

# Pacific Earthquake Engineering Research Center

an NSF-administered Engineering Research Center  
under cooperative agreement number EEC-9701568

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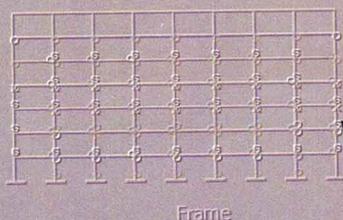
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# 8th Year Progress Report and Renewal Proposal

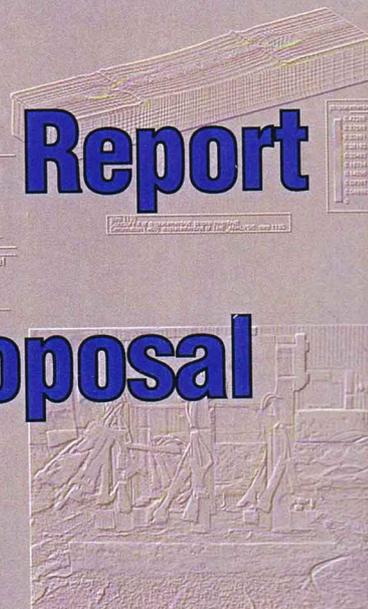
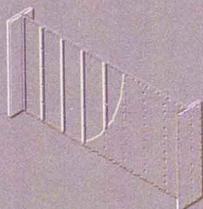
## Volume 2



Frame



Interior Frame



Buckled Reinforcing Model



Foundation



**Jack P. Moehle**

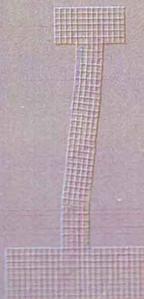
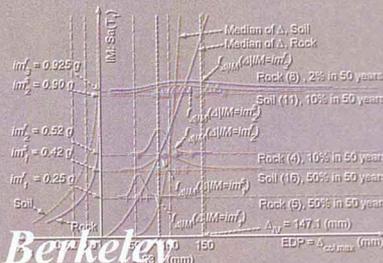
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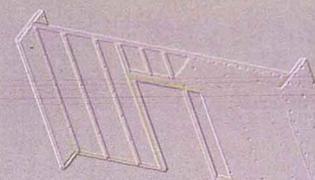
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**Submission Date**  
**April 2005**



# PEER YEAR 8 PROGRESS REPORT

## Volume II

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# **Section A**

## **Supplemental and Special Purpose Awards to PEER from the ERC Program**

**REU Supplement**

**Principal Investigator:**

Moehle, Jack P.

**Amount:**

\$58,000

**Award Number:**

EEC-9701568

# **Section B**

## **Project Summaries**

<b>Project Title—ID Number</b>	<i>Downtime Modeling and Consequences for Decision Variables</i> —1202004		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	CA-Gen
<b>Project Leader (boldface) and Other Team Members</b>	<b>Mary Comerio (UCB/F)</b> , Howard Blecher (UCB/GS), Ariane Fehrenkamp (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 focus on the downtime component of building losses and how it affects decision-making based on performance. To do this I will build on work completed in year 7 which defines long-term closure conditions. Additional work is needed to link DMs to long-term closure estimates. In year 8, I will investigate the damage conditions that trigger short-term closures and the occupancy conditions that trigger closure (even without damage). These factors will be combined to answer how downtime should be modeled in the PEER methodology.

### Role of this project in supporting PEER's mission (vision)

This project will define the downtime methodology in the PEER loss estimation component of performance based earthquake engineering.

### Methodology employed

To illustrate damage measures (DMs), we are conducting a detailed review of building damage conditions, and their relationship to damage states as described in ATC 20 and FEMA 356, to determine their influence on downtime. In addition, we will review and document external conditions that trigger downtime (separate from damage). A journal paper describing and defining these conditions will be the deliverable. Development of the relationships between EDPs and DMs will be linked to downtime to enable the loss estimating methodology proposed within the Buildings and Systems Thrust Area to include downtime modeling.

### Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments

In year 7, I began work on estimating downtime in the loss modeling component of the PEER methodology. Other loss modeling work in PEER focused on estimating financial losses and construction costs for repairs. My work developed a description of the rational (construction time related) downtime and the "irrational" component (financing, business operations, politics, etc.) and documented building closures at Stanford after Loma Prieta, and In Los Angeles apartment buildings after Northridge. An article titled "Estimating Downtime in Loss Modeling" is under review at the journal *Earthquake Spectra*.

