to answer the unanswered questions remaining from the descriptive/inductive pilot Phase I approach. This continued research offers significant benefits, not only to lifeline organizations but to any organizations facing low probability high consequence events such as our countries' current efforts to defend critical infrastructure against terrorist acts.

8. Author(s), Title, and Date for the final report for this project

Robershotte, M. A., Seaver, D. A., and Baker, K. A., Earthquake Risk-Decision Making in Lifeline Organizations Phase I (Pilot Study) Report, March 2003

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Validation of Probabilistic Seismic Hazard Computer Programs*—**607**		
Start/End Dates	11/1/01 – 4/30/04	Budget/ Funding Source	$93,692 / Caltrans
Project Leader (boldface) and Other Team Members	**Wong (URS)**		

1. Project goals and objectives

Despite its relatively widespread use both nationally and internationally, only a few publicly available and proprietary probabilistic seismic hazard analysis (PSHA) computer codes have been developed. In large part, this is because PSHA calculations are still being done by a relatively small proportion of the professional community. Because of the importance of PSHA in seismic design, the PEER Center's Lifelines Program sponsored a Working Group to validate both the numerical approaches and computer software used in PSHA.

The objective of the project was to develop a set of standard exercises that can be used by current and future PSHA software developers to validate their codes. The validation process will also provide the means for the PEER Lifeline Program sponsors (CALTRANS, PG&E, and the CEC) to insure that work done for them by others, including consultants, is done using qualified software.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

In the past three decades, the approach to estimating earthquake ground shaking hazard, particularly of critical and important facilities, has slowly evolved from the traditional deterministic earthquake scenario analysis to PSHA. A prime example is the very comprehensive PSHA that was performed to evaluate both ground shaking and fault displacement hazards at Yucca Mountain, the site of the nation's first nuclear waste repository. The National Seismic Hazard Maps developed by the U.S. Geological Survey, which form the basis of building codes in the U.S. (e.g., International Building Code) are based on PSHA.

Results from PSHA also form the basis for: (1) design ground motions specified in structural codes and standards (e.g., AASHTO for bridges); (2) site-specific design of important and critical facilities such as all U.S. Department of Energy facilities (e.g., national laboratories and Yucca Mountain); (3) site-specific design for nuclear power plants and interim nuclear waste storage sites; (4) safety analysis evaluations of important/critical facilities such as U.S. Bureau of Reclamation dams; (5) loss estimation to establish insurance rates; and many other uses. PSHA is now being used by Federal and state agencies, which have traditionally only used a deterministic approach for estimating ground motions. Examples of such agencies are the U.S. Army Corps of Engineers and the California Division of Safety of Dams. Thus PSHA has become the primary tool in estimating seismic hazards in the U.S. and is gaining widespread use worldwide.

3. Brief description of the accomplishments of the project

This project provided an opportunity for the developers of the most important PSHA codes in the U.S. to validate and in some cases, revise the numerical approaches used in their codes. The project, test cases, and their answers will be published in a PEER final report, posted on the PEER website (http://peer.berkeley.edu), and documented in publications that will provide widespread distribution to PSHA software developers interested in validating their codes. This will be of value to the other engineering centers and to other countries in their development or use of PSHA codes.

4. Describe any instances where you are aware that your results have been used in industry

Results not available yet.

5. Methodology employed

The Working Group tested both publicly available codes as well as proprietary codes that have been used extensively in hazard evaluation in the U.S. and worldwide. Members of the Working Group consisted of code developers from government agencies and engineering firms. The focus of the project was the numerical verification of the codes and analysis and comparison of their various features. The validation exercises consisted of two sets of cases that tested fundamental aspects of the codes including how they modeled (1) faults, areal sources, and complex fault geometries, (2) recurrence models and rates, and (3) attenuation relationships and their uncertainties. The test cases ranged from the simplest to more sophisticated. The simplest cases have analytical

solutions, but the more complex cases do not. "Acceptable" answers to the test cases were defined either through analytical solutions or consensus results from the Working Group.

