PEER

5th Year Progress Report

Volume II

Section B
Project Summaries

***Project Title*—ID Number**	*Adoption and Implementation Considerations for Performance-Based Earthquake Engineering (PBEE)*—**1152001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/00—9/30/02	Current Year Budget Funding Source	$35,000.00 NSF
Project Leader (boldface) and Other Team Members	**Peter May (UW/F)**, Chris Koski (UW/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

This project is aimed at identifying barriers for adoption and implementation of performance-based earthquake engineering (PBEE). The specific goals of this project are: (1) identify a set of past earthquake engineering innovations that are useful for thinking about PBEE prospects; and (2) document from secondary sources the factors that influenced their adoption and implementation.

Methodology employed

The research employs case studies of earthquake engineering innovations as supplemented by literature review of the relevant literature on adoption and implementation of innovations.

Role of this project in supporting PEER's strategic plan

This study contributes to thinking about the steps that PEER and other organizations need to take in order to enhance the adoption and implementation of PBEE methods and products.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

The research entailed a review of the literature on diffusion of innovations and a set of case studies concerning earthquake innovations. Three cases have been selected for this study: (1) Seismic (base) isolation as an example of a methodology/technology that took a long period of time to gain currency, reflective of differences of opinions about the approach and cost of implementing it; and (3) Load and Resistance Factor Design (LRFD) as a methodology for engineering that serves as a basis for much of the thinking about PBEE; and (3) PBEE as a methodology that has been evolving and is the foci of PEER research. Secondary data have been collected for each of the cases and working papers have been authored concerning the initial findings.

The main accomplishment for Year 5 will be completion of a PEER report that describes prospects and issues for PBEE adoption and diffusion.

Plans for Year 6 *(if project is proposed to continue)*

Project will end in Year 5.

Other relevant work being conducted within and outside PEER and how this project differs

MCEER has funded research on "Incentives and Impediments for Adoption of Structural Innovations." This research addresses the adoption of seismic improvements by firms/organizations – with particular attention to hospitals in southern California -- and policy innovations by communities. While the foci of the MCEER work differs from that of this PEER project, the generic issues of adoption, innovation, and diffusion are similar. There has been close communication with these researchers and a sharing of working papers.

Expected milestones

PEER report to be completed by end of year 5.

Deliverables

PEER report and related conference papers/presentations:

"Thinking Ahead: Issues for Adoption of PBEE," Presentation at the PEER Annual Meeting, Oakland, January 2002.

"Going Beyond Earthquake Life-Safety: Reconsidering Performance-Based Earthquake Engineering," Paper presented at the XVth International Sociological Association, World Congress of Sociology, Brisbane, Australia, July 7-13, 2002

***Project Title*—ID Number**	*Assessing the Benefits and Costs of PBEE*—**1162001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/98—9/30/02	Current Year Budget Funding Source	$70,000.00 NSF
Project Leader (boldface) and Other Team Members	**Richard Zerbe (UW/F)**, Stephanie Chang (UW/F), Anthony Falit-Baiamonte (UW/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The overall objective of this multi-year project is to develop and demonstrate a benefit-cost analysis protocol for performance-based earthquake engineering (PBEE).

Methodology employed

In the current reporting year, we have been expanding the benefit-cost protocol in parallel with gathering empirical data from the 2001 Nisqually earthquake. Protocol development has included work on the sources of uncertainty and how they can be treated in a benefit-cost framework. It is also addressing the issue of how the perspectives of multiple groups of stakeholders (e.g., building owners versus occupants) can be incorporated in benefit-cost analysis.

Data collection is intended to support the protocol development. It will improve our ability to formulate appropriate decision variables for a benefit-cost analysis of PBEE efforts for buildings, as well as enable us to develop realistic, empirically supported examples. The methodological approach involves conducting in-person interviews with business managers/owners (building occupants) and building owners who were impacted by the 2001 Nisqually earthquake. The survey gathers an essentially complete sample of businesses in 2 of the hardest-hit business districts in Seattle.

Role of this project in supporting PEER's strategic plan

This project contributes to PEER's overall research framework by examining the relevance of benefit-cost analysis, a key decision tool, in evaluating PBEE efforts. We have developed a benefit-cost protocol for PBEE and applied it to the case of marine ports. In this reporting year, our emphasis has been on expanding the protocol to the case of buildings. Results will enable us to contribute to PEER's science building testbed.

Year 5 accomplishments and brief description of Year 4 accomplishments *(if continuation)*

- Two papers have been developed dealing with the issue of inclusion of moral sentiments in benefit cost analysis. One of these has been presented at a symposium on environmental economics in London in the summer of 2001. The other more theoretical paper will be presented at two conferences this June and July. The June conference is at the Second World Congress on Environmental and Resource Economics. The July conference is the annual meeting of the Western Economic Association. The implication for earthquake lies in an enhanced valuation for buildings due to historic preservation values. One of these papers is being published in *Research in Law and Economics*. The more theoretical paper has been submitted to an economics journal. In addition, another paper has been started on the precautionary principle in earthquake decision-making.

- A PEER Synthesis report has been completed on benefit-cost analysis for PBEE. This peer-reviewed report is in press. Some of the material developed as part of the PEER research is being incorporated into a benefit cost primer to be used as a textbook.

- We have completed data collection for businesses impacted by the Nisqually earthquake. Data analysis has yielded new insights on how business losses are influenced by building damage and other factors. We have presented findings at the Cascadia Regional Earthquake Working Group (CREW) conference, the PEER annual meeting, and the Association of American Geographers annual meeting. A journal article has been submitted for review.

Plans for Year 6 *(if project is proposed to continue)*

We anticipate completing this project in Year 5. However, we are proposing to follow up on important issues emerging from this project in Year 6. Specifically, we propose to develop a model of how individual choices about building performance may have unintended consequences for neighboring buildings and stakeholders. This would be applied to PEER's UCB Campus testbed. In addition, we propose to expand our work on stakeholder perspectives and on decision-making under uncertainty.

Other relevant work being conducted within and outside PEER and how this project differs

We are aware of (and in some cases involved in) other projects that are collecting data from the Nisqually earthquake; however, the current work is unique in being a detailed study of businesses in the Pioneer Square and SoDo areas, in gathering data on impacts and perspectives of multiple stakeholder groups in the same area, and in attempting to integrate the findings into a benefit-cost framework for PBEE assessment. Similarly, there has been very little work in the benefit-cost literature on multiple stakeholder perspectives or on uncertainty in the hazards context.

Expected milestones

- Building owner survey completed.
- Discussion paper written on PBEE decision variables for buildings and their incorporation in a benefit-cost framework.
- Background paper written on uncertainty in benefit-cost analysis.

Deliverables

- Discussion papers as noted above.
- Final technical report.

***Project Title*—ID Number**	*Organizational Decision Processes for Earthquake Mitigation* — **1172001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/00—9/30/02	Current Year Budget Funding Source	$70,000.00 NSF
Project Leader (boldface) and Other Team Members	**Jacqueline Meszaros (UW/F)**, Ufuk Ince (UW/F)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

- To understand which of several already-identified financial models best describe how managers from different industries and different functions frame earthquake-mitigation decisions.
- To understand the tradeoffs managers tend to make with regard to performance-focused mitigation and insurance opportunities.
- To model the implications of these frames and tradeoffs for some performance-based earthquake engineering measures.

Methodology employed

Case studies, surveys, literature review, Monte Carlo simulation.

Role of this project in supporting PEER's strategic plan

-This work provides a link between the PBEE framework and actual decision processes in firms (i.e., potential adopters of PBEE mitigation strategies).
-Provide background to enable better communication between engineers and firms with regard to earthquake mitigation needs and strategies.

Year 5 accomplishments and brief description of Year 4 accomplishments *(if continuation)*

- *Model of organizational decision processes related to mitigation investments*
  Based on case study research conducted over the previous two years, this model captures the heuristics and decision processes that many for-profit organizations seem to rely upon when making decisions about large investments to prevent losses. The results should be useful both to firms seeking to make the best possible decisions and to engineers seeking to communicate with firms about investments in earthquake mitigation.

- *Review of financial investment-assessment models pertinent to earthquake mitigation*
  The principal financial models firms use for capital investment projects focus primarily on anticipated gains. Since investments for earthquake mitigation focus primarily on prevention of losses, we have identified financial tools and approaches that are currently used in industry (i.e., that are familiar to practicing managers) that may be appropriate for earthquake mitigation investment decisions. These are to be used in simulations on the Van Nuys Testbed to identify the relative attractiveness of various mitigation options.

Knowledge Advancement in Years 3 and 4:

- *Communicating about Earthquake Mitigation Options*
  Based on a review of literature on biases in heuristics in decisions about low-probability, high-consequence risks, we explain how practicing managers are likely to respond to

information about such risks in hopes of enabling more effective communication between engineers and clients.

- *Lessons from Nisqually: High-impact Neighborhoods*
  We interviewed approximately half the merchants in a neighborhood in Olympia, WA, that was seriously affected by the Nisqually earthquake in order to characterize the lessons the merchants had drawn about possible future earthquakes and mitigation as a result of their experience.

- *Lessons from Nisqually: Small Businesses in the Puget Sound Region*
  We surveyed over 900 CEOs of small businesses throughout the Puget Sound Region in order to explore the lessons the CEOs drew about risks of future earthquakes and their intent to mitigate as a result of their experience. Finally, we explored some dispositional traits in order to assess which of these may contribute to risk perceptions and mitigation propensity.

Plans for Year 6 *(if project is proposed to continue)*

-Continued support of Van Nuys testbed, including financial simulation.
-Reliability studies assessing the organizational and financial decision models developed so far based on case studies.

Other relevant work being conducted within and outside PEER and how this project differs

Surveys of losses from the Nisqually Earthquake, for the Economic Development Authority, Department of Commerce. These surveys focus on economic impacts and losses. Work for PEER focuses on effects on risk perceptions and propensity to mitigate. The same samples are involved.

Expected milestones

- Working paper 1: describing organizational decision models based on case studies.
- Working paper 2: describing financial models based on literature review and case studies.
- Working paper 3: describing the application of financial models to the Van Nuys testbed.

Deliverables

- Paper 1 above: 7/31/2002
- Paper 2 above: 8/31/02
- Paper 3 above: 10/15/02
- The simulation has been initiated and is undergoing continual refinement in collaboration with other Van Nuys researchers.

***Project Title*—ID Number**	*Building Loss Assessment*—**1182001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$70,000.00 NSF
Project Leader (boldface) and Other Team Members	**Eduardo Miranda (Stanford/F)**, Hesameddin Aslani (Stanford/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The main objective in this project is to develop a methodology to estimate the expected annual loss in buildings. Instead of having discrete qualitatively performance levels of a structure, this project describes the seismic performance of the building in a continuum way, and more specifically in terms of annual dollar losses. Emphasis is on losses associated with damage to structural components. This project is being conducted in connection with a PEER testbed structure consisting of a seven-story reinforced concrete testbed. Loss estimation associated to non-structural components is being conducted in another project (Project # 5242001).

Methodology employed

The methodology employed in this project involves five main "steps": (1) Estimation of the seismic hazard at the site; (2) Estimation of structural response parameters at different locations of the structure as a function of the ground motion intensity; (3) Estimation of the level of physical damage (damage state) in each component as a function of structural response parameters; (4) Estimation of the economic loss in each component associated with each damage state; (5) Estimation of the expected annual losses in the building as a function of the loss in each component. The methodology follows a fully probabilistic approach in each of these five "steps".

Role of this project in supporting PEER's strategic plan

One of the main strategic plans of the Pacific Earthquake Engineering Research (PEER) Center is developing a methodology to provide improved information about the seismic performance of structures in order to help owners, financial institutions and other interested parties make better decisions regarding their structures. This project aims to implement PEER's performance methodology using a component-based approach. The methodology is fully probabilistic and permit the explicit incorporation of various sources of uncertainty in the estimation of earthquakes losses.

Year 5 accomplishments and brief description of Year 4 accomplishments *(if continuation)*

One key step in building loss assessment is to develop functions relating the structural response to the physical damage in the components. The structural response in this project is described in terms of Engineering Demand Parameters. The main EDP's considered in this study are the peak interstory drift ratio at each story and the peak absolute floor acceleration at each floor level.

The main effort in year 4 has been devoted to obtain a probabilistic estimate of the building seismic response as a function of the ground motion intensity. A procedure has been proposed that can be applied to any structure to estimate the probability parameters of any EDP of interest.

In year 5, efforts have concentrated on the development of motion-damage relationships in structural components with special emphasis on structural components present in the Van Nuys 7-story reinforced concrete testbed structure. Physical damage described in terms of discrete damage states referred generically as damage measures, DM's. The DM's have carefully been selected based on the course of actions required to be taken to either repair or replace the component.

The probability of exceeding a damage state conditioned on the EDP has been presented in terms of fragility functions. In connection with the Van Nuys testbed structure, fragility functions of three types of structural components are being developed: slab-column connections, beam-column connections and columns. At this point the fragility functions for the slab-column connections have been completed and the fragility functions for beam-column connections are currently under development.

The approach to develop fragility functions for structural components is based on the results of experimental programs that provide information on the physical damage in the component as a function of the component deformation. The family of fragility functions developed for slab-column connections are based on the results of 8 experimental programs, including a total of 73 specimens. For each specimen 4 different damage states were identified. Two of the damage states are expressed as a function of the level of gravity load on the slab-column connection. The fragility functions that have been developed permit the estimation of the probability of being in one of four damage states as a function of the interstory drift ratio to which the slab-column connection is subjected to.

Plans for Year 6 *(if project is proposed to continue)*

Development of damage-cost functions relating the cost of repair/replacement as a function of previously defined damage measures for each component. Uncertainty propagation.

Other relevant work being conducted within and outside PEER and how this project differs

Current Performance-Based Earthquake Engineering approaches consist on verifying 3 or 4 discrete performance levels of the structure (e.g. operational, immediate occupancy, life safety, near collapse) when subjected to discrete levels of ground motion intensity (e.g. frequent, rare, very rare). However, no clear connection exists between the performance of individual components and the performance of the whole structure. This project is aimed at expressing performance as dollars losses in the whole building and in a continuum way. Hence providing a variation of the expected value of the loss as a function of the ground motion intensity level and the expected annual loss.

Expected milestones

- Damage-motion relationships for beam-column connections. June, 15, 2002
- Damage motion relationships for columns. September, 30, 2002

Deliverables

Damage-motion relationships for slab-column connections, beam-column connections and columns of the testbed structure.

***Project Title*—ID Number**	*Building Loss Assessment*—**1192001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 9/2/98—9/30/02	Current Year Budget Funding Source	$50,000.00 CA-General
Project Leader (boldface) and Other Team Members	**Mary Comerio (UCB/F)**, John Stallmeyer (UCB/GS), Kenny Hung (UCB/GS), Young Im Kim (UCB/GS), Sophia Lau (UCB/GS), Alidad Hashemi (UCB/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The overall goals for this project were 1) to model the potential losses in three earthquake scenarios affecting the UC Berkeley campus, 2) to study the economic impacts of various earthquake scenarios on the university, 3) to develop a method for surveying and classifying nonstructural contents and conditions in a modern science building, 4) to design and estimate costs for a nonstructural retrofit of the science building, and 5) to develop a manual on the mitigation of nonstructural hazards in existing and new laboratory buildings.

The project was primarily funded by the Federal Emergency Management Agency and the University of California, Berkeley. The loss estimate and economic impact study involved numerous faculty and professional consultants. These included Professor Emeritus, Vitelmo Bertero, Degenkolb Engineers, Forell Elsesser, and Rutherford and Chekene, and Davis Langdon Adamson, as cost consultants, on the loss study. Professor John Quigley, worked with consultants Lynn Sedway Associates, and George Goldman on the economic impacts. The loss estimate and economic impact report has been widely published.

The survey of contents and retrofit designs for a modern concrete shear wall science building are planned for completion in the Fall of 2002. This building has been chosen to be part of the PEER testbed research. In this project, PEER has supported the development of the Manual for Mitigation of Hazards in Laboratory Buildings and this will also be complete in Fall, 2002.

Methodology employed

In this project, the data collected on testbed building contents will be sorted according to four categories: 1) importance to researchers, 2) value, 3) life safety hazard and 4) chemical hazard. This will allow for a hierarchy of retrofit needs. The contents will also be coded according to the results of a previous PEER study on the costs of retrofit for laboratory contents (Year 4 Project 1082000). The PEER portion of this project will then use the results of the work on the testbed building to devise a Manual to describe generic solutions to the retrofit of laboratory contents and present examples of how to apply these guidelines in new and existing buildings.

Role of this project in supporting PEER's strategic plan

This PEER funded project will publish the results of the larger effort supported by FEMA and UC Berkeley to develop retrofit designs and cost estimates for the contents of laboratory buildings. The project is a part of the overall effort of the LSA testbed—designed to use real facilities to assess the strengths and weaknesses in the implementation of the PEER methodology. The LSA testbed uses a modern, and seismically sound building to assess the potential for losses in nonstructural elements and contents, through engineering evaluations and shake table tests, as well as the calibration of loss models.

Year 5 accomplishments and brief description of Year 4 accomplishments *(if continuation)*

The Economic Benefits of a Disaster Resistant University: Earthquake Loss Estimation for UC Berkeley was published by the PI in April 2000.

Nonstructual Loss Estimation: The UC Berkeley Case Study will be published as a PEER Report # 2002-01 (forthcoming).

The data collection and inventory is complete, and work is progressing on the retrofit designs, costs, and the Manual.

Plans for Year 6 *(if project is proposed to continue)*

Other testbed work will be funded in Year 6, but this project will be complete at the end of year 5.

Other relevant work being conducted within and outside PEER and how this project differs

The US Department of the Interior Seismic Safety Program has put out "Nonstructural Hazards Rehabilitation Guidelines" on October 2001. This is a binder of Xerox copies of various products available for anchoring nonstructural systems and contents. No research is being conducted on the performance of these recommendations nor is research being done on how these solutions change the potential for losses after installation. The PEER program is the only effort to address these systematically.

Expected milestones

- The LSA Nonstructural Report will be completed in Fall 2002.
- The Manual funded in Year 5 by PEER will be ready in Fall 2002.

Deliverables

A publishable report on the retrofit of laboratory contents.

***Project Title*—ID Number**	*Nonstructural Hazard Mitigation in Life Sciences Building Testbed*—**1202001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$50,000.00 CA-General
Project Leader (boldface) and Other Team Members	**Mary Comerio (UCB/F)**, John Stallmeyer (UCB/GS), Ryan Smith (UCB/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

As manager of the LSA testbed, the PI will coordinate the activities of the various researchers contributing to this demonstration project. This includes those directly funded for testbed research (Khalid Mosalam, Nicos Makris, Tara Hutchinson, and Jim Beck) as well as those with related projects (Filip Filipou, Stephanie Chang, John Ellwood). The second goal is to evaluate the degree of uncertainty contributed to the overall losses estimated for the UC campus by nonstructural components and contents. The data from the LSA project will provide the first building data that may allow some calibration of the loss model.

Methodology employed

Data from the shake table tests will be used to re-calibrate the loss to contents in the PI's model for loss estimation for a campus facility.

Role of this project in supporting PEER's strategic plan

This is a critical component of the demonstration of the effectiveness of the PEER methodology. This project begins to define the data needed to evaluate the effectiveness of performance engineering on capital expenditures and operating costs.

Year 5 accomplishments and brief description of Year 4 accomplishments *(if continuation)*

Past year's accomplishments are detailed in Project #1192001. To date, Mosalam has completed an analysis of the LSA building in Open Sees, and Makris and Hutchinson are preparing their test plans. I am working with Beck on loss-modeling issues, and preparing the data sheets to accept new information from LSA and from other researchers.

Plans for Year 6 *(if project is proposed to continue)*

Not planned to continue in year 6 at this time.

Other relevant work being conducted within and outside PEER and how this project differs

Prof. Jim Beck is working on loss modeling that he has applied to other building types and attempting to make it useful to the analysis of any campus of buildings. This project is scenario-based, and Beck's is probabilistic.

Expected milestones

Input of data into model at end of summer

Deliverables

Report on revised loss estimates and issues of uncertainty.

***Project Title*—ID Number**	*Regional Loss Modeling for Highway Network* —**1212001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$20,000.00 CA-Transportation
Project Leader (boldface) and Other Team Members	**Peter Gordon (USC/F)**, Donghwan An (USC/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

How can integrated earthquake loss modeling be done? How can it aid policy makers? The USC group has developed a spatially disaggregated economic impact model shows losses by small areas and is simultaneously responsive to damage of industrial and infrastructure capacity. That model, SCPM2 (Southern California Planning Model 2), is continuously being updated. Industrial losses reduce (and change) the demand for shipments and simultaneous highway network losses (in particular bridges and overpasses) reduce the capacity to complete such shipments.

As part of PEER's Testbeds effort, specifically the I-880 bridges study, the question has emerged whether a similar approach is feasible for the Bay Area. In an economy as complex as the 6.9 million population Bay Area, a major earthquake would engender elaborate substitutions of routes resulting in new system equilibrium flows and costs on thousands of highway links. This research is a "scoping study" that involves the identification of the necessary model building blocks. We have determined that the various data sets required to assemble such a model for the Bay Area are available or within reach.

Methodology employed

This scoping study involved the analysis of various suitable data files available for the Bay Area.

Role of this project in supporting PEER's strategic plan

PEER's current efforts are organized into various Testbed projects. As part of the I-880 Testbed, the question arose whether an integrated model for the Bay Area could be built to reliably estimate the economic impacts of I-880 bridge losses.

Year 5 accomplishments and brief description of Year 4 accomplishments *(if continuation)*

An integrated modeling approach would utilize bridge damage data and combine it with data on other losses to model a new highway network equilibrium that is consistent with a new regional economic equilibrium. Losses from reduced highway capacity and reduced productive capacity would be simultaneously modeled.

Plans for Year 6 *(if project is proposed to continue)*

This is a one-year "scoping" project. It has established the feasibility of integrated loss modeling for the Bay Area. Carrying out such an effort would probably be a two-year project.

Other relevant work being conducted within and outside PEER and how this project differs

See above allusions to useful results from A5. The only similar modeling known to us is the SCPM2 work for the Los Angeles metropolitan area, some of which has been supported by PEER in Project G4 (1999-103)

Expected milestones
A Final Report will be drafted and submitted by September 30.

Deliverables
The Final Report will fully describe all of the required data files and will include recommendations for their use in model construction.

Project Title—**ID Number**	*Building Performance and Loss Measures*—**1222001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$50,000.00 NSF
Project Leader (boldface) and Other Team Members	**James Beck (Caltech/F)**, Keith Porter (Caltech/F)*, Rustem Shaikhutdinov (Caltech/GS) **=not financially supported by project*		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

Develop and illustrate damage- and loss-analysis portions of PEER's PBEE methodology for modern structures with high-value equipment and contents. The important impacts of earthquake to this type of facility, and consequently the focuses of risk-management, are operational failure and life-safety failure associated with equipment and content damage. The overall objectives are to select the parameters of damage and decision-making, to develop a methodology for calculating these as a function of structural response, and to illustrate the methodology using the UC Science Building testbed.

In detail, we will select (parameterize) decision variables, denoted by DV, to measure these impacts, and in collaboration with PEER researchers performing equipment tests (Hutchinson and Makris), define the damage measures, denoted by DM, most closely associated with DV. We will coordinate with other PEER researchers who will select the measures of structural response, called engineering demand parameters (EDP), that are produced by PEER's structural analysis methodology, and that can be used to estimate DM.

Once EDP, DM, and DV are parameterized, they must be related mathematically. We will develop a methodology for evaluating p[DV|DM], where p[x|y] refers to the probability distribution of x conditioned on y. We will collaborate with Hutchison and Makris on a methodology for evaluating p[DM|EDP]. Desiderata for these methodologies:

- General applicability to this category of facilities;
- Not requiring technical skills far in advance of practitioners;
- Treat uncertainty and correlation among EDP, DM, and DV;
- Allow one to limit DV by controlling EDP.

This last is analogous to load and resistance factor design (LRFD), in which the DV is the probability of life-threatening damage, and the EDP is maximum force in a structural member or connection, under a (factored) loading condition (Ellingwood *et al.,* 1980). The member force is calculated and compared with a factored strength (or resistance). If factored force is less than factored resistance, the design is acceptable because it implies an acceptable DV, without explicit evaluation of DM or DV. Similarly, in a new PBEE methodology, it is hoped that one can calculate a factored EDP "demand" under seismic excitation that can be compared with a factored "capacity," where the capacity, denoted here by C, is the level of EDP at which the facility exceeds a performance level, namely operational failure or life-safety failure. If the inequality is met, it implies a satisfactory DV without the need to calculate DM and DV explicitly.

Methodology employed

Parameter selection: operational failure will be defined based on work performed by Comerio, who in collaboration with facility occupants has created a database of scheduled equipment, and identified those that are deemed operationally critical, and that pose a hazmat threat. We will use the database to identify categories of components that would represent life-safety threats from sliding or overturning, based on their size and weight. Two fault trees will be created, one with operational failure as the top event, the other with life-safety failure as the top event. The occurrence probability of the top events will comprise DV. Basic events will be the failure of individual pieces of equipment. The occurrence of basic events will comprise DM.

We will determine an expression for this top-event capacity for the UC science Building and for a few hypothetical facilities of varying number, redundancy, and capacities of equipment. We may use Monte Carlo simulation (MCS) or an analytical approach to expressing top-event capacity in terms of basic-event capacities.

Finally, in collaboration with PEER researchers working on structural analysis (Mosalam and others), we will express a reliability inequality in terms of structural demand (EDP) and facility capacity (C), and use reliability methods to determine the factors by which seismic excitation and component capacity can be multiplied to express the inequality, which, if satisfied, would indicate the facility failure probability to be less than some tolerable amount.

Role of this project in supporting PEER's strategic plan

This project will produce the first elucidation of the DM and DV analysis portions of PEER's methodology for this facility type, and part of the first end-to-end performance of the entire methodology for a real facility, illustrated in a single document. It will help to identify development needs for the methodology.

Year 5 accomplishments and brief description of Year 4 accomplishments *(if continuation)*

In year 4 we identified the dominant sources of uncertainty that effect the future repair cost of the Van Nuys testbed building (Porter *et al.*, 2002a,b). Our year-5 research has involved developing aspects of the basic fault-tree methodology. Our progress is now limited as we await results from other researchers working on the LSA testbed.

Plans for Year 6 *(if project is proposed to continue)*

The work described here will probably require continuance into year 6, with its reliance on data that is just becoming available or still to come from other testbed researchers.

Other relevant work being conducted within and outside PEER and how this project differs

PEER researchers are performing related work on the Van Nuys testbed. That work focuses on older facilities where the focus is on repair costs, repair duration, and collapse potential and not so much on the building contents. ASCE/FEMA 356 is also concerned with the overall performance of facilities, but its treatment of equipment systems is limited.

Expected milestones

Interim report in September, 2002, on the research described here.

Deliverables

Ongoing contribution through October 2003 to a joint report for the entire testbed.

***Project Title*—ID Number**	*Earthquake Risk Decision–Making in Lifeline Organizations* —**Lifelines 604**		
Current Year Start/End Dates	6/1/01—4/30/02	Current Year Budget Funding Source	$173,972.00 FEMA
Project Leader (boldface) and Other Team Members	**David Seaver (Batelle/I)**		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The overall goal of the proposed research is to better understand earthquake risk decision-making in the lifeline sector. The specific objective is to identify the decision processes, criteria, and heuristics that the managers in life line organizations use when deciding whether or not to invest in earthquake damage mitigation measures or other risk management strategies. This information can then be used to identify optimal models and processes for effective decision making by practicing utility, transportation, and other agency personnel.

Methodology employed

The methodology developed for this study had the following characteristics:

- The study focused on specific past earthquake risk decisions rather than general organizational decision processes
- A decision analysis framework was developed to identify key characteristics of the decisions that should be described and analyzed
- Specific issues relative to these decision characteristics were identified based on known decision biases and other descriptive information
- In-depth interviews were conducted to obtain the information about the decisions
- Multiple people with direct involvement in the decisions were interviewed

Using the decision analysis framework, the information to be obtained was identified. It focused on an overall description of the decision, the decision context, decision alternatives, decision criteria, uncertainties, and decision implementation. A detailed set of specific questions was developed to guide the interviews. The interviews were conducted by two interviewers, each with a background in decision analysis and were approximately one and a half hours in length.
The interviewees were selected for each decision by the organizational liaisons with advice from the project research team and from other staff within their organizations. They were selected based on their knowledge of and role in the specific decision. They were also selected to cover a range of perspectives on the decision.

Role of this project in supporting PEER's strategic plan

A realistic understanding of the key factors that drive the decisions made to implement earthquake risk reduction is necessary to provide the decision makers with the right types of information.

Year 5 accomplishments and brief description of Year 4 accomplishments *(if continuation)*

The project Advisory Group was formed, and 3 meetings with the group were held at various stages: to discuss the direction and execution of the project scope; to review the interview protocol and planning prior to the interviews; and to review the results of those interviews. A total of 26 interviews were conducted with personnel having different roles in the decision-making process -- at PG&E, two or three people were interviewed for each decision, for a total of 8. At Caltrans, five to nine people were interviewed for each decision, for a total of 18. Analysis and reporting of the conclusions from these interviews are ongoing.

Plans for Year 6 *(if project is proposed to continue)*

Other relevant work being conducted within and outside PEER and how this project differs

This project is a Pilot Study for potential further work in the area of decision making in Lifeline Organizations, and as such its results will figure into the scope and approach of the following work.

Expected milestones

- First Project Advisory Group Meeting – 4^{th} week of the project
- Second Project Advisory Group Meeting –10^{th} week
- Completion of interviews – as scheduled with subject organizations
- Final Project Advisory Group Meeting – following review of draft report

Deliverables

- Creation and chartering of the Project Advisory Group (AG)
- Report from the 1^{st} AG meeting
- Phase 1 Interview Protocol (for selected lifeline organization managers)
- Report from 2^{nd} AG Meeting
- Working paper describing outcome of pilot interviews
- Detailed plan for completing subsequent phases of the research program in report.

***Project Title*—ID Number**	*Simulation of Ground Deformation in OpenSees*—**2202001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$100,000.00 CA-Transportation
Project Leader (boldface) and Other Team Members	**Ahmed Elgamal (UCSD/F)**, Zhaohui Yang (UCSD/PD), Jinchi Lu (UCSD/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

- Implement solid-fluid fully coupled 2D (4-node and 9-node) quadrilateral elements in OpenSees.
- Further refine/calibrate soil constitutive models (already implemented in OpenSees), based on new data sets from laboratory sample tests and centrifuge experiments.
- Contribute to the Humboldt Bay Bridge Simulation Testbed.
- Assist OpenSees PEER users in using the newly developed geotechnical algorithms.

Methodology employed

Development and refinement of geotechnical and numerical algorithms within the PEER OpenSees Platform.

Role of this project in supporting PEER's strategic plan

- Provide geotechnical computational tools for computation of seismic demand on structures
- Complement the OpenSees Platform with geotechnical capabilities.
- Develop numerical tools for simulation of ground deformations from the PBEE point of view.
- Allow for computational simulation of PEER Bridge Testbeds in a comprehensive ground-foundation-bridge modeling framework.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

In Year 4, a total of 3 soil constitutive models were included in OpenSees. These models are capable of representing cohesionless and cohesive static/seismic soil response. Unique capabilities are included for modeling of liquefaction and associated ground deformation.

In Year 5, solid-fluid fully coupled plane-strain elements are being added into OpenSees. Combined with the soil constitutive models, the new elements provide capabilities of simulating generation/dissipation of pore pressure and liquefaction-related large shear deformations. This will allow for modeling a broad range of soil and soil-foundation-structure interaction scenarios. The above numerical developments are playing a major role in the PEER Testbed studies, and are being employed by many PEER researchers at UCB, UCD, UCSD, U. Washington and elsewhere.

Plans for Year 6 *(if project is proposed to continue)*

- Develop/Implement procedures for spatial definition of input ground motion.
- Further verify and calibrate the soil constitutive models using the UC Berkeley laboratory testing data and Centrifuge ground remediation Centrifuge research.
- Contribute to the Humboldt Bay Testbed computational simulation efforts.
- Work with Professor Greg Fenves on implementation of a Parallel version of OpenSees at the San Diego Supercomputing Center.
- Work towards development of 3-dimensional geotechnical computational simulation capabilities in OpenSees (coupled solid-fluid formulation).

Other relevant work being conducted within and outside PEER and how this project differs

Solid-fluid fully coupled Finite Element formulations are an effective means for advanced computational simulations of soil response. Coupled formulations have been employed extensively in the geotechnical engineering community. In OpenSees, such rigorous geotechnical formulations are combined with a large number of readily available state-of-the-art structural elements and materials. In this regard, OpenSees is becoming the most advanced Platform for simulation of seismic response of soil-structure systems.

Expected milestones

- Jan. 02: Implement coupled formulation for 4-node quadrilateral element. Refine Humboldt Bay Bridge model to include detailed modeling of soil-structure-interaction (SSI) and transmitting boundary effects.
- March 02: Test/calibrate the coupled element along with soil models. Test/calibrate the entire Humboldt Bay Bridge model using actual earthquake records.
- May 02: Analyze Bridge model simulation results. Refinement of the Bridge model. Implement coupled formulation for 9-node plane-strain element.
- August 02: Compare analyses using 4-node vs. 9-node elements, and coupled vs. uncoupled elements.
- Sep. 02: Documentation.
- Throughout project: Assist PEER users in conducting computational simulations using the developed geotechnical algorithms.

Deliverables

Calibrated and verified geotechnical and soil-structural interaction numerical algorithms within OpenSees, for use by the PEER community and by others worldwide.