This Year 8 project has three principal activities. Part 1 will be to define the damage conditions that cause short-and long-term building closure after earthquakes. This work will involve a review of post-earthquake building tagging, data from past earthquakes, and discussions with inspectors (building officials, engineers, and facility managers) in order to develop concise lists of structural and nonstructural damage conditions that can be related to closure times. Part 2 will

involve a review of building closures that are not a direct result of damage conditions. Examples include street closures, utility interruption, and owner/business uncertainty, etc. We will try to ascertain if these occupant-driven conditions can be modeled (or need to be modeled in the PEER methodology. Part 3 will involve a review of other decision variables – costs based on losses, and casualties and injuries in order to evaluate how downtime should be integrated into the PEER loss estimating methodology.

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

Very little work on downtime estimates for buildings is known outside PEER, however there is work on downtime in the lifelines area, as well as in transportation (e.g. highways, bridges, ports). This work will benefit from methods and terminology used in those areas.

**Plans for Year 8 if this project is expected to be continued**

This work will fold into the packaging and simplified methodology for loss estimating to be developed in Year 9.

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

The University of California, Berkeley has a Disaster Mitigation Grant from FEMA to re-evaluate the loss potential on the campus now that numerous seismic strengthening projects have been undertaken. The work is being done by professional engineers (Craig Comartin and Charles A. Kircher), who are using Comerio's original estimates of losses and downtimes done in 1998 as a basis for comparison. They are consulting with the research team on incorporating PEERs approach into their downtime estimates.

**Expected milestones & Deliverables**

Journal articles and loss estimating methodology to be incorporated into PEER technologies.

<b>Project Title—ID Number</b>	<i>Facilitating the Use of the PEER PBEE Methodology in Engineering Practice —1292004</i>		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	NSF
<b>Project Leader (boldface) and Other Team Members</b>	<b>Helmut Krawinkler (Stanford/F)</b> , Farzin Zareian (Stanford/GS)		

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

### Project goals and objectives

This project is a basic step of the Building Packaging/Outreach Program, whose objective it is to communicate the PEER methodology to the users and to facilitate the use of the methodology in engineering practice.

### Role of this project in supporting PEER's mission (vision)

For the next three years the PEER research program on buildings will have a focus on the following three areas:

1. benchmarking the PBEE methodology on code-conforming structures,
2. decision making based on performance, and
3. outreach and packaging the PBEE methodology.

This project addresses specifically the third area, but is closely linked also to the other two. In particular, it will take advantage of the work performed in parallel in the benchmarking effort, and of past work performed in the Van Nuys testbed study and in several related project.

### Methodology employed

We will synthesize the methods and tools developed by PEER researchers and communicate them in a format that will greatly facilitate their implementation in engineering practice.

The objectives of this project will be achieved by:

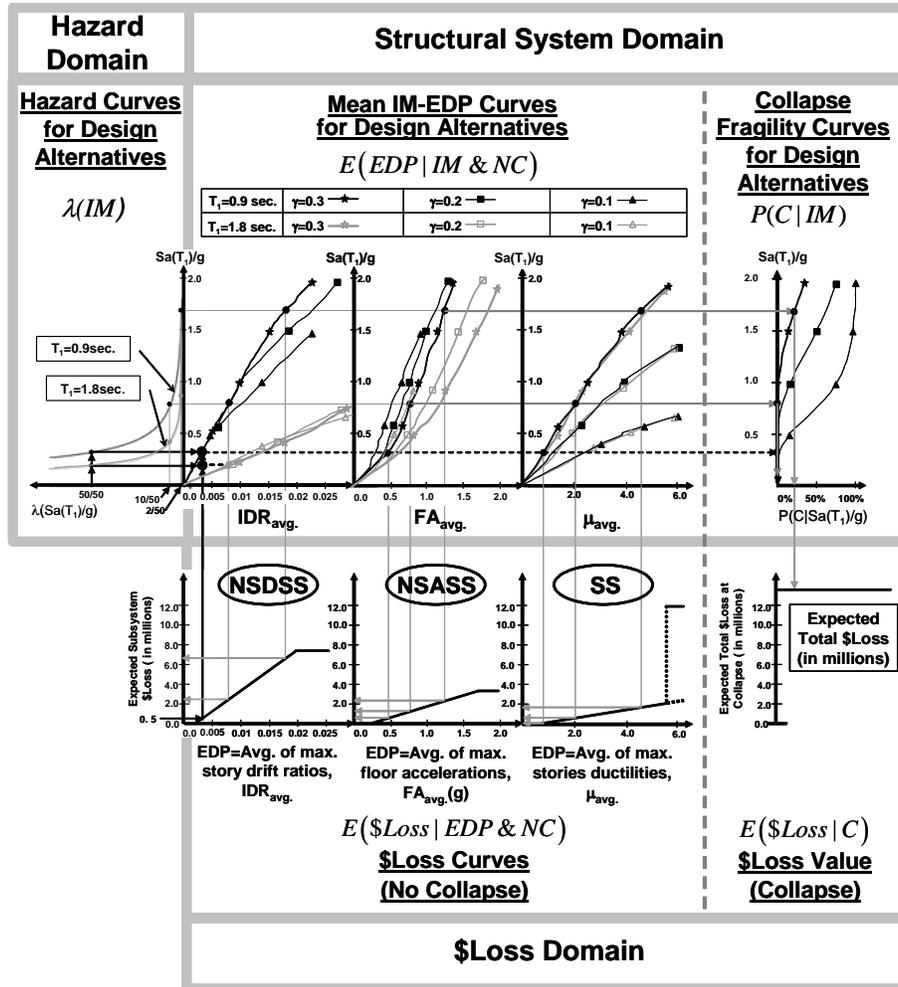
1. performing additional research on simplified approaches to performance assessment and on the development of basic criteria for performance-based design, and
2. synthesis of available research information and communication through short user-friendly documents.