The test case sets (e.g., Figure 1) were developed by the PIs and were distributed to each member of the Working Group. Each member ran the test cases and sent their results back to the PIs. The results were compiled for the whole Working Group and sent back to each participant without identifying the names of the codes except for their own code. This initial feedback allowed for each code developer to identify numerical errors, errors in interpretations, or limitations in their codes and the opportunity to correct them. In some cases, this resulted in modifications of the codes. For each test case set, the above steps were followed and a workshop was held to discuss the group results, to identify discrepancies and the reasons for them, particularly if differences were due to differences in assumptions, numerical solutions, and hence features of the codes. A third and final workshop was held to discuss the results of each test case and to select the "acceptable" answers for each test case. Recommendations of minimum standards for meeting the benchmark results (e.g., 10% in probability level) were also defined to qualify the hazard codes.

6. Other related work conducted within and/or outside PEER

None.

7. Recommendations for the future work: what do you think should be done next?

The current state-of-the-practice in PSHA is to assume earthquakes behave in a Poisson manner. In the near future, time-dependent probabilistic seismic hazard analyses will be performed as the required seismic source data become available A topic of future work will be development of time-dependent models as employed in PSHA codes. These will also require validation as such codes become increasingly used.

8. Author(s), Title, and Date for the final report for this project

Ivan G. Wong, Patricia A. Thomas, and Norm Abrahamson "The validation of software used in probabilistic seismic hazard analysis," December 2004.

Figure 1. Fault and Site Geometry for Test Case Set #1

Final Project Summary — PEER Lifelines Program

Project Title—**ID Number**	*Rapid Ground Motion Estimates*—**701**		
Start/End Dates	5/1/00 – 4/30/01	Budget/ Funding Source	$65,000/ PG&E/CEC
Project Leader (boldface) and Other Team Members	**Dreger (UCB),** Kaverina (UCB), Gee (UCB), Lombard (UCB), Neuhauser (UCB)		

1. Project goals and objectives

The objective of this project was to develop an automated system for the analysis of earthquake finite source parameters such as fault length, orientation and slip distribution quickly after the occurrence of an event and to use this information to determine rapid estimates of near-fault strong ground shaking. The ground motion estimates that take fault finiteness and rupture directivity into account are then used to augment ShakeMaps in sparse monitoring situations or in cases where data telemetry failures preclude the recovery of near-realtime strong motion data. This system was developed to improve ShakeMap capability for magnitude greater than 6 events throughout California.

2. Benefits of the results of this project to develop technologies and protocols to mitigate the vulnerability of electric systems and other lifelines to damage directly and indirectly caused by earthquakes. Also, benefits to develop assessment techniques to evaluate damage to electric systems caused by earthquakes and to assess fiscal impacts due to the loss of electric service to the community.

The results of this project benefit the rapid assessment of earthquake effects on electrical systems and other lifelines by providing the capability to map the distribution of near-fault strong ground shaking. Because of the distributed nature of lifeline systems it is necessary to have a method that can operate under sparse monitoring conditions as well as in densely instrumented urban regions. With the strong motion ShakeMaps users can assess the impact of the earthquake on lifelines systems facilitating inspection and repair. This system was recently tested by the December 22, 2003 San Simeon, California earthquake (Mw6.5), which occurred in a sparsely instrumented region yet killed two people and caused substantial damage. Section 4 describes how this method contributed to the rapid assessment of this earthquake.

3. Brief description of the accomplishments of the project

In this project we successfully updated our finite-source inversion software, integrated this software into the realtime earthquake monitoring system at the Berkeley Seismological Laboratory, defined a protocol for communicating results to USGS colleagues and for updating published ShakeMaps. This involved working closely with scientists at the Menlo Park and Golden offices of the USGS as well as at PG&E to ensure that data formats for the exchange of information was suitable for ShakeMap, the general audience, as well as for the needs of PG&E.

In addition a web-based analyst interface was developed to streamline the review and updating of the results.

4. Describe any instances where you are aware that your results have been used in industry

This system was operational at the time of the December 22, 2003 Mw6.5 San Simeon, California earthquake, which occurred in a region with few nearby strong motion stations. The initial ShakeMap was based entirely on estimates of strong ground shaking using the epicenter and an attenuation relationship since there were no available near-source, near-realtime strong motion stations to provide actual ground motions. As a result this initial map failed to predict the elevated shaking to the southeast in the community of Paso Robles where unreinforced masonry buildings collapsed and two people died (See Figure 1a).