***Project Title*—ID Number**	*3D Soil Simulation Models in OpenSees*—**2212001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$55,000.00 CA-Transportation
Project Leader (boldface) and Other Team Members	**Boris Jeremic (UCD/F)**, Zhaohui Yang (UCD/GS), Xiaoyan Wu (UCD/GS), Kevin Murakoshi (UCD/US)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

1) Develop three dimensional, elastic-plastic formulation and implementation for OpenSees. Develop a number of test examples and theory, implementation and user's manuals.
2) Develop formulation and implementation for three dimensional, fully coupled, solid-fluid (multi-physics) capabilities for OpenSees. Develop a number of test examples and theory, implementation and user's manuals.
3) Develop a series of models, models database and simulations for 3D soil-structure interaction analysis. The models vary in complexity and are organized in an emerging database of models, elements and simulation procedures.
4) Continue testing and performance improvement of the OpenSees code. Perform testing on regular basis and publish various testing results on the web.

Methodology employed

The methodology used for this project can be characterized by our aim to accomplish both the von Neumann computability, and the Turing computability. The von Neumann, or physical problem computability refers to how well a physical process can be computed or how well a simulation can predict the response of a mechanical system. In this sense our work on

a) elastic-plastic template computations,
b) fully coupled, solid-fluid computations, and
c) analysis of large scale soil-structure interaction problems,

represent a step forward in employing a rigorous, rational mechanics formulation and it's implementation in order to accurately predict the response of infrastructure system during earthquake event. The Turing, or computer science computability problem refers to the existence of an algorithm that can solve the discretized problem in a finite number of steps.

Role of this project in supporting PEER's strategic plan

One of the main ingredients of the performance based earthquake engineering methodology is the assumption that there are available tools to perform accurate and detailed calculations of the infrastructure response to seismic excitations.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

Year 5 accomplishments (so far and planned)

1) completion of the formulation and implementation of the fully coupled, solid-fluid solid elements into OpenSees, and initial testing of the formulation for liquefaction analysis,
2) development of models and analysis of static and dynamic soil-structure interaction. Initial results are described in our publications (see bellow),
3) development of an initial database of models, elements and algorithms, to ease the simulation of complex finite element models,
4) initial development of a postprocessor system for solid models for OpenSees.

Year 4 accomplishments

1) implementation of nDarray tools and 3D solid elements into OpenSees,

2) development and implementation of Template Elastic-Plastic constitutive driver
3) initial development of the quality of implementation control tools for OpenSees,
4) initial analysis of soil-structure effects,

Plans for Year 6 ***(if project is proposed to continue)***

1) Development of the highly optimized version of OpenSees for sequential and parallel platforms. The issue of computational performance is becoming critical as we start to simulate testbed problems. This development will encompass the fine grain enhancements (speed-up of matrix, vector and tensor calculations) and the coarse grain speed-up (SMP and DMP parallelism),
2) Initial development of the grid aware version of OpenSees. As OpenSees becomes more popular within PEER (and around the world) it would benefit PEER projects if there are tools developed for OpenSees that would help researchers generate models and perform simulations using grid-aware OpenSees. This will make it possible to allow researchers to access to a full range of software and hardware tools and focus on the engineering problem at hand while leaving von Neumann and Turing computability problems (see above) to the OpenSees development team. This item is closely related to the item #1.
3) Continuing development of the database of models, elements, and algorithms. This item is closely related to the item #2 above.
4) Continuing development of models and analysis for static and dynamic soil-structure interaction. Development of a series of models with different sophistication, and demonstration of their capabilities and analysis of levels of model sophistication for given site conditions
5) Continuing development of a Joey3D postprocessor system for solid (and possibly structural) models for OpenSees. Work on portability (to include MS windows platforms, as Joey3D is based on OpenGL).

Other relevant work being conducted within and outside PEER and how this project differs

There are two somewhat similar projects within PEER

a) Professor Elgamal at UCSD is developing a 2D, locally undrained soil model
b) Professor Fenves at UCB is leading the OpenSees development team while mostly focusing on structural engineering applications. This project is focused on the development of methods and implementations for geomechanics, solids.

Expected milestones

1) initial SMP version of OpenSees by the end of 2002, continuing development through 2003,
2) work on DMP parallel OpenSees,
3) fine grain optimizations (matrix vector and tensor calculations) by spring 2003,
4) initial experiments with OpenSees-grid for testbed projects by winter 2003, continuing development through fall 2003,
5) initial experiments with the database of models, elements and algorithms by winter 2003, continuing through fall 2003,
6) initial public release of Joey3D by winter 2003, continuing development through fall 2003.

Deliverables

See above.

Project Title—ID Number	*Performance of Improved Ground*—**2222001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/98—9/30/02	Current Year Budget Funding Source	$40,000.00 CA-General
Project Leader (boldface) and Other Team Members	**Nicholas Sitar (UCB/F),** Elizabeth Hausler (UCB/GS), Corinne Cipiere (UCB/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The overall objective of this project is to improve and validate techniques for predicting the response of improved ground through a combination of physical tests and computer simulations. The project is anticipated as a two-year effort that will extend previous work on improved ground and leverage external resources and test data from related projects

Methodology employed

The overall project was subdivided into the following tasks

Task 1. Compilation and evaluation of quantitative data on the performance of improved sites during earthquakes, and the evaluation of field data on the influence on the thickness the improved layer on seismically induced ground deformations. Task is completed, and the report is published on the web at: http://www.ce.berkeley.edu/~hausler/casehistories.html

Task 2. Review of existing design guidelines, codes, and recommendations for remediation zone geometry and review of previous experimental work using centrifuge and shaking table models. This task was completed in early 2000 and it was an essential prerequisite for the experimental part of the research which was commenced in June 2000.

Task 3. Centrifuge modeling of the influence of the improved site geometry on the performance of the improved zone. This task consisted of 4 centrifuge experiments at the Center for Geoetchnical Modeling at UC Davis and 2 centrifuge experiments at the Public Works Research Institute in Tsukuba, Japan. This experimental program was completed in mid-2001.

The models tested at UC Davis consisted of baseline cases without improvement with and without structures, and cases with different remediation zone geometries with structures. The largest remediation zone penetrated the entire liquefiable thickness and extended laterally beyond the structures to a distance equal to the improved depth. Other model cases were constructed with remediation zone geometries half and one-quarter of the size of the largest zone. In prototype scale, all cases tested consisted of a 1 m bearing layer of dense sand overlain by 18 m of fine-grained Nevada sand and a 1 m layer of coarse nonliquefiable fill. The target relative density for improved areas of Nevada sand was 80%, unimproved 50%. The models tested at PWRI were used to evaluate the reproducibility of the Davis experiments and were funded by NSF. The whole experimental test program was completed in the summer of 2001.

Task 4. Observation and monitoring of a full-scale blast-induced liquefaction eperiment at Tokachi Port, Japan. This task was a direct result of the cooperative research with researchers at the Port and Airport Research Institute in Japan. The experiment involved the monitoring of 3 zones improved by in-situ mixing. Explosives were used to induce liquefaction in an 8m deep deposit of liquefiable soil.

Task 5. Interpretation and modeling of the experimental data. Empirical analysis and numerical analyses are currently being employed to interpret the experimental data in order to develop predictive tools for performance based design.

Role of this project in supporting PEER's strategic plan

Ground improvement is an essential step in dealing with mitigation of potential liquefaction hazard. The objective of the project has been to provide the necessary experimental and analytical foundation for a rational design of remedial measures and for the evaluation of their expected performance in the context of performance based design.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

Majority of the effort this last year was directed to the interpretation of the experimental data obtained from the centrifuge and field experiments. The field experiment in particular was very time intensive and the initial schedule, early October, ended up getting pushed into mid November as a result of the complexities of the experimental procedure experienced by the Japanese managers of the project. As a result, the analytical work has been somewhat delayed. We expect that all the analytical work on the interpretation of the centrifuge experiments will be completed by August 2002 and the interpretation of the field experiment will be completed by December 2002.

In addition, the preliminary numerical modeling of the centrifuge experiments is currently being completed.

Plans for Year 6 *(if project is proposed to continue)*

The preliminary analysis of the centrifuge data using total stress based model FLIP shows that accurate numerical predictions of deformations are not possible, unless we can model the pore pressure dissipation. Such model is currently being completed as a part of the PEER research. The centrifuge data is ideal for testing of the model and, more importantly, while we expect to have a set of empirical guidelines for design of remediation schemes, more accurate numerical modeling will be essential in order to take full advantage of performance based design. Thus, we propose to continue the numerical analyses of the centrifuge data using a fully coupled mode.

Other relevant work being conducted within and outside PEER and how this project differs

This project is being coordinated with an NSF Funded project entitled *Performance of Improved Ground Under Strong Seismic Loading*

Expected milestones

We expect to be able to show first tangible results of the coupled modeling effort by December 2002.

Deliverables

Elizabeth Hausler's dissertation and PEER report will be completed in August 2002.

A comparison of the UC Davis and PWRI experiments is being presented this summer at the International Conference on Physical Modelling in Geotechnics, St. John's, Newfoundland, Canada, July 10-12, 2002

Project Title—ID Number	*Field Test Data and Simulation of Pier Foundations*—**2232001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$40,000.00 CA-General
Project Leader (boldface) and Other Team Members	**Nicholas Sitar (UCB/F)**, Gang Wang (UCB/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The current project objective is to document and analyze data from a series of full-scale pier tests which were conducted as part of a seismic rehabilitation and construction program at the U.C. Berkeley campus in the Fall of 2001. The focus of these tests (and this research project) was the axial response of piers to earthquake-induced forces. Axial pier response is a commonly encountered question in both rehabilitation and new design of buildings, where piers are used to support walls or other structural elements subjected to large overturning forces. The traditional design, however, is based solely on the results of static tests and, consequently, the design parameters tend to be exceedingly conservative. The expectation is that by developing rational quantitative measures of dynamic pier response, it will be possible to optimize the design and introduce significant cost savings and efficiencies in the overall seismic design.

Methodology employed

Six prototype drilled piers were instrumented and tested by UC Berkeley using a dynamic pile load tester. The piers were instrumented with strain gauges and accelerometers so that the actual dynamic deformations could be measured during the load application.

Role of this project in supporting PEER's strategic plan

Soil-structure interaction is an essential part of performance based design in all types of structures. Since piers and/or piles are typically used to handle uplift loads on most of multi-story structures, this project has a very broad applicability.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

Extensive data set was collected as a part of the UC Berkeley test program. The tests showed that the dynamic axial capacity of the piers was roughly three times as large as estimated by conventional methods and the dynamic stiffness was at least twice as large as predicted. The data collected during the tests are being analyzed to identify the basic parameters governing the pier response and to develop a database suitable for numerical modeling of the pier response.

Plans for Year 6 *(if project is proposed to continue)*

The logical extension of this initial phase of data collection and data analysis is to develop appropriate predictive tools. Thus, the next step is to use a numerical model to analyze the observed response and then use this model to make predictions for the purposes of performance based design. Since, UC Berkeley, has now adopted the PLT test as a standard test to be performed as future projects come on line, there will be several opportunities to obtain actual field data for model calibration and verification with very low cost to the PEER project.

Other relevant work being conducted within and outside PEER and how this project differs

None that Principal Investigator is aware of.

Expected milestones
The field test data has already been collected. The basic interpretation of the data and preliminary numerical analyses should be completed by the end of August 2002.

Deliverables
A PEER report containing the data from the tests and data interpretation will be completed by the end of September 2002.

***Project Title*—ID Number**	*Identification and Prediction of Performance-Related Ground Motion*—**2242001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 5/1/00—9/30/02	Current Year Budget Funding Source	$25,000.00 CA-Transportation
Project Leader (boldface) and Other Team Members	**Jonathan Bray (UCB/F)**, Thaleia Tavarsarou (UCB/GS), Norman Abrahamson (PG&E/I)* **=not financially supported by project*		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The objectives of this research project are two-fold: (1) to identify those ground motion parameters that best correlate to the performance of soils, foundations, and structures, and (2) to develop empirical predictive relationships for those parameters. The project builds upon previous work completed by PEER researchers identifying ground motion parameters that are good indicators of damage, and it completes aspects of previous work on near-fault seismic site effects.

Methodology employed

The previously stated research objectives are satisfied as follows. First, the engineering demand parameters that are related to particular structural and geotechnical problems were identified. Next, their correlation to specific ground motion intensity measures was explored. Ground motion parameters that are best correlated to the corresponding demand parameters were identified. Lastly, regression analyses are performed to estimate their variation depending on key factors such as magnitude, distance, and site conditions.

The identification of damage parameters was carried out through a comprehensive literature review and by receiving input from other PEER researchers. The meeting at the PEER Annual Conference on this topic was extremely helpful in this regard. An additional focused meeting was held on April 26, 2002 with fewer participants to refine this process and to develop consensus regarding the most promising IMs and EDPs. For example, the inter-story drift imposed on a structure by an earthquake excitation is judged to be closely related to the incipient level of damage and hence a good EDP. In geotechnical engineering, the seismically induced permanent displacement is probably the most appropriate EDP for slope stability problems, and the liquefaction factor of safety or the level of earthquake-generated excess pore pressures are better related to the performance of sites that could potentially liquefy. The ground motion intensity parameter that is traditionally correlated with the dynamic response of structures is the spectral acceleration at the fundamental period of the structure (S_A). Other spectral combinations and vectors, as well as ground motion parameters such as Arias Intensity, peak ground velocity (PGV), and pulse period, were also identified as promising IMs. Procedures for evaluating the efficiency and sufficiency of IMs were outlined.

Role of this project in supporting PEER's strategic plan

As suggested by the hazard integral of the PEER performance-based engineering framework, it is essential to quantify the conditional probability of the engineering demand parameter (EDP), such as inter-story drift or seismic displacement, exceeding a certain value given a ground motion intensity measure (IM), such as spectral acceleration or Arias Intensity, to compute the rate of exceedance of a threshold value by a specified damage measure. This intensity measure, or equivalently ground motion parameter, should be well correlated with the engineering demand parameter in question. This project identifies IMs that can efficiently estimate EDPs, and then develops attenuation relationships for these IMs, which other PEER researchers can employ in their research and which engineers can use in practice.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

Initially this research project focused on the development of empirical predictive relationships for velocity related parameters such as the PGV and pulse period for the near-fault case. The ground motion database that was used included records from the recent earthquakes in Turkey and Taiwan. Having as a reference the problem of slope stability, a sensitivity study was conducted to identify ground motion parameters or sets of ground motion parameters that when correlated with seismically induced permanent displacement result in a significant reduction of the scatter of the calculated displacement. Arias Intensity was found to be a useful parameter for this problem as well as for structural response analyses of stiff systems, so an empirical attenuation relationship for Arias Intensity was developed and provided to PEER researchers.

Plans for Year 6 *(if project is proposed to continue)*

N/A

Other relevant work being conducted within and outside PEER and how this project differs

The PEER-sponsored workshops and meetings have been useful in helping us explore key issues and identify preliminary ground motion parameters of interest to structural and geotechnical researchers. The April 26, 2002 focused meeting of 11 PEER researchers involved in the EDP/IM problem allowed each of us to share preliminary findings, identify promising IMs and EDPs, and to discuss procedures for evaluating IMs.

Similar work is not being currently performed outside of PEER by the PI. In the past, research was performed to identify important ground motion parameters for slope deformation and a corresponding predictive relationship was developed. This work was completed in 1998 and supported by the Packard Foundation.

Expected milestones

1. Identify promising IMs by the end of Year 4.
2. Develop attenuation relationships for these IMs by the end of Year 5.

Deliverables

The deliverable for this project is a technical report that summarizes the research methods used and presents the performance-related ground motions parameters as well as empirical relationships for their prediction. This research project has the opportunity to provide researchers and practitioners an important product since past and ongoing research have shown the benefits of identifying key ground motion parameters and of developing robust empirical predictive relationships that include a rigorous estimation of the uncertainty associated with the prediction.

***Project Title*—ID Number**	*Empirical Characterization of Basin Effects on Site Response*—**2252001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$50,000.00 CA-Transportation
Project Leader (boldface) and Other Team Members	**Jonathan Stewart (UCLA/F)**, Robert Graves (URS/I), Yoojoong Choi (UCLA/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

Current site classification schemes for characterization of site response are based on engineering or geologic characteristics of near surface sediments. In a PEER Year 2-3 project (PI: Stewart), nonlinear amplification factors were derived for three such schemes based on the following types of data: (1) detailed surface geology, (2) average shear wave velocity to a depth of 30 m, and (3) geotechnical data. The quality of the schemes was assessed in part by the intra-category standard error terms, which quantify the degree to which sites within a given category exhibit similar amplification levels. These errors would be minimized for a "good" site classification scheme. It was found that standard error terms were somewhat lower for detailed surface geology schemes (which incorporate information on depositional environment or texture) than for general surface geology schemes (age-only), the 30-m Vs scheme, or the geotechnical data scheme. However, the error terms for all of these schemes are high, being of approximately the same order as error terms from attenuation relations. Another interesting feature of the results were large standard error terms for large spectral periods.

To further improve amplification factors, classification schemes must incorporate information beyond the near-surface sediments. This project is identifying whether information on the deeper basin structure can reduce bias and uncertainty in amplification factors. Limited work in this regard has been performed by SCEC. This work found a significant correlation between amplification factors for the LA basin and depth-to-basement.

Methodology employed

Within the PEER Lifelines Program and SCEC, significant effort has been devoted in recent years to the calibration of numerical basin response simulation techniques against empirical data. These calibrated simulation procedures have enabled the identification from analysis of geometric basin parameters that are most likely to correlate to ground motion amplification. The parameters identified to date include depth to basement and distance to basin edge, measured in direction of wave propagation from source.

These basin geometric parameters are being compiled for strong motion sites in southern and northern California using available basin models. Regression analyses will later be employed to identify the effect of these parameters on amplification factors and intra-category error terms.

This work is significant in that it will provide the first direct empirical quantification of basin effects. More importantly for the PEER center, the work will likely significantly improve existing site response amplification factors, both in terms of bias and dispersion. These amplification factors are critical to the probabilistic characterization of intensity measures for performance based design.

Role of this project in supporting PEER's strategic plan

The project will allow for more robust evaluations of ground motion intensity measures for use in Probabilistic Seismic Hazard Analysis (PSHA), which in an integral component of Performance-Based Earthquake Engineering (PBEE).

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

The Year 2-3 work has resulted in one PEER report (PEER-2001/10) and two papers submitted to journals. Moreover, the results of this work are helping guide the deliberations of NEHRP Technical Subcommittee 3 (of which the PI is a member) with regard to site factors in the NEHRP Provisions and Commentary for new buildings.

Plans for Year 6 *(if project is proposed to continue)*

We anticipate adding to our database data from non-California earthquakes such as Taiwan, Japan, and Turkey. We will also evaluate amplification factors for IMs other than spectral acceleration.

Other relevant work being conducted within and outside PEER and how this project differs

A recent project funded by the Southern California Earthquake Center (PI: Ned Field) evaluated the effect of basin depth on spectral acceleration using data from southern California. This project is examining additional basin geometric parameters and an additional region (northern California). Therefore, the results will be more comprehensive, and more thus more useful for performance-based engineering.

An ongoing project funded by the California Strong Motion Instrumentation Program (CSMIP) (PI: Graves) is examining the generation of basin induced surface waves and their correlation with geologic parameters such as distance to basin edge. Simulations performed in this CSMIP project are being leveraged for the subject PEER work.

Expected milestones

1. Identification from numerical simulations of basin geometric parameters that correlate to the amplification of ground motion intensity measures.
2. Assemble database of critical basin parameters for strong motion stations in active regions.
3. Develop statistical models through formal regression analysis of ground motion amplification associated with basin effects. These models will quantify amplification beyond that associated with existing amplification models.

Deliverables

1. A ground motion amplification model that can be used to define the statistical moments of a probability density function for the intensity measure of spectral acceleration as a function of near-surface site conditions and parameters describing deeper basin structure.
2. A report documenting the means by which the model was developed.

Project Title—ID Number	*Performance of Shallow Foundations*—**2262001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$70,000.00 CA-General
Project Leader (boldface) and Other Team Members	**Bruce Kutter (UCD/F)**, Key Rosebrook (UCD/GS), Sivapalan Gajan (UCD/GS), Justin Phalen (UCD/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

Understanding the nonlinear behavior of shallow building foundations under large amplitude loading (moment, shear and axial loading) is an important aspect of performance-based earthquake engineering (PBEE). The goals of PEER researchers (at UCI, USC, and UCD) on this topic are to develop and test procedures to account for the foundation nonlinearity in PBEE. So far, it is established that soil yielding beneath foundations can be a very effective energy dissipation mechanism. However, foundation yielding may lead to excessive permanent deformations. The primary goal of the research at Davis is to produce archived test data at prototype stress levels, regarding the cyclic and permanent deformation behavior of shallow foundations over a typical range of moment to shear ratio, shear to axial load ratio, foundation embedment, and soil type. For the present study, the typical range of parameters investigated in the experiments is relevant to shear walls for low- to mid-rise buildings. A secondary goal of the researchers at Davis is to begin to develop a plasticity-based "constitutive model" to simulate the cyclic rotation, sliding, and settlement of a shallow foundation subject to combined moment, shear and axial loading.

Methodology employed

Centrifuge model tests are being conducted on the large centrifuge at UC Davis to generate test data at the prototype stress levels. Models of shear wall-foundation systems are being tested using a variety of foundation dimensions, embedment depths and footing shapes. Some footings are tested only in axial loading, others are being tested under a constant axial load while slow-cyclic lateral load is applied to the wall at the effective height above the foundation. In other tests, model buildings are subject to base shaking using the shaking table mounted on the UC Davis centrifuge. Each model container contains several shearwall-footing systems. Results from each container are being posted at http://cgm.engr.ucdavis.edu for use by collaborators and others. Researchers at UCI are using the centrifuge data, and other data available in the literature to test the implementation of interface elements in OpenSees.

Role of this project in supporting PEER's strategic plan

It is now well understood that for many buildings, shallow foundations may suffer large loads that cause yielding or non-linear behavior in the soil beneath the foundation. A better understanding of the foundation non-linearity is needed in order to accurately assess the performance of the supported structures. We are now focusing on investigation of parameters that are considered critical to performance-based design of foundations for shear walls in non-ductile concrete frame buildings. Therefore, this project directly supports the overall theme of performance based earthquake engineering and is relevant to performance based design of nonductile concrete frame buildings. The project also supports the OpenSees project.

Year 5 accomplishments and brief description of past accomplishments ***(if continuation)***

A few specific findings to date: The cyclic hysteretic moment-rotation relationships for the model tests were less sensitive to the axial load on the footing than we had anticipated (based on conventional bearing capacity factor analysis). The settlement of the footings due to cyclic loading was, as expected, quite sensitive to the axial load on the footing. We were also pleased to find that the slow cyclic moment-rotation relationships corresponded nicely to the dynamic moment-rotation relationships measured during dynamic shaking.

Plans for Year 6 ***(if project is proposed to continue)***

In year 6, we will extend the experimental database to include shear and uplift translation. The analysis of the experimental results will include the investigation of the displacements and rotations of the foundation when subjected to cyclic combined axial, shear and moment loading. The general yielding of foundation soil and the behavior of the footing in V-H-M (vertical load-horizontal load-moment) space will be explored using the experimental results. We will implement and test the single element foundation-soil interface constitutive model that couples the effects of moment-rotation-load-displacement behavior.

Other relevant work being conducted within and outside PEER and how this project differs

Work performed at UCI (Tara Hutchinson, PI) focuses on developing numerical tools for modeling this rocking behavior and predicting associated foundation and building settlements, and validating these models against available experimental data. Numerical studies at UCI will be based on a nonlinear Winkler-type framework for modeling the soil response (i.e., using nonlinear springs and dashpots, with gapping elements). Experimental data provided from centrifuge tests conducted at UCD, as well as other available data, will be used for validation of the analytical approach. Initial validation of the numerical models will lead to further parametric studies, which consider the combined dissipation of energy through non-linearity in structural elements (e.g. in shear walls, at beam-column joints) and non-linearity of foundation elements (through yielding of the soil).

The work conducted at USC entails the oversight and integration of work performed at UCD and UCI. This includes sequencing and prioritizing model tests and analysis directions and implementing analysis and experimental data into the framework of a performance based engineering design approach. The work performed by USC will also include interfacing with practicing engineers in the US and Europe involved in implementation of nonlinear SSI into seismic design guidelines or codes.

Expected milestones

Three test series were completed in the previous year. These results have been documented in the data reports. Two test series are proposed in this year. The first series will be performed in June -- the first tests to be conducted after upgrade of the NEES centrifuge to at Davis (from 40 g to 80 g). The second test series will be performed at the end of the summer 2002. The major milestones are the completion of these two series of tests and the corresponding data reports.

Deliverables

1. Two data reports for centrifuge model tests completed and posted on the web site.
2. Final report synthesizing experimental and analytical results, put in context with other results in the literature.

***Project Title*—ID Number**	*Performance of Shallow Foundations*—**2272001.1**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$30,000.00 NSF
Project Leader (boldface) and Other Team Members	**Geoffrey Martin (USC/F)**		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The goals of PEER researchers (at UCI, USC, and UCD) on this topic are to develop and test procedures to account for the foundation nonlinearity in PBEE. So far, it is established that soil yielding beneath foundations can be a very effective energy dissipation mechanism. Collaborating researchers at UCI and USC will be utilizing the experimental data provided by UCD primarily for performing numerical analysis using OpenSees. A main task in OpenSees will be to implement interface elements that allow satisfactory simulation of cyclic and permanent deformations of the soil-foundation interaction.

Methodology employed

Researchers at USC and UCI are using the centrifuge and other data available in the literature to test and develop interface elements in OpenSees. Our initial approach has been to use a Beam-on-Nonlinear-Winkler (BNWF) framework (e.g. using spring, dashpot, gap elements) for modeling the nonlinear soil response. Several different constitutive relations for the base elements have been investigated, two that are particularly promising are shown in Figure 1. The parallel tension capacity (PTC) material is a composite material formed of the ENT (elastic-no tension material), several parallel elasto-plastic gap elements and a dashpot if required. It is envisioned to be easily reproducible in different analytical platforms and is appealingly simplistic. The qzMaterial developed by Professor Boulanger of UC Davis (primarily for capturing the uplift response at the tip of piles) provides suitable nonlinear compression capacity coupled with minimal tension capacity and gap growth features. These features are common with the PTC material with the exception of a softer pre-yield and stiffer unloading behavior. For comparison, the commonly used steel02 model is superimposed on these plots.

Role of this project in supporting PEER's strategic plan

Our role in the overall PEER strategic plan is to provide a framework for PBEE as applied to shallow foundation systems. While the foundation below the Van Nuys test bed building is not of the nature we are considering in these studies, uncoupled mechanistic spring elements provide a reasonable approach for capturing the vertical, horizontal, and rocking resistance of the friction piles integrated with pile-caps. In addition, the shallow foundation supporting reinforced concrete shear walls can be an effective retrofit strategy for this structure and the numerical modeling will study response of these types of combined systems.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

Continued analytical work during the remainder of year 5 will focus on evaluating dynamic BNWF approaches (thus far our emphasis has been on the pseudo-static cyclic data available) and modeling one-g experimental datasets (e.g. Wiessing, Bardet, and Negro). Upcoming centrifuge experiments by Kutter and Gajan will also explore embedment depth and data available from these tests will allow us to evaluate the placement and definition of base lateral springs for representing passive pressure due to foundation embedment.

Plans for Year 6 ***(if project is proposed to continue)***

Year 6 will allow us to continue analytical studies; verification against data provided from centrifuge and other experiments as well as formalize recommendations for shallow foundation modelers, particularly those using interface BNWF approaches. Little validation of this approach for shallow rocking foundations has been conducted and the abundance of recent experimental data provides this unique opportunity.

We plan to expand the complexity of the model footing and develop a parametric study to include various structural systems, particularly considering combined systems. The validated BNWF model will be combined with structural elements anticipated to exhibit energy dissipation during cyclic earthquake loading (e.g. in shear walls, at beam-column joints). The advantage of the yielding foundation may be best utilized in the retrofit condition, where coupled structural systems (MRF's and shear walls combined) are often used. An additional objective of this study is to compare seismic response results using different modeling platforms and different approaches for capturing the soil and structural element characteristics. During year 6 we plan to perform pilot studies using select sets of data and other readily used analytical platforms.

Other relevant work being conducted within and outside PEER and how this project differs

Within PEER, this work is closely coordinated with UCI (Hutchinson) and UCD (Kutter). Work conducted at UCD includes providing experimental data and guidance for use of the data in analytical modeling. While work conducted at USC entails the oversight and integration of work performed at UCD and UCI. This includes sequencing and prioritizing model tests and analysis directions and implementing analysis and experimental data into the framework of a performance based engineering design approach.

Laboratory and experimental work is active in this area, especially in Europe. Professor Martin has made contact with at least two research groups in Europe (Peckar and Paloucci), including Engineers in Europe that are in the process of implementing provisions for nonlinear SFSI for shallow foundations in the Eurocode. One-g experiments have recently been completed at the ELSA laboratories in Italy and Professor Negro of ELSA has expressed his support for sharing with us his one-g test results conducted on sand for use in our numerical studies.

Our analytical studies will be unique in that most studies either include nonlinearity of soil elements, or nonlinearity of structural components of the system.

Expected milestones

1. Complete analytical studies using KRR, ELSA and other data sets – Summer 2002
2. Development of a matrix of representative combined systems – Fall 2002
3. Complete analytical studies of combined systems – Spring 2003

Deliverables

1. Developed and tested mesh generator using the BNWF approach for modeling the soil-foundation interface
2. Preliminary Van Nuys test bed foundation recommendations

***Project Title*—ID Number**	*Performance of Shallow Foundations*—**2272001.2**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$40,000.00 NSF
Project Leader (boldface) and Other Team Members	**Tara Hutchinson (UCI/F)**, Chad Harden (UCI/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

Understanding the nonlinear behavior of shallow building foundations under large amplitude loading (moment, shear and axial loading) is an important aspect of performance-based earthquake engineering (PBEE). The goals of PEER researchers (at UCI, USC, and UCD) on this topic are to develop and test procedures to account for the foundation nonlinearity in PBEE. So far, it is established that soil yielding beneath foundations can be a very effective energy dissipation mechanism. However, foundation yielding may lead to excessive permanent deformations. The primary goal of researchers at UCI and USC is to implement interface elements that allow satisfactory simulation of cyclic and permanent deformations of the soil-foundation interaction.

Methodology employed

Researchers at USC and UCI are using centrifuge and other data available in the literature to test and develop interface elements in OpenSees. Our initial approach has been to use a Beam-on-Nonlinear-Winkler (BNWF) framework (e.g. using spring, dashpot, gap elements) for modeling the nonlinear soil response. Several different constitutive relations for the base elements have been investigated, two that are particularly promising are shown in Figure 1.

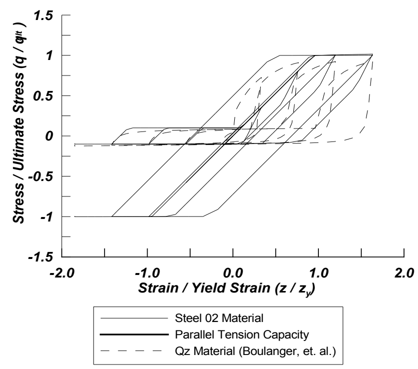


Figure 1. Sample material models selected for representing rocking foundation response (Steel02 shown for comparison).

Role of this project in supporting PEER's strategic plan

Our role in the overall PEER strategic plan is to provide a framework for PBEE as applied to shallow foundation systems. Analytical studies will also contribute to the use and continued development of the PEER OpenSees platform.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

Thus far, we have developed a TCL mesh generator to allow us to study the sensitivity of the BNWF model parameters for capturing the salient features of the rocking strip foundation. Our parameter study has considered different: (i) base spring lateral distributions, (ii) pressure distributions, and (iii) variable material models. Base spring lateral distributions of interest include both the number of springs (as a function of the footing length) and the type of spacing of the springs (uniform versus non-uniform). Pressure distributions being considered include uniform, triangular, trapezoidal, and parabolic. Thus far, the later three are in fairly good agreement, while we have observed, for the footing founded on medium or dense sand, that the uniform distribution tends to over-predict permanent rocking-induced settlements, as shown in Figure 2. Initial analytical studies confirm observations during centrifuge experiments, which indicate that the settlement of the strip footing due to cyclic moment loading is fairly sensitive to the axial load imposed on the footing. Analytical results also support experimental observations that the hysteretic moment-rotation relation is less sensitive to the axial load on the footing.

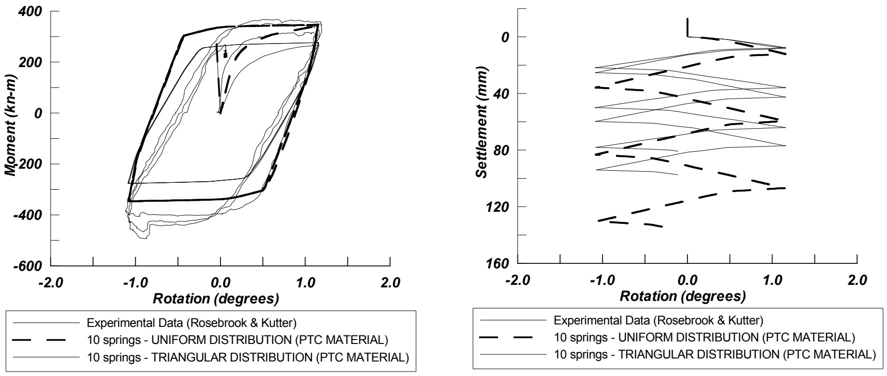


Figure 2. Sample results of combined reversed cyclic rocking and vertical compression loading – BNWF approach for uniformly spaced springs using a parallel tension capacity material with uniform and triangular base pressure distribution.