A guideline document will be developed that comprises the essentials of the whole performance assessment methodology, but the additional user-oriented documents will have a focus on the domain expertise of the PI, i.e., they will emphasize the structural engineering aspects of the PBEE methodology.

### Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments

This project relies heavily on work performed during year 7 on criteria for performance-based design. Last year the concepts for performance-based design based on collapse fragility curves

and mean hazard curves, loss curves, and IM-EDP curves were developed, resulting in the 3-domain (hazard, loss, and structural system domains) graphical representation illustrated below. This graphical representation will become the foundation for more development (in this project primarily of IM-EDP curves in the structural system domain) and for communication to engineering practice and guideline writers. Emphasis will be placed on developing and communicating design and assessment criteria for acceptable mean annual losses and for a tolerable mean annual frequency of collapse. Additional emphasis will be on the development of collapse fragility curves that permit relatively simple design for collapse safety. Such curves are already available for regular and soft story moment resisting frame structures.



If these ingredients are available, effective conceptual PBD can be performed with the semi-graphical process illustrated below. The proposed process permits design decision-making based on constraints imposed by multiple performance objectives, considering trade-offs between different structural system choices and between strength, stiffness, and ductility characteristics. The proposed process also permits a consistent evaluation of the costs and benefits derived from the use of innovative technologies, such as base isolation and internal energy dissipation devices.

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

This project is closely linked with the Year 8 project on Benchmarking Performance of New RC Frame Buildings, and also to all the other year 8 projects in the Building Thrust area. Interaction is also needed with the Bridge Thrust area research projects so that the assessment methodologies pursued and documented for buildings and bridges are compatible.

Development and implementation of PBEE concepts have become a priority for research and practice in many countries, as documented in the proceedings of the International Workshop on Performance-Based Design – Concepts and Implementation, held in Bled, Slovenia, in June 2004. At this workshop it became clear that different countries are pursuing different approaches to PBEE, but that the PEER PBEE approach has matured much more than approaches pursued in other countries.

**Plans for Year 9 if this project is expected to be continued**

The process of synthesizing the PEER PBEE methodology and packaging it into a format suitable for engineering implementation will continue in Year 9.

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

The SAC (Scientific Advisory Committee) identified communication of the PEER PBEE methodology to the profession as the highest priority for the PEER Years 8 to 10 activities. This project addresses this priority and will develop documents intended to encourage adoption of PBEE in engineering practice. It is anticipated that the ATC-58 project will take advantage of the PEER methodology.