Using the method that we developed we were able to determine the rupture extent of the earthquake, and that the rupture was to the southeast causing elevated ground motions in that direction (Figure 2). Information from a line source inversion with results essentially the same as shown in Figure 2 was used to update the ShakeMap (Figure 1

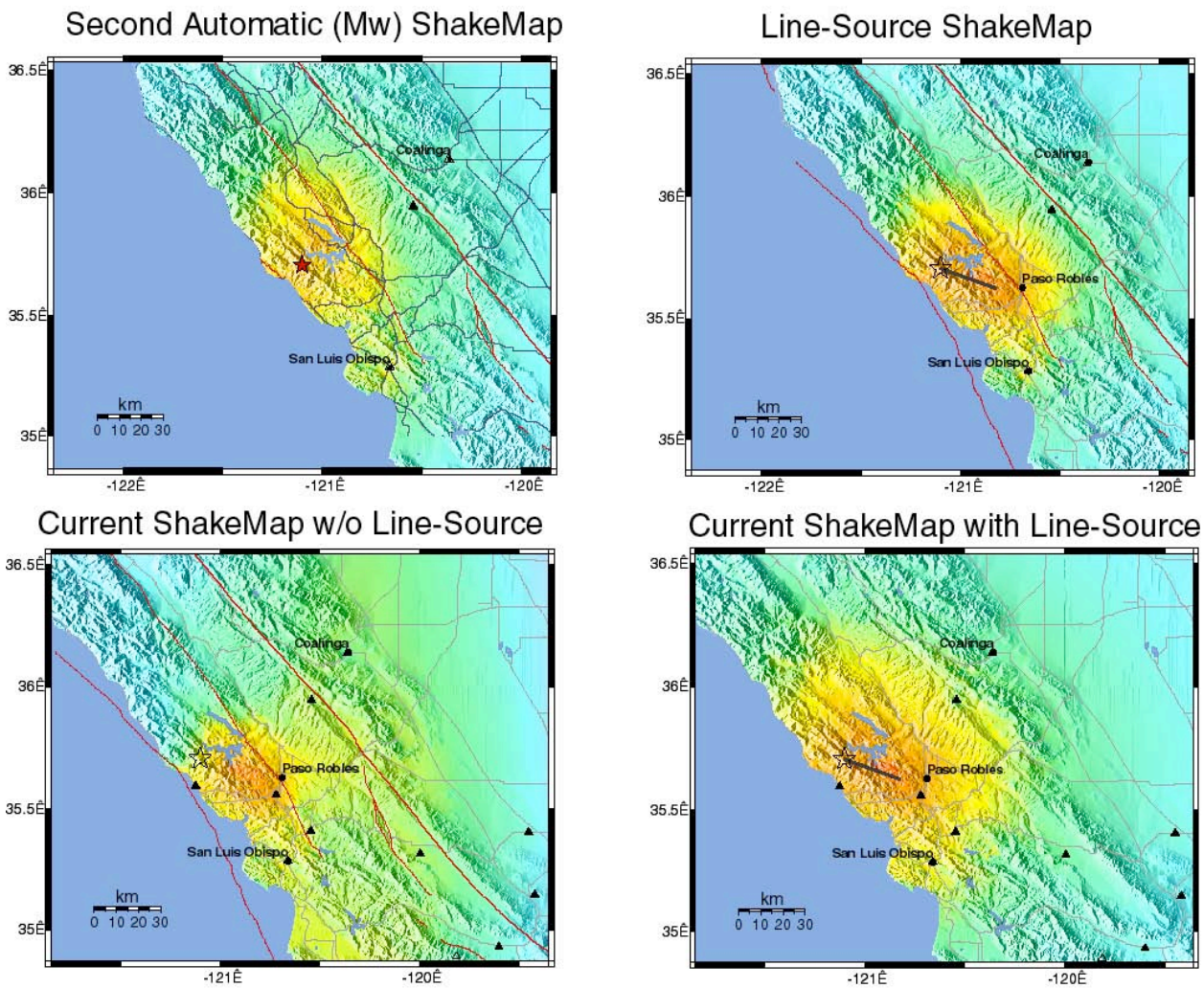
upper right). The favorable comparison of this corrected map (without near-fault stations) with one that incorporated near-fault stations (Figure 1 lower left) shows that the addition of finite-source information greatly improved the accuracy of the estimated ground motions southeast of the epicenter, and at a time when the near-fault data was not yet available.