Plans for Year 6 *(if project is proposed to continue)*

Year 6 will allow us to continue analytical studies; verification against data provided from centrifuge and other experiments as well as finish recommendations for shallow foundation modelers, particularly those using interface BNWF approaches. We plan to expand the complexity of the model footing and develop a parametric study to include various structural systems, particularly considering combined systems. The validated BNWF model will be combined with structural elements anticipated to exhibit energy dissipation during cyclic earthquake loading (e.g. in shear walls, at beam-column joints). The advantage of the yielding foundation may be best utilized in the retrofit condition, where coupled structural systems (MRF's and shear walls combined) are often used.

Other relevant work being conducted within and outside PEER and how this project differs

Within PEER, this work is closely coordinated with USC (Martin) and UCD (Kutter). Work conducted at UCD includes providing experimental data and guidance for use of the data in analytical modeling. While work conducted at USC entails the oversight and integration of work performed at UCD and UCI.Laboratory and experimental work outside of PEER is active in this area, especially in Europe. Our analytical studies will be unique in that most studies either include nonlinearity of soil elements, or nonlinearity of structural components of the system. During year 6, we plan to expand our study to combine these two contributions and study the response of structural systems founded on rocking strip footings. Results of these numerical studies will also provide extensive evaluation of modeling approaches against the available set of experimental data provided by both centrifuge (>20g) and other (~1g) tests on shallow foundations.

Expected milestones

Major milestones in our numerical studies include: (i) Complete analytical studies using KRR, ELSA and other experimental data sets – Summer 2002, (ii) Develop a matrix of representative combined systems – Fall 2002, and (iii) Complete analytical studies of combined systems – Spring 2003

Deliverables

Year 5 deliverables include: (i) Developed and tested mesh generator using the BNWF approach for modeling the soil-foundation interface and (ii) provide preliminary Van Nuys test bed foundation recommendations

Project Title—**ID Number**	*Effects of Uncertainties on EDPs*—**2282001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$30,000.00 NSF
Project Leader (boldface) and Other Team Members	**Steve Kramer (UW/F)**		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

To work, in collaboration with the PI of 3162001, to evaluate the effects of geotechnical uncertainties on engineering demand parameters. Sources of epistemic uncertainty in geotechnical response prediction will be identified and evaluated; this information will be combined with the results of a previous summary of aleatory geotechnical uncertainty to investigate how geotechnical uncertainty affects engineering demand parameters.

Methodology employed

The project will focus on identification and characterization of primary aleatory and epistemic sources of uncertainty in geotechnical aspects of performance prediction, and on the effects of those sources of uncertainties on engineering demand parameters. The work will be accomplished in the following planned series of tasks:

Task 1. *Characterization of geotechnical aleatory uncertainty*. Regional geologic information and site-specific subsurface investigations for the Van Nuys testbed site will be reviewed and analyzed. The available information will be considered, along with compilations of statistical data for various geotechnical parameters, to characterize aleatory uncertainty in pertinent soil parameters at the site.

Task 2. *Characterization of geotechnical epistemic uncertainty*. Sources of epistemic uncertainty, such as amount of available geotechnical data, accuracy of geotechnical response estimation method, and number of response analyses, will be identified and investigated to allow characterization of epistemic uncertainty. This work will be conducted in consultation with Prof. Allin Cornell of Stanford University who is working on parallel topics from the structural engineering perspective.

Task 3. *Characterization of hazard uncertainty*. Uncertainty in the ground motion hazard at the Van Nuys site will be evaluated and characterized. This work will be conducted in consultation with Prof. Cornell.

Task 4. *Propagation of geotechnical uncertainties through PEER framework*. The effects of the uncertainties identified and characterized in the first three tasks on engineering demand parameters will be investigated by propagating them through the PEER framework. This task will involve a series of OpenSees analyses of the Van Nuys testbed soil-structure system. The aspect of the work will be conducted in consultation with Profs. Cornell and Conte (UCSD).

Task 5. *Preparation of final report*. A final report describing the investigation and its results will be prepared.

Role of this project in supporting PEER's strategic plan

This project will help quantify geotechnical uncertainties so that they can be propagated, along with other uncertainties, through the PEER framework for performance evaluation.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

Year 5 work to date has focused on identification and characterization of primary sources of geotechnical uncertainty, particularly with respect to the Van Nuys testbed site. Because geotechnical factors are not extremely significant at Van Nuys, a modified approach is being studied. Potential modifications include changing the soil/foundation conditions beneath the Van Nuys structure, and using a different testbed to evaluate geotechnical uncertainties. The Humboldt Bay Bridge, for which an OpenSees model is already available, may offer a significantly better opportunity to investigate the effects of geotechnical uncertainties on EDPs. Upcoming work will focus on propagation of geotechnical uncertainties through OpenSees models of the soil/foundation/structure system at either the Van Nuys or Humboldt Bay Bridge testbed sites.

Plans for Year 6 *(if project is proposed to continue)*

There are no continuation plans formulated at this time.

Other relevant work being conducted within and outside PEER and how this project differs

This project is closely related to Project 3162001, and the PI will consult with the PI of that project to ensure that the work is complementary. No work on this topic is being conducted outside of PEER.

Expected milestones

1. Review of aleatory uncertainty summary report (January, 2002)
2. Review of available literature on epistemic uncertainty (March, 2002)
3. Investigation of ground motion modeling uncertainty (June, 2002)
4. Investigation of propagation of geotechnical uncertainty through PEER framework (Sept, 2002)
5. Preparation of final technical report (October, 2002).

Deliverables

1. Progress reports at required intervals
2. Presentations at PEER meetings
3. Participation in testbed activities
4. Final technical report

***Project Title*—ID Number**	*Evaluation of Post-Liquefaction Residual Strength and Stress-Deformation Behavior*—**2292001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$10,000.00 CA-Transportation
Project Leader (boldface) and Other Team Members	**Juan Pestana (UCB/F)**, Jiaer Wu (UCB/GS), Ann Kammerer (UCB/GS), Raymond Seed (UCB/F)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The main objective of this project is to summarize and disseminate a comprehensive and coordinated program of laboratory testing developed at UC Berkeley to date on Nevada and Monterey sand.

Methodology employed

This testing program focused on the behavior of sand in the Simple Shear mode of deformation and addressed issues associated with the engineering evaluation and treatment of post-liquefaction "residual" strength and stress deformation behavior of potentially liquefiable soils. The testing work covered the entire range from initiation (i.e., triggering of liquefaction) to the development of large strains. The work is instrumental for use in quantitative assessment of "small to moderate" (<1m) cyclically-induced ground deformations; a range in which "cyclic softening", dilation and cyclic inertial forces are all important.

Role of this project in supporting PEER's strategic plan

The impact of the resulting database is very significant to the evaluation and calibration of models for performance based design and multiple targeted research areas/issues within PEER. Through the validation of numerical models, this database will find direct application in the prediction of soil, foundation and structural response. There is a special need for multi-directional and irregular loading data, and this current project appears to be the only, at this time, able to provide this vital physical data. Accurate and reliable engineering prediction and modeling of small to moderate liquefaction-induced deformations and resultant structural displacements is the key frontier in liquefaction work at this time. We are well able to predict the occurrence of liquefaction, and we are well able to predict "large" displacements through empirical regression of “case history” failures. Moderate displacements (0.01-0.75 m) controlling structural performance appear to be elusive and they are not predicted accurately. In particular, the performance of improved ground (i.e., densification) remains untested. Constitutive models are evolving rapidly to describe the response of denser soils, but there is a critical lack of both field and laboratory data against which to calibrate these models.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

This project has provided a series of tests on Nevada sand developed collaboratively by PEER researchers (UC Davis and UC San Diego). This sand has been used extensively in the centrifuge and the “element level” information has been used to calibrate and refine simplified constitutive models for sands. Most recent work was directed towards the completion of a consistent database for Monterey sand for three-four typical ranges of relative density and confining stress level for level ground conditions. In addition to level ground conditions, several more sophisticated two dimensional tests have been conducted to date to address the issue of multidirectional loading in level-ground and sloping ground conditions. This year’s effort was directed at the evaluation and validation of results obtained for internal consistency and quality rating of the tests. Subsequently, the interpretation of key elements affecting material response was performed. The main effort was then directed at the creation of a Web page containing Dissemination of the work will allow the calibration and refinement of constitutive models for this type of loading. This work will continue to feed into PEER projects at UC Davis (Kutter, Boulanger), UC San Diego (Elgamal), and U. of Washington (Kramer).

Plans for Year 6 ***(if project is proposed to continue)***
N/A

Other relevant work being conducted within and outside PEER and how this project differs
To date, UC Berkeley has the only simple shear device that can perform two-directional cyclic simple shear testing, and one of the few devices that can impose chamber pressure on the sample. The use of chamber pressure allows for the testing of saturated (instead of the usual dry) samples. This is important as the field conditions of interest are fully saturated. This system is also one of only several in the world that can apply irregular (earthquake-like) loading under controlled conditions. Combined, these attributes render this the only system in the world that can reproduce the actual conditions that occur during earthquakes (irregular, bi-directional, cyclic simple shear loading of saturated soils) and assures that work done in this area at UC Berkeley is unique.

Expected milestones

- Provide a summary and documentation of laboratory tests on Monterey sand for three typical relative densities and two levels of confining pressure for level ground conditions. A hardcopy report will summarize findings through graphs of cyclic stress ratio vs. number of cycles to liquefaction and selected stress-strain response. A digital report (pdf format) will be posted on the web and digital information for all the tests will be distributed
- Provide a summary and documentation of laboratory tests on Monterey sand for level ground conditions under multidirectional shaking as well as for sloping ground under one directional and multidirectional excitation. Similarly to 1, a hardcopy report will summarize findings and illustrate response through selected stress-strain response. A digital report (pdf format) will be posted on the web and digital information for all the tests will be distributed

The digital data will be posted on the web and a limited number of CDs will be produced for distribution. This type of information can be easily downloaded from the internet and ensures wide dissemination of the work. These reports will contain all tests conducted as part of PEER projects as well as those partially supported by the NSF award CMS- 9623979.

Deliverables
Listed under 'Milestones' section above.

***Project Title*—ID Number**	*OpenSees Implementation and Validation of P-Y and T-Z Models to Simulate Nonlinear Pier Response*—**2302001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 5/1/00—9/30/02	Current Year Budget Funding Source	$15,000.00 CA-Transportation
Project Leader (boldface) and Other Team Members	**Juan Pestana (UCB/F)**, Gregory Fenves (UCB/F), Ed Love (UCB/PD), Juan Mayoral (UCB/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

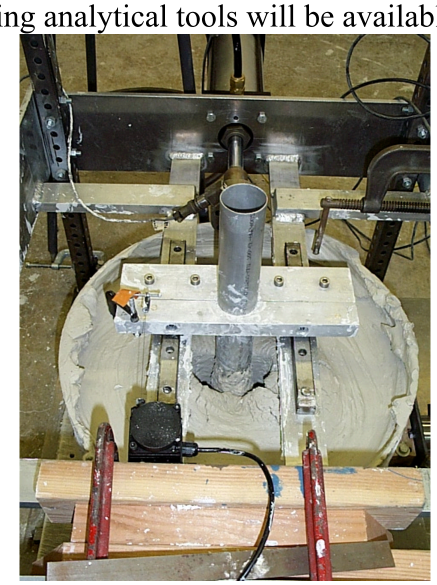
The resulting analytical tools will be available to all members of the PEER community. The project focuses on two primary issues for the description of deep foundation systems: 1) refinement of material models incorporating realistic soil non-linearity and the robust implementation in a finite element formulation for the seismic site response analyses under multidirectional excitation (i.e., 2D and 3D simulations), and 2) the development of simplified one dimensional elements describing the complex "near field" (including gapping) soil-pile response interface.

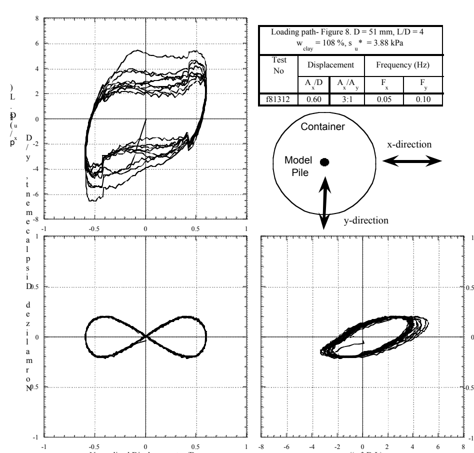
Methodology employed

Computer simulations and calibrations with laboratory testing of multidirectional pot-tests.

Role of this project in supporting PEER's strategic plan

A robust and extensively validated numerical tool is required for the reliable estimation or prediction of performance of a wide range of structural and foundation elements if one is to be successful at articulating a performance based design criteria for design in earthquake engineering. Once completed, the OpenSees platform will have the ability to predict the behavior of complex soil-structure systems under a very general set of boundary conditions. The resulting analytical tools will be available to all members of the PEER community.





Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

This work introduces the key elements of a simple discrete model to simulate the behavior of the interface soil-pile during multidirectional loading for soft clays. In the proposed model, the force-displacement relationship is defined in terms of the radial displacements of a plastic and a loading surface with respect to the original position of the pile. The model is currently being calibrated with experimental results from a unique experimental set-up.

Plans for Year 6 ***(if project is proposed to continue)***
N/A

Other relevant work being conducted within and outside PEER and how this project differs
The OpenSees platform is unique and a key development of the PEER Center. This work is complementary of other PEER related effort directed at the development/ implementation and validation of numerical tools in the OpenSees computational platform for predicting seismic soil-foundation-structure interaction.

Expected milestones

- Fully documented OpenSees source code and executable files for the pier interface elements
- Set of document results for calibration and validation of the models, guidelines and illustrative examples on how to apply the models for simulating the response of bridge and building foundations.

Documentation will be made available on-line through the OpenSees website. Other written documentation should be included in a PEER report

Deliverables
Given in "Milestones" section.

***Project Title*—ID Number**	*Simulation of Soil-Foundation-Structure Interaction of Deep Foundations*—**2312001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$50,000.00 CA-Transportation
Project Leader (boldface) and Other Team Members	**Ross Boulanger (UCD/F)**, Boris Jeremic (UCD/F), Dongdong Chang (UCD/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The objectives of this project are to develop and validate improved nonlinear p-y, t-z, and q-z models for simulating the load transfer between deep foundations (e.g., piles) and soil as part of a complete soil-pile-structure interaction analysis, including the effects of liquefaction. The resulting models are to be implemented into the OpenSees platform.

Methodology employed

The majority of work under this project is numerical in nature, but draws from the existing literature and experimental data in addressing the various needs of the project. In particular, dynamic centrifuge tests of soil-pile-structure systems in liquefiable soil profiles have recently been performed at UC Davis and the results used to back-calculate the load transfer mechanisms. The results of that research project are being used (1) to guide the development of the p-y and t-z relations for liquefaction conditions and (2) for assessing the uncertainties in the numerical model predictions of observed pile performance.

Role of this project in supporting PEER's strategic plan

This project provides support for some of the test-bed projects by developing and implementing the required p-y, t-z, and q-z models in the OpenSees platform. The project also supports the strategic plan by quantifying the effects of liquefaction on pile foundation performance and assessing uncertainties in the numerical predictions of observed pile performance.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

We have implemented nonlinear p-y, t-z, and q-z elements for non-liquefying soils into OpenSees, and provided these models to researchers working on the test bed projects. We have also developed and implemented p-y and t-z elements that incorporate the effects of liquefaction, and are currently evaluating them against centrifuge test data. We provided preliminary versions of these elements to test bed researchers, and will be updating them with revised/improved elements in late May. Subsequent efforts will continue on the numerical modeling of the centrifuge test results to further evaluate the numerical methods and the uncertainties in predicting observed performance.

Plans for Year 6 *(if project is proposed to continue)*

Plans for Year 6, which follows some work that starts in the remainder of Year 5, include (1) three-dimensional FEM modeling of soil-pile systems to address some unresolved issues in practice, such as how p-y behavior is affected by soil layering with strong stiffness/strength contrasts, (2) centrifuge tests of piles subjected to multidirectional lateral and axial loading, with the goal of guiding the development of generalized three-dimensional p-y/t-z elements, and (3) the continued development and updating of p-y, t-z, and q-z elements within OpenSees and their evaluation by comparing analysis results against centrifuge test or field loading data.

Other relevant work being conducted within and outside PEER and how this project differs

We are unaware of any efforts within or outside of PEER to implement p-y, t-z, and q-z elements that incorporate liquefaction effects into OpenSees. A PEER project by Pestana and Fenves is also expected to implement p-y and t-z elements for nonliquefying soils, but their project does not encompass the effects of liquefaction. There are ongoing efforts by non-PEER investigators to understand lateral loading behavior of pile foundations in liquefied soils (e.g., Dobry, Abdoun, O'Rourke, Tokimatsu, Hamada, Ishihara, Kagawa, and others), but we understand that their efforts do not include developing FEM modeling tools similar to those being developed under this project.

Expected milestones

The milestones for Year 5 of this project are (1) p-y, t-z, and q-z models for simulating pile response in non-liquefied and liquefied soils that are implemented in OpenSees with technical and user documentation that includes written procedures and examples for OpenSees modeling of pile-supported structures, (2) an evaluation of the uncertainties in FEM predictions, using OpenSees models, of pile foundation performance in liquefiable soil deposits, as judged by comparisons against existing experimental data from centrifuge studies or case studies.

Deliverables

The deliverables for Year 5 follow directly from the milestones listed above, and hence include (1) the source code and documentation for the p-y, t-z, and q-z models, and (2) a final report summarizing the evaluation of the FEM tools against existing centrifuge or case history data.

***Project Title*—ID Number**	*Ground Motions for Testbeds*—**2322001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$30,000.00 NSF
Project Leader (boldface) and Other Team Members	**Paul Somerville (URS/I)**, Nancy Collins (URS/I)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

Provide sets of hazard specific ground motions for four testbed sites:

- Van Nuys building
- UC Berkeley Life Sciences building
- Humboldt Bay bridge
- I-880 Interchange

Methodology employed

- The hazard levels for which ground motions are to be generated are
  - 2/50
  - 10/50
  - 50/50
- For each hazard level and site, appropriate uniform hazard spectra were provided, along with brief descriptions of the governing fault zones and deaggregation on the hazard data upon which the ground motions are based. For near-fault sites, the uniform hazard spectra were modified to include near-fault rupture directivity effects in an approximate way, producing larger spectra in the fault normal direction than in the fault parallel direction at periods longer than 0.5 seconds.
- The manner in which near-fault effects were considered in the selection of records was documented.
- The number of ground motion time histories per hazard level and site is not less than 10, and more than 10 recordings were provided where possible. All of the time histories come from ground motion recordings.
- For each "ground motion" three components were documented, with the two horizontal components preferably oriented in the fault-normal and fault-parallel directions, or rotated from those orientations to longitudinal and transverse orientations to be specified by the users.
- The ground motions were provided (a) unscaled, and (b) in some cases, scaled to the appropriate hazard level at a period specified by the users, with the reasons for the scaling procedure fully documented.

Near the end of the first year of the testbed study, the ground motion selection process should be reevaluated based on the findings of the ground motion selection project by Allin Cornell.

Role of this project in supporting PEER's strategic plan

Provision of appropriate site-specific time histories is required for rigorous testing of the PBEE methodology.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

Reports describing the ground motions for the four testbeds, files containing the time histories, and plots of the time histories and their response spectra, can be found on the website **www.peertestbeds.net.**

Plans for Year 6 *(if project is proposed to continue)*

None

Other relevant work being conducted within and outside PEER and how this project differs

None

Expected milestones

- The sets of ground motions were developed and documented by March 12, 2002
- A final report will be provided by August 31, 2002, in which the procedure for the ground motion selection is contrasted with the findings of the Cornell study.

Deliverables

Reports and Time Histories (see website **www.peertestbeds.ne**t)

***Project Title*—ID Number**	*Rupture Model of the Duzce, Turkey Earthquake*—**Lifelines 1C03**		
Current Year Start/End Dates	4/4/01—3/31/02	Current Year Budget Funding Source	$49,947.00 PG&E/CEC
Project Leader (boldface) and Other Team Members	**Paul Somerville (URS/I)**, Hong Kie Thio (URS/I), Robert Graves (URS/I)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives
Development of a rupture model for the 1999 Duzce, Turkey earthquake.

Methodology employed
Strong motion recordings and teleseismic seismograms of the Duzce earthquake were used in an inversion procedure to develop a rupture model of the Duzce earthquake. The rupture model describes the spatial and temporal evolution of slip on a rectangular fault plane.

Role of this project in supporting PEER's strategic plan
The rupture model will be used in validating strong ground motion simulation procedures in a related Lifelines project.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*
The November 12, 1999 Duzce earthquake had a moment magnitude of Mw 7.2. It ruptured the eastern extension of the Kocaeli earthquake of August 17 the same year. The fault rupture extended over a length of 50 km with an east-west strike, consistent with the surface rupture, and reached a maximum slip of 5.5 meters. The earthquake had a relatively simple slip distribution, with a single main asperity located slightly east of the hypocenter with dimensions of 20 x 25 km and centered at a depth of about 10 km. The rupture duration of the earthquake was approximately 15 seconds.

Plans for Year 6 *(if project is proposed to continue)*
N/A

Other relevant work being conducted within and outside PEER and how this project differs
In work funded by Ohsaki Research Institute, Inc. that is part of a cost-sharing agreement with the PEER Lifelines Program, URS has generated rupture models of the 1999 Kocaeli, Turkey and Chi-Chi, Taiwan earthquakes using the same method used in this study.

Expected milestones
The rupture model was distributed to PEER Lifeline Program investigators on March 6, 2002. A report entitled "Rupture process of the 1999 Duzce Earthquake" was delivered to PEER.

Deliverables
A report entitled "Rupture process of the 1999 Duzce Earthquake" was delivered to PEER. The rupture model was distributed to PEER Lifeline Program investigators on March 6, 2002.

***Project Title*—ID Number**	*Utilization of Physical Model Data to Validate Numerical Procedures for Simulating Near-Field Motions*—**Lifelines 1D02**		
Current Year Start/End Dates	9/1/01—8/31/02	Current Year Budget Funding Source	$120,042.00 PG&E/CEC
Project Leader (boldface) and Other Team Members	**Steve Day (SDSU/F)**, Walt Silva (PEA/I), Paul Somerville (URS/I), Yuehua Zeng (UNR/F)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

Validate numerical procedures for simulating near-fault ground motions. The study will quantify the ability of existing simulation procedures to reproduce directivity, polarization, and distance decay effects observed in scale-model experiments. A second objective is to explore the broader potential of the scale-model experiments to improve ground motion simulation procedures. The explorations should provide the basis for a second project phase in which scale-model experiments are used to quantify the uncertainties in parameter estimates obtained from earthquake slip model inversions, as well as to validate dynamic rupture simulation methodologies.

Methodology employed

Each co-PI has previously developed and applied a numerical simulation method. This project will quantify the ability of the respective methods to predict near-fault ground motion in the idealized case in which detailed information about the source geometry and kinematics is available. We will do so by comparing simulated ground motion time histories with corresponding time histories recorded in the foam rubber experiments. Key to the testing is the fact that each method has a distinct set of parameters that may be adjusted to reflect event-specific conditions. The experiments record fault motion as well as ground motion, and the recorded fault motion provides information that may be used to constrain these modeling parameters.

Role of this project in supporting PEER's strategic plan

Existing simulation methods differ in the parameterization of the earthquake source as well as in the representation of wave propagation effects, and these differences lead to substantially different predictions of ground motion, especially of forward directivity effects. The project will identify the sources of the differences and provide an improved understanding of the requirements for a simulation procedure to be valid in the near-fault regime. This understanding may in turn provide a foundation for development of new simplified procedures modeling near-fault directivity effects.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

Task 1. (a) Each co-PI's has provided a description of his method, including a list of model parameters that are to be determined from recordings of the fault slip. (b) The PI, in consultation with the co-PI's a meeting in March 2002, has selected the first experiment to be modeled. (c) the PI has assigned values to those parameters which are to be kept common to all modeling methods (e.g., wavespeeds and Qs of the foam, rupture velocity, source dimensions and moment). (d) PI has defined a format for the simulation results.

Task 2. The PI (with a graduate student) has performed dynamic rupture simulations of experiment to be modeled. This was done to (a) verify the estimates of model parameters such as the wave speeds, density, Q's, and rupture velocity (b) identify the timing and character of boundary reflections and free oscillations in the experimental records, (c) improve the understanding of the underlying physics of the experiments.

The Co-PIs will be simulating the target experiments using their own procedures, and providing the results to the PI in a consistent format for comparison and validation with the measured data. This will take place over the summer of 2002.

Plans for Year 6 ***(if project is proposed to continue)***

Other relevant work being conducted within and outside PEER and how this project differs

The project uses data being acquired under Lifelines project 1D01, Study of Rupture Directivity in a Foam Rubber Physical Model. The three Co-PIs have been funded in earlier Lifelines projects to validate their models against recordings from the Turkey and Taiwan events of 1999.

Expected milestones

A project coordination meeting involving all key project personnel will be held to identify the recorded events best suited for simulation in this study.

The modeling results will be summarized and discussed by the participants at a one-day workshop. A goal of the workshop will be to develop and document an improved understanding of what characteristics a simulation method should have to successfully capture the most important characteristics of near-fault motion.

Deliverables

The project will deliver a report which

(1) describes aspects of the simulation procedures relevant to the prediction of near-fault effects,
(2) documents the input parameters used in the validation study,
(2) details the results of the validation study,
(3) documents modifications made, or proposed, to the procedures as a result of the study
(4) assesses the broader utility of the scale-model experimental results for addressing issues of relevance to PEER.

***Project Title*—ID Number**	*Seismic Moment Tensors and Finite-Source Analysis of Chi-Chi Aftershocks*—**Lifelines 1E06**		
Current Year Start/End Dates	5/1/02—4/30/03	Current Year Budget Funding Source	$44,899 PG&E/CEC
Project Leader (boldface) and Other Team Members	**Douglas Dreger (UCB/F)**, J. Rhie (UCB/GS), Peggy Hellweg (UCB/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The objective of this project is to estimate the earthquake source parameters for aftershocks of the Chi-Chi earthquake and other Taiwanese events that will be needed in future research. The source parameters that will be determined will include hypocenter location, scalar seismic moment, and fault plane solutions. For the larger earthquakes the fault plane will be identified by inverting for the extent of slip using one of two different finite-source inverse methods. The waveform data that will be used was obtained from Project 1E04 and the source parameters derived during the course of this study will be provided to the PI of Project 1E05 to be used in the analysis of the observed strong ground motion attenuation.

Methodology employed

In this study the source parameters of 33 Chi-Chi aftershocks will be determined. Event locations will be reviewed and updated as needed, seismic moment tensors will be determined, and finite-source inversions will be used to determine the orientation and dimension of the causative fault planes.

Hypocenters will be reviewed and revised using a gridsearch program that utilizes P and S phase measurements as well as P-wave azimuth information (e.g. Dreger et al., 1998; Uhrhammer et al., 2001). This approach is useful because it combines arrival time and azimuth information, and the gridsearch parameter space defines the uncertainty in the solution.

Seismic moment tensors will be determined using a complete waveform inverse approach developed at the Berkeley Seismological Laboratory (e.g. Romanowicz et al., 1993; Pasyanos et al., 1996; Dreger et al., 1998).

Finite-source inversions will be performed using software developed for a project previously funded by the PEER Lifelines program to simulate ground motions for emergency response (e.g. Dreger and Kaverina, 2000 and Kaverina et al., 2002). An alternative approach that will be employed for smaller aftershocks inverts seismic moment rate functions derived from empirical Green's function (EGF) deconvolution (e.g. Mori and Hartzell, 1990 and Dreger, 1994).

Role of this project in supporting PEER's strategic plan

This project supports the Lifelines Program's goal of providing data, models and methods to improve the earthquake reliability and safety of lifelines systems by developing a database of parametric earthquake source information, seismic inputs, which will be used to refine strong ground motion attenuation relationships. The results of this project will be directly utilized by project 1E05.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

The projected accomplishment of this project is a catalog of aftershock source parameters that includes scalar seismic moment, source depth, fault plane orientation, dimension, and distribution of slip. This information will be used directly to update attenuation relationships (1E05), and to investigate the nature of the collisional tectonics in Taiwan (Wu Cheng Chi's dissertation topic).

Plans for Year 6 *(if project is proposed to continue)*

N/A

Other relevant work being conducted within and outside PEER and how this project differs

This project differs for other projects outside PEER in that a unique strong motion data set collected for the purpose of engineering ground motion applications will be used to determine the source parameters of the aftershocks. In addition, a unique aspect of this study is the close coordination between our group and the researchers who will be using our results for refining and updating strong ground motion attenuation relationships.

Expected milestones

- 1st Quarter: Review of the waveform data (station coverage, signal-to-noise), measurements of P and S wave arrivals, and P-wave polarity. Review and revision of event locations. Finite-source inversions for the larger M>6 aftershocks. Present progress at coordination meeting.
- 2nd Quarter: Determination of seismic moment tensor solutions for the events in Table 1. Continued analysis of finite-source inversions for M>6 aftershocks, and begin analysis of 5<M<6 aftershocks. Present progress at coordination meeting.
- 3rd Quarter: Continued finite-source inversions for M>5 aftershocks. Present progress at coordination meeting.
- 4th Quarter: Finalize analysis of remaining events and prepare and present final report.

Deliverables

- 1st Quarter: Delivery of finite-source parameters for M>6 earthquakes already under study.
- 2nd Quarter: Delivery of event location and seismic moment tensor results for 33 aftershocks. These results will include estimates of source depth, scalar seismic moment, moment magnitude, and strike, rake and dip of nodal planes.
- 4th Quarter: Delivery of finite-source parametric data for aftershocks using either of the two approaches described above. The parametric information will include scalar seismic moment, moment magnitude, orientation of the causative fault plane, and the dimensions of the fault plane.

***Project Title*—ID Number**	*Surface Fault Rupture Design Model: Hazard Model Inputs*—**Lifelines 1J01**		
Current Year Start/End Dates	3/1/01—3/31/04	Current Year Budget Funding Source	$138,368.00 Caltrans
Project Leader (boldface) and Other Team Members	**David Schwartz (USGS/O)**, James J. Lienkaemper (USGS/O)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

In conjunction with Projects 1J02 and 1J03, the overall goal of this 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 as a design tool and as trial fault rupture hazard maps. Task 1J01 will provide "hazard model inputs" for estimating surface fault rupture based on analysis of data sets from historical earthquakes, including Hector Mine, Landers, 1906 San Andreas, Chi-Chi, and Izmit. These relevant inputs are: 1) a "mapping accuracy model" probability density function using pre-rupture mapped fault traces; 2) a "secondary rupture model" probability density function; and 3) quantifying effects of variable surface material (soil, rock, sediments) on rupture width and complexity. Model sensitivities will be examined, and refinements made in light of these findings and input from the technical coordination panel and project review panel.

Methodology employed

Task 1J01 will take advantage of the active fault data and expertise of the US Geological Survey to develop a set of input parameters to the fault rupture hazard calculations using both published and unpublished data from major surface ruptures. An experienced MA-level (GS-9) earthquake geologist (funding requested in proposal budget) under the supervision and guidance of David Schwartz (Chief, San Francisco Bay Area Earthquake Hazards Project) and Jim Lienkaemper, will quantify and develop inputs on variability of slip along strike, lateral and along-strike occurrence and width of secondary rupture, relation and quantification of fault complexity/slip/secondary deformation to surface geological properties, and mapping accuracy. These fault input parameters will provide the basis for the initial fault hazard modeling calculations.

Role of this project in supporting PEER's strategic plan

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 through design tools and as trial fault rupture hazard maps. The model would be structured to yield rupture hazard as a function of earthquake parameters, distance from mapped fault, and footprint area of a facility. A probabilistic measure of fault rupture hazard is a necessary input for PBEE close to active faults

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

This project has just been initiated in the Spring of 2002, so it is very early in the project life. The project Kickoff meeting was held on May 16th 2002, bringing together all three research teams in the 1J series, the Technical Working Group, and the Project Review Panel to discuss and define the best approaches for completing the scope of work.

Plans for Year 6 ***(if project is proposed to continue)***

Other relevant work being conducted within and outside PEER and how this project differs

Project 1J02 will be developing computer codes which will implement the models using the "model inputs" supplied by 1J01. Project 1J03 will be responsible for assembling and coordinating the efforts of several Advisory bodies, including a Technical Coordination Panel and a Project Review Panel, who will meet periodically with the research team. 1J03 will also produce fault rupture hazard maps using the results of the other projects if the advisory bodies find that such maps are warranted.

Expected milestones

The key milestones for the overall project are convening of the Project Review Panel within 12 and 24 months of project initiation to review the v1 and v2 models, respectively.

Deliverables

Under Task 1J01, "model inputs", comprised of several conditional probability functions, will be developed for each of the two models. Version 1 will be developed within 6 months, and will be based on the most available data sets supplemented with expert opinion from the Technical Coordination Panel, with the goal of implementing the model for 2 faults within 12 months. Version 2 will be developed and implemented based on more complete analysis of data sets, taking advantage of sensitivity studies, along with other lessons learned and Advisory body feedback from v1.

Project Title—**ID Number**	*Surface Fault Rupture Design Model: Hazard Models—* **Lifelines 1J02**		
Current Year Start/End Dates	2/1/02—3/31/04	Current Year Budget Funding Source	$20,000.00 Caltrans
Project Leader (boldface) and Other Team Members	**M. Petersen (USGS/O)**, Arthur Frankel (USGS/O)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

In conjunction with Projects 1J01 and 1J03, the overall goal of this 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 as a design tool and as trial fault rupture hazard maps. Project 1J02 is developing the computer codes which will implement the models using the "model inputs" supplied by 1J01. The codes will take two forms: 1) PC spreadsheets or computer codes for site-specific design applications, and 2) mainframe codes for regional mapping applications. The PC form will be distributed to PEER-Lifeline sponsors for design applications, and the mainframe codes will be transferred to CDMG for test mapping applications in project 1J03.