**Expected milestones & Deliverables**

The following products will be the deliverables of the Year 8 study:

- A set of “guidelines” to be followed in carrying out a performance assessment
- A document summarizing the process and data for simplified approaches to performance assessment
- A document summarizing data and criteria that can form the basis for performance-based seismic design
- Interaction with ATC-58 for consideration of the PEER methodology in code development
- Assessment of the utility of the PEER PBEE methodology for protocol development for experimentation and data collection, in the context of NEES and ATC-58

<b>Project Title—ID Number</b>	<i>Effect of modeling uncertainty in loss estimation and on financial decision variables —1302004</i>		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	NSF
<b>Project Leader (boldface) and Other Team Members</b>	<b>Eduardo Miranda (Stanford/F)</b> , Hesaam Aslani (Stanford/GS), <b>Danielle D. Dowling (Stanford/US)</b>		

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

**Project goals and objectives**

The main goal of this project is to develop knowledge and tools that will enable practicing structural engineers to conduct loss assessments of buildings using PEER’s performance-based methodology.

Specific objectives of this research are: (a) development of fragility functions for generic nonstructural components; (b) development of generic loss curves for building stories; (c) development of tools to facilitate loss estimation calculations and delivering loss information to decision makers.

**Role of this project in supporting PEER’s mission (vision)**

This project provides information and tools to facilitate loss assessment in building. It is anticipated that this project will have a major impact toward the implementation of PEERs research and technologies in practice. In particular, the loss estimation toolbox will conduct all required calculations involved in loss estimation allowing the user to fully concentrate in the data going in and out of the process, and on the identification of major sensitivities as opposed to spending time in the “mechanics” of the loss estimation. The tool will provide a way not only to produce loss assessment results but also a tool to visualize and analyze the results, and ultimately to assist decision makers make more informed decisions. The toolbox will, for example, help identify where should one start investing, or executing other risk management actions in order to reduce losses in the most effective way. The toolbox could also become a major outreach vehicle for PEER

**Methodology employed**

PEER has developed a general framework to estimate the performance of structure in future earthquakes. PEER’s approach is distinctively different from existing performance based approaches currently being used by some practicing structural engineers (e.g., FEMA 356). Namely, it provides measures of seismic performance that are directly relevant to stakeholders such as dollar losses, downtime and casualties/fatalities. Furthermore, it provides continuous variables as measures of seismic performance as opposed to discrete, and somewhat arbitrarily selected, performance levels. Another distinct feature is that it provides a fully probabilistic framework which permits the incorporation and propagation of all relevant uncertainties involved in the estimation of the ground motion, the structural response, the damage and the losses.

While PEER's methodology provides a rational way of estimating losses produced by earthquakes, concerns have been expressed in the sense that, in its present form, it cannot be easily used by practicing engineers. Hence, there is a need to develop and implement various simplifications to the methodology that will facilitate its adoption and that at the same time facilitates the visualization and interpretation of loss estimation results.

One of the main objectives of this project is the development of generic story loss functions that will permit the estimation of losses in building stories as a function of scalar Engineering Demand Parameters (EDPs) such as interstory drift ratio or peak floor acceleration. In particular, the generic loss functions will provide information on the probability that a certain dollar loss will be reached or exceeded conditioned on the structure undergoing a specific EDP level. The availability of these generic loss functions will bring many benefits some of which are:

- (a) will allow users of the methodology to have information that indicates how losses increase as the level of structural response is increasing without having to deal with fragility functions of many individual components, each having various discrete damage states and with the probability that the various individual components will reach or exceed those discrete damage states. Fragility functions and loss functions of generic components would be only internally used;
- (b) generic loss functions can be combined with simulation/analysis results providing probabilistic information of building response conditioned on the ground motion intensity (IM) to obtain loss estimates on each story of the building as a function of IM;
- (c) permit the computation of building losses conditioned on no collapse by adding losses calculated in individual stories;
- (d) will allow users to combine loss information when the building does not collapse with losses produced when the building suffers a structural collapse by having information on the probability that the building will collapse at a certain level of ground motion intensity.
- (e) will enable users to be able to quickly identify and disaggregate structural losses, nonstructural losses, drift-based losses, acceleration-based losses, influence of collapse on the losses, etc.

Previous research by the PI has indicated that correlation between losses in individual components can have a large influence on the dispersion of the loss. Information on the dispersion of the loss is needed to estimate loss curves. Therefore, this project is conducting sensitivity analyses on generic stories to develop simplified approaches to account for this correlation that will enable obtaining estimates of the dispersion of the losses in a story as a function of the level of EDP.

One of the main challenges of this research is the lack of data necessary to develop detailed fragility functions for various damage states for structural components, but particularly for nonstructural components. For this purpose this project will complement existing experimental information with building performance data of buildings (both damaged and non-damaged)

located in the vicinity of strong-motion recording sites. In this investigation structural motion based fragility functions will be developed by using simplified building models developed by the PI and his research students. The simplified building models are defined by a very small number of parameters which will be treated as non-deterministic. These models are currently being validated by comparing the displacement and acceleration response computed with the simplified model and those recorded in a very large set of buildings that are instrumented and have been subjected to various earthquake of various levels of intensity.