The line-source ShakeMap was published several hours after the earthquake and was used to improve loss estimates by the California Office of Emergency Services (see The CISN San Simeon Report., 2004).

For more detailed information regarding the application of the developed method to the San Simeon earthquake see:

Hardebeck, J. L., et al. (2004). Preliminary report on the 22 December 2003, M6.5 San Simeon, California earthquake, Seism. Res. Lett., 75, 155-172.

CISN San Simeon Report (2004). Performance of the CISN during the 2003 San Simeon earthquake, http://www.cisn.org/docs/CISN_SanSimeon.pdf



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	*<.17*	*.17-1.4*	*1.4-3.9*	*3.9-9.2*	*9.2-18*	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	*16-31*	*31-60*	*60-116*	*>116*
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 1. Various intensity ShakeMaps. The epicenter is shown as a star, strong motion stations as triangles and the rupture extent as a thick black line. Upper left: automatic point-source ShakeMap. Because there are no nearby stations constraining the actual ground motion levels the estimated intensity is relatively low in Paso Robles inconsistent with the damage distribution and reported intensity (e.g. Hardebeck et al., 2004). Upper right: Intensity ShakeMap using the rupture extent determined by finite-source inversion to compute distances. The estimated intensity is greater near the fault and extends southeast to Paso Robles. Lower left: ShakeMap updated by adding non-telemetered near-fault data (e.g. the Templeton station is near Paso Robles). Lower right: The preferred and final ShakeMap that incorporates both the near-fault data and the finite-source information.