Methodology employed

Under Task 1J02, the USGS-Golden team will participate in periodic project advisory meetings established by CDMG for purposes of guiding the selection of the hazard model forms and the development of the model inputs. Upon receipt of model inputs from the USGS-Menlo team, the USGS-Golden team will develop computer codes for calculating probabilistic ground rupture. The initial coding work is expected to be complete within 3 months, and the codes will be transferred to CDMG and PEER-Lifelines partners for trial implementation. Revisions recommended by the advisory panel will be implemented, and revised codes and documentation will be distributed to project partners and sponsors. The USGS-Golden team will also contribute to Advisory Panel assessments of the methodology for applicability to design, and discussion about desirable future refinements.

Role of this project in supporting PEER's strategic plan

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 through design tools and as trial fault rupture hazard maps. The model would be structured to yield rupture hazard as a function of earthquake parameters, distance from mapped fault, and footprint area of a facility. This project will provide the codes for calculating such hazard from input that is provided in a specific form. A probabilistic measure of fault rupture hazard is a necessary input for PBEE close to active faults.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

This project has just been initiated in the Spring of 2002, so it is very early in the project life. The project Kickoff meeting was held on May 16th 2002, bringing together all three research teams in the 1J series, the Technical Working Group, and the Project Review Panel to discuss and define the best approaches for completing the scope of work.

Plans for Year 6 ***(if project is proposed to continue)***

Other relevant work being conducted within and outside PEER and how this project differs

Within PEER there are two projects directly interacting with this one: the objective of 1J01 is to provide "hazard model inputs" for estimating surface fault rupture based on analysis of data sets from historical earthquakes, which will serve as input to the 1J02 project. Project 1J03 will be responsible for assembling and coordinating the efforts of several Advisory bodies, including a Technical Coordination Panel and a Project Review Panel, who will meet periodically with the research team.

Expected milestones

The key milestones for the overall project are convening of the Project Review Panel within 12 and 24 months of project initiation to review the v1 and v2 models, respectively.

Deliverables

Under Task 1J02, the primary deliverables are the computer codes developed to implement the v1 and v2 models. Source code and draft documentation will be provided to the Lifelines sponsors (PC spreadsheets) and project partners (mainframe) within 9 months. Revised code and final documentation will be delivered upon project completion.

Project Title—**ID Number**	*Surface Fault Rupture Design Model: Statewide Mapping Products*—**Lifelines 1J03**		
Current Year Start/End Dates	1/1/02—6/30/04	Current Year Budget Funding Source	$50,000.00 Caltrans
Project Leader (boldface) and Other Team Members	**Chris Wills (CGS/O)**, Bill Bryant (CGS/O), Tianqing Cao (CGS/O)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

In conjunction with 1J01 and 1J02, 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. 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. The consensus hazard model will provide lifeline organizations with the information needed to better site and/or design important facilities near faults.

Project 1J03 will be responsible for assembling and coordinating the efforts of several Advisory bodies, including a Technical Coordination Panel and a Project Review Panel, who will meet periodically with the research team. 1J03 will participate in the research team by reviewing the fault rupture data input for consistency, participating in the review of codes for calculating the probability of fault rupture and assisting in the assembly of a report on the feasibility and utility of probabilistic fault rupture mapping, based on the consensus of the advisory bodies. 1J03 will also produce fault rupture hazard maps using the results of the other projects if the advisory bodies find that such maps are warranted.

Methodology employed

Under the supervision of Chris Wills (supervising geologist for regional geologic and hazards mapping), Bill Bryant (senior engineering geologist) and Tianqing Cao (senior seismologist) will review fault hazard input, models and codes developed by USGS Menlo Park (1J01) and Golden (1J02) offices. They will organize meetings of the Technical Working Group and the Project Review Panel to explore the potential for consensus on fault rupture hazard. CDMG will implement the v1 and v2 codes for the test cases (currently the Hayward and Bartlett Springs faults) in preparation for the Project Review Panel meetings. After testing, CDMG will explore the possibility of developing statewide probabilistic ground rupture maps

Role of this project in supporting PEER's strategic plan

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 through design tools and as trial fault rupture hazard maps. The model would be structured to yield rupture hazard as a function of earthquake parameters, distance from mapped fault, and footprint area of a facility. This project will coordinating the work of developing model inputs and the codes for calculating the hazard as well as facilitating the reviews and recommendations of the procedure from a large and highly respected collection of experts engaged in an Advisory capacity. This regular input to the development should help to ensure that the resulting conclusions of the study reflect the views of a broad cross-section of the engineering seismology community, and thus represent consensus results. Probabilistic measures of fault rupture hazard are necessary inputs for PBEE close to active faults.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

This project has just been initiated in the Spring of 2002, so it is very early in the project life. The project Kickoff meeting was held on May 16th 2002, bringing together all three research teams in the 1J series, the Technical Working Group, and the Project Review Panel to discuss and define the best approaches for completing the scope of work.

Plans for Year 6 *(if project is proposed to continue)*

Other relevant work being conducted within and outside PEER and how this project differs

Within PEER there are two projects directly interacting with this one: 1J01 is providing "hazard model inputs" for estimating surface fault rupture based on analysis of data sets from historical earthquakes, which will serve as input to the 1J02 project, which is developing the computer algorithms and codes for calculating the hazard.

Expected milestones

Under the first two years of Task 1J03, the milestones in this project will be the trial application of the models to 2 faults (e.g. Hayward and Bartlett Springs) and the conduct of focused meetings of two working groups established to provide specific guidance to the overall project.

Deliverables

The product of the working group meetings will ultimately include a consensus assessment of the v1 and v2 models. Assuming that a consensus develops that such maps are both feasible and useful for design professionals, deliverables of the final phase will be statewide surface fault rupture hazard maps.

***Project Title*—ID Number**	*Coordination of SMA Site Data from Taiwan: Phase 1—* **Lifelines 2A02d**		
Current Year Start/End Dates	9/1/01—5/31/02	Current Year Budget Funding Source	$90,000.00 Caltrans
Project Leader (boldface) and Other Team Members	**Robert Nigbor (USC/F)**, Afshin Asghari (USC/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

This proposal seeks to utilize the ROSRINE methodology and experience to assist NCREE in their efforts to characterize important strong motion sites related to the 1999 Chi-Chi Earthquake in Taiwan. This NCREE effort has already begun in Taiwan, with 33 sites already drilled and logged. A total of 60 sites are planned for 2001. It is vital that these important data are obtained with accuracy and consistency.

Methodology employed

We will assist the NCREE/Taiwan project team in implementing high-quality field measurements using methods similar to those used in ROSRINE. It is expected that data will be disseminated in a manner similar to ROSRINE.

Role of this project in supporting PEER's strategic plan

This project will add to the understanding of the ground motions generated by the Chi-Chi Earthquake. Detailed site characterizations corresponding to important strong-motion recordings will allow more accurate deconvolution of site response from source and path effects.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

To date, we have opened our collaboration with the NCREE researchers and are assisting them in planning and training. A visit to Taiwan in October 2001 opened the project. We are now waiting for NCREE to define their 2002 field program. When this is defined, we will open specific collaborative efforts.

Plans for Year 6 *(if project is proposed to continue)*

We expect to formally collaborate with the NCREE project team in site investigations now planned for summer and fall, 2002.

Other relevant work being conducted within and outside PEER and how this project differs

PEER has funded a similar project in the US, ROSRINE (Resolution of Site Response Issues in the Northridge Earthquake). This project has similar goals but for the site conditions in Taiwan.

Expected milestones

Our first tasks of initial contact and an initial site visit were done in late 2001.
The other project tasks will be completed in 2002.

Deliverables

Deliverables include open dissemination of the NCREE site data from 2000 and 2001, and coordination of future data dissemination.

In addition, 2 or more sites will be considered as "PEER-NCREE Collaborative Sites" where joint work will be done and published.

Project Title—ID Number	*Application of SASW to U.S. SMA Sites*—**Lifelines 2C01**		
Current Year Start/End Dates	6/1/01—5/31/02	Current Year Budget Funding Source	$80,000.00 Caltrans
Project Leader (boldface) and Other Team Members	**Kenneth Stokoe II (UT/F)**		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The original goal of this project was to evaluate shear wave velocity (Vs) profiles at 16 to 20 sites in the Imperial Valley and Los Angeles areas in California using noninvasive seismic technology. The seismic source will be a large, acquisition-controlled vibroseis, which should enable profiling to depths of 45-75 m.

The results of the Vs profiles will fulfill three purposes. First, some sites will be drilled and logged in the near future under PEER Lifelines Task 2A01. The Vs profiles will be used in "blind" comparisons with subsequent profiles measured with the suspension logger. Second, some sites (such as some of those near El Centro) have "old" Vs profiles; that is, Vs measurements perform by downhole testing in the late 1960's and early 1970's. The new Vs profiles will permit evaluation of the validity of the older data. Third, at many of the sites, new information will be generated for PEER Lifelines Task 2G01 where profiles to depths in excess of 30 m would be beneficial.

Methodology employed

In-situ seismic testing will be conducted using the spectral-analysis-of-surface-waves (SASW) test. This test is noninvasive, with all equipment placed on the ground surface. In this project, a large vibroseis will be used as the seismic source. A vibroseis is a truck-mounted shaker which is used in petroleum exploration on land. This particular vibroseis has been modified to permit it to be controlled by the digital recording and analysis equipment used by the PI. With this equipment, profiling to depths of 45 to 75 m will be used to investigate the Vs,30 criterion (Vs profile in the top 30 m) used in the Unified Building Code.

Role of this project in supporting PEER's strategic plan

The Vs profiles will be used as basic site data in response studies and ground-motion attenuation studies. These data are necessary calibration and validation of models which predict the distribution of earthquake shaking at the ground surface resulting from a particular event. The uncertainties in predicting ground motions are critical elements to probabilistic earthquake engineering.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

To date, the field work at over 25 sites in the Imperial Valley has been completed using the SASW method. Interpretation of the raw data is ongoing, and further testing in the Los Angeles area is still anticipated later in the year.

Plans for Year 6 *(if project is proposed to continue)*

Other relevant work being conducted within and outside PEER and how this project differs

The current work is being coordinated with the ROSRINE 5b Project and Prof. Robert Nigbor (PEER Lifelines Project 2A01), which is obtaining related subsurface information through different borehole techniques. The results of the work will also be provided to Professor Jon Stewart of UCLA (Project 2G01) because of these subsurface characterizations may assist his efforts in developing calibration sites for the validation of nonlinear site-response codes.

Expected milestones

Deliverables

- Approximately 20 Vs Profiles and Dispersion Curves in a digital format for posting on the ROSRINE and PEER web sites from selected strong motion sites in the Imperial Valley and Los Angeles.
- Digital and hard copies of final report documenting Test Procedures, Results and Conclusions.

***Project Title*—ID Number**	*Workshop on Ground Motions for Treasure Island National Geotechnical Experimental Site* —**Lifelines 2K01**		
Current Year Start/End Dates	9/1/01—12/31/02	Current Year Budget Funding Source	$30,000.00 Caltrans
Project Leader (boldface) and Other Team Members	**Pedro De Alba (UNH/F)**		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

Over the last decade, researchers in seismology have produced a number of sophisticated techniques for predicting strong ground motion. Practitioners are thus presented with an array of possibilities in selecting design motions for a particular site, each with its own inherent uncertainty.

To study the capabilities of different prediction techniques, at least three major earthquake prediction exercises have been carried out since 1990. The basic idea has been to attempt to model recorded ground response and/or to predict response for sites at which recordings have not been made, permitting different methods of prediction to be compared. Unfortunately, it is fair to say that these attempts were only moderately successful, for two basic reasons:

1. Uncertainty about the regional geology, leading to a large range of assumptions on earthquake source-to-site path characteristics on the part of predictors. This in turn had an important effect on the answers, an effect which was independent of the uncertainties inherent in the prediction techniques themselves.

2. Understandably, the organizers were reluctant to restrict participation in any way, but unfortunately this resulted in numbers of predictions made by essentially the same techniques, while other approaches were not represented.

This project attempts to get around these difficulties by focusing on one very well-documented site, Treasure Island California, and asking for predictions of motion for two extensively studied faults, the Hayward and the San Andreas. Recent compilations of geologic data for the San Francisco Bay Area by USGS and by CALTRANS have drastically reduced path uncertainty problems.

The various phases of the prediction are being supervised by a panel of well-known seismologists and earthquake engineers. Predictors will be selected only after submitting results for two, progressively more complex, qualification exercises. Once predictions for this well-documented setting are made, uncertainties implicit in the different methods will be easier to quantify at a final workshop, which will also be open to practitioners, and students in seismology and earthquake engineering.

We should clarify that the National Science Foundation Geoenvironmental Engineering and GeoHazards Mitigation Program is providing approximately 75% of the direct support to this effort; the additional support provided by PEER will permit us to fully accomplish the exercise.

Methodology employed

In December of 2001, an open invitation was issued to the US seismological and earthquake engineering community, inviting them to pre-qualify for this exercise. Time histories and response spectra were requested for 20 sites which had been subjected to the 1994 Northridge, California earthquake. 19 different researchers expressed interest, and six complete responses were received. These data are currently (May 2002) being examined by the project selection committee.

For those responses deemed satisfactory, a second round of predictions will be requested, tentatively for five historic earthquakes similar to the scenario earthquakes of the final prediction. The basic objective of this second round is to calibrate the different models for known events.

Finally, for the Treasure Island prediction, we propose two causative earthquakes, following the scenarios selected by Schneider et al. (2000) for their study of ground motion hazards in the San Francisco Bay Area:

- A moment magnitude 7.1 event on the Hayward Fault.
- A moment magnitude 7.9 event on the San Andreas Fault.

Participants will be expected to produce time histories and response spectra for free-field rock conditions at Treasure Island.

Role of this project in supporting PEER's strategic plan

This project is in direct support of Research Topic 1 of the Lifelines Program.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

See above.

Plans for Year 6 *(if project is proposed to continue)*

See milestones below. No additional funds will be requested.

Other relevant work being conducted within and outside PEER and how this project differs

None.

Expected milestones

- Problem statement for second qualification round, and selection of second round participants: by May 30, 2002.
- Second-round results due: September 30, 2002.
- Participant workshop for determining parameters of final prediction: November 2, 2002.
- Final workshop: May, 2003.

Deliverables

We envisage that the final product of the prediction exercise and associated workshop will be a publication starting with an overview by the General Reporter followed by the individual papers written by the predictors. The general report would include consensus guidelines and recommendations for practice developed at the workshop on the applicability of different methods, and the uncertainties associated with each. The general report would also identify areas where future research should be focused.

***Project Title*—ID Number**	*Liquefaction Site Characterization in Taiwan*—**Lifelines 3A02**		
Current Year Start/End Dates	9/1/01—8/31/02	Current Year Budget Funding Source	$78,217.00 Caltrans
Project Leader (boldface) and Other Team Members	**Jonathan Stewart (UCLA/F)**, Daniel Chu (UCLA/GS), Emily Gugliemo (UCLA/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The principal objective of this research is to develop case histories for a liquefaction triggering database from the Chi Chi Taiwan earthquake. A second objective is to document soil conditions at sites where interesting liquefaction effects occurred, such as lateral spreading or soil bearing failures beneath building foundations.

Methodology employed

The major tasks in this one-year study will include (1) collection of data being prepared by Taiwanese investigators, (2) field and laboratory work by the PI's including CPT and SPT profiling, and (3) compilation and documentation of liquefaction case histories. Details associated with each task are presented below.

Compilation of Field Performance Data and Taiwanese Subsurface Data

In our data collection work to date we have obtained detailed field reconnaissance and preliminary subsurface data compiled by NCREE for the inland cities of Wufeng, Nantou, and Yuanlin as well as several coastal hydraulic fills (at Taichung Harbor, and the Mai-Liau and Chang-Bin Industrial Parks). Additional data is also available from engineering firms. In particular the firm RESI has performed numerous investigations with SPT and CPT in areas affected by the earthquake, and has agreed to share this data with us.

Field and Laboratory Work

Our subsurface exploration work is focused in Wufeng and Nantou because of the strong shaking at these locations. Our work in Wufeng to date has occurred at one lateral spread site, several developed urban areas with significant ground failure (building settlement, tilting, etc.) and one developed urban area with no observed ground failure. Our work in Nantou has occurred at a spread site and in a developed area with observed lack of ground failure and with ground failure. The work performed at all sites consists of CPT, seismic CPT, and SPT with energy measurements. At selected sites with fine-grained soils, piston tube samples have been obtained for strength/consolidation testing. Index tests have been performed for all SPT samples, including sieve, plasticity, and hydrometer.

Case History Documentation and Dissemination

The data collected in the above tasks is being compiled and documented according to a pre-established PEER format. The data presented for each site includes:

- Soil conditions: description of soil type including gradation and plasticity, penetration resistance data (both CPT and SPT), as available.
- Ground water depth.

- Estimated ground motion amplitude, duration, equivalent number of uniform stress cycles, and Arias Intensity. An estimate of the coefficient of variation on each ground motion parameter will be made.
- Descriptions of field reconnaissance supporting the occurrence or non-occurrence of liquefaction at each site. For lateral spread sites, this would include maps of the feature and estimated displacements.

These data will eventually be disseminated on the PEER web site.

Role of this project in supporting PEER's strategic plan

Well documented field case histories form the basis of contemporary procedures for analysis of liquefaction triggering and liquefaction effects. The Lifeline Program is seeking to develop probabilistic models for liquefaction-induced ground deformations, and data such as that being developed in this project is vital to the development of such models.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

A first phase of field work (approximately 75% of total) was completed in September-October 2001 in both Nantou and Wufeng. Laboratory work on the collected specimens is also complete. All CPT logs have been compiled, and velocity profiles have been developed for all seismic CPT. Preparation of boring logs is ongoing.

Plans for Year 6 *(if project is proposed to continue)*

I do not know if this project will be continued, but there remain significant opportunities for additional data collection in Taiwan. This includes previously unidentified sites that have come to our attention in the past year, and obtaining high-quality samples from silty-clayey sands for detailed laboratory investigations in the U.S.

Other relevant work being conducted within and outside PEER and how this project differs

Similar work has been performed in Turkey by Jonathan Bray (UCB) and Les Youd (BYU).

Expected milestones

- Phase I field work (complete)
- Phase I laboratory work (complete)
- Compilation of CPT logs and velocity profiles from Phase I (complete)
- Compilation of boring logs from Phase I (ongoing)
- Phase II exploration and documentation (summer 2002)

Deliverables

Web page documenting ground condition, field observations, and shaking parameters at investigated sites.

***Project Title*—ID Number**	*Update Database for Liquefaction Data*—**Lifelines 3A04**		
Current Year Start/End Dates	5/1/01—4/30/02	Current Year Budget Funding Source	$24,385.00 Caltrans
Project Leader (boldface) and Other Team Members	**Jean-Pierre Bardet (USC/F)**, Jennifer Swift (USC/PD), Jianping Hu (USC/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The main research objective is to update previously developed databases of case histories of liquefaction-induced ground deformation. This improved database is intended for developing deterministic and probabilistic models of liquefaction-induced ground displacement. The specific objectives are (1) to continue data collection on the existing case histories and the 1999 Kocaeli and Duzce, Turkey, earthquakes, and (2) to enhance the GIS access and display of case histories of liquefaction-induced ground deformations. The case histories will be focused in the range of displacement of interest of lifelines engineering (i.e., less than 2 meters). The additional funding in Year 5 is being used to screen the quality of the data more closely, and add supplemental data that will make the cases more useful.

Methodology employed

Additional information is being added to the cases in the database in order to provide a complete set of data needed for validation of models for prediction of liquefaction deformation. In addition to the field test results and displacement vectors originally collected, this requires adding information on groundwater levels, the distribution of ground motions, and high resolution topographic data. For locations and events in the database for which the data density is sufficiently high across these categories, "high quality" case histories can later be extracted and documented as consensus cases for validation work.

Role of this project in supporting PEER's strategic plan

Computational methods for estimating displacements of liquefied soils are important for calculating the hazard at many alluvial sites, but many of the developing methods have yet to be validated against well-defined field cases, which is needed to develop confidence in their accuracy, and to estimate the degree of uncertainty appropriate for such results.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

The database for liquefaction related deformations has been fully integrated with Arcview GIS and IMS formats, which allow Internet display and query of data related to case histories of liquefaction-induced ground deformations (Bardet et al., 2000a, http://geoinfo.usc.edu/peer/).

In addition, during the first year of the current work, data from the 1994 Northridge and 1995 Hyogoken Nanbu earthquakes were collected and added into the existing relational databases of liquefaction induced ground deformation. Example data for Northridge are shown in Figure 1.

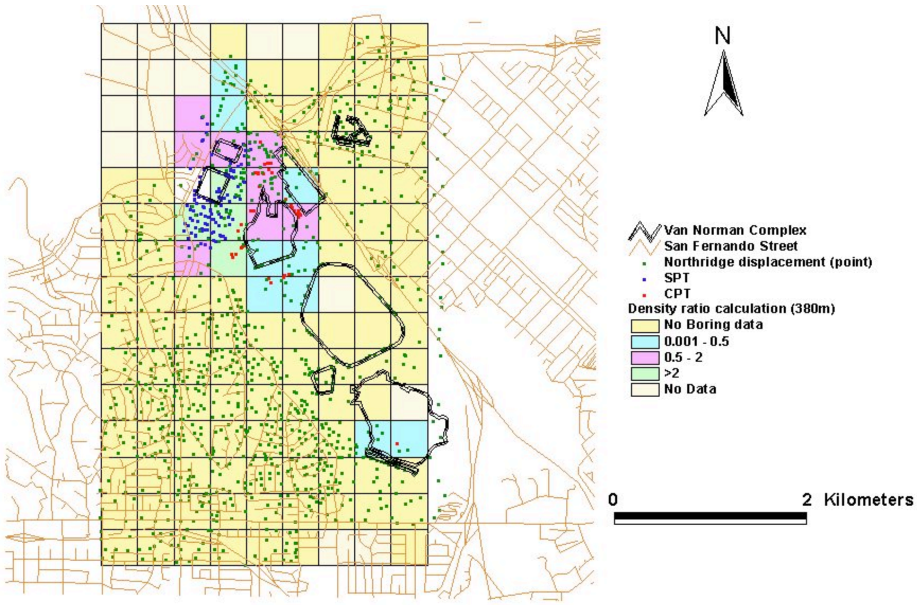


Figure 1. Density ratio for data in the 1994 Northridge Earthquake liquefaction database.

Plans for Year 6 ***(if project is proposed to continue)***

Other relevant work being conducted within and outside PEER and how this project differs

While there are no immediately similar projects ongoing, there are several future projects planned within PEER which will rely to some extent on this work. Models for predicting deformations of liquefied soils could be validated by comparison with good quality case histories developed from this work. Data from another project (3A01b) by the same PI will consist of similar displacement vectors obtained from aerial photographs, and could be added to this database if sufficient supporting data is available.

Expected milestones

- Quarters 1-3: Add digital topographic and water table information, and other original geological and geotechnical data, to databases; further implement QA/QC system; continue data collection and database entry.
- Quarter 4: It is anticipated that the enhanced database of case histories will be completed and ready for use by other researchers.

Deliverables

A final version of a master CD-Rom of case histories of liquefaction-induced ground deformation via ESRI ArcExplorer and Microsoft Access; An additional series of CD-Roms will provide all of digital map data compiled during this project.

***Project Title*—ID Number**	*Probabilistic Liquefaction Assessment by Shear Wave Velocity*—**Lifelines 3D03**		
Current Year Start/End Dates	4/1/01—12/31/02	Current Year Budget Funding Source	$47,450.00 PG&E/CEC
Project Leader (boldface) and Other Team Members	**Rob Kayen (USGS–UCB/F)**		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

This task will (1) greatly expand the shear wave velocity data-set at liquefaction sites subjected to high intensity earthquake motions through a field data collection effort in Japan, India, Taiwan and China, and (2) produce deterministic and probabilistic shear wave velocity-based liquefaction potential assessment relationships.

Methodology employed

It is proposed that liquefaction sites are investigated by shear wave velocity using the spectral analysis of surface waves (SASW) method. The USGS system employs an Agilent spectral analyzer and an array of 1 Hz Kinemetrics Ranger geophones. A 110 kilogram (kg) electromechanical shaker (Figure 1) is used as an active source for generating surface waves. The shaker sweeps though a range of frequencies (i.e., swept sine mode) controlled by the spectral analyzer. Using a shaker in swept sine mode gives higher signal to noise than random source SASW. The shaker also allows for the characterization of low strain damping of soil. In practice, 3-4 sites can be tested in a full day, as a given site requires approximately two to three hours. Once at a site (1) seismometers and cables are connected to the analyzer; (2) the shaker is lowered to the ground with a mechanical lift; and (3) a generator is taken out of the van and started to power the amplifier and analyzer. Analysis of the data includes calculation of dispersion curves for each site, followed by determination of velocity profiles that fit the dispersion curves, through either approximate l/3 estimation or more theoretical Haskell-Thompson inversion methods.

Figure 1. Electromechanical shaker in the field for swept sine wave SASW profiling.

Role of this project in supporting PEER's strategic plan

This project is building upon the PEER Lifelines Program's already successful work in evaluating the liquefaction triggering potential of soils in a probabilistic framework (by Seed and others), by extending the methods to include in situ shear wave velocity measurements. This will provide information on liquefaction hazard and associated levels of uncertainty for use in earthquake engineering analyses

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

Approximately 200 sites in Japan and Taiwan have been characterized in the field at locations which have experienced historically documented liquefaction. Dispersion curves and velocity profiles for these sites continue to be developed from this field data.

Plans for Year 6 *(if project is proposed to continue)*

Other relevant work being conducted within and outside PEER and how this project differs

PEER Lifelines Projects 1D01 and 1D02 have developed the probabilistic framework for interpreting Standard Penetration Tests (SPT) and Cone Penetration Tests (CPT) for liquefaction triggering, and a similar approach will be used in this project, which will instead use shear wave velocity data from SASW testing.

The correlation of shear wave velocity with liquefaction has been examined and a database developed by Andrus and Stokoe (2000), though the data points in their catalog are limited primarily to low-to-moderate intensity motions (CSR<0.35) and shallow (<8m) deposits. This project will expand the database possibly doubling it, by generating data at historic sites exposed to shaking levels greater than CSR of 0.35. The current project will also process the database using Bayesian techniques to extract information about the uncertainties amongst the parameters.

Expected milestones

Quarterly reports will be produced documenting the location of sites where data are collected, dispersion curves, and shear wave velocity profiles.

Deliverables

A final data report will be produced in June 2002 that will synthesize the data collected and present a preliminary deterministic liquefaction correlation based on effective stress normalized shear wave velocity. A final report will be produced before December 31, 2002 that includes deterministic and probabilistic curves for shear wave-based liquefaction assessment utilizing both CSR and Arias intensity.

***Project Title*—ID Number**	*Performance of Lifelines Subjected to Lateral Spreading: Full-Scale Experiment*—**Lifelines 3F01**		
Current Year Start/End Dates	6/13/01—6/30/02	Current Year Budget Funding Source	$622,597.00 Caltrans
Project Leader (boldface) and Other Team Members	**Scott Ashford (UCSD/F),** Ahmed Elgamal (UCSD/F), Chia-Ming Uang (UCSD/F), J. Meneses (UCSD/PD)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The goal of this PEER Lifelines Program collaboration is to evaluate the performance of lifelines subjected to lateral spreading. This will be accomplished through installing a series of pile foundations and a pipeline in the zone of lateral spreading. Specifically, our objectives are to:

- Conduct damage and performance assessments of a single pile, 4-pile group, and 9-pile group subjected to lateral spreading.
- Conduct damage and performance assessments of a natural gas pipeline subjected to lateral spreading.
- From instrumentation in the piles and pipeline, evaluate loading conditions on the structures during the lateral spreading.
- Utilize developing numerical platforms with PEER to analyze performance (OPENSEES), as well as utilize simpler models and empirical methods derived from past earthquakes.

By accomplishing these objectives, we will be able to assess current design procedures and provide recommendations for the cost effective design of lifelines facilities subjected to lateral spreading. Using the detailed information obtained from this unique full-scale experiment, improved performance of pipelines and pile foundations during seismic events can be expected once these recommendations are implemented.

Methodology employed

Lateral Spreading Experiment: The full-scale lateral spreading experiment was carried out during September 2001 in the Port of Tokachi on the island of Hokkaido, Japan. This US$2 million effort is being lead by Professor Masanori Hamada of Waseda University and Dr. Takahiro Sugano of the Port and Airport Research Institute. During the test, nearly 300 blast holes, each consisting of several charges, were detonated in a 100 m by 100 m area, in order to liquefy the ground.

Pile Experiment: Three foundation systems will be installed: a single pile, a 4-pile group, and a 9-pile group in order to allow us to determine the effect of groups on the pile response. Each was installed in the zone of expected lateral spreading, and in addition to the soil flowing around the pile, the top portion of the pile was be loading by a non-liquefied soil "cap" riding on top of the liquefied layer.

Pipeline Experiment: Two sections of 500-mm steel pipe representing gas pipelines and one section of 200-mm steel pipe representing electrical conduit, each 30-m long and with a 6-mm wall thickness, were installed at a depth of approximately 1 m. The entire area was marked with a surface grid for interpretation of the ground movements a result of lateral spreading using high-resolution aerial photography.

Analysis: The analyses will consist of essentially two phases. The initial phase of the analyses was simply to reducing the data obtained from the test, including strain gauge and tilt meter data, into a usable form. The second phase of the analyses was interpretation of this data.

Role of this project in supporting PEER's strategic plan

This ground deformation experiment supports the Lifelines Program strategic plan by providing detailed data on the full-scale performance of lifeline facilities, specifically bridge foundations, gas pipelines, and electrical conduits, subjected to lateral spreading. These data provide direct information on lifeline performance as well as a basis for assessment of numerical models currently under development by other PEER researchers.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

Two successful lateral spreading experiments were carried out in November and December 2001, resulting in a total of over 80 centimeters of down slope movement of the soil mass. Over 450 channels of data were collected from 2 gas pipelines, 1 electrical conduit, and 14 piles, including 2 pile groups. Ground surface movement was monitored used survey points and real-time GPS units. The data is currently being finalized for PEER researchers in a report to be published in June 2002.

Plans for Year 6 *(if project is proposed to continue)*

It is anticipated that the PEER Core Program will fund the final phase of the analyses in Year 6. The final phase of the analyses will be the assessment of our numerical models based on the valuable data we've collected from the experiment. PEER's computational platform, OPENSEES, will be utilized and assessed during this phase of the research for both the pipeline and pile group portions of the project. However, simpler models for pipelines (e.g. O'Rourke, 1966 and well as those under development by the PI, will also be utilized, in addition to comparisons with data from past earthquakes.

Other relevant work being conducted within and outside PEER and how this project differs

This is the only full-scale lateral spreading test ever conducted. It complements work ongoing large-scale shake table experiments at UC San Diego and small-scale centrifuge experiments carried out at UC Davis and Renssalaer Polytechnic Institute. It also complements ongoing efforts within PEER Core to numerically model lateral spreading.

Expected milestones

- July 2001: Award research contract.
- August 2001: Install instrumented piles and pipeline.
- September 27, 2001: Conduct full-scale lateral spreading test.
- December 2001: Complete preliminary data reduction.
- June 2002: Complete final data report.

Deliverables

- Final Test Report – June 2002
- PEER Quarterly Reports

***Project Title*—ID Number**	*Pilot Application of Regional Liquefaction Ground Deformation Models*—**Lifelines 3G01**		
Current Year Start/End Dates	5/15/01—12/31/02	Current Year Budget Funding Source	$103,999.00 PG&E/CEC
Project Leader (boldface) and Other Team Members	**Keith Knudsen (CGS/O)**, Anne Rosinski (CGS/GS), Jiaer Wu (UCB/GS), Marvin Woods (CGS/O)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

(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.

Methodology employed

The two main methods we plan to apply 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 (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 will be done utilizing geographic information systems (GIS).

Role of this project in supporting PEER's strategic plan

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 regionally applicable 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.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

We are converging on methods to be applied/tested and are nearing finalization of the geotechnical dataset that will be used in our analyses. We have researched available existing methods, identified the most suitable methods, performed sensitivity analyses, and have refined one to two methods for our purposes. We have collected and compiled a variety of subsurface geotechnical information, obtained digital terrain information, and have on file ground motion information. Additionally, we have participated in PEER lifelines quarterly meetings.

Plans for Year 6 *(if project is proposed to continue)*

The first year of this project has mainly been one of data collection, researching existing methods, sensitivity analyses and modifying methods to be used in year two. Year two of this project will include use of the methods and data to develop maps. Most importantly, at the end of year two, we will assess the viability of producing regional maps and the usefulness of existing methods/approaches.

Other relevant work being conducted within and outside PEER and how this project differs

Outside related work: (1) The CDMG SHMP is synthesizing comprehensive geologic and geotechnical data sets for key urbanized regions (Los Angeles and San Francisco Bay Area) 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 evaluating liquefaction hazard and potentially 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)

Within PEER there are ongoing projects whose results and methods may be employed in this study. Our study is different from the other PEER studies in that we are attempting to develop methods for producing regional maps of displacement from liquefaction. The results of other ongoing PEER and outside projects may provide tools that can be used in this pursuit.

Expected milestones

By the Fall of 2002, we plan to have completed the geotechnical database for the project. We also plan to have ready historical high ground-water data, seismological data, and topographic data. Interpretation of the three-dimensional geology will be well underway and we will be developing the computer code to perform the analyses described above. The making of maps will not happen until at earliest Winter of 2002/2003.