An important portion of this project will be devoted to the development of the PEER loss estimation toolbox. The proposed loss estimation toolbox will consist on a system that will: (i) enable users to view and modify parameters used to internally compute generic loss curves; (ii) combine generic loss curves with OpenSees simulation results or analyses results from any other structural analysis program to conduct all loss estimation calculations providing option to view intermediate results or to only view final results; (iii) conduct deaggregation to identify the ground motion intensities and type of components that are primarily contributing to losses; (iv) by means of dials and scrollbars the proposed toolbox will allow users to conduct sensitivity studies to identify changes in losses resulting from changes in any of the variables involved.

It is anticipated that the PEER loss estimation toolbox will not only provide an excellent tool for students and investigators within PEER but can become a major outreach vehicle for implementing PEER’s loss estimation methodologies

**Brief description of past year’s accomplishments and more detail on expected Year 8 accomplishments**

In prior years a fully-probabilistic building-specific loss estimation was developed. The methodology breaks the problem into four steps consisting on obtaining a probabilistic estimation of the ground motion hazard at the site through a seismic hazard analysis; obtaining a probabilistic estimation of the structural response through a seismic demand analysis; a probabilistic estimation of the damage in the structure through a fragility-function-based damage analysis and obtaining estimation of earthquake losses through a probabilistic loss analysis. This research builds on previously developed research by generating new knowledge which will allow its use through a series of simplifications. Figure 1 shows the variations of losses in a seven story RC building as ground motion intensity increases. Figure 2 illustrates that economic losses in buildings are often dominated by losses produced by damage in non-structural components.

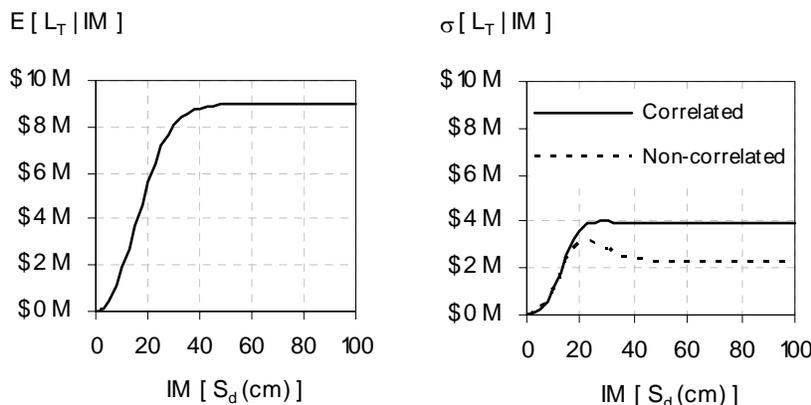


Figure 1 - (a) Expected loss at different levels of intensity, (b) dispersion of loss at different levels of intensity

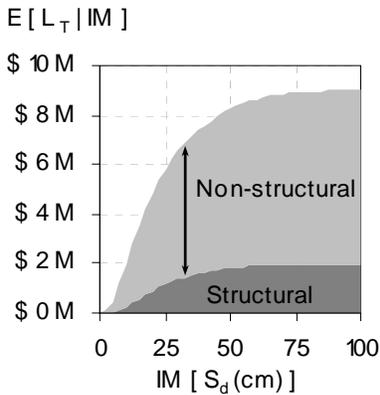


Figure 2 - Deaggregation of losses in structural and non-structural components.

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

At PEER Deierlein and Porter are conducting a benchmarking study of reinforced concrete moment-resisting frame buildings designed according to current building codes. Also at PEER Prof Krawinkler is developing preliminary design concepts using PEER's framework. This project will generate generic loss functions that could greatly facilitate the application of PEER's loss estimation methodology.

### Plans for Year 9 if this project is expected to be continued

Most of the most will be extended into year 9 (see milestones and deliverables below)

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

A simplified version of PEER's loss estimation methodology was recently adopted by two of our business industry partners (Rutherford and Chekene and Comartin and Associates) for a building in Berkeley, CA.