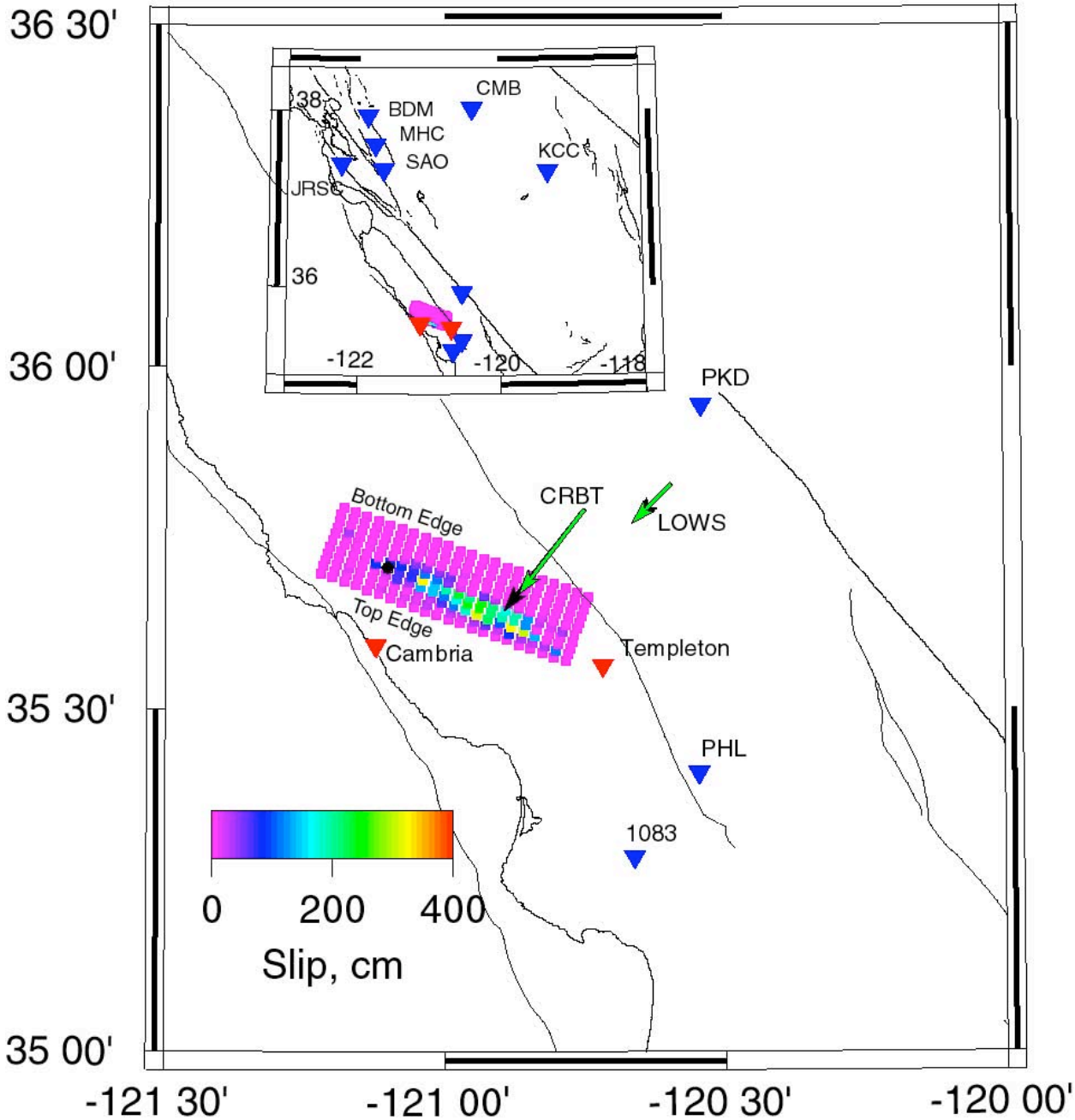


Figure 2. Map showing the locations of seismic stations (inverted triangles), observed (black arrows) and predicted (Green arrows) GPS deformation, and the slip distribution obtained by simultaneously inverting the seismic and geodetic data. The black circle shows the epicenter. Note that the slip extends about 25 km to the SE toward Templeton and nearby Paso Robles.

5. Methodology employed.

The method is described in the following publications that are available online.

Dreger, D. S. and A. Kaverina (2000). Seismic remote sensing for the earthquake source process and near-source strong shaking: a case study of the October 16, 1999 Hector Mine earthquake, *Geophys. Res. Lett.*, 27, 1941-1944.
http://www.seismo.berkeley.edu/~dreger/1999GL011245.pdf

Kaverina, A., D. Dreger, and E. Price (2002). The combined inversion of seismic and geodetic data for the source process of the 16 October, 1999, Mw7.1 Hector Mine, California, earthquake, *Bull. Seism. Soc. Am*. 92, 1266-1280.
http://www.seismo.berkeley.edu/~dreger/kaverina-etal-bssa2002.pdf

6. Other related work conducted within and/or outside PEER

Funding for some aspects of the realtime implementation of this system came from the California Office of Emergency Services. Funding for the initial conceptual work and the development of the regional distance finite-source methodology came from the USGS National Earthquake Hazards Mitigation Program.

7. Recommendations for the future work

We are presently working on updating the method by incorporating near-realtime GPS data. The GPS data will be used independently to determine earthquake source parameters and to provide additional constraints in combination with seismic waveform data. This effort is being funded by the USGS National Earthquake Hazards Mitigation Program.

Future work should include an investigation of methods for the simulation of high frequency strong ground motions from finite-source models, the development of a method for the utilization of GPS derived finite-source models for near-fault strong ground motion simulation, as well as refinements to the analyst interface. Additionally, various moment tensor improvements may be made to extract finite-source and directivity information more quickly, albeit at lower resolution. Dr. Spudich's isochron directivity method should be incorporated to improve strong ground motion estimates from the derived finite-source models.

8. Author(s), Title, and Date for the final report for this project

Dreger, D. S., A. Kaverina, P. Lombard, L. Gee and D. Neuhauser, Development of Procedures for Rapid Estimation of Ground Motions, February 2002.