Deliverables

Two reports will be generated. The first will document the methods and results of the detailed geologic and liquefaction susceptibility characterization of a part of the Santa Clara Valley. It will include maps and cross sections depicting geologic conditions and relative susceptibility to liquefaction. The second will summarize the results of our liquefaction-induced deformation analysis and will include a discussion of the variety of methods available and the reasons for choosing the regional methods we will be using. The maps and supporting report text will discuss results, related uncertainties, and perhaps key differences between results of alternate models. The two draft final reports will be submitted on the termination date of the project with the final reports submitted 30 days after this date. Additionally, progress reports will be submitted each quarter.

***Project Title*—ID Number**	*Working Group for Validation of Probabilistic Seismic Hazard Computer Programs*—**Lifelines 607**		
Current Year Start/End Dates	10/1/01—9/30/02	Current Year Budget Funding Source	$73,699.00 Caltrans
Project Leader (boldface) and Other Team Members	**Ivan Wong (URS/I),** Patricia Thomas (URS/I)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

Probabilistic seismic hazard analysis (PSHA) is a commonly used approach for assessing earthquake ground shaking hazard. The approach was first developed by Allin Cornell of Stanford University in 1968 and this was followed by a publicly available code developed by Robin McGuire. Since then, PSHA codes have been developed by numerous individuals.

As seismic source characterization has advanced and source models have become more complex in terms of source geometry and earthquake recurrence, PSHA codes have become more sophisticated. In most cases, analytical checks cannot be conducted for the hazard codes. Preliminary comparisons of the hazard computed using various computer programs found large differences in the results for some cases.

In this project, a working group on PSHA code validation has been formed to develop standard validation exercises, and test existing hazard codes. Both publicly available codes as well as proprietary codes that have been used extensively in hazard evaluation in California will be tested. The focus of this evaluation will be numerical verification of the codes and analysis and comparison of their various features.

PG&E, Caltrans, and the CEC use PSHA results, which may be computed by consultants using different computer programs. Thus there is a need to develop standard validation tests to qualify seismic hazard codes.

Methodology employed

The Working Group consists of 15 persons involved in developing or using PSHA computer programs. The Working Group will develop about 20 to 25 test cases which will range from the simplest to more sophisticated. The simplest cases have analytical solutions, but the more complex cases will not. Test Case Set #1 was provided to each of the participants on 12 March 2002. Most of the participants provided their results to URS by 26 April 2002. Two publicly available codes are being tested by URS.

The results of the initial test case set are being provided to each participant without identifying the names of the codes (except for the participants own code). This initial feedback is intended to allow the code developers to identify numerical mistakes and to correct them. For the publicly available codes, the results will be sent to the authors. The test cases will then be re-run with the revised code and submitted to URS.

A second set of more complex test will be sent out in early June. The results will again be compiled by URS and distributed to all of the participants with the names of the programs identified. Differences in the codes will be examined and a workshop will be held to go over the detailed differences in program features. A final workshop will be held in October for final evaluations.

Role of this project in supporting PEER's strategic plan

In addition to providing a means for Caltrans, PG&E, and the CEC to qualify hazard codes, the results of this project will also be useful to the PEER program as it begins to implement the PEER framing equation, which will require new hazard calculations for a vector of parameters. PEER will need to adopt a hazard code or codes that it will use.

Year 5 accomplishments and brief description of Year 4 accomplishments *(if continuation)*

Almost all milestones completed in Quarters 1 and 2.

Plans for Year 6 *(if project is proposed to continue)*

None

Other relevant work being conducted within and outside PEER and how this project differs

None

Expected milestones

The project is scheduled to be completed in 12 months from the date of authorization. Expected milestones include:

- Establish Working Group
- Develop test cases
- Convene first workshop to discuss project approach
- Participants complete Test Case Set #1
- Complete Initial Feedback
- Participants complete revised runs for Test Case Set #1
- Participants complete Test Case Set #2
- Complete feedback
- Convene workshop to review revised results
- Develop consensus results for test cases
- Develop acceptance criteria for "passing grade"
- Convene final workshop
- Prepare final report

Deliverables

A report describing the test cases, the identification of errors, and the differences in the features of the codes will be prepared. We anticipate that consensus hazard results can be identified for the test cases that can serve as benchmark for other codes. We expect that this verification exercise will identify errors in some of the existing hazard codes and it will clearly identify the differences in features and assumptions in the hazard codes. The report will recommend minimum standards for meeting the benchmark results (e.g., 20% in probability level) that can be used to qualify hazard codes.

The test cases and their results established as part of this project will be entered on the PEER website to allow other interested parties to evaluate their codes. This will be of value to the other Engineering Centers and to other countries in their development or use of probabilistic hazard codes.

***Project Title*—ID Number**	*International Workshop on Performance-Based Earthquake Engineering*—**3162001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$40,000.00 NSF
Project Leader (boldface) and Other Team Members	**Jack Moehle (UCB/F)**		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The goal of this project is to enhance at an international level the exchange of the latest research and professional practice information on performance-based earthquake engineering.

Methodology employed

The project is accomplished by convening a meeting involving major researchers and practitioners in the field of performance-based earthquake engineering. At the meeting, researchers and practitioners present their latest results, engage in lively discussion, and suggest new directions and research needs. Given the strong and coordinated programs in the US and Japan, most participants are from those countries. The view from both the US and Japan sides is that performance-based earthquake engineering will accelerate reduction in earthquake losses through its emphasis on quantitative measures of performance over qualitative measures, precision over approximation, explicit consideration of uncertainty, and expression of performance in terms suitable for decision-makers. Although the participants share this common view, the details of their perspectives are markedly different; bringing together these diverse ideas leads to enhanced thinking about performance-based earthquake engineering.

Role of this project in supporting PEER's strategic plan

This project serves the PEER strategic plan by promoting more rapid development and exchange of performance-based earthquake engineering technologies among leading practitioners and researchers. Ongoing PEER research project personnel are encouraged to accelerate presentation of their findings, and overall project information is enhanced by introducing knowledge and ideas developing outside PEER.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

This project is a continuation of prior projects that hosted the 1st through 3rd US-Japan Workshops on Performance-Based Earthquake Engineering for Reinforced Concrete Building Structures. The 1st and 2nd Workshops (Maui, September 1999; Sapporo, September 2000) resulted in publication of important symposium proceedings including all presented papers.

This past year we convened the 3rd Workshop in Seattle (August 2001). The meeting was timed and located to coincide with two other meetings; a major project meeting of the US-Japan Cooperative Research In Urban Earthquake Disaster Mitigation, sponsored in Japan by the Ministry of Education, Science, Sports, and Culture, and in the U.S. by the National Science Foundation; and a project meeting of the FIB working groups developing state-of-the-art documents on displacement-based design and seismic retrofitting. By aligning different meetings, we were able to attract a broader international pool of attendees, including participants from Greece, Italy, Japan, Mexico, Slovenia, Taiwan, and USA (Figure 1). The meeting included plenary sessions, breakout sessions on specific topics, closing presentations by selected individuals, resolutions, and a visit to a nearby construction site where the design utilized performance-based concepts. It was resolved to convene a 4th workshop during Fall 2002.

The meeting is organized for the US side by PEER Director Jack Moehle. PEER provides travel funds for all US participants, which include PEER researchers, PEER Business and Industry Partners, and other selected researchers from the US. The Japan-side organizer is Professor Toshimi Kabeyasawa of the University of Tokyo.

Plans for Year 6 *(if project is proposed to continue)*

The plan is to continue this workshop series in Year 6, or to support a similar international effort.

Other relevant work being conducted within and outside PEER and how this project differs

This project exists to enhance ongoing research in many PEER projects related to performance-based earthquake engineering or concrete buildings. Research and practice of performance-based earthquake engineering is being done by individuals in several countries. We aim to include key researchers and practitioners as part of the program.

Expected milestones

Proceedings for the 3rd Workshop are in preparation at the time of this writing, and should be available May 2002. Additional work for Year 5 includes planning for the 4th workshop, including selection of a venue, selection and invitation of participants, solicitation of papers, and convening the meeting. The final decision on venue is to be reached during a meeting in Tokyo in May 2002.

Deliverables

Proceedings from 3rd and 4th Workshops.

Front Row: Toshikatsu Ichinose, Mario Rodriguez, Hitoshi (Jin) Tanaka, Kangning Li, Eduardo Miranda, Matej Fischinger , Masaru Teraoka , Shunsuke Otani, Dawn Lehman. *Next Row*: Minehiro Nishiyama, Chin-Hsiung Loh, Daisuke Kato, Masaki Maeda. *Back*: Hitoshi Shiohara, Michele Calvi, Peter Fajfar, Paulo Pinto, Jack Moehle, Michael Valley, KC Tsai, Manabu Yoshimura, Marc Eberhard, Craig Comartin, Gregory Deierlein, Mark Aschheim, Wilfred Iwan, James Jirsa, Masaomi Teshigawara, Mervin Kowalsky, Sharon Wood, Toshimi Kabeyasawa, Michael Fardis, Julio Ramirez, Kazuhiro Kitayama, Akira Tasai, and Koichi Kusunoki.

Figure 1 – Participants in the 3rd Workshop

***Project Title*—ID Number**	*Methodology for Selection in Input Ground Motions for PBEE and Propagation of Uncertainties from IM to EDP*—**3172001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$70,000.00 NSF
Project Leader (boldface) and Other Team Members	**Allin Cornell (Stanford/F)**, Fatemeh Jalayer (Stanford/GS), Jack Baker* (Stanford/GS), Paolo Giovenale* (U. of Rome/GS) **=not financially supported by project*		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

Provide methods for several key steps in EDP determination: selecting records, IM definitions, processing nonlinear response results, propagating uncertainties.

Methodology employed

Study of alternative IM-EDP methods via the Van Nuys testbed structures.

Role of this project in supporting PEER's strategic plan

Provides procedures for the IM to EDP uncertainty assessment step. Provides IM and record selection and use development.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

This project has addressed several issues related to ground motions, intensity measures, and uncertainty.

We have developed further methods for estimating the conditional probability distribution of EDP given IM = x as a function of x for nonlinear structures. This is one of the functions in the PEER framing equation. Our focus of late has been on the near-failure regime where the dependence is changing and nonlinear, and where there may be a significant fraction of the records that induce non-converging (and/or "collapse") results. This region has proved difficult capture by previous methods. One new method is based on log-linear fits to individual record IDAs for the better-behaved regime coupled with an estimate of the fraction of collapses (vs. x). The method provides drift hazard results that compare very well with (non-parametric) empirical integrations. The log-linear IDA can be estimated by only two runs per record, permitting focus of resources on seeking the collapse level. This approach also admits to an analytical solution for the drift hazard, and hence to practical checking limit state procedures.

We have developed a comparatively simple first-order, second-moment scheme for conducting the (aleatory and epistemic) uncertainty propagation through the several, long correlated random vectors of EDPs and DMs to the DVs in the PEER framing equation. The results are the first and second moments of the DVs given IM = x. These can be used with the IM hazard curve to produce mean and variance of each DV, and, with an appropriate distribution assignment, the DV "hazard curve", i.e., the annual probability of exceeding DV level y vs. y. It is presumed that this scheme will be adequately accurate for treatment of these intermediate variables given the comparative uncertainty dominance of the IM variable. The method is being implemented by Prof. Miranda in his loss analysis project.

The project has investigated the use of the nonlinear response results from records scaled to several fixed values of first-mode spectral acceleration to study the effectiveness of other candidate IM's, without having to re-scale (to fixed values of the candidate) and to re-run the records. We have studied whether simple regressions will work (despite evidence that they should not) and we have developed an indirect, post-processing method that promises to provide more accurate conclusions. This will encourage the study of alternative IMs by reducing the barrier associated the many, time-consuming nonlinear dynamic runs that are necessary otherwise. The first application will be to the testbed structures.

We studied the problem of record selection for PEER PBEE purposes. We have a developed a scheme that will make the conclusions comparatively insensitive to the properties (e.g., magnitude) of the records selected. The method makes use of PSHA de-aggregation results thereby considering that the site-specific nature of the problem. The method recognizes, for example, that larger magnitudes are more likely to cause the large ground motion levels. We have begun to apply the method to the near-source problem.

Plans for Year 6 *(if project is proposed to continue)*
The record selection work and application to near-source conditions will be carried into the second-year of the test bed structures.

Other relevant work being conducted within and outside PEER and how this project differs
Y. K. Wen (U of I) is doing related work. This work differs in that we use recorded ground motions, not simulated records. J. Bray, S. Kramer, and Joel Conte, among others, are PEER researchers with strong IM interests.

Expected milestones
IM selection and procedures for testbeds (9/02); records for year 2 of testbeds (9/02).

Deliverables
Several papers are in progress. A thesis/report by Miss Jalayer is expected by 10/02.

***Project Title*—ID Number**	*Bridge Fragility and Post Earthquake Capacity*—**3182001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$50,000.00 CA-Transportation
Project Leader (boldface) and Other Team Members	**Bozidar Stojadinovic (UCB/F)**, Kevin Mackie (UCB/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The goal of this project is to evaluate the post-earthquake traffic load capacity of typical California highway overpass bridges. The objectives are:

- Evaluate damage caused to a bridge by first-hit earthquakes associated with selected seismic hazard levels;
- Evaluate additional damage caused to a bridge by aftershocks associated with realistic aftershock scenarios (aftershock hazard levels);
- Assess post-earthquake bridge functionality in terms of traffic load capacity, addressing both vehicle weight and vehicle traffic flow.

Methodology employed

PEER hazard dis-aggregation methodology is applied. The probabilistic seismic demand model (deliverables 1 and 2) relate ground motion intensity measures and bridge engineering demand parameters, corresponding to the EDP-IM component of the PEER integral. Three methods for deriving this relation, the log-normal distribution fit, the stripe method, and the IDA method are used.. The fragility curves (deliverable 3) are an extension of the probabilistic seismic demand model that incorporates seismic hazard data and probabilistic component and system capacity data derived by other PEER researchers, implementing PEER dis-aggregation methodology. They will provide the basis for a bridge rating system (deliverable 4).

Role of this project in supporting PEER's strategic plan

This project will have an impact because it will enable:

- Rational evaluation of traffic network capacity using fragility curves that directly address traffic load-bearing capacity of a damaged bridge; and
- Constitution of a bridge post-earthquake rating system.

This project is horizontally linked to loss modeling components in PEER bridge testbeds, as well as structural modeling tasks involved in developing models for repeated damage and deterioration. The results of this project will contribute to developing PEER methodology for treatment of hazard imposed on a structure already damaged in a first-hit earthquake. This methodology involves a definition of a likely damaged state and probabilistic seismic demand or traffic demand analysis that starts form such damaged state. Thus, this project will give input to the methodology tasks in all six PEER testbed projects.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

Milestones 1, 2, 3 and 6 have been completed. Current work is focused on Milestones 4, 5, 8 and 9. Selection of aftershock scenarios is done in two ways. First, existing records of first-shock and after-shock earthquakes are collected and prepared for analysis. Examples include 1994 Northridge and 2001 Turkey and Taiwan records. Second, PEER I-880 testbed records will be re-run as aftershock records in an IDA-type analysis. This way the uncertainty in after-shock return period intensity will be covered. Milestone 5 is accomplished by updating bridge models developed in project 312 as new OpenSees elements become available. Work on milestones 8 and 9 is done through verification of the newly introduced OpenSees components and running of the necessary analyses.

Plans for Year 6 *(if project is proposed to continue)*

Continue working on Milestones 7, 10, 11, and 12. Milestone 7 (and to some extent milestone 4) requires further coordination with PEER researchers in the Highway Network Testbed. Milestones 10, 11 and 12 require additional computational work, as well as further improvement of OpenSees deteriorating component models.

Other relevant work being conducted within and outside PEER and how this project differs

A major project on the development of a risk-based methodology for assessing seismic performance of highway systems, conducted in cooperation between MCEER and USC, is similar to this project. The differences are: (1) the fragility curves developed in this project will be based on PEER probabilistic performance-based methodology and developed using sophisticated non-linear bridge computer models, while the USC/MCEER project uses simplified bridge models or empirical fragility curves; (2) USC/MCEER project has a significantly wider aim, while this project is focused on rational evaluation of bridge post-earthquake traffic load capacity and development of bridge rating system only.

Expected milestones

- Select optimal EDPs for evaluation of bridge post-earthquake traffic load capacity.
- Select hazard levels appropriate for use in the I-880 and the Highway Network testbeds.
- Select first-hit earthquake ground motions corresponding to the chosen hazard levels.
- Select aftershock scenarios and ground motions corresponding to the chosen hazard levels.
- Update the highway bridge models used in PEER Project 312 by incorporating new deterioration elements in OpenSees as well as realistic models of bridge abutments.
- Develop a portfolio of bridge models representing typical California overpass bridges and bridges used in the I-880 and the Highway Network testbeds.
- Develop bridge traffic load scenarios and implement them in OpenSees.
- Determine EDP levels corresponding to first-hit seismic hazard levels using PSDA approach.
- Model bridge damage at different first-hit seismic hazard levels and implement in OpenSees.
- Develop PSDMs for damaged bridges and aftershock scenarios.
- Develop fragility curve for bridge traffic function for varying first-hit seismic hazard levels.
- Develop fragility curve for bridge traffic function for varying aftershock seismic hazard .

Deliverables

- Probabilistic seismic demand models (demand hazard corves) for first-hit earthquake scenarios at seismic hazard levels relevant for the I-880 and Highway Network testbeds.
- Probabilistic seismic demand models (demand hazard curves) for aftershock scenarios at seismic hazard levels relevant for the I-880 and Highway Network testbeds.
- Bridge traffic load fragility curves, describing the ability of the bridge to function in terms of carrying vehicles of a given weight and carrying average traffic loads at given speed and vehicle number, relevant for the I-880 and Highway Network testbeds.
- Basis for constituting a rating system to evaluate post-earthquake traffic load capacity of simple bridges, akin to a tagging system used for buildings.

***Project Title*—ID Number**	*Engineering Assessment Methodology*—**3192001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	\$90,000.00 NSF
Project Leader (boldface) and Other Team Members	**Helmut Krawinkler (Stanford/F)**, Luis Ibarra Olivas (Stanford/GS), Farzin Zareian (Stanford/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The objective is to develop quantitative information and simplified procedures that permit approximate performance assessment by means of commonly employed engineering analysis methods, and with a focus on the most relevant engineering demand parameters (EDPs) and damage measures (DMs). Performance will be expressed in terms of confidence levels and mean annual frequencies of exceedance of selected performance parameters (collapse, story drifts, inelastic deformations, and selected damage measures). The expected outcomes of the research are information and procedures that will assist the engineering profession in carrying out performance assessment with currently available tools and with tools that are under development by the research community.

Methodology employed

This research builds on the knowledge and information generated by the PI and other investigators within and outside PEER. In the context of the PEER framework equation, the work focuses on IM-EDP-DM relationships (IM = intensity measure). Evaluation of decision variables (DVs) is not within the scope, except for the assessment of global collapse. The research will consist of extensive simulations, synthesis of simulation results, assessment of uncertainties, derivation of bias factors for standard engineering analysis methods, development of EDP and DM hazard curves, and development of simplified procedures for performance assessment that are based on standard engineering analysis methods but account for important sources of uncertainty.

Role of this project in supporting PEER's strategic plan

PEER's Year 1 to Year 4 efforts have focused on a rigorous performance assessment methodology, with an emphasis on the probabilistic evaluation of decision variables associated with discrete limit states (e.g., collapse) or with losses and downtime. This rigorous approach may be too complex for most of the performance assessment tasks encountered in engineering practice (at least in the near future). It is the subject of this research to develop quantitative information and simplified procedures for an engineering approach to performance assessment.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

The following issues are being dealt with in the context of developing IM-EDP-DM relationships:

Intensity measures. In Year 5, the spectral acceleration (or displacement) at the first mode period, $S_a(T_1)$ [$S_d(T_1)$], is being used as the primary IM.

Engineering demand parameters. EDPs for structural, nonstructural, and content damage are being evaluated in Year 5. The objective is to (a) evaluate the sensitivity of EDPs to IMs, modeling assumptions, and analysis procedures, (b) develop EDP/IM relationships and EDP hazard curves that account for important sources of uncertainty, and (c) develop simplified relationships that will become part of the engineering performance assessment approach.

Damage measures. Other researchers in PEER are working on the development of damage "fragility curves" (DM/EDP relationships) and also on local collapse "fragility curves". Such curves relate the probability of exceeding a damage limit state (e.g., the need to replace a partition), or of having local collapse (e.g., a flat slab dropping because of shear failure around a column), to a relevant EDP. In this study it is assumed that such "fragility curves" are known (e.g., DM/EDP is known). The task is to evaluate, for instance, the mean annual frequency of exceeding this limit state, i.e., l(DM), considering the postulated DM/EDP and all important uncertainties in EDP and IM. The results then need to be simplified to be useful in an engineering performance assessment approach. This will be a focus of the Year 6 effort.
Decision variables. Only the intermittent decision variable of global collapse is being studied in this project. Global collapse can be viewed as an "intermittent" DV because in the PEER framework life safety is a primary performance target and global collapse is only one source (albeit the most relevant one) for loss of lives. Work on assessment of global collapse probability is in progress and will be completed in the middle of Year 6. In this part of the research, collapse "fragility curves" (probability of collapse, given IM) are being developed for various types of deteriorating systems. If such a collapse "fragility curve" is integrated over an IM hazard curve, the mean annual frequency of collapse (together with an assessment of epistemic uncertainties) can be obtained.

Plans for Year 6 *(if project is proposed to continue)*
Please see section on accomplishments.

Other relevant work being conducted within and outside PEER and how this project differs
This research forms an integral part of the PEER assessment methodology development effort. As such, it takes advantage of knowledge generated by others within and outside PEER.

Expected milestones

- Selection of the most relevant IMs, EDPs, and DMs through interaction with researchers and practicing engineers.
- Quantification of the sensitivity of EDPs and DMs to intensity measures (IMs).
- Quantification of the sensitivity of EDPs to modeling assumptions (e.g., first mode period)
- Quantification of the sensitivity of EDPs and DMs to customary engineering analysis procedures (elastic static, elastic dynamic, and inelastic pushover)
- Quantification of the relationships between EDPs and SDOF response parameters (some of which serve as candidates for improved IMs).
- Quantification of EDP hazard curve and DMs for regular frame and wall structures.
- Quantification of collapse fragility curves and collapse probabilities for regular frame and wall structures.
- Assessment of the importance of various sources of uncertainty in the EDP and DM hazard curves.
- Development of simplified procedures for performance assessment

Deliverables
The deliverables include written documentation of the results of each milestone, databases of results wherever appropriate, and modeling and analysis tools to facilitate implementation of performance assessment in engineering practice.

Project Title—ID Number	*Relating Structural Collapse and Casualties* —**3202001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$20,000.00 NSF
Project Leader (boldface) and Other Team Members	**Allin Cornell (Stanford/F)**, Gee Like Yeo* (Stanford/GS) **=not financially supported by project*		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

Summarize existing and improve methods for the estimation of the casualty decision variable probability distribution.

Methodology employed

The first step is to review and summarize current methods. This is to be followed by the consideration of various improvements that might be made consistent with the PEER objectives and methods. The approach to the latter will be consistent with empirical data being collected or that might be collected as an incremental addition to current activities by such investigators.

Role of this project in supporting PEER's strategic plan

One of PEER's three identified decision variables is the number of fatalities. A probability distribution combining the ground motion input hazard, structural response, and fatality estimation given response is needed.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

In this project we have collected the literature on this field and contacted various investigators active in the field of earthquake casualties. This is being summarized in a unified way in a report. We also reviewed how casualty estimation is conducted in probabilistic risk assessments of offshore structures. We considered how improvements to casualty modeling could be made in the PEER context of building-specific assessment involving modern nonlinear analyses. We ultimately have opted for a method that captures the location of occupants and the location and nature of potential structural damage. This has been implemented in the form of an example 3-story steel moment resisting frame. The possibility, for example, of severe structural response leading to shear failure of a beam-column connection and the concrete slab it supports falling on the occupants below is captured in the model. The number and spatial distribution of such failures is predicted via nonlinear dynamic analysis of the structure under multiple ground motion records at various levels of intensity. This statistical information is coupled with the likelihood of the motions to produce a curve of annual probability of x or more fatalities. The method can be easily extended to include losses due to non-structural elements. The need for data to calibrate such models is critical and limits the current accuracy of any such level of modeling. We shall address just what kind such data might be added to current data collection activities with marginal additional effort.

Plans for Year 6 *(if project is proposed to continue)*

N/A

Other relevant work being conducted within and outside PEER and how this project differs

There is no similar research within PEER. Work on data collection for post-earthquake planning is being collected by K. Shoaf at UCLA.

Expected milestones

Review of literature: Jan., 02; improved method: June, 02.

Deliverables

Report reviewing current approaches and a new procedure: Sept. 02

***Project Title*—ID Number**	*Seismic Hazard Simulation of Bay Area Highway Network Damage Assessment*—**3212001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 8/1/98—9/30/02	Current Year Budget Funding Source	$70,000.00 CA-Transportation
Project Leader (boldface) and Other Team Members	**Anne Kiremidjian (Stanford/F)**, Emily Chang (UCSD/US), Ayse Hortascu (Stanford/GS), Nesrin Basoz (Stanford/F), Meredith Williams (Stanford/O), Dimitris Pachacis (Stanford/GS), Ozgur Yazlali (Stanford/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The objectives are to develop appropriate analytical and computational methods for evaluating the performance of a highway system through economic impact analysis and to illustrate the utility of these methods through an application to a region. The three main components of the project are identified as follows:

- Development of methods and tools for identifying damaged/failed links and critical paths.
- Development of models and tools for highway risk assessment. The risk is measured in terms of direct and indirect economic impact from the failure of highway links and nodes. These models and tools are fundamental for the development of bridge performance definitions.
- Development of a representative example to illustrate the method for highway and port damage and direct economic loss estimation; this will involve the aggregation of databases and other pertinent information. The East Bay highway system with emphasis on the "Maze" and the Port of Oakland are the application areas.

Methodology employed

Site hazard analysis for ground shaking, liquefaction and landslide assessment; bridge damage assessment methods due to ground shaking and vertical and horizontal ground displacements; use of database management system for large bridge inventory data integration and manipulation; use of geographic information systems for integration and manipulation of spatial information and analysis results; network optimization methods.

Role of this project in supporting PEER's strategic plan

The ultimate goal is to support "Decision-Making (Thrust Area 1) – Outcomes from the Impact Assessment lead to decision-making by engineers, owners, lenders/insurers, and government policy-makers and emergency planners." The overarching goal being to make design decisions about transportation networks that reflect specific Performance Objectives (Thrust Area 1).

This project is also of central importance to the Highway Testbed. The combined activities at USC and Stanford leverage the research done on buildings and bridges by tying these findings to seismic hazard and transportation network performance. The project is intended to serve as a template for leveraging research findings in the context of the testbed.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

This research focuses on earthquake risk assessment of a transportation system. The loss considered in this research includes both direct cost of damage to individual components and cost due to time delay in the damaged system. Only highway bridges, rather than all the transportation components, are addressed in this research. Bridges are most vulnerable to earthquake hazard yet most critical in keeping the whole system functioning.

Plans for Year 6 *(if project is proposed to continue)*
Research during year 6 will focus on the design of an experiment that will attempt to identify key contributors of uncertainty in the overall risk or bridge/highway performance methodology. Two sources of uncertainty will initially be investigated. These include the uncertainty in the ground motion attenuation function and the uncertainty in the fragility functions.

A second area of interest is the assessment of post retrofit bridge performance and comparison of post and pre retrofit losses. This component of the analysis is contingent on the development of appropriate retrofit fragility functions. A graduate student at Stanford is currently working on the development of post-retrofit fragility functions for one bridge class.

Other relevant work being conducted within and outside PEER and how this project differs
This work is closely coordinated with a PEER Project underway at the University of Southern California. The work completed at USC focuses on the transportation network modeling and functionality loss analysis as described above.

There is relevant work continuing at MCEER funded out of TEA-21 (Transportation Equity Act for the 21st Century). This work focuses on a validation exercise that applies MCEER's REDARS (Risks from Earthquake DAmage to Roadway Systems) program to the Los Angeles region. A major distinction between the PEER work and that within REDARS is the consideration of street level network analysis and the development of emergency response capabilities. In addition, landslide and liquefaction analysis are not yet considered in the REDARS software. Similarly, the number and types of bridge fragility functions is limited to those developed earlier by MCEER and do not include all bridge types that included in the current study.

There is relevant work continuing at MAE that focuses on inter-metropolitan network performance. This contrasts with the intra-metropolitan focus of the work proposed here. The MAE research project includes and explicit treatment of the regional, inter-metropolitan economy. The MAE effort is credible and potentially useful, but does not reflect the level of integration between transportation and earthquake engineering proposed here.

Expected milestones
The project team will normally participate in scientific meetings organized by PEER, and acknowledge PEER sponsorship in any papers published as a result of this research. A year 5 report is being planned for the joint Stanford-USC project.

Deliverables
Deliverables associated with PEER project 3212001 include brief quarterly reports submitted at intervals defined by PEER, and a comprehensive final report at the conclusion of the project. The final report will be coordinated with the final report document provided by the USC team. In addition at least one journal paper is being planned to be submitted during the coming year.

***Project Title*—ID Number**	*Seismic Hazard Simulation of Bay Area Highway Network Transportation Analysis*—**3222001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 8/1/98—9/30/02	Current Year Budget Funding Source	$70,000.00 CA-Transportation
Project Leader (boldface) and Other Team Members	**James Moore II (USC/F)**, Yue Yue Fan (USC/GS), Bumsoo Lee (USC/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The goals are to develop appropriate analytical and computational methods for evaluating the impact of a transportation system on an urban area and to illustrate the utility of these methods through an application to a region. In general, risk analysis of highway transportation systems is performed with the objective to provide:

- appropriate information in the retrofit and disaster mitigation decision process (in the pre-event and post-event period, it is necessary to determine which bridges are to be retrofitted/repaired/replaced, in what order and to what design level); and
- models and tools for estimating the socio-economic impact of transportation systems that have been damaged by an earthquake, and the benefits (losses foregone) of current and proposed retrofit and reconstruction programs affecting transportation structures.

One of the main objectives of this project is to apply the methodology to the Bay Area highway transportation system. During the first PEER Transportation Risk Analysis Workshop held in 1998, the workshop participants recommended that the application area be the San Francisco Bay region. The rationale for the selection was that the region has a very complex transportation network with limited redundancy.

Methodology employed

Nonlinear programming (for network equilibrium analysis and gravity model estimation), economic modeling, trial and error.

Role of this project in supporting PEER's strategic plan

The ultimate goal is to support "Decision-Making (Thrust Area 1) – Outcomes from the Impact Assessment lead to decision-making by engineers, owners, lenders/insurers, and government policy-makers and emergency planners." The overarching goal being to make design decisions about transportation networks that reflect specific Performance Objectives (Thrust Area 1).

This project is also of central importance to the Highway Testbed. The combined activities at USC and Stanford leverage the research done on buildings and bridges by tying these findings to seismic hazard and transportation network performance. The project is intended to serve as a template for leveraging research findings in the context of the testbed.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

This research focuses on earthquake risk assessment of a transportation system. The loss considered in this research includes both direct cost of damage to individual components and cost due to time delay in the damaged system. Only highway bridges, rather than all the transportation components, are addressed in this research. Bridges are most vulnerable to earthquake hazard yet most critical in keeping the whole system functioning.

Plans for Year 6 *(if project is proposed to continue)*

The ultimate product of our research is intended to be tools for decision support. Decisions concerning seismic risks to transportation networks must be made both before and after earthquakes. Pre-event decisions focus on allocation of resources to retrofit, construction, and network design options. Post-event decisions focus on resource allocation to repair, reconstruction, replacement, and capacity management options.

Retrofitting or reconstruction facilities prior to an earthquake can best summarized as an exercise in stochastic network design. Given scarce resources, which links in the network should be improved to best mitigate uncertain seismic risks to system performance? This is obviously a very challenging question. Deterministic network design problems involving such discrete investments are well investigated, and standard approaches have been developed. Stochastic network design problems have been stated, but have not been treated analytically beyond the level of toys. Still, public agencies in seismically active areas cannot afford to ignore this question. Every seismic event results in temporary opportunities for public authorities to intensify public investments in the mitigation of seismic risk, and this includes the stochastic network design decisions that are made every time a transportation structure is retrofitted.

Other relevant work being conducted within and outside PEER and how this project differs

This research is informed by and informed the work on PEER project 1212001, the Regional Loss Modeling for Highway Network scoping study completed by Prof. Peter Gordon at USC.

This work is closely coordinated with a PEER Project underway at Stanford University. The work completed at Stanford focuses on Port impacts, bridge reconstruction costs, bridge response, and hazard analysis, all of which is needed to continue the work proposed here and by Prof. Kiremidjian at Stanford.

Prof. Moore participated in three major research coordination meetings with Caltrans Headquarters research staff, most recently on October 24, 2001. This most recent meeting gave PEER, MCEER, and Caltrans researchers and important opportunity to compare assumptions, priorities, and results. The first meeting focused on work in MCEER. The second focused on work in PEER. PEER observers participated actively in the MCEER presentation to Caltrans.

Expected milestones

The project team will normally participate in scientific meetings organized by PEER, and acknowledge PEER sponsorship in any papers published as a result of this research.

Deliverables

Deliverables associated with PEER project 3222001 include brief quarterly reports submitted at intervals defined by PEER, and a comprehensive final report at the conclusion of the project. The final report will be coordinated with the final report document provided by the Stanford team.