### Expected milestones & Deliverables

There are four major milestones in this research investigation:

- (1) Identification of the types of lateral structural resisting systems that will be considered, as well as the types of building uses and corresponding nonstructural components/systems that will be considered. Identification of the scope of the level of simplification that will be used in the project.
- (2) Development of simplified approaches of estimation of generic story loss dispersions and in particular of way of accounting for correlation between losses in individual components.
- (3) Development of structural motion-seismic performance pairs from ATC-38 and SAC datasets. This involves first modeling each of the buildings and then computing peak responses on each story. Software tools will be developed specifically for this purpose. It is anticipated that this activity will be developed during year 9.
- (4) Development, testing and calibration of the PEER loss estimation toolbox. This activity will be initiated in year 9, particularly the design of the user interface, while the rest of the development and testing will be done in year 10.

There will be three main deliverables from this investigation:

- (I) A research report and papers documenting the development of the generic story loss functions;
- (II) A database summarizing computed responses and observed seismic performance of buildings located within 1000 ft of a recording station, and corresponding structural motion-performance data points
- (III) The Excel-based PEER loss estimation toolbox

<b>Project Title—ID Number</b>	<i>IM and Ground Motion Selection for EDP Hazard Assessment</i> —1312004		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	NSF
<b>Project Leader (boldface) and Other Team Members</b>	<b>C. Allin Cornell (Stanford/F)</b> , Jack W. Baker (Stanford/GS), Molly Ziergiebel (Stanford/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 recommended IMs for various site/building cases and recommended procedures for selection and processing of ground motion accelerograms for EDP hazard assessment. The recommendations will follow from development, consideration, study, and demonstration of alternatives, including the identification of their weaknesses and strengths. Included will be both scalar and vector schemes for IMs. For example, for first-mode dominated buildings the preferred scalar may well be inelastic spectral displacement whereas an alternative for important and/or taller structures may be a vector consisting of elastic  $S_a$  coupled with spectral ratios and/or epsilon. Far and near-source situations shall be considered; the latter may require extra care and/or modified IMs. The recommended process will include record selection and processing such as scaling and/or “shaping”, recommended number and kinds of NLTA analyses, and suggested post-processing of response output. Fundamental engineering insights shall be derived by recognition of the highly inter-related issues of record selection, scaling and processing - as it relates to a specific site and structure. Structures are, in general, three-dimensional and with different natural periods in different directions. The project will address this 3-D problem and provide recommendations but in depth studies will likely require additional future work.

### Role of this project in supporting PEER’s mission (vision)

This project address the key step of coupling seismology and structural analysis, or in PEER terms the integration of IM and EDP to produce EDP hazard curves.

### Methodology employed

As discussed above the project will pull together past work and conduct new work as resources permit in order to provide a complete set of recommendations for the related problems of IM selection and record selection and processing for PEER PBEE application. Based on (1) recent progress in the "vector IM" project, on (2) the interaction both with PEER NGA and with the Beroza/Cornell NSF-US/Japan parallel efforts to produce several sets of multiple realizations of probabilistic synthetic ground motions to supplement the limited empirical set, and on (3) lessons learned from the testbed experience and PEER interactions such the session IM-EDP at the annual meeting, the following scope has been planned and is underway:

1. Develop deeper understanding of the interrelationships between: record scaling, "epsilon", and vector IMs with the objective of making final recommendations on how to deal with record selection, scaling, and (new ideas for) “pre-processing” for given IM choices and for given IM-EDP pairs. This requires a suite of representative structural models (we'll use the results from

PEER studies by Krawinkler students: Medina and Ibarra), representative sites (far and near-field), alternative IMs and EDPs (scalars and vectors).

2. Related to the above we shall seek to find a replacement for the imperfect concept of the "Uniform Hazard Spectrum" as the "target" for selecting, scaling and pre-processing records for a site. We shall address why the UHS is "wrong" for IM-EDP purposes and what should replace it. This process will draw on insights from the IM-EDP studies and especially the vector IM consisting of multiple spectral ordinates.

3. Introduction of inelastic spectral displacement in the vector IM. This will draw on parallel NSF work that has produced an attenuation law for this IM and on the vector hazard code of the SCEC co-project by Paul Somerville. This IM promises to improve both the far- and near-field cases.

4. Consider different record selection strategies and their implications with respect IM, IM-EDP, and EDP hazard accuracy and confidence band width. Make recommendations for the preferred approach. Example record selection strategies: random from a catalogue; best current practice based on the "M-R-bar" scenario from disaggregation of the Sa PSHA (e.g., the Somerville set for the testbeds); "M,-R-Epsilon-bar" scenario (which we proposed and Jonathan Stewart has implemented for the benchmarking project; multi-scenarios; near-far source scenarios (with/without "forward directivity pulses"); fully and "partially" (and narrowly) "spectrum compatiblized" records.

5. Develop a set of parallel options for the 3-D building. There has been very little IM-EDP work in this area (Bazzurro, Carballo, Wen, McCrae are limited examples – none for PEER). There is some fundamental thinking necessary followed by testing. Unfortunately there will be too few resources to do that well given, for example, the lack of PEER efforts, element models, analyses, etc. with 3D structural models. We shall test the proposals first on simple nonlinear oscillators with two degrees of freedom (XX, YY), and follow with as much as time permits.

6. Set down direct recommendations. These will likely take the form of a "simpler" and a "better" IM option for each of several site-structure combinations as mentioned in the objectives with a discussion of the pros and cons. Record selection via "scenario" plus IM-based scaling and/or pre-processing will possibly be the two options for this step. Finally there will suggestions for one or two options for the NLTA's (e.g., IDA vs. stripes) and post-processing (smoothing, medians, treatment collapses, etc.) based on Jalayer's past PEER work plus recent vector extensions by Baker. The recommendations will be backed by discussions of the pros and cons.

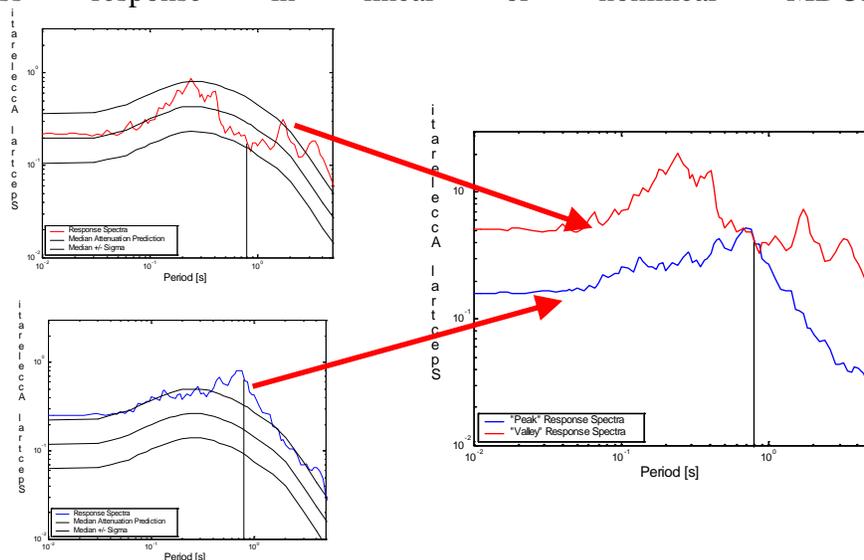
#### **Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments**

The last year and the beginning of this year have produced important new insights into the questions addressed. Perhaps the single most visible is the role of "epsilon" as an effective measure in the prediction of structural response. As shown in the figure records with high values of epsilon, as are associated with current, rare design basis spectral accelerations, are also associated with peaks in response spectra and hence comparatively weak nonlinear response. (The reverse is true for negative epsilon records.) Coupled with (first-mode-period) spectral

acceleration epsilon one has a vector IM that is both readily available in a PSHA sense (via conventional deaggregation results) and is effective in reducing both bias and variability that are identified in current recommendations. Further we have recently shown that with the addition of epsilon there is less sensitivity to magnitude and scaling implying that record selection and processing are simplified and improved. A paper has been accepted for publication in EESD describing this work.

Parallel studies are underway for inelastic spectral acceleration as an IM as proposed by N. Luco under the US-Japan project. It too greatly improves magnitude insensitivity and scaling bias and hence record selection and processing. Finally two papers have been submitted for publication, one relating to an issue associated with how the two horizontal components are currently treated in hazard and response coupling (with preliminary recommendations for 3D structures) and one providing an exhaustive set of spectral acceleration correlation results for all three components and all period pairs. These will be essential in future efforts to improve vector IMs and will be incorporated in the vector PSHA software under development in a companion SCEC project under Paul Somerville.

Figure 1 The left-hand side shows two natural records' spectra relative to a conventional attenuation law prediction (median plus/minus one-sigma). For 0.8 second (the natural period of the PEER testbed structure under study), the lower case has a peak and a positive epsilon (defined as the number of sigmas by which it deviates from the median predicted value). The upper case is a negative sigma record. When scaled to the same spectral acceleration at 0.8 seconds, as we have recommended for PEER practice, as shown in the right-hand side, one positive epsilon record has lower spectral ordinates everywhere else and hence is expected to cause less response in linear or nonlinear MDOF structures.