***Project Title*—ID Number**	*Life Sciences Testbed Simulation*—**3242001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$69,568.00 NSF
Project Leader (boldface) and Other Team Members	**Khalid Mosalam (UCB/F)**, Tae-Hyung Lee (UCB/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

Develop a state-of-the-art computational model and perform nonlinear dynamic analysis of the UC-Berkeley Life Sciences building using the OpenSees simulation platform to demonstrate PEER performance-based earthquake engineering assessment and design methodologies. The projects has dual objectives: (1) Testbed for simulation in OpenSees using actual buildings, and (2) Developing floor displacement and acceleration time histories to be utilized in testing building contents.

Methodology employed

1) Collect information about the structural system of the testbed, including member sizes, foundation type, material properties, and configuration and layout of any non-structural components.
2) Survey available modeling options in OpenSees for representing structural elements including current nonlinear elements for geometric and material effects. This survey considered modeling issues related to soil conditions and interfaces between structural and non-structural elements.
3) Develop a 2-D model where emphasis is on the structural systems and boundary conditions using the available options in OpenSees.
4) Conduct time history analysis of the several available ground motions developed for the building site to address uncertainty in the ground motion details.
5) Simulate the building with different properties addressing variability in mass, damping, and force-deformation relations of the different structural components.
6) Extend the structural model to 3-D to account for multi-directional ground motion effects.

Role of this project in supporting PEER's strategic plan

The project is a realistic demonstration for the computational platform of PEER, namely OpenSees. Moreover, through the simulations, assessment of the importance of a number of uncertain variables will be conducted. This includes not only ground shaking details but also mass, damping, modeling assumptions (e.g. 2-D versus 3-D) and component force-deformation behavior of the selected building.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

- 2-D working nonlinear model in OpenSees of the coupled shear wall lateral load-resisting system in the transverse direction (normal to the Hayward fault).
- Account for modeling foundation and soil conditions of the 2-D model.
- Develop floor accelerations and deformation to be used for the shake table tests of the building equipments using several ground motions developed by other researchers for the building site.

Plans for Year 6 *(if project is proposed to continue)*

- Extend the model to 3-D which will be one of the major tasks. This will allow the time history analyses of the building under multi-directional ground motions.

- Address the different modeling uncertainties by varying building mass, damping, and force-deformation relationships of the different structural components.

Other relevant work being conducted within and outside PEER and how this project differs

Other testbeds includes the study of the Van Nuys building the I880 bridges. This project is unique in that fact it represents shear wall building designed according to modern codes and standards.

Expected milestones

- May 2002: Complete the 2-D model of the building and its associated simulations.
- Sept 2002: Identify the important uncertain variables based on the 2-D working model
- Jan 2003: Finalize the 3-D model of the building
- April 2003: Complete the simulations using the 3-D model and investigate the important uncertain variables
- June 2003: Address the modeling issues related to any non-structural components, such partitions or building contents
- Sept 2003: Summarize results and produce the final report

Deliverables

- A working 2-D model of the building
- A working 3-D model of the building
- A complete suite of time histories of displacements and accelerations of for the building floors under the effect of the developed ground motions for the site.
- Quantification of the importance of the different uncertain variables affecting the structural performance of the building

***Project Title*—ID Number**	*I-880 Testbed Simulation*—**3252001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$50,000.00 CA-Transportation
Project Leader (boldface) and Other Team Members	**Sashi Kunnath (UCD/F)**, Boris Jeremic (UCD/F), Anna von Felton (UCD/GS), Keith Bauer (UCD/GS), Jinxiu Liao (UCD/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The primary objective of the project is to apply evolving PEER performance-based earthquake engineering methodology to evaluate the seismic response of a section of the I-880 viaduct. A major component of the methodology involves the estimation of seismic demand parameters through simulation of adequate and reliable computer models of the target system. The sensitivity of ground motion characteristics and critical modeling parameters in estimating seismic demands will be investigated, since they can have a significant impact on the implementation of the PEER performance-based methodology. Another major goal of the project is to investigate soil-foundation-structure interaction effects and considerations of spatial variability of the ground motion. The project will also provide input to the development of OpenSees as new needs are identified during the modeling and simulation tasks.

Methodology employed

Several models, ranging from simple frame-type elements to more detailed two-dimensional and three-dimensional fiber-section models, of the selected section of the viaduct will be developed. Most of the simulations will be carried out using the OpenSees computational platform, however, limited comparative studies will also be conducted using alternative software. Simulation exercises will include both static (pushover) and transient analysis using selected ground motions. Engineering demand parameters and damage measures will be synthesized and parametric studies will be carried out to study effects of modeling sensitivity, ground motion characteristics and soil-foundation-structure interaction.

Role of this project in supporting PEER's strategic plan

One of the goals of PEER is to develop and validate performance-based seismic design technologies. The accurate estimation of seismic demands is a key component in performance-based seismic engineering and consequently, accurate and reliable modeling of structural systems becomes a critical component of the methodology. The simulation models developed as part of this testbed will be utilized by other PEER researchers involved in developing component and system fragilities, identifying decision variables, and other implementation issues in the PEER performance-based methodology. Findings from this project will assist in identifying shortcomings in the proposed PEER methodology and thereby help define future research directions.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

A typical bent was first selected for detailed evaluation in order to verify and investigate modeling features in OpenSees that was best suited for the eventual simulation tasks. A sensitivity analysis was carried out to determine the level of the core discretization required to obtain reliable results. Several discretizations were evaluated and an appropriate mesh size was selected for nonlinear static and transient analysis of the bent.

Three nonlinear modeling options were considered for the column elements: (a) a two-dimensional nonlinear Beam-Column elements with fiber sections; (b) a two-dimensional model with finite plastic hinges at the ends of the column (Beam-with-Hinges element); and (c) a three-dimensional nonlinear fiber beam element. In all cases, the beam was modeled as a beam with elastic properties.

Separate studies investigating the adequacy of the integration scheme and the length of the plastic hinge length were carried out. Four Gauss-Lobatto quadrature points and a plastic hinge length of 10% of the element length at both ends were found to produce good results. Sub-dividing the piers into smaller elements was found to cause numerical instability, hence each pier is modeled with a single element only.

Both pushover and transient analyses of the typical bent have been carried out. Two-dimensional and three-dimensional models of complete frame systems comprising the entire viaduct are being developed. Separate analyses of the soil-foundation system are underway to establish equivalent spring properties to be used at the base of the piers. Finally, a complete 3D model of the soil-foundation subsystem is also being developed. These ongoing tasks will provide a range of modeling options for subsequent parametric studies.

Plans for Year 6 ***(if project is proposed to continue)***

Issues related to spatial variability is a significant issue that needs to be addressed. Work on the implementation of the "Domain Reduction Method" ("Plastic Bowl" or "Soil Islands") will have commenced in Year 5 but is expected to continue into Year 6. Detailed soil-foundation modeling vs. simplified approaches used in current CALTRANS design practice will be investigated. Some comparative studies between OpenSees models and currently used evaluation tools such as SAP2000 and DRAIN needs to be carried out. Interaction effects resulting from adjoining frame response requires some study in order to validate methods used in current practice. Finally, the modeling of potential shear failure modes in short columns needs to be investigated.

Other relevant work being conducted within and outside PEER and how this project differs

The basic framework of the simulation study parallels ongoing work in other testbeds. However, several aspects of the modeling and simulation tasks vary from one testbed to another. Additionally, the advanced 3D modeling with SFSI effects and consideration of spatial variability is unique to this project.

Expected milestones

Summer 2002: Complete 2D and 3D modeling of two complete frames with simplified spring representations of the soil-foundation system. Complete initial set of parametric studies utilizing suite of ground motions and compare pushover vs. time-history analyses.

December 2002 (End of Year 1): Detailed pushover and time-history analyses of a single bent with full 3D soil-foundation subsystem will be completed. 3D analyses of multiple frames will also be completed. Full utilization of Domain Reduction method.

Deliverables

Interim Summary Report and Annual Progress Report.

Project Title—ID Number	*Coordination of Methodology Testbed Research*—**3262001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$103,200.00 NSF
Project Leader (boldface) and Other Team Members	**Keith Porter (Caltech/F)**		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

Coordinate PEER research on five testbed projects (Van Nuys hotel, UC Science Building, Humboldt Bay Bridge, I-880 highway viaduct, and university campus). Assist testbed managers in ensuring that researchers within testbeds understand their role, deliverables, and schedule in the overall project. Assist testbed managers in ensuring that outputs of preceding analytical steps match the inputs of succeeding steps, and are delivered in a timely fashion. Assist testbed managers in soliciting the participation of practitioners from PEER's business and industry partner (BIP) program. Assist campus testbed manager to develop campus methodology.

Methodology employed

The four main tools employed to meet the testbed objectives are the conduct of regular testbed meetings; the organization of crosscutting research teams; the use of a single report for each testbed; and emphasis on unambiguous deliverables. Testbed meetings have occurred approximately twice quarterly, and have focused on increasing understanding the physical and function properties of the testbeds; the parameterization of the variables in PEER's PBEE framing equation; and frequent discussion of each researcher's inputs, outputs, and methodology. To facilitate the exchange of information, a website (**www.peertestbeds.net**) has been created and maintained. Where necessary research has not been undertaken by other researchers, the PI of the present project has pursued the topic as a side research project.

Role of this project in supporting PEER's strategic plan

To date, PEER's research has emphasized in-depth research project on a variety of disparate topics, unified under five topical headings (thrust areas), without a great deal of emphasis on the tight synthesis of research results into a larger whole. The testbeds project, by contrast, will produce the first coherent integration of the research to date, in the form of six end-to-end seismic analyses of engineered systems using PEER's performance-based earthquake engineering (PBEE) methodology. Each testbed combines a seismic hazard analysis, structural analysis, damage analysis, and loss analysis in a single study. However, each will exercise and illustrate a different subset of the PEER methodology, by focusing on an engineered facility whose function, seismic setting, performance objectives, and vulnerability differ substantially from the others'.

There are three main challenges to the successful completion of these testbed projects. First, each testbed requires careful coordination of several research teams. Second, the overall effort must be coherent: it must not produce six incompatible approaches but rather show six facets of a single PBEE approach, with consistent parameterization and calculation of intensity, engineering demand, damage, and decision variables. Each much consistently and carefully treat uncertainty. Third, the testbed projects must involve at a deep level a variety of business and industry partners (BIPs), whose perspective is crucial to ensuring that PEER produces a methodology that, while advancing the state of the art, does not require a skillset vastly different from that available in practice. Furthermore, BIP participation is crucial to ensuring that PEER's efforts truly align with the real-life concerns of facility owners, designers, and other stakeholders.

Coordination across these three dimensions requires an understanding of the overall goals, principles, and analytical techniques of seismic loss estimation, as well as a perspective that bridges both academia and professional practice, and a comprehension of bridge design, building design, performance of equipment systems, network analysis, portfolio analysis, and risk management.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

- Coordinated and maintained unified reports for the two building testbeds and encouraged the creation of unified reports for the bridge testbeds;
- Arranged meetings between PEER researchers and facility stakeholders of the Van Nuys building, the Humboldt Bay Bridge, and the I-880 highway viaduct.
- Arranged or coordinated testbed progress meetings and meeting sessions;
- Created and maintained **www.peertestbeds.net** website;
- Initiated efforts to assess competing measures of seismic intensity (since taken up by another PEER researcher);
- Led the effort to develop decision variables (numerical measures of seismic performance in terms most meaningful to stakeholders) for bridges; and
- Initiated an effort to define a metadata standard for consistent documentation and treatment of component fragility

Plans for Year 6 *(if project is proposed to continue)*

The testbed projects are planned to last through year 6. The work described here will continue as in year 5, with testbed meetings once or twice quarterly, dissemination of documents via the website, integration of research results in testbed reports, and marshalling of crosscutting research projects to the service of testbed researchers. Efforts to develop bridge decision variables and secure the contribution and endorsement from Caltrans will continue unless a dedicated project to do so is assigned to others.

Other relevant work being conducted within and outside PEER and how this project differs

First, consider similar PBEE methodologies. Two related efforts to develop a PBEE methodology are embodied in Vision 2000 (Office of Emergency Services, 1995) and ASCE/FEMA 356 (Federal Emergency Management Agency, 2000). These projects produced methodologies to assess the seismic performance of engineered facilities. Both however favor deterministic estimation of performance rather over explicit treatment of uncertainty. Neither explicitly assesses fatality risk (beyond collapse potential), repair costs, loss-of-use duration or cost, or other economic measures of performance. PEER's methodology addresses these issues.

Expected milestones

Archiving of research documents and the coordination of a variety of progress meetings.

Deliverables

The main deliverable will be the completion of testbed reports in October 2003.

Project Title—**ID Number**	*Van Nuys Simulation*—**3272001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$70,000.00 NSF
Project Leader (boldface) and Other Team Members	**Laura Lowes (UW/F)**, Chaitanya Paspuleti (UW/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The research effort seeks to use the OpenSees framework to develop a new standard for nonlinear dynamic simulation of civil structures. The PEER Van Nuys building is used as a testbed for the project. Specific research objectives include the following:

- Develop tools to facilitate the building and application of numerical models for earthquake simulation.
- Develop model assessment and verification procedures.
- Quantify epistemic uncertainty introduced through simulation of building response to earthquake loading.
- Develop global structural performance measures.
- Develop a prototype GUI, specific to the Van Nuys structure, to support the simulations.

Methodology employed

This research effort comprises three types of activities: software design to support nonlinear dynamic analysis of RC frame structures, modeling of existing and newly designed RC buildings, and statistical analysis of numerical data to quantify modeling uncertainty. A modular, parametric approach to model building has been adopted in the initial phase of the project; standard software design methods will be employed in developing a modeling environment specific to the Van Nuys building.

Role of this project in supporting PEER's strategic plan

The research activities included in this project support PEER's strategic plan in three ways. First, the results of this project support the PEER Center's mission is to develop, validate, and disseminate performance-based seismic design technologies. Specifically, performance-based design and assessment requires prediction of structural performance at multiple earthquake hazard levels. Nonlinear, dynamic simulation offers the greatest potential for accurate prediction of response. The results of this project advance model building and application techniques as well as contribute to verification of the component and system models included in the OpenSees platform. Second, the cooperative efforts of PEER researchers to apply the PEER earthquake loss-estimation methodology to the Van Nuys building is providing improved understanding of the methodology. This heightened level of understanding will enable improvement in the performance-based design tools and technologies developed by the PEER Center. The results of this research effort are a key component of the testbed activities. Data generated using the models developed as part of this study enable research advancements by others. Additionally, tools developed to facilitate the building and application of multiple models of variable sophistication and resolution, will enable testbed researchers to assess the impact of modeling on the loss-estimation methodology. Third, the results of this study include quantification of the uncertainty introduced through the model-building process.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*
Research accomplishments constitute primarily development, verification, documentation and dissemination of structural models. A parameterized two-dimensional model of the Van Nuys testbed building has been developed using the OpenSees analysis platform. This model provides researchers with the ability to vary, with minimal effort, most modeling decisions (e.g., level of discretization used within the model, the type of component models used, the type of analysis to be completed, etc.).

The initial effort to develop a beam-column joint model appropriate for use in simulating the response of older and newly design RC frame structures has been completed. This works has been accepted for publication in the ASCE Journal of Structural Engineering and the Transportation Research Record. Currently this beam-column joint model is being incorporated into the OpenSees model of the Van Nuys testbed building along with joint-component models developed by other research groups (Deierelein et al., Lehman et al.). An outcome of this Year 5-6 research effort will be an evaluation of the impact on building frame response of explicit modeling beam-column joint strength and stiffness loss.

Plans for Year 6 *(if project is proposed to continue)*
- Expand the current model of the Van Nuys test bed building to include more sophisticated component models, including models that show progressive shear failure.
- Continue development of verification protocols and procedures for comparison of multiple models.
- Develop, evaluate and refine a graphical modeling environment specific to the Van Nuys building.

Other relevant work being conducted within and outside PEER and how this project differs
The PI is actively involved in engineering-society committees related to the seismic response and modeling of reinforced concrete structures, including ASCE/ACI Committees 447 (FE Analysis), 445-1 (Strut-and-Tie Modeling) and Methods of Analysis. However, this research effort is unique in a number of ways:
- The emphasis on parameterization of the analysis.
- The development of tools to facilitate the modeling process.
- The focuses on quantifying the impact of modeling decisions on the predicted response of RC building systems.

Expected milestones
- Completion of the 2-D and 3-D Van Nuys building frame models.
- Statistical analysis of numerical data to quantify uncertainty of modeling decisions.
- Completion and documentation of validation procedures and comparison procedures.
- Completion of the building-specific graphical modeling environment.

Deliverables
- Simulation data generated using the 2- and 3-D models.
- 2- and 3-D models of the Van Nuys testbed building for use by other PEER researchers.
- Quantification of model uncertainty.
- Model verification and comparison procedures for RC frame buildings.
- A building-specific graphical modeling environment.

Project Title—ID Number	*Evaluation and Assessment of PBEE Methodology*—**3292001**		
Current Year Start/End Dates Overall Start/End Dates	1/2/02—9/30/02	Current Year Budget Funding Source	$20,000.00 NSF
Project Leader (boldface) and Other Team Members	**Jon Heintz (Degenkolb/I)**		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The objective of this project is to provide an engineering practitioner's critique the PEER PBEE assessment methodology through a detailed comparison of the PEER methodology with current state-of-practice techniques. A related goal is to support the Van Nuys testbed effort by performing an independent seismic evaluation of the building, which will serve as a benchmark against which the PEER PBEE methodology can be judged.

Methodology employed

This project entails a detailed seismic assessment of the Van Nuys testbed building using state-of-practice techniques as outlined in FEMA 273 and 356. The PI for this project is on the development team for FEMA 356, and he is intimately familiar with the assessment procedures. The assessment involves developing a computer model of the structure, performing static pushover analyses, evaluating target displacements with site-specific hazard information, and evaluating building performance using existing standards. This independent assessment of the Van Nuys testbed provides one basis for judging the accuracy and merits of a parallel effort by PEER university researchers to assess the building using the methodology and OpenSees simulation tools being developed by PEER. The project assessment report will include recommendations for seismic retrofit strategies for the building, which may be incorporated in future studies of the Van Nuys testbed.

Role of this project in supporting PEER's strategic plan

One of the primary deliverables of PEER will be a comprehensive PBEE assessment and design methodology. This project will provide direct involvement of engineering practitioners in the evaluation and improvement of this methodology, which will help identify stakeholder needs and ensure that the PEER methodology addresses these needs.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

The PI has completed the initial assessment of the Van Nuys testbed building and presented a preliminary report at the May 2002 testbed coordination meeting, held at PEER headquarters. Work is continuing to fully document this study and to contrast the results of this approach with the PEER PBEE methodology. Coordination meetings with PEER researchers have provided excellent opportunities for discussion of the shortcomings/limitations of current methods and ideas for how PEER can address critical needs in earthquake engineering practice.

Plans for Year 6 *(if project is proposed to continue)*

Other relevant work being conducted within and outside PEER and how this project differs

This project employs assessment methodologies and technologies that represent the best in current (2002) engineering practice. The project fills a critical need to involve practicing engineers in the testbed exercise, to both ensure realism in the exercise and provide feedback on the PEER PBEE methodology.

Expected milestones

- Initial seismic assessment of testbed (completed, May 2002)
- Written documentation of assessment (anticipated Sept. 2002)

Deliverables

Chapter contribution to the PEER report on the Van Nuys Testbed

Project Title—ID Number	*Advanced Building Assessment Guidelines*—**Lifelines 507**		
Current Year Start/End Dates	1/1/01—2/28/02	Current Year Budget Funding Source	$132,435.00 PG&E/CEC
Project Leader (boldface) and Other Team Members	**Allin Cornell (Stanford/F)**, C. Menun (Stanford/F), Maziar Motahari (Stanford/GS), Paolo Bazzurro (AIR/I), Joe Maffei (R&C/I)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The objective of this two-phase project is the development of a new level of guidelines for the assessment of existing buildings. The scope is limited to typical PG&E 1-3 story buildings often of older and mixed construction. The limit states considered will be those of direct system-reliability interest, e.g., collapse and (red or yellow) tagging, the latter because of their operability implications. An advanced state-of-practice engineering will be employed, e.g., the structural engineer will provide a nonlinear (NL) static pushover analysis (SPO). In keeping with stated needs and recent SAC and PEER developments, the guidelines will incorporate both aleatory and epistemic uncertainty measures, and the guidelines' output products will include limit state "fragility curves", i.e., probability of limit state given ground motion intensity (IM) level, that reflect these various uncertainties. The first-year objective has been a "beta-version" of these guidelines, using results of only the first year's research and default methods and parameter values where necessary. Nonetheless this first-year version is "operational", i.e., up to or beyond current practice in all respects, such that it can be tested by a top-level structural engineering firm in the second year.

The objectives of the second-phase efforts are to guide, assist, monitor, and evaluate the "beta-testing" of the guidelines in order to critique the first version and to prepare ultimately a second, improved, final version of the guidelines. These improvements will also include the results of research into two subjects identified in the first year as requiring basic study: aftershock-hazard-based tagging criteria/procedures, and joint treatment of the effects of the two horizontal components of ground motion.

Methodology employed

The engineer will use state of practice NL static methods. These have been improved to utilize a new "SPO2IDA" spread sheet that predicts the dynamic response to a complete range of ground motion intensities from static input, and to apply the procedure to various levels of the damaged structure as well.

Role of this project in supporting PEER's strategic plan

It is anticipated that PG&E will use these products in a seismic system-level reliability study of their network.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

In the first year we have delivered a set of guidelines that have evolved over the last twelve months to become what we believe is a completely workable six-step procedure. In brief, the engineer prepares a static pushover (SPO) of the intact structure, from which he identifies a set of several potentially interesting structural damage states. For each of these possible damage states the nonlinear static model is first loaded to that state, then unloaded and finally resubjected to a static pushover; together this sequence represents (statically) the main shock followed by an aftershock. The aftershock capacity of each of these (mainshock) damage states is determined, and used as a basis, along with one or more decision rules, to determine which of the damage states should be chosen to represent the onset of a condition that merits yellow tagging or red tagging, should the state be observed in the post-mainshock inspection. (These steps will be the subjects of further research in the second year.) The initial, intact SPO is then processed by a new "SPO2IDA" spreadsheet tool, developed in another project, that translates this static assessment into a median IDA (Incremental Dynamic Analysis). From this one can determine the two values of mainshock spectral acceleration (Sa) necessary to put the structure into the two damage states determined above to be the states associated with the onset of yellow and red tagging. These two Sa levels become the median values of the yellow and red tag fragility curves. (In fact this same spreadsheet tool is used to determine, from the "aftershock SPOs" of the damage states discussed above, the capacities of these states in Sa terms, i.e., what aftershock ground motion level would cause life loss should the building be occupied after the mainshock.) To complete the fragility curves one needs "betas", measures of randomness and uncertainty. The record-to-record randomness "beta" is provided by the same spreadsheet. The remaining uncertainty, that due to the engineer's limited information (materials properties, appropriate nonlinear model, etc.) must be obtained primarily by subject judgement. Based on the literature and interviews with local engineers we have prepared tables of such values and detailed guidance to the engineer in assigning these values. Finally we have worked systematically on two quite detailed application case studies, a three-story pre-Northridge SMRF with fracturing connections and a tiltup. In both cases the static procedures have been applied as per the guidelines as illustrations for the user, and, furthermore, the results have been confirmed by nonlinear dynamic analyses presented after the examples. The former building case study has intentionally used quite inexpensive commercial software (RAM Perform); the tiltup analysis has used in-house software but the static model could have been done with typical commercial software.

Plans for Year 6 *(if project is proposed to continue)*

The second year has three main tasks to begin March 1, 2002. The first is the beta test of the guidelines, and the second two are investigations of subjects identified in the first year of the project as needing further study before implementation in these guidelines or elsewhere: two-component ground motion response issues and aftershock-based, main-shock assessment criteria.

Other relevant work being conducted within and outside PEER and how this project differs

We are not aware of similar work elsewhere.

Expected milestones

Draft Guidelines (2/02 Done).

Deliverables

A set of guidelines for beta-testing, followed in year two by updated guidelines reflecting the testing and other second year work. Reports and papers.

Project Title—**ID Number**	*PEER Analysis Platform for Demand Simulation*—**4102001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/98—9/30/02	Current Year Budget Funding Source	$100,000.00 CA-General
Project Leader (boldface) and Other Team Members	**Gregory Fenves (UCB/F),** Filip Filippou (UCB/F), Francis McKenna (UCB/PD), Michael Scott (UCB/GS), Edward Love (UCB/PD)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The object of the project is to design, develop and implement the computational simulation framework, OpenSees (Open System for Earthquake Engineering Simulation), an enabling technology in PEER's performance-based earthquake engineering methodology. This project is developing the core simulation methodology for use in other PEER projects. The major subgoals are (i) development of models, with an emphasis on degrading models for reinforced concrete structural components, (ii) support for computational methods for nonlinear static and dynamic analysis, on single and multiple processor computers, and (iii) support for advanced database and visualization methods to aid engineers and users in simulating the effects of earthquakes. OpenSees is an open-source, modular software framework that is intended to be a flexible and extensible platform as community software for earthquake engineering.

Methodology employed

The project has three distinct components. The first is the development process of the software. This involves following rigorous software development procedures of specification, software design, implementation, and testing. The concurrent versioning system (CVS) is used for maintaining all software, documentation, and examples. The second component is development of nonlinear modeling and solution capability, primarily for reinforced concrete components. The third component is support for users in PEER, including examples, workshops, workshop materials, and direct user support.

Role of this project in supporting PEER's strategic plan

PEER's strategic plan is to develop the underlying methodologies and technical basis for performance-based earthquake engineering. Central to accomplishing this strategy is new computational simulation methods and software. This project is critical for achieving this strategic goal. Within the PEER strategic plan, OpenSees is one of the most important enabling technologies. It provides models, computational procedures, and advanced databases and visualization for performance-based earthquake engineering.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

In Year 5, the efficiency of the models and computational procedures has been improved by profiling and optimization. Critical sections of the software have been recoded for improved speed. The extension of the analysis procedures has verified the flexibility of the OpenSees software architecture. Work continues on integrating improved modeling and visualizing tools, including interfaces with databases being developed by other projects. Software support for gradient computation continues for use in reliability, system identification, and optimization functions. The gradient computation has been developed for force-based elements, which is an important advance.

Significant education and training of users has been undertaken in Year 5. A very successful four-day OpenSees workshop was held at PEER Headquarters in August 2001. The first day was devoted to introducing new and potential users to simulation capability and providing examples. The following three days were hands-on instruction for developers. More than 20 faculty and students from PEER and non-PEER schools attended the developer's workshop. Another workshop is scheduled for the first week of September 2002. By special invitation from the organizers of the ASCE Structures Congress, two special sessions on OpenSees were organized by PEER to present the new simulation capability to the wider structural engineering community.

Plans for Year 6 *(if project is proposed to continue)*

As an enabling technology, development will continue for models, solution procedures, interfaces with information technologies, and user support. Increased effort will be devoted to scalability as the large models for the testbed projects begin to reach the limit of single processor computers. User support, including web-based documentation, will become an increasing focus. Major aspects will be to develop a set of examples and validation documents for models and solution procedures.

Other relevant work being conducted within and outside PEER and how this project differs

OpenSees is a central component of the PEER research programs. All of the thrust area 4 projects relate to the framework development. The four building and bridge testbed projects are using OpenSees for the simulation aspects of the performance-based evaluation. Several thrust area 5 projects are developing and/or calibrating models based on experimental data.

Outside PEER, discussions have begun with collaborating on simulation research at the MAE Center (through Dr. Amr Elnashai) and MCEER (through Dr. Andrei Reinhorn). With MAE, discussion is considering using OpenSees for applications in the consequence-based engineering approaches under development at that center. The other outside interaction is associated with NSF's George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES). OpenSees has been identified by the system integrator as one of the simulation tools that will be made available in the software repository for NEES users.

Expected milestones

- Complete accelerated Newton method using Krylov subspace
- Formalize user services working under S. Mazzoni
- Provide support for testbed projects
- Complete sensitivity framework, including distributed processing
- Update web page with documentation, validation cases, and examples, for V2.release
- Continue to provide user support for testbed projects
- Integrate other Year 5-6 Thrust Area 4 projects into framework, including reliability computation and databases
- Incorporate current developments into release of Version 2 of OpenSees
- User and developer workshop for Version 2
- Conduct user survey to assess future needs for OpenSees

Deliverables

The deliverables follow the milestones listed above and are in the form of source and executable software and associated documentation and examples, all available on the OpenSees website.

***Project Title*—ID Number**	*Structural Performance Database*—**4112001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$75,000.00 CA-General
Project Leader (boldface) and Other Team Members	**Jack Moehle (UCB/F)**, Gregory Fenves (UCB/F), Deborah Bartling (UCB/O), Marc Eberhard (UW/F)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The objective of this project is to continue initiatives to develop structural and nonstructural performance databases for buildings and bridges.

Methodology employed

The database design and development involves defining the meta-data required to represent the component, test environment, loading, sensor data, and processed data. Graphical and numerical data are stored in a relational database with a web-based interface to the search engine. Linkages are established between the performance databases and OpenSees. The developed format enables (but at this stage does not implement) archival of computed results simulation databases. The goal is to provide engineers the capability to search for experimental data relevant for a structure, use the data to calibrate a simulation model in OpenSees using system identification functions, perform a simulation, process the simulation data in a database, and compare simulated performance with the damage observed in the original experiments of the prototype components.

The project is conducted as a collaborative effort between the University of California, Berkeley (Moehle and Fenves) and the University of Washington (Eberhard). The database development and implementation will utilize the skills of Deborah Bartling, a programmer analyst at the Earthquake Engineering Research Center at UC Berkeley.

Role of this project in supporting PEER's strategic plan

This project supports PEER's efforts at advancing simulation and performance-modeling capabilities through the development of accessible databases.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

This project is scheduled to begin during summer 2002. Progress to date has been limited to definition of a work plan and identification of basic structures for the database.

Plans for Year 6 *(if project is proposed to continue)*

This project is planned to continue into Year 6 through no-cost extension. It will overlap with Year 6 proposed project number 4162002, RC joints and Subassemblies Database.

Other relevant work being conducted within and outside PEER and how this project differs

The structural performance databases in PEER will support the NEES goal of a curated data repository. PEER researchers will work with the NEES system integrator and NEES consortium development team in defining data and meta-data standards for national experimental and simulation databases.

Expected milestones
The project is anticipated to result in an updated on-line database by mid-spring, 2003.

Deliverables
On-line database of column data. Prototype for development of extended online databases.

Project Title—ID Number	*Development and Validation of Performance Models*—**4122001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$90,000.00 NSF
Project Leader (boldface) and Other Team Members	**Greg Deierlein (Stanford/F)**, Rohit Kaul (Stanford/GS), Arash Altoontash (Stanford/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

High fidelity simulations are essential to the PEER PBEE methodology to accurately model seismic response, damage and collapse of buildings and bridges. Central to the effort of thrust area 4 is the development of OpenSees (Open System for Earthquake Engineering Simulation) - a versatile computing framework that integrates analysis models for seismic hazard, ground motions, soil response, soil-foundation structure interaction, and structural response. The focus of this project is to develop and validate generalized hinge models for simulating strength and stiffness degradation in reinforced-concrete structures. Emphasis is on spring assemblies, generalized hinge elements, and cyclic hysteretic models for beam-columns and their connections that are sufficiently robust to capture highly nonlinear response at collapse, yet practical for application to large systems.

Methodology employed

Our model formulations are based on principles of concentrated stress-resultant plasticity models, which are fairly well established for hardening behavior. We are extending these basic hardening models to include strength and stiffness degradation under reverse cyclic loading effects, including the interaction of axial-flexural-shear effects and large deformations. We developing and implementing the models in the native C++ modular object-oriented framework of OpenSees. Calibration and validation studies are making use of existing test data from other PEER projects and from prior research by the PI and others on reinforced concrete and composite steel-concrete structures.

Role of this project in supporting PEER's strategic plan

We are developing and implementing structural analysis models for OpenSees in collaboration with other researchers in thrust area 4 – primarily the team led by Fenves and Filippou at Berkeley. We are also collaborating with Lowes of the Univ. of Washington who is developing detailed meso-scale models and damage indices for beam-column joints. The generalized hinge models we are developing complement more computationally demanding fiber-type models that Filippou has developed. We are making use of research results from other PEER projects including: (a) tests on non-ductile beam-columns and beam-column joints by Moehle and Lehman, (b) tests of bridge piers by Mahin, Xiao, Ashford, and Pardoen, (c) sensitivity formulations by Der Kiureghian and Conte, and (d) the column performance database assembled by Eberhard. We are also collaborating with researchers in Japan and Taiwan who are conducting tests of RC and composite steel-concrete subassemblies.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

This project builds on a previous PEER project, in which we implemented a beam-column element subassembly with rotational and shear springs for large-deformation response. The prior implementation included a super-element assembler to combine springs and several nonlinear uniaxial material models. The material models were developed in collaboration with a project directed by Krawinkler on the performance of stiffness and strength degrading structures. Over the course of implementing these elements, we worked with Fenves and the OpenSees development team to resolve bugs and limitations that we discovered in OpenSees.

Since October 2001 (Year 5), we realized the following accomplishments:

- Theoretical development and implementation of a new 2D yield surface beam-column element has been completed. The implementation utilizes object-oriented modular programming to allow convenient extension of the model to include different yield surface function, hardening/softening parameters, damage indices, and hysteretic response variables.
- Implementation of a 2D beam-column joint model to account for joint panel deformations and member-based bond-slip response. Inelastic behavior is included through single or parallel/series material uniaxial material models. Transformation equations handle large deformation behavior.
- Investigation of spurious internal forces arising from alternative definitions of viscous damping. Our study discovered the source of the problem and reaffirms the practice of specifying either discrete damping coefficients or mass/stiffness proportional damping using the updated tangent stiffness.
- Preliminary calibrations of the beam-column and joint elements have been completed.
- We are collaborating with researchers at the NCREE center in Taiwan to utilize OpenSees for assessing the nonlinear response of a full-scale composite frame.

Plans for Year 6 ***(if project is proposed to continue)***

During Year 6, our plan is to extend these to 3D structures and to include P-M-V interaction in the beam-columns and to implement sensitivity parameters and investigate their ability to detect global changes in nonlinear frame response from changes in beam, column, and joint properties.

Other relevant work being conducted within and outside PEER and how this project differs

What most distinguishes this project from other research on inelastic analysis is that (1) it takes advantage of state-of-the-art computational technologies available in the object-oriented OpenSees framework, (2) the elements capture rapid stiffness/strength degradation that occurs in concrete frames as they approach their collapse limit-state, (3) integration with other models for structural and geotechnical components and probabilistic performance assessment tools, and (4) the emphasis on calculating damage parameters to evaluate the component performance in the context of the PEER PBEE methodology.

Expected milestones

- June 2002 - Formal release of 2D beam-column and joint models in OpenSees.
- Sept. 2002 – Provide training module on new elements at OpenSees workshop
- January 2003 - Release of P-M-V beam column and 3D models.
- June 2003 – Submittal of final project report

Deliverables

- New 2D and 3D beam-column models, joint models, and material models in OpenSees
- On-line user and developer documentation
- PEER Project Report (based on 2 PhD theses)
- Journal Publications on element formulations and sensitivity analyses

Project Title—ID Number	*Computational Reliability for Design*—**4132001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$50,000.00 CA-Transportation
Project Leader (boldface) and Other Team Members	**Joel Conte (UCSD/F)**, Yuyi Zhang (UCSD/GS), Gabriel Acero (UCSD/GS), Quan Gu (UCSD/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

- Develop, implement, and document sensitivity and reliability analysis modules in OpenSees to facilitate solution of the PEER PBEE framework equation.
- Identify and model uncertainties (characterizing the seismic loading, system parameters, modeling assumptions, etc.) and track their propagation through nonlinear earthquake response analysis (using OpenSees) of the Humboldt Bay Bridge testbed structure.
- Investigate seismic reliability assessment of non-ductile structures with degrading components.

Methodology employed

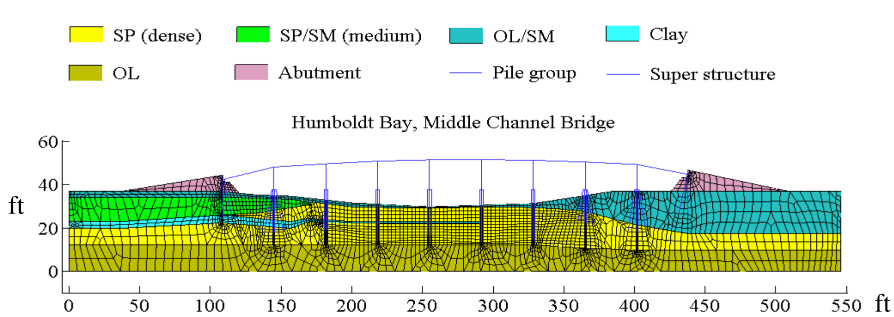
This project is based on advanced numerical modeling of the Humboldt Bay Bridge testbed structure using the PEER software framework OpenSees. Soil, foundation, and structure are all modeled using state-of-the-art material models and finite elements recently developed and implemented in OpenSees by other PEER researchers. The probabilistic assessment methodology consists of bridging together probabilistic seismic hazard analysis, nonlinear seismic response analysis of the soil-foundation-bridge structure system performed using OpenSees, and probabilistic capacity analysis for various potential failure modes. The nonlinear seismic response analysis is performed for ensembles of real ground motion records corresponding to different seismic hazard levels as defined by the local seismicity and the spectral acceleration at the fundamental period of the soil-foundation-structure system.

Role of this project in supporting PEER's strategic plan

This project will contribute to the computational tools for reliability analysis developed and implemented in OpenSees and assess the applicability of OpenSees to conduct a probabilistic seismic response analysis of an existing testbed bridge structure. This real-world application example will foster the integration of the methodologies and numerical tools developed, will naturally bring up some deficiencies and gaps in these methodologies, and thus will point the way to their refinement and completion.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

A 2-D, yet advanced finite element model of the soil-foundation-structure system was developed in OpenSees for the Humboldt Bay Middle Channel Bridge as shown in the figure at left.



Soil, foundation, and structure are modeled using state-of-the-art, nonlinear soil and structural material models available in OpenSees. The multi-surface soil plasticity model incorporates liquefaction effects. We are collaborating with Prof. Ross Boulanger of UC Davis to model the soil-pile interface using P-Y springs accounting for soil gapping and friction effects of soil flowing around piles during lateral spreading events in liquefiable soils.

Potential failure modes of this testbed bridge system have been identified, as well as pairs of demand and capacity terms able to characterize/capture these failure modes.

Collaboration is also underway with Dr. Paul Somerville in order to define ground motion ensembles to be used in the demand hazard analysis. With a robust nonlinear model of the testbed bridge system in hand, we are now starting to engage into a probabilistic performance assessment of the bridge system.

Plans for Year 6 *(if project is proposed to continue)*
In year 6, an alternative approach of probabilistic performance assessment of the Humboldt Bay Bridge testbed will be applied and exercised. This alternative approach consists of the finite element reliability method, several ingredients of which are being implemented in OpenSees by Prof. Der Kiureghian and co-workers at UC Berkeley, with whom we will collaborate.

The two probabilistic performance assessment methodologies will be directly compared based on the Humboldt Bay Bridge testbed.

Other relevant work being conducted within and outside PEER and how this project differs
FE reliability codes have been developed and used by NASA, Boeing, SouthWest Research Institute, Det Norske Veritas, and a number of other large engineering enterprises as well as by the University of Munich (reliability analysis software STRUREL) and the Technical University of Denmark (PROBAN software). To our knowledge, none of these softwares is under an object-oriented platform, or aimed specifically at seismic reliability problems. In this sense, the reliability analysis component of OpenSees is rather unique.

Expected milestones

- Identify missing components in OpenSees and associated reliability analysis module to conduct a probabilistic seismic response analysis of the Humboldt Bay bridge testbed. Develop and implement these missing components in cooperation with PEER researchers involved in the development of OpenSees (Fenves and co-workers) and its reliability analysis module (Der Kiureghian and co-workers).
- Develop application example of probabilistic seismic response analysis using OpenSees based on the Humboldt Bay Bridge testbed.
- Document probabilistic seismic response analysis of the testbed bridge structure using OpenSees.

Deliverables
Develop and document application example of probabilistic seismic response analysis and performance assessment using OpenSees based on the Humboldt Bay Bridge testbed.

***Project Title*—ID Number**	*Computational Reliability Tools for Design*—**4142001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 5/1/99—9/30/02	Current Year Budget Funding Source	$50,000.00 CA-General
Project Leader (boldface) and Other Team Members	**Armen Der Kiureghian (UCB/F)**, Terje Haukaas (UCB/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

- Develop, implement, and document reliability and sensitivity methods in the OpenSees computational simulation framework.
- Identify and track the propagation of uncertainties through the probabilistic performance-based earthquake engineering assessment procedure.
- Investigate performance criteria (limit-state functions) applicable to non-linear degrading reinforced concrete structures.
- Perform practical analysis for the I-880 bridge testbed structure.
- Implement sensitivity analysis by the "direct differentiation method" (DDM) in OpenSees as needed for reliability analysis and to obtain parameter importance measures and resource allocation indicators.

Methodology employed

Advanced reliability methods are employed to evaluate the probability of exceeding user-defined performance criteria. First-order reliability methods and importance sampling simulation techniques are implemented. The work continues the pioneering work at UC Berkeley on finite element reliability methodologies. Response sensitivities with respect to structural model parameters are essential in the reliability analysis and are also useful as stand-alone importance measures and cost-saving resource allocation indicators. The efficient and accurate "direct differentiation methods" (DDM) is developed and implemented for a range of non-linear material models. Applications include non-linear and dynamic simulation of structural behavior. Ground motion input can be modeled as a discretized random process, allowing for computation of mean out-crossing rates of user-defined thresholds.

Role of this project in supporting PEER's strategic plan

This project addresses the propagation of uncertainties through the performance-based design process. An essential part of performance-based earthquake engineering is simulation of structural behavior. The methodology and software provided by this project allow assignment of probabilistic distributions to the simulation model parameters. Probability of exceeding user-defined performance criteria can then be computed.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

- Development of a Matlab toolbox for finite element reliability analysis that serves as a learning tool and a testbed for further developments.
- Adding an object-oriented software framework to OpenSees for finite element reliability and sensitivity analysis.
- Completed the implementation of the first-order reliability method (FORM) and importance sampling simulation techniques in OpenSees.
- Implemented a comprehensive library of probability distributions.

- Developed and implemented finite element sensitivity analysis algorithms for selected materials and elements, including models for degrading structures.
- Added a new discretized random process model to OpenSees, allowing for computation of mean out-crossing rates for non-linear dynamic structures.

Plans for Year 6 *(if project is proposed to continue)*

Needed additional work includes:

- More general formulation of performance criteria (limit-state functions) to allow flexibility in the specification of failure events.
- Development and implementation of sensitivity routines for additional material models suitable for advance reliability analysis.
- Development of algorithms for second-order reliability (SORM) analysis.
- Development and implementation of algorithms for system reliability analysis involving multiple limit-state functions.
- Improve stability and robustness of the existing sensitivity and reliability algorithms, including the important algorithm for finding "design" points.
- Practical applications to exemplify typical analysis schemes, perform convergence studies and to refine the software or methodology as needed.
- Comprehensive application to I-880 testbed bridge.

Other relevant work being conducted within and outside PEER and how this project differs

The project is being conducted in collaboration with Professor Joel Conte at UC San Diego.

Finite element reliability codes have also been developed and used by NASA, Boeing and SouthWest Research Institute. General-purpose reliability analysis codes have been developed by Det Norske Veritas (PROBAN), the University of Munich (STRUREL) and UC Berkeley (CalREL). The on-going work in OpenSees is unique in several aspects. The object-oriented programming paradigm focuses on extensibility and maintainability of the code. This is crucial for future development of such a research tool. Previous work in the field has been aimed at linear or ductile structures. Our emphasis is on non-ductile degrading systems, as is typical for reinforced concrete structures subjected to strong-motion earthquakes. The ability to compute mean out-crossing rate is a unique capability within OpenSees. The sensitivity routines developed and implemented in OpenSees are also unique.

Expected milestones

- Complete implementation and testing of FORM, SORM and importance sampling algorithms (May 2003).
- Complete development, implementation and testing of sensitivity routines for degrading systems under dynamic load (June 2003).
- Example applications, including a comprehensive analysis of I-880 testbed (Sep 2003).
- Writing of documentation for reliability modules within OpenSees, with example apps.

Deliverables

A comprehensive and modern computer software framework for finite element reliability and sensitivity analysis. Practical applications in probabilistic performance-based earthquake engineering: e.g., the I-880 testbed structure. Complete on-line documentation.

***Project Title*—ID Number**	*Data Management for OpenSees Simulations*—**4152001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$60,000.00 NSF
Project Leader (boldface) and Other Team Members	**Kincho Law (Stanford/F)**, Jun Peng (Stanford/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

This research project, in collaboration with researchers at PEER center, aims to develop a software platform that assists the application of performance-based earthquake engineering (PBEE) assessment and design methodologies. The project focuses on supporting testbed applications, data and project management, and archival capabilities. One objective is to develop an interface to provide a persistent storage for the interim and selected analysis results for OpenSees. Mechanisms are developed to support project management and to archive testbed projects data. A data management system is designed and implemented for the information related to seismic inputs, simulation models, and simulation results such that performance metric, demand parameters, and damage measures can be derived from the simulation results. Finally, an easy-to-use user interface is provided to query the data via a web interface or an application program such as MATLAB.

Methodology employed

- Commercial off-the-shelf (COTS) database systems are integrated with OpenSees to provide persistent data storage.
- The Internet is utilized as a data delivery vehicle.
- We propose an alternative approach to store only selected data in COTS database systems. One example of selected data storage strategy is SASI (Sampling At a Specified Interval), which may find applications in nonlinear analyses, where the state information, instead of the entire analysis results, is saved in a specified interval (e.g. every 10 steps or other appropriate number of steps). The total amount of required storage space is substantially reduced compared with traditional data storage method without severe performance penalty.
- The internal data structure of OpenSees is organized in an object-oriented fashion, thus cannot be easily mapped into a relational database. We choose to use matrix-type data (ID, Vector, and Matrix) to represent object state. The advantage of this approach is that new classes can be introduced without the creation of new tables in the database.
- Through the query language, users of OpenSees can have uniform access to the analysis results by using a web-browser or other application programs (such as MATLAB).

Role of this project in supporting PEER's strategic plan

We envision that the data and project management infrastructure developed in this project will become a common tool for which PEER researchers can use for the testbed applications. This work involves an internet-enabled architecture that would allow users to access the platform on-line as well as allow researchers to develop and to integrate their works with OpenSees.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

In summary, we have accomplished the following tasks for the data management and archiving:

1. Data and Storage Structure

2. Internal and External Data Representation
3. Data Input and Query Processing
4. Project Management Support
5.

In addition to the proposed data and project management tasks, a robust Lanczos procedure has been developed and implemented with OpenSees, and is ready to be released.

Plans for Year 6 ***(if project is proposed to continue)***

The focus of year 5 was the design and implementation of the data management system. We plan to continue the current work to extend the OpenSees platform in the following three areas:

- **Online Data Access System**. We propose to develop a user-friendlier interface for researchers to manipulate data and query analysis results.
- **Project Management**. The project management system can be employed to be the central achieve of testbed projects data with version control and access control.
- **Parallel and Distributed Computing**. We intend to integrate a parallel solver with OpenSees to improve the solution of large-scaled engineering problems.

Other relevant work being conducted within and outside PEER and how this project differs

A project entitled "ParCYCLIC: Internet-Enabled Simulation of Earthquake Liquefaction Response on Parallel Computers", which was approved and funded by NSF, is a joint effort with Prof. Ahmed Elgamal of UCSD. The focus of the project was on the development of sparse matrix solution algorithms, parallel algorithms, and distributed program development. The results of the project will be very useful towards the next phase of OpenSees. First, it will enhance future development of OpenSees; especially the developed parallel solver can greatly improve the performance of OpenSees simulations. Furthermore, it will enhance further incorporation of geotechnical analysis capabilities into the OpenSees platform.

Expected milestones

- Design of database schema for project management purpose.
- Integration of database with OpenSees
- Design and implement a data query language
- Develop an online access interface using web technology.
- Develop an interface to allow external application program (specifically MATLAB) to access the simulation results from OpenSees
- Evaluate the data management schemes by conducting a test with a specific testbed application project.
- Re-design and re-implement the data management interface, if necessary.
- Deploy the data management framework to support testbed applications.

Deliverables

- A preliminary design of database schema has been finished and applied to both Oracle 8i and MySQL database systems.
- A data query language has been defined and a string parser has been implemented according to the defined data query language.
- Both web-based interface and MATLAB-based interface to the data management system have been constructed and tested.
- A project management system with version control and access control is being implemented and tested on Humboldt Bay Middle-Channel Bridge project.

***Project Title*—ID Number**	*COSMOS-GEOINFO Standards for Archiving & Dissemination of Geotechnical Data*—**Lifelines 2L01**		
Current Year Start/End Dates	5/15/01—11/15/01	Current Year Budget Funding Source	$45,208.00 PG&E
Project Leader (boldface) and Other Team Members	**Carl Stepp (COSMOS/O)**, Jennifer Swift (USC/PD)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

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.

Methodology employed

The project brought together 46 professionals and researchers representing geotechnical data providers, database developers, information technology researchers and developers, geotechnical data development contractors, and data users in a two-day workshop. Thirteen summary topical papers were prepared and distributed prior to the workshop then presented and discussed in the workshop. The papers were grouped in the four topical areas: Life Cycle Development Case Studies, Data Dictionary and Data Formatting Standards, Database Architecture, and Data Quality Assessment Criteria. Three discussion panels were formed to develop recommendations and identify actions for archiving and web dissemination formats, implementation action plan, and long-term funding. The invited papers together with the findings and recommendations of the discussion panels were published in workshop proceedings.

Role of this project in supporting PEER's strategic plan

The work performed under this project supports geotechnical database development, coordination, and implementation.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

The workshop developed the concept of a central hub that would function as a virtual geotechnical data center through which data providers share as well as disseminate their 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 using existing technologies. The primary needs are to: 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.

Plans for Year 6 ***(if project is proposed to continue)***

The plan for the next phase of this project includes four main tasks: 1) define geotechnical data user scenarios for a pilot virtual geotechnical data center system that links the CDMG and Caltrans geotechnical databases, also including PG&E and USGS to the extent these are made available, 2) develop a data dictionary standard for the pilot system which can be expanded to a larger system linking multiple databases, 3) integrate these results to implement the pilot 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 web-based system for archiving and linked dissemination of geotechnical data. A Work Group will be developed for each of the first three tasks. The Work Groups will meet together to initiate the project and will hold an interim project meeting to share progress and plan the remaining efforts needed to complete their respective tasks. The Work Group's reports will constitute the main body of material for the planned invited workshop to obtain geotechnical community consensus.

Other relevant work being conducted within and outside PEER and how this project differs

This work is relevant to PEER Lifelines research. It is different in that it is focused on integrating distributed geotechnical databases and developing optimal methods for data archiving, transfer and dissemination.

Expected milestones

- Conduct workshop
- Draft workshop proceedings
- Final workshop proceedings distributed

Deliverables

- Detailed plan for implementing a Pilot Virtual Geotechnical Data Center.
- Workshop proceedings.

Project Title—**ID Number**	Large-scale Seismic Performance of Urban Regions—**PEER-CMU-MSU**		
Current Year Start/End Dates	10/1/01—9/30/02	Current Year Budget Funding Source	$128,062.00 NSF (through MSU)
Project Leader (boldface) and Other Team Members	**Gregory Fenves (UCB/F)**, Bozidar Stojadinovic (UCB/F), Jaesung Park (UCB/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The goal of this project was to integrate new simulation tools to evaluate the performance of an entire urban region in an earthquake. The project is a multi-disciplinary, multi-campus effort. It has three major components, each performed by three universities working closely in a collaborative environment. The first is earthquake ground motion modeling for a prescribed geological structure and earthquake source (by CMU). The second is evaluation of structural damage and performance of buildings and bridges, including soil-structure-foundation interaction (by PEER). The third is the development of visualization tools for dynamic motion in three-dimensional domains for use in understanding seismic performance of urban regions, and the development of computational middleware for distributed and collaborative computing for large-scale simulations (by MSU-ERC).

Methodology employed

The methodology for structural simulation utilizes PEER's OpenSees software framework. OpenSees offers an excellent platform with the modeling capability and the extensibility to allow use of multiple-processors for simulating the earthquake response at more than 25,000 grid points. This project works closely with CMU and MSU-ERC to integrate the ground motion generation, with the structural simulation, and the new visualization tools for understanding the spatial effects of structural performance.

Role of this project in supporting PEER's strategic plan

This project extends PEER's performance-based earthquake engineering methodology to large-scale simulation of entire urban regions. The knowledge gained in the PEER research programs on performance of individual buildings and bridges is extended to understand the spatial distribution of performance and aggregate performance. This will extend the application of the PEER methodology for use by planners and decision makers in understanding the impacts of earthquakes by scientific simulation capability.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

From ground motion simulation by CMU for a strike-slip event, we found large differences in ground motion over a region will have a substantial effect on the spatial distribution of damage to structures in the region. We examined this question by simulation of a simple structural model. It is well known that the overall seismic performance of a building or bridge can be represented approximately as an inelastic single degree-of-freedom system. The lateral force-deformation of a structure is represented by an elastic perfectly-plastic (EPP) cyclic relationship. The structures were parameterized by an elastic vibration period, the lateral strength represented as portion of the weight of the structure (the seismic yield coefficient, Cy), and the damping coefficient.

The response of structures is often expressed in terms of the ductility demand, which is the maximum displacement of the structure due to the earthquake divided by the yield displacement (at which the lateral strength is reached). An important relationship for structural design is between the seismic yield coefficient and the maximum ductility demand, which we computed for a wide range of parameters at each of the 25,000 grid points on the surface for the SDF system aligned in eight orientations. The results provided dramatic evidence of the near-fault effects on the spatial distribution of damage. Separate simulations using UBC provisions showed that a very uneven distribution of damage would result. Future study will focus on alternative procedures for accounting for near-fault effects in performance-based specifications.

Plans for Year 6 *(if project is proposed to continue)*

Year 6 will expand to include a broad range of building frames (reinforce concrete and steel) to determine more detailed information about performance and damage. This will provide many challenges for selecting meaningful parameters for the structural systems, damage measures, and visualization of the results, not to mention the large-scale computation required. Initial efforts will begin for identifying statistical samples of building types and parameters, in addition to beginning consideration of site response effects and soil-structure interaction.

Other relevant work being conducted within and outside PEER and how this project differs

To our knowledge this is the only research that is looking at simulation of earthquake effects in entire regions. The HAZUS project for loss-estimation uses a probabilistic procedure for loss-estimation. This project could eventually provide a more-scientific simulation capability for HAZUS-type loss estimates.

Expected milestones

Quarter 1:

- Identify classes and parameters for buildings, begin modeling
- Complete SDF results for thrust-fault scenario

Quarter 2

- Preliminary results for simulation of buildings
- Identify computational issues and plan for scaling to large cluster
- Finalize interfaces for ground motion and visualization

Quarter 3

- Improve computational speed
- Identify typical highway bridge models
- Preliminary visualization

Quarter 4

- Complete simulations of buildings with selected ground motion scenarios, including visualization
- Identify methodology for selecting building inventories in selected region
- Preliminary models, computation models, and interface for surficial soil and SSFI

Deliverables

The deliverables will be in the form of software (using OpenSees), including the interfaces for ground motion and visualization with the middleware used for the project. Several papers will be completed in the next year documenting the methodology and the results for the scenario earthquake events.

***Project Title*—ID Number**	*Performance of Building Nonstructural Systems*—**5242001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$60,000.00 NSF
Project Leader (boldface) and Other Team Members	**Eduardo Miranda (Stanford/F)**, Shahram Taghavi (Stanford/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The objective of this study is to develop functions relating engineering demand parameters (EDP) to damage states (damage measures or DM) of nonstructural components and functions relating damage states (DM) to repair/replacement cost (decision variable or DV) of nonstructural components.

The EDP – DM functions are developed as fragility functions that describe the probability of being in or exceeding a certain damage states as a function of the structural motion to which the nonstructural component is subjected to.

The DM – DV functions are developed to provide the probability of exceeding a certain dollar amount knowing that a certain nonstructural component is in a certain damage state.

The nonstructural components that are being studied in this project correspond to those in the seven-story reinforced concrete Van Nuys testbed building.

Methodology employed

In order to develop fragility functions of nonstructural components it is first necessary to obtain information about structural motions associated with different levels of damage. These are commonly referred to as motion-damage pairs. In this project motion-damage pairs are being developed using three sources of information. (i) results of experimental research on nonstructural components, (ii) earthquake records of instrumented buildings for which relatively detailed damage reports exist, (iii) non-instrumented buildings with damage reports but with free-field records available at less than 1 km from the structure. In the latter case the response of the structure is first estimated using response history analyses using a simplified model of the structure. Fragility functions are being developed as a function of interstory drift ratio for some nonstructural components and as a function of peak floor acceleration for others.

Role of this project in supporting PEER's strategic plan

This project provides vital information to PEER's goal related to Performance Based Earthquake Engineering. In particular it provides information that is necessary to relate structural motion with physical damage that may occur in nonstructural components and the to relate that physical damage to economic losses.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

- Identification and classification on nonstructural components
- Cost information related to the installation of new nonstructural components
- Information on the performance of nonstructural components in previous earthquakes
- Development of a database with classification and performance of nonstructural components
- Identification of nonstructural components in the testbed structure.

- Development of two fragility functions using results of experimental research.
- Development of motion-damage pairs for various types of drift and acceleration sensitive nonstructural components using earthquake records and damage reports of instrumented buildings.
- Development of a simplified model to estimate engineering demand parameters in various locations of non-instrumented buildings using nearby free-field records
- Development of motion-damage pairs for various types of nonstructural components using earthquake damage reports of non-instrumented buildings with nearby free field records.
- Development of damage-cost functions for two types of nonstructural components.

Plans for Year 6 *(if project is proposed to continue)*

Emphasis up to now has been on the development of fragility functions. The loss estimation methodology currently permits the estimation of the expected annual loss but no a loss curve describing the probability of exceedance of various dollar losses in the building. Plans for year 6 would be in two areas: damage-cost functions and estimation of the loss curve. The latter activity requires knowledge about the dispersion and correlation of various response quantities, dispersion and correlation between various damage measures and the dispersion and correlation of losses in individual components. The expanded formulation will permit the propagation of uncertainties associated with the presence of nonstructural components in a building.

Other relevant work being conducted within and outside PEER and how this project differs

Within PEER:

1. Building loss assessment: PI Eduardo Miranda, Stanford University, Project No. 1182001. Loss assessment with emphasis on structural components.
2. Building loss assessment: UC Berkeley case study; PI Mary Comerio, UC Berkeley, Project No. 1192001. Project associated with another testbed structure with emphasis on building contents.
3. Performance Characteristics of Building Contents: PI Nicos Makris, UC Berkeley, Project No. 5302001. Experimental project of performance of building contents.

Outside PEER:

1. One project being conducted at USC related to nonstructural components in hospitals.

Our project is more focused on developing fragility curves of specific nonstructural components installed in commercial buildings and complements other projects in PEER that develop these functions for structural elements and contents. It also develops cost functions for different nonstructural components.

Expected milestones

1. EDP/DM and DM/DV relationships
2. Aug 15th, Draft of the report
3. October 1st, Final report

Deliverables

Fragility curves and cost functions for selected nonstructural components

***Project Title*—ID Number**	*RC Frame Validation Tests*—**5252001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$100,000.00 CA-General
Project Leader (boldface) and Other Team Members	**Jack Moehle (UCB/F)**, Ken Elwood (UCB/GS), Halil Sezen (UCB/GS), Dae Hwan Kim (UCB/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The goal of this project is to develop validation data on the nonlinear response, component failure, and internal force redistribution as collapse occurs in a building frame representative of older reinforced concrete construction.

Methodology employed

First, this project is completing prior studies on behavior of structures having columns susceptible to shear and axial load failures. These studies provide the fundamental information and procedures needed to develop a test specimen for collapse studies. Subsequently, a test specimen will be constructed for testing either statically or on the earthquake simulator.

Role of this project in supporting PEER's strategic plan

This project supports the PEER strategic plan by providing performance data and validation tests for further development of the simulation capabilities of OpenSees. Performance data and simulation are central to the PEER mission of developing performance-based earthquake engineering methodologies, in this case with particular application to the Van Nuys building testbed.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

We previously have completed pseudo-static and dynamic shaking table tests of specimens sustaining shear and axial-load failures. These serve as the basis for analytical model and computational procedure development.

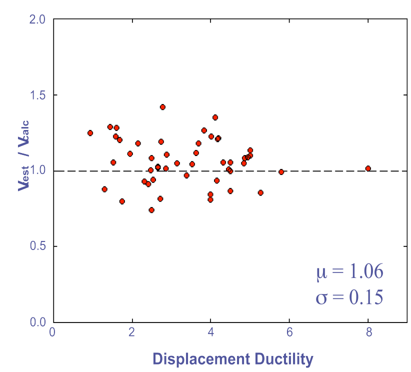


Figure 1 Ratios of measured shear strengths to calculated shear strengths.

Models for shear strength have been developed and checked against available data for representative columns tested both within PEER and by other organizations. Some comparison with test results is in Figure 1.

Models for axial-load failure following shear failure have been developed and compared with available data. These models show a correlation between axial load, transverse reinforcement, and drift at failure. We are developing this into a model for implementation in OpenSees. In the model, Figure 2, a three-spring representation is being considered for bending, shear, and axial load resistance and deformation. When the flexural deformation reaches a critical point, it initiates shear failure. After shear deformations reach a critical level defined by loading variables, this initiates axial-load failure. The model has shown reasonable results for some example cases, but requires further development.

Implementation in OpenSees has been hampered somewhat by computation challenges related to component softening. Excellent collaborations with other PEER team members is resulting in important progress toward final implementation.

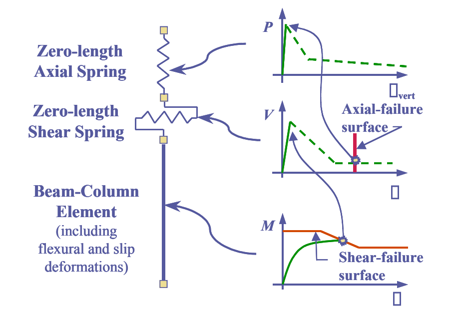


Figure 2 – Conceptual approach for nonlinear model

Following completion of the model development, we will begin parameter studies that will be of direct benefit for understanding collapse behavior of concrete structures, but also will provide direction on development of a test specimen for complete system collapse studies.

Plans for Year 6 *(if project is proposed to continue)*
We anticipate selecting frame details before the end of Year 5. Year 6 will be devoted to construction and testing of a three-dimensional frame specimen for frame collapse studies. The test specimen will be constructed by subcontract to an outside construction company, followed by testing. The tests may be done statically, or dynamically using the earthquake simulator; current thinking is that this test needs to be done dynamically.

Other relevant work being conducted within and outside PEER and how this project differs
Researchers in Japan and Taiwan have carried out similar work. The details and configurations used in those tests are different from those considered common and most critical for existing US buildings. However, we remain in close contact with our counterparts in other countries so that we can take advantage of their conceptual thinking, data, and analysis models.

Expected milestones

1. Completion of model development for axial load collapse of reinforced concrete columns sustaining shear failures, including implementation in OpenSees (June 2002).
2. Complete prior studies of collapse and idealized analytical models (December 2002).
3. Define three-dimensional test specimen for collapse studies (December 2002).
4. Complete tests on the selected specimen (July 2003). Basic data on the completed test will be available September 2003.

Deliverables

- Analytical models for shear and axial load behavior.
- Validation test data from 3-D collapse test.

***Project Title*—ID Number**	*RC Joint Component Validation & Analyses*—**5262001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/00—9/30/02	Current Year Budget Funding Source	$80,000.00 NSF
Project Leader (boldface) and Other Team Members	**Dawn Lehman (UW/F),** Laura Lowes (UW/F), John Stanton (UW/F), Daniel Alire (UW/GS), Meredith Anderson (UW/GS), Catherine Pagni (UW/GS), Brad Johnson (UW/US)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

1. To advance the existing beam-column joint model to improve simulation of experimentally observed response modes (e.g., crushing of joint core concrete, deterioration of bond strength under cyclic loading).
2. To validate the improved model using experimental research results.
3. To calibrate a practical beam-column joint model for use in analyses of large frames.
4. To develop performance models to relate engineering demand parameters (EDP) to damage measures (DM).

Methodology employed

This project builds on two previous projects and is a collaborative effort of the researchers from the previous projects. The first project, categorized as a fundamental study, used experimental research methods to establish performance states and develop experimental data for reinforced concrete beam-column joints without joint reinforcement. In the second study, analytical methods were employed to develop a macro-element model capable of analytically assessing performance. In this study, the researchers have joined forces to validate and improve the existing model using the measured experimental results and to develop performance models for beam-column joints.

Role of this project in supporting PEER's strategic plan

The PEER strategic plan seeks to develop technologies to support performance-based earthquake engineering. In part the research effort is working towards developing enabling technologies, including robust computational models to assess the system performance. For non-ductile reinforced concrete frame buildings, these types of tools are required for the structural components. In this effort, we are developing enabling technologies for beam-column joints in non-ductile frames.

The results of this research effort also support the development of reliability-based earthquake loss estimation techniques. For older reinforced concrete frames, earthquake loss includes costs associated with structural repair as well as down-time losses. Thus, loss estimation requires relationships linking EDP's and DM for components. The results of this project include probabilistic relationships between joint-specific EDP's and DM's.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

The effectiveness of the existing macro-element joint model was assessed using the experimental research results. The model was developed assuming that the bond and joint shear mechanisms were independent. However, the measured response indicated that these two mechanisms influenced one another and the macro-element model is being updated to ensure that this influence is captured. The experimental data has been used to validate the individual response components, namely the bond-slip springs and the joint shear panel elements. The force-displacement response of the experimental specimens is being used to validate the performance of the model.

Although the macro-element models are useful for research efforts, engineers are interested in simpler models for use in large frame analyses. Research has begun on developing a model that is suitable for such use. Currently, two frame models are being developed: one with single element spring models to model the joint behavior, and the other with a slightly more complex joint model configuration. The parameters of the simplified models will depend on the geometry, reinforcement, and material properties of each joint. Using the macro-element model, a parametric study will be performed to determine values for the single-element models.

In a parallel effort, relationships between EDP's, DM's and ultimately DV's for RC joints are being developed using data from PEER-sponsored and other experimental studies. Data from approximately 10-12 previous investigations have been collected and used to develop a three-tiered performance scale for older beam-column joints. Performance states are associated with repair techniques: repair, recast and rebuild. Damage measures such as crack width and spacing, extent of concrete crushing and extent of strength deterioration define each performance state. Experimental data are used also to define the probability of achieving a specific performance state given and joint-specific EDP.

Plans for Year 6 *(if project is proposed to continue)*

This research effort will contribute to the efforts being made to assess the performance of non-ductile reinforced concrete frame buildings. However, more realistic models of beam-column joints are required to model eccentric beams (common in older structures) and to assess the interdependence of the performance of adjacent elements (beams and columns) on the joint. Additional experimental and analytical research is required to develop appropriate methods to capture these effects.

Other relevant work being conducted within and outside PEER and how this project differs

We have found very little research into the seismic performance of non-ductile beam-column joints. However, this research project will complement ongoing research into modeling of beam-column joint elements, using experimental and analytical methods, in that most of that research focuses on joints in new construction.

Expected milestones

- Calibrated simple joint model. This model will be appropriate for use in the initial simulation model for the Van Nuys testbed.
- Validated improved joint model. This model will provide a more sophisticated and higher-resolution representation of the experimentally observed beam-column joint response mechanisms.
- Performance models to relate EDP to DM and, ultimately, DV.

Deliverables

- Calibrated single-element model
- Validated multi-element macro-element model
- Performance model for R/C beam-column joints in existing frame buildings

Project Title—**ID Number**	*Bridge Bent Shaking Table Validation Tests*—**5272001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/03	Current Year Budget Funding Source	$100,000.00 CA-Transportation
Project Leader (boldface) and Other Team Members	**Stephen Mahin (UCB/F)**, Mahmoud Hachem (UCB/GS), Eric Anderson (UCB/GS), Andres Espinoza (UCB/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The goal of this project is to conduct a test on a simple reinforced concrete model bridge system, resulting in development of validation data on nonlinear response, component yielding/damage, and internal force redistribution during ductile response.

Methodology employed

A series of structural models are designed, constructed and tested on the shaking table. The specimens are carefully instrumented to allow determination of local response and damage parameters used in the PEER methodology. Focus is on obtaining data to calibrate the OpenSees modeling capabilities for ductile reinforced concrete bridges, and in conjunction with those working on OpenSees improve modeling capabilities. The main specimens will consist of a two column frame from a single column viaduct. The two columns will have different strengths and stiffnesses, resulting in different sequence and intensity of damage in each, significant redistributions of internal forces, and producing three-dimensional response including torsion. This data will then be compared to predictions made using OpenSees models having different levels of complexity, ranging from conventional design assumptions, to highly refined models to assess local behavior.

Role of this project in supporting PEER's strategic plan

This project support activities in Thrust Area 5 to better understand the behavior of bridge systems and characterize their capacity. Specifically, it provides data for the calibration and improvement of OpenSees models of indeterminant reinforced concrete bridge structures undergoing three dimensional excitations. It directly supports the bridge test bed activities.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

This is the first year of this project. This project builds upon an earlier sequence of tests of column components. A final report on the first milestone is nearly complete, assessing the ability of OpenSees to model the behavior of single columns. An extensive series of analyses of possible test specimens with various configurations and column designs is complete. The design of the first two column test specimen is nearly complete, and construction is expected over summer 2002 with testing in the early fall.

Plans for Year 6 *(if project is proposed to continue)*

The second year of this project includes analysis and interpretation of the results obtained in the first test conducted at the end of year 5, extensive analytical calibration and assessment work, plus the construction of a second series of tests to examine issues more relevant to the test beds and performance criteria being established for new bridge structures.

Other relevant work being conducted within and outside PEER and how this project differs

Similar experimental work has been carried out by researchers in Japan. The details and configurations used in those tests differ significantly from those considered common in US bridges. Analytical correlation studies are also underway in Taiwan, Japan and the US. Nearly all of these studies are based on results of quasistatic component tests, not using results from indeterminant shaking table tests. However, we remain in close contact with our counterparts in the US and other countries.

Expected milestones

The first milestone is to complete model assessment for ductile reinforced concrete columns, using OpenSees focusing on effects of degree of refinement in model and ability to predict residual displacements (June 2002). The second milestone is to design and conduct studies on shaking table tests on a two column test specimen (December 2002). The third milestone is to define an appropriate second test specimen, based on the results of the first specimen, and to support the testbed program (July 2003). Basic data on the completed test will be available September 2003.

Deliverables

Report on bridge column modeling, design and construction of the first test series, and testing initiated during year 5. Completion of first tests, analysis of results, design, construction and testing of second series competed, along with -preparation of final report, in Year 6.

***Project Title*—ID Number**	*Database and Acceptance Criteria for Column Tests, Couple Database Effort* —**5282001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$70,000.00 NSF
Project Leader (boldface) and Other Team Members	**Marc Eberhard (UW/F)**, Michael Berry (UW/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

This project will develop and calibrate tools for assessing reinforced concrete column seismic performance, including data and models for both seismically conforming (ductile) and non-conforming (brittle) columns.

Methodology employed

- Expand the scope of existing PEER column databases, which were developed in years 1-4. This database will provide the basis with which to evaluate seismic design and assessment tools. The online database can be accessed at http://ce.washington.edu/~peera1.
- Working jointly with Professor Greg Fenves (Thrust Area 4 project), improve the capabilities of the online database.
- Develop and apply performance models to relate numerical data from simulation models to damage states that represent column performance in the PEER PBEE methodology. The selection of the models will be coordinated with Professors Fillipou and Deierlein.
- Exercise and validate the OpenSees model for columns in collaboration with Professors Fenves, Fillippou and Deierlein.
- Implement these models as part of the I-880 bridge testbed. The column performance models will incorporate uncertainties and inaccuracies in column behavior and be able to track the effects of these factors through the analysis.

Role of this project in supporting PEER's strategic plan

PEER's mission is "develop, validate and disseminate performance-based seismic-design technologies." To achieve this goal, it is necessary to relate deformation demands placed on structural members with the likelihood of reaching particular levels of damage. For example, at a particular level of deformation, what is the likilhood that the reinforcing bars in a column will have buckled? This project provides the data and tools necessary to construct this link for reinforced concrete columns, one of the most vulnerable and critical structural components of building and bridges.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

DATABASE: The size and scope of the database have been expanded during the past year. Most importantly, the online database not only provides test properties and digital, force-deflection histories, it also now provides the peak level of column deformation preceding the observation of each level of damage.

Although users of the database have not been required to register their names to use the website, informal e-mail contacts indicate that the database is being used by many researchers inside and outside of PEER. For example, the principal investigator has been contacted by researchers at

Cornell University, Purdue University, Stanford University, University of California, Berkeley, University of Kansas, University of Houston, University of Wisconsin, Madison, as well as by researchers in Canada, Italy and Japan.

FORCE-DISPLACEMENT RESPONSE: The accuracy of models of column, force-displacement response was documented in two theses, two workshop papers, and a PEER research report.

PROGRESSION OF DAMAGE: A series of non-dimensional measures of column deformation (drift ratio, displacement ductility, plastic rotation, nominal compressive strain and nominal tensile strain) have been evaluated to determine the suitability for predicting the onset of spalling and bar buckling. For each of these measures of deformation, methodologies have been developed and the accuracy of these methodologies has been evaluated statistically.

Plans for Year 6 *(if project is proposed to continue)*

(1) Continue to improve and expand database.
(2) Develop and calibrate damage models that account for deformation history (instead of accounting just for peak deformation).
(3) Implement, validate and exercise damage models (based both on peak deformation and displacement history) using OPENSEES.
(4) Implement the damage models within the framework of the I-880 testbed.

Other relevant work being conducted within and outside PEER and how this project differs

This work does not duplicate research performed by others, but it does depend on extensive interaction with other PEER researchers, as described in methodology steps 3-5.

Expected milestones

Milestones are given within the section on deliverables.

Deliverables

- A column-performance database (continuously updated).
- A PEER report that documents the accuracy of many existing column-performance methodologies (Summer 2002).
- An enhanced database, including a search capability (Summer 2002).
- A PEER report summarizing the proposed PBEE column performance models, including validation studies that quantify the accuracy of the models (Spring 2003).
- The corresponding source code and performance models for RC columns (implemented in OpenSees) (Summer 2003).

***Project Title*—ID Number**	*Performance Characterization of Floor- and Bench-Mounted Equipment*—**5292001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$60,000.00 CA-General
Project Leader (boldface) and Other Team Members	**Tara Hutchinson (UCI/F)**, Gerard Pardoen (UCI/F), Roberto Villaverde (UCI/F), Charley Hamilton (UCI/GS), Two Sham (UCI/US)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

Modeling and evaluating the response of nonstructural equipment and contents is important for determining the overall economic losses associated with an earthquake event. The particular objectives of studies at UCI, which complement studies by researchers at UCB (Makris), are to characterize the seismic performance of bench and shelf-mounted equipment and contents within a biological/chemical building. In this case, the emphasis is on equipment and contents present in the Life Sciences Addition (LSA) building.

Methodology employed

Our approach has been largely experimental thus far. Three experimental studies are currently underway: (i) full-scale shake table tests (creating a mock-laboratory environment), (ii) bench and shelf characterization, and (iii) small shake table (chemical glassware) experiments. The mock-laboratory environment provides information for modeling system interactions, while the bench and shelf characterization is intended to provide fundamental dynamic properties of these systems (as isolated units). Small shake table studies investigating the response of chemical glassware are intended to provide an indication of the risk associated with the motion of these elements, as well as an evaluation of retrofit strategies used for chemical containers. Description and select results from each of these are described in the following section.

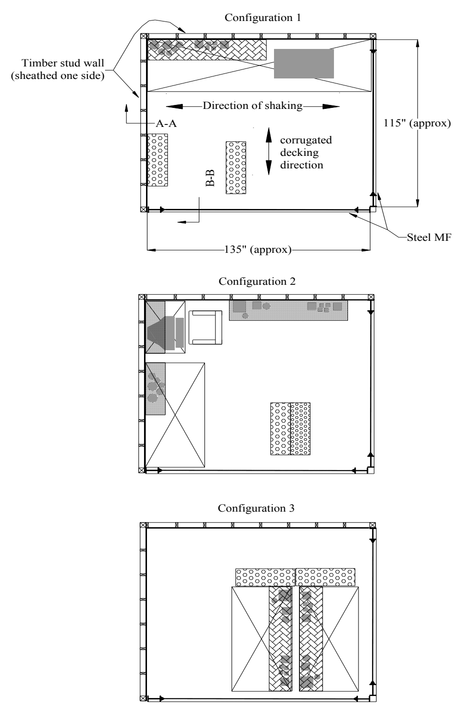


Figure 1. Plan configurations on shake table – 3 proposed layouts.

Role of this project in supporting PEER's strategic plan

This project supports several aspects of the overall PEER strategic plan. Analytical studies conducted will provide continued use and development of the PEER OpenSees platform. Experimental studies will provide evaluation of these simple analytical models for performance evaluation of bench and shelf-mounted equipment. In addition, a unique experimental database will be developed for researchers within PEER. Our work will also contribute to the development of engineering demand parameters needed for the overall classification system used for scientific equipment and building contents.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*
Full-scale Shake Table Experiments – Mock Laboratory Space
Bench and Shelf Characterization
Sliding and Rocking Sensitivity of Chemical Containers

Plans for Year 6 *(if project is proposed to continue)*
At the end of year 5 we will have completed the chemical glassware studies and the mock laboratory experiments. The bench and shelf characterization portion of our studies will likely continue into the beginning of year 6. In addition, if additional mock-laboratory configurations are desired, these will likely be conducted in the subsequent year.

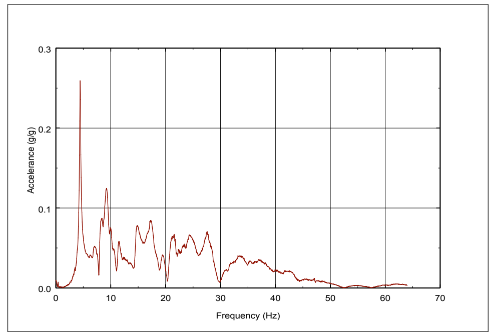


Figure 2. Frequency response of a laboratory bench shelf combination, based on shaker-excited modal

Year 6 will allow us to evaluate and formalize analytical approaches for modeling the seismic response of equipment and contents mounted on benches and shelves. Through the comparison of simple analytical models with the database of experimental results, a refined approach for performance assessment will be developed.

Other relevant work being conducted within and outside PEER and how this project differs
Experimental and analytical studies of heavy equipment within the LSA and other chemical/biological laboratory environments are being conducted by Professor Makris at UCB. Our work complements these studies, since our emphasis is smaller equipment and contents mounted on shelves or benches.

Expected milestones
(i) Complete mock-laboratory experiments – Summer 2002
(ii) Complete chemical glassware experiments – Summer 2002
(iii) Complete bench and shelf characterization – Fall 2002
(iv) Conduct analytical validation – Winter-Summer 2003

Deliverables
Year 5 deliverables include:
(i) Data report summarizing the chemical glassware studies.
(ii) Contributions the LSA test bed report.

Year 6 deliverables include:
(i) Data report summarizing the mock-laboratory and bench and shelf characterization experimental studies.
(ii) Final report synthesizing the experimental and analytical results, including documented examples of the OpenSees analytical modeling.

***Project Title*—ID Number**	*Performance Characteristics of Building Contents*—**5302001**		
Current Year Start/End Dates Overall Start/End Dates	10/1/01—9/30/02; 10/1/01—9/30/02	Current Year Budget Funding Source	$80,000.00 NSF
Project Leader (boldface) and Other Team Members	**Nicos Makris (UCB/F)**, Dimitrios Konstantinidis (UCB/GS), Margarita Constantinides (UCB/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

In this project, experimental and analytical studies are proposed to provide greater understanding and quantitative characterization of the vulnerability of equipment within buildings that are subjected to ground shaking. The equipment of interest are low temperature refrigerators, liquid nitrogen tanks, centrifuges, gas chromatographs and other heavy equipment of the Life Science Addition (LSA) building at the U.C. Berkeley campus.

The dynamic behavior of either free-standing or anchored equipment is very sensitive to the characteristics of the base input (mainly acceleration amplitudes and frequency content), the frictional characteristics of the equipment-base interface, the restrainer strength and ductility, and the structural rigidity of the equipment.

The objective of this project is to improve our understanding of the seismic response of building contents. The project includes experimental investigations on the mechanical properties of the equipment supports (values of coefficient of friction of non-slip pads, strength and ductility of restrainers), shake table tests followed by analytical/numerical studies. The project will lead to a practical methodology for assessing likely performance of equipment consistent with the overall PEER performance-based earthquake engineering evaluation methodology.

Methodology employed

The methodology employed combines experimental and analytical studies. First, a preliminary simulation analysis is conducted to validate computer software and estimate the anticipated response. Subsequently, experimental studies are conducted to estimate the coefficient of friction at the equipment-floor interface. The preliminary simulations are refined with the experimentally determined coefficient of friction. Shake table studies are conducted on the equipment of interest that is supported on a base with interface properties equal to the properties of the floor of the LSA building. Finally, the studies will conclude with the development of a methodology to characterize equipment performance in probabilistic terms.

Role of this project in supporting PEER's strategic plan

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

Prior to the shake table tests, anticipated response is estimated with simulation studies. Two commercially available computer codes were evaluated to calculate the sliding and rocking or rigid blocks. These codes, ABAQUS and Working Model, yielded results that are in qualitative agreements. The shake table tests will be conducted at the RFS shake table which has a displacement limitation of ±6 inches. With these limitations, we can test floor motions due to shaking of 50% and 10% in 50 years hazard levels.

At present, we are conducting experimental studies to determine the coefficient of friction between the equipment and the floor of the LSA building. These studies include the preparation of a sliding surface with tiles identical to the tiles of the LSA building.

Plans for Year 6 *(if project is proposed to continue)*

- Data analysis and reduction.
- Validation of simulation procedures with experimental data.
- Development of a methodology to characterize equipment in probabilistic terms.
- Compilation of results and preparation of final report.

Other relevant work being conducted within and outside PEER and how this project differs

Expected milestones

- Quarter 1: Identification of typical heavy equipment of interest, collect information of geometric configuration and mechanical properties of their support (coefficient of friction along equipment/base interface; stiffness, strength and ductility of restrainers).
- Obtain floor motions from the LSA building that will be computed under various earthquake scenarios and other recorded strong floor motions from similar types of buildings (for instance, records from the USGS SMIProgram) for preliminary analysis.
- Quarter 2: Conduct preliminary dynamic analyses (simulation studies) of free-standing and anchored equipment by considering the frictional interface properties and restrainer strengths identified in Quarter 1. This task will indicate which equipment tend to slide, which tend to uplift, and which tend to rock appreciably—and possibly overturn. The simulation studies will use the input motions identified in Quarter 1 and will provide valuable guidance to the experimental studies.
- Quarter 3: Establish the set of motions that will be used as shake table motions. This task will be conducted in association with the other research team and PEER, in order to compile a set of floor motions from the LSA building that can be satisfactorily simulated by the shaking table (there are frequency and displacement constraints on table motions). Prioritization of equipment to be tested, collection of equipment to be tested and planning of shake-table testing.
- Quarter 4: Shake table testing of free-stranding and anchored equipment. Instrumentation, identification of structural properties, recording of equipment accelerations and displacements (including uplift) during serviceability levels and violent bi-directional shaking. Video-recording of response.
- Quarter 5: Data analysis and reduction. Classification of response patterns and correlation of them with the geometric characteristics of the equipment, interface properties and the kinematic characteristics of the table motions.
- Quarter 6: Validation of simulation procedures with experimental data. Calibration of predictive analytical and numerical tools to simulate the recorded motions. Validation of predictive tools for additional parametric studies and understanding of their limitations.
- Quarter 7: Development of a methodology to characterize equipment performance in probabilistic terms.
- Quarter 8: Compilation of results and preparation of final report with detail documentation on the experimental studies, simulation studies and the proposed performance based engineering methodology.

<table>
<tr><td>Project Title—ID Number</td><td colspan="3">Substation Equipment Interaction – Experimental Models of Flexible Bus Connectors—Lifelines 403</td></tr>
<tr><td>Current Year Start/End Dates</td><td>7/01/00—09/30/02</td><td>Current Year Budget
Funding Source</td><td>$51,046.00
PG&E/CEC</td></tr>
<tr><td>Project Leader (boldface) and Other Team Members</td><td colspan="3">Andre Filiatrault (UCSD/F), Derry Evanger (UCSD/GS), Christopher Stearns (UCSD/US)</td></tr>
</table>

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The main objective of this research project is to develop guidelines for the design of flexible bus (cable) systems in order to minimize or eliminate the seismic interaction between connected electrical substation equipment. These guidelines will be formulated in terms of generic recommended cable configurations and will be based on the results of experimental studies conducted in this project and analytical studies conducted in another project at the University of California, Berkeley.

Methodology employed

The project consist of 3 parts: Part 1: Definition of dynamic properties of substation equipment items; Part 2: Quasi-static bending testing of flexible cables; and Part 3: Shake table tests of interconnected generic equipment.

Role of this project in supporting PEER's strategic plan

Electrical distribution and transmission systems are particularly vulnerable to earthquake loading. Electrical equipment components are typically designed primarily to meet electrical function requirements as opposed to structural performance requirements. Furthermore, electrical bus conductors are used to interconnect substation equipment components, thereby complicating their structural dynamic response. Flexible bus ("cables") can exert significant forces depending on their slackness and flexural stiffness. During recent earthquakes in California, it is suspected that significant structural dynamic interaction and equipment damage due to forces transferred through the connectors occurred. This project is aimed at better understanding the dynamic interaction of interconnected equipment. The project will contribute to the reduction of the seismic hazard to electrical substation equipment. In particular, the project could lead to the establishment of guidelines for the design of substation equipment interconnected with flexible buses.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

Part 1: Definition of dynamic properties of substation equipment

The first part of the project deals with the definition of Single-Degree-of-Freedom (SDOF) properties to model the dynamic behavior of substation equipment. For this purpose, dynamic properties of various substation equipment items were collected from past investigations and available qualification data from various utilities. Dynamic properties data from 283 different substation items have been collected. These data were obtained in partnership with Pacific Gas and Electric Company and Hydro-Quebec who graciously collected and provided a significant amount of seismic qualification data. The physical parameters collected for each equipment item are: the voltage, the fundamental frequency, the first modal damping ratio, the first modal participation factor, the total seismic weight, and the first modal weight. A computerized database has been developed in this project to centralize the dynamic characteristics of substation equipment. This database includes in downloadable Excel format all the data collected for the 283 equipment items. The database is accessible from the Internet at the following website: **http://seismic.ucsd.edu/peer/substation.html**

Part 2: Quasi-static bending testing of flexible cables
In the second part of the project, full-scale quasi-static bending tests were performed on two different flexible bus (cables) in order to characterize their flexural stiffness. These tests were performed in the transverse direction of the cables under prescribed initial slackness and displacement history.

Part 3: Shake table tests of interconnected generic equipment
In the third part of the project, shake table tests were performed on five pairs of generic substation equipment connected with three different flexible bus assemblies. 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 the flexible bus assemblies, the slackness of the flexible bus assemblies, the simulated ground motions, and the intensities of the simulated ground motions.

Plans for Year 6 ***(if project is proposed to continue)***
N/A

Other relevant work being conducted within and outside PEER and how this project differs
This project is the continuation of an investigation on substation equipment interaction performed in Phase II of the PEER-PG&E program. Analytical studies performed in the Phase II program suggested that bending properties of flexible cables might affect the behavior of short jumpers and some "long" cables. Very limited dynamic interaction experiment involving equipment models interconnected by flexible cables has been performed to evaluate the importance of this dynamic interaction effect. Also, no method exists for evaluating the bending properties of flexible cables that can be used in the dynamic analysis of interconnected equipment. The experimental studies in this project conducted are conducted in parallel with another analytical project at the University of California, Berkeley.

Expected milestones
At the time of writing, Parts 1 and 2 have been completed and Part 3 is near completion. It is expected that the project will end at the expected end date.

Deliverables
- Computerized database of dynamic characteristics of substation equipment
- CD-Rom of all filtered and biased experimental data.
- Guidelines for the design of flexible bus (cable) systems in order to minimize or eliminate the seismic interaction between connected electrical substation equipment

***Project Title*—ID Number**	*Substation Equipment Interaction - Analytical Models of Flexible Bus Connectors*—**Lifelines 403**		
Current Year Start/End Dates	7/01/00—6/30/02	Current Year Budget Funding Source	$82,153.00 PG&E/CEC
Project Leader (boldface) and Other Team Members	**Armen Der Kiureghian (UCB/F)**, Jerome Sackman (UCB/F), K.-J. Hong (UCB/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The objective of this project is to identify generic configurations of flexible bus conductors (including profiles, amount of slack, type of connection to the equipment, size and type of conductor) that minimize or eliminate the adverse effect of interaction on attached equipment and that are stable under earthquake excitation. The study will develop and employ a refined mechanical model of the flexible conductor and account for the prevailing uncertainties in the dynamic characteristics of the connected equipment items and the flexible conductor as well as the stochastic nature of future ground motions.

Methodology employed

An improved mechanical model of the flexible conductor is developed, accounting for friction and slippage between the constituting wires. A large-deformation, inelastic finite element formulation is used to determine the dynamic response of equipment items connected by the flexible conductor. A statistical model is developed to predict the effect of interaction (in the form of the ratio of peak responses in the connected and stand-alone configurations of each equipment). The model accounts for the stochastic nature of the ground motion. Through a large number of simulations, conductor configurations that reduce the interaction effect are identified. Guidelines for design are developed based on these simulations. Thus, the approach involves mechanical modeling of the behavior, nonlinear finite element dynamic analysis, statistical model development, and simulation.

Role of this project in supporting PEER's strategic plan

This project will provide guidelines for reducing the adverse effect of interaction between electrical substation equipment connected by flexible conductors. The results of this project will help improve the earthquake reliability and safety of electrical power lifelines system.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

So far we have developed a vastly refined model of the conductor cable, accounting for the nonlinear effect of friction and slippage among wires constituting the helically wrapped cable. A finite element model has also been developed, accounting for large deformations and inelastic behavior of the cable. Comparisons are made with experimental results developed by researchers in UC San Diego and in Hydro Quebec, Canada. A large number of simulation studies have been carried out. Presently, statistical predictive models are being developed that account for the stochastic nature of the ground motion. These models directly provide measures of interaction (mean and standard deviation of response ratios) in terms of system properties. Guidelines for design will be developed based on these predictive models.

Plans for Year 6 ***(if project is proposed to continue)***

This project is expected to end this year. However, the results from this study, particularly the refined mechanical model of the conductor cable and the finite element model for nonlinear dynamic analysis, offer opportunities for other related studies, e.g., dynamic analysis of power transmission lines under wind loads.

Other relevant work being conducted within and outside PEER and how this project differs

Experimental work on a similar topic is being conducted at UC San Diego and in Hydro Quebec and other places in Canada. To our knowledge, no other analytical work is being conducted on this subject.

Expected milestones

1. Improved mechanical model of helically wrapped cables (completed).
2. Finite element model for large deformation, inelastic dynamic analysis of conductor cables (completed).
3. Models for predicting the dynamic interaction between equipment items connected by conductor cables (May 2002).
4. Guidelines for reducing the effect of effect of interaction between electrical substation equipment connected by flexible conductors (June 2002).

Deliverables

See 'Milestones' section above.

***Project Title*—ID Number**	*Improvements to Modeling Substation Equipment*—**Lifelines 404**		
Current Year Start/End Dates	7/15/01—7/14/03	Current Year Budget Funding Source	$65,000.00 PG&E/CEC
Project Leader (boldface) and Other Team Members	**Gerard Pardoen (UCI/F),** Charley Hamilton (UCI/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

This proposed project intends to improve the methods used for modeling electric substation equipment through a combination of experimental and analytical studies.

Methodology employed

The experimental studies are combining (a) laboratory experimental modal analyses and (b) laboratory shake table tests of specific, stand alone equipment as well as (c) in-situ field measurements of this equipment at five sites selected from PG&E, Bonneville Power Administration and BC Hydro facilities. The experimental modal analyses consider the linear response of the equipment (frequency, mode shape, damping) under low level excitation whereas the shake table tests consider the dynamic response of the equipment within the linear and, probably, nonlinear ranges. The in-situ tests document the low level response of the equipment itself due to impacts of force-calibrated hammers of various sizes.

The analytical studies will interpret the vibration data using commercially available software in order to define the frequency, mode shape and damping characteristics of the equipment. Multiple degree-of-freedom, lumped parameter modal models will be developed for the equipment that is assumed to respond in the linear range. 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 analytic studies will recommend methods for modeling equipment and major components.

Role of this project in supporting PEER's strategic plan

The short term societal impacts from large urban earthquakes can be greatly affected by the seismic performance of utility systems, as one of the so-called Lifelines of a region's infrastructure. The functional performance of such utilities depends on the response of the major components in the network of facilities and equipment that constitute the electrical grid. Assessment of the likely response of this equipment is therefore important to characterizing the impact of scenario events on a given region, and helps to identify weak links in the existing systems.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

An improved testing method combining laboratory impact testing, laboratory shaking table testing and field testing of components has been developed. Initial lab and field testing have been performed on a variety of transformer bushings of various sizes and capacities. While the results of some of these have been surprising, and thus warrant careful re-examination, the methodology appears to provide the properties identified as significant in analyzing this equipment. Based on feedback from the utilities and other likely users of the data, future emphasis will be placed on the larger, higher capacity equipment as these are the elements have seem to sustain most of the seismic damage in past earthquakes.

Plans for Year 6 ***(if project is proposed to continue)***

Other relevant work being conducted within and outside PEER and how this project differs

This project follows an earlier PEER Lifelines project in Phase II (Project 2D), which initiated work in characterizing the dynamic properties of substation equipment. The current project is building on the lessons learned from that earlier work, particularly regarding the most applicable methods for measuring the desired properties

Expected milestones

The specific steps being carried out include:

A: Define substation equipment to be tested in UCI laboratory

B: Define substations to conduct in-situ tests

C: Conduct experimental modal analysis tests of substation equipment – provide preliminary results

D: Conduct shake table tests of substation equipment – provide preliminary results

E: Conduct in-situ tests at substation – provide preliminary results

F: Develop analytical models

G: Write project report

Deliverables

a) a CD of the frequency response function data for the substation equipment (in **S**tandard **D**ata **F**ormat) from the force-calibrated hammer and shake table; the CD will also include the ASCII data files of the modal parameters as well as *.AVI files of the animated mode shapes.

b) a preliminary report following each significant experimental investigation that interprets the vibration data in terms of frequency, mode shape and damping characteristics of the substation equipment.

c) a series of analytical models from the experimentally-acquired laboratory and field data will be developed with ME'Scope.

d) a final report that compiles the experimental results as well as providing the analytic studies that recommend methods for modeling equipment and major components.

***Project Title*—ID Number**	*Seismic Qualification Requirements for Transformer Bushings—* **Lifelines 406**		
Current Year Start/End Dates	10/1/01—9/30/02	Current Year Budget Funding Source	$110,000.00 PG&E/CEC
Project Leader (boldface) and Other Team Members	**Andre Filiatrault (UCSD/F)**, Howard Matt (UCSD/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

The purpose of this research project is to improve the qualification requirements for transformer bushings. This project will focus on the qualification of bushings rated at and above 161kV, since this class of bushings is believed to be the most vulnerable. This project has two main specific objectives:

- Identify the critical parameters of supporting structures that affect the seismic performance of a bushing. Quantify the ranges of values for the critical parameters to ensure that bushing tests defined in 2. Remain valid.
- Define changes to the requirements for bushing shaking table tests that are consistent with the critical parameters identified in 1.

The integrated qualification requirements summarized in the items above would be submitted for incorporation into the next revision of the IEEE 693 standard in 2002. The project will be conducted in collaboration with Mr. Rulon Fronk who will act as an advising subcontractor for the project.

Methodology employed

The proposed research project will consist of the following three main phases:

- *Phase 1: Static and Dynamic Testing of Supporting Structures for Transformer Bushings*
  Manufacturers will be approached to donate a complete supporting structure for transformer bushings above 161kV. The supporting structure will be anchored to a strong floor next to a reaction wall. In order to determine its lateral stiffness, strength and failure mode, the supporting structure will be loaded laterally by a hydraulic actuator anchored between the supporting structure and the reaction wall. The load will be applied at a distance above the top of the supporting structure in order to simulate the eccentric loading provided by the inertia force originating at the center of gravity of the bushing. From the results of these tests, the important sources of flexibility in the bushing support assembly will be identified.

- *Phase 2: Dynamic Modeling of Supporting Structures for Transformer Bushings*
  Based on the experimental results obtained in Part 1, a finite element model will be developed to predict the dynamic response of the supporting structure. Using this model, Frequency Response Function (FRF) curves will be constructed for each of these dynamic models in order to determine the Dynamic Amplification Factor (DAF) for a wide range of harmonic base excitation and to determine the range of excitation frequencies resulting in a DAF below 2. Finally, "top of supporting structure" response spectra will be generated under base input motions compliant with the IEEE 693 standard in order to evaluate the effect of the supporting structure on the seismic input at the support of a bushing. Again, various designs will be considered to limit the amplification to a maximum of 2.0.

- *Phase 3: Shake Table Testing of a Supporting Structure - Transformer Bushing Assembly* For the third phase of the project, the supporting structure tested in Phase 1 of the project will be tested on the uniaxial seismic simulation system at the University of California, San Diego. These tests will provide a unique opportunity to measure the actual DAF provided by the supporting structure at the connecting point of the bushing and to evaluate the accuracy of the dynamic models developed in Phase 3.

Role of this project in supporting PEER's strategic plan

The IEEE 693-1997 standard specifies seismic qualification requirements for transformer bushings that include shaking table tests with the bushing mounted on a rigid test stand, for rated voltages exceeding 161kV. The standard requires the use of ground motions that match a specified response spectrum that is amplified by a factor of 2 to account for amplification resulting from the structure supporting the bushing. Shaking table tests conducted in previous PEER projects have raised questions about the adequacy of qualification requirements currently in use. Except for the amplification factor of 2 given in IEEE 693 for bushing qualification, no guidance is given to the transformer designer on how the bushing support structure should be designed. This project will contribute in elaborating such guidance.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

At the time of writing, the project has been active for less than three months. A 500 kV transformer tank structure has been identified for donation. The finite element modeling of this structure is underway.

Plans for Year 6 *(if project is proposed to continue)*

N/A

Other relevant work being conducted within and outside PEER and how this project differs

None

Expected milestones

Because of late start of the project, it is expected that the project will end approximately 3 months after the anticipated end date.

Deliverables

Set of design guidelines to transformer designers.

***Project Title*—ID Number**	*Development of Improved Methodology for buildings With Rigid Walls and Flexible Diaphragms*—**Lifelines 504**		
Current Year Start/End Dates	5/1/00—8/30/02	Current Year Budget Funding Source	$64,993.00 PG&E/CEC
Project Leader (boldface) and Other Team Members	**James Anderson (USC/F)**, Vitelmo Bertero (UCB/F), Mohsen Karaghi (USC/GS), Zwei Jiang (USC/GS)		

F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other

Project goals and objectives

Develop a methodology for evaluating the seismic performance of low rise buildings with masonry or concrete walls and timber floor and roof diaphragms and assessing the implications for design and upgrade

Methodology employed

Develop analytical models using commercial computer programs used by engineering firms and evaluate their ability to determine building response. Use instrumented buildings that have recorded response to strong ground motions as prototype structures. Compare recorded response with calculated. Subject the buildings to stronger earthquake ground motion and evaluate the changes in the response. Compared recorded and calculated responses to criteria used in current building codes and suggest changes to include for upgrading old buildings and new construction.

Role of this project in supporting PEER's strategic plan

Improve the reliability of typical buildings of this type found in electrical system facilities.

Year 5 accomplishments and brief description of past accomplishments *(if continuation)*

Evaluated the responses of a tilt-up concrete building that has recorded response for four major earthquakes. Modified the detail to include the removal of pilasters and the segmenting of the walls. Evaluated the response of two instrumented masonry buildings

Plans for Year 6 *(if project is proposed to continue)*

N/A

Other relevant work being conducted within and outside PEER and how this project differs

None.

Expected milestones

Project will be completed on schedule August 30.

Deliverables

A comprehensive PEER report covering the work on the two masonry building that is currently in review. A similar report on the two tilt-up concrete buildings that is currently in preparation.