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

Although many researchers inside and outside PEER are now studying IMs, the connections between IM, record selection, and processing are not being made elsewhere to our knowledge.

**Plans for Year 9 if this project is expected to be continued**

Incorporate new NGA work especially as relates to near-source issues. Put additional effort into 3D structural issues. Focus the efforts on very severe response (local and global collapse regime), especially on global collapse capacity as represented by different IM's.

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

The Yucca Mountain High-Level Waste Repository is using the IM-EDP scheme developed for PEER and has made IM studies to help select the best choice.

**Expected milestones & Deliverables**

End of Year: recommendations, a major report, and a set of papers.

<b>Project Title—ID Number</b>	<i>The Impact of Modeling Uncertainty and Improved Cost Estimates on PBEE Decisions —1322004</i>		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	NSF
<b>Project Leader (boldface) and Other Team Members</b>	<b>Ufuk Ince (UW/F)</b>		

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

### Project goals and objectives

This project continues the work in the critical area of bridging the gap between engineering analysis of seismic risk and the ultimate decision maker who is often not an engineer and is increasingly attuned to financial performance metrics rather than engineering performance measures. Building on a decision making template that outlined the trade off between purely financial performance levels and the corresponding death and downtime estimates, I refine and extend the decision making framework in two critical directions: 1.) Examine the impact of modeling uncertainty on the decision outcome, 2.) Improve cost estimation in three areas of the financial analysis.

### Role of this project in supporting PEER's mission (vision)

This project directly supports PEER's mission of improving seismic decision making by laying out the choice of performance goals and trade offs.

### Methodology employed

Modeling and simulating the financial outcomes of various performance levels using investment decision tools frequently utilized by business decision makers.

### Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments

In the previous years, we outlined a prototype decision making template across three decision variables: death, downtime, and damage. In the current extension, this template is improved by using actual cost estimates for investments that will lead to desired levels of performance.

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

I am currently developing an NSF proposal that examines the role of behavioral characteristics of business decisions makers on their seismic risk mitigation choices. This project focuses on the financial analysis and the resulting seismic mitigation decisions for a single structure as opposed to working with a large sample of businesses. Also, this project does not focus on behavioral characteristics. Instead it assumes a risk-neutral decision maker that cares about monetary outcomes for the most part.

**Plans for Year 9 if this project is expected to be continued**

Future extensions could include further refinement in estimating financial implications of PBEE decision making. One of the impediments of PBEE adoption appears to be the cost of PBEE analysis such as engineering fees and related downtime. It would make sense to explicitly factor in these costs in the financial analysis of PBEE decisions. Another such improvement could be in the area of post-earthquake downtime estimation in terms of dollars rather than number of days.

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

N/A

**Expected milestones & Deliverables**

Improved retrofit cost estimation: March 2005. Improved and refined modeling and simulation results: August 2005. During the remaining time, until October 2005, results will be integrated and written as one or more papers/reports.

<b>Project Title—ID Number</b>	<i>Societal Implications of Performance-Based Earthquake Engineering</i> —1332004		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	NSF
<b>Project Leader (boldface) and Other Team Members</b>	<b>Peter May (UW/F)</b> , Chris Koski (UW/GS), Josh Sapotichne (UW/GS)		

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

### Project goals and objectives

Characterize the societal implications of the use of performance-based approaches to regulation with particular attention to PBEE:

- Characterize the societal benefits and costs of this shift with particular attention to PBEE;
- Draw implications for efforts to implement PBEE methodologies with respect to potential societal benefits and costs.

### Role of this project in supporting PEER's mission (vision)

This project fits into the PEER agenda of understanding the payoffs of PEER's efforts. In particular, this research seeks to move beyond the generalities provided to date in various commentaries about the potential impacts of PBEE.

### Methodology employed

- Categorizing what has been claimed about benefits of PBEE.
- Consideration of relevant stakeholders and potential impacts.
- Consideration of parallel efforts (e.g., "green buildings") and how technologies were converted into broader societal benefits.
- Casting all of this within a framework for understanding societal implications (e.g., value of information)

### Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments

This research extends research undertaken during year 6 and 7 on the "Regulatory System Implications of Performance Based Approaches." That research led to insights about performance-based regulatory frameworks that were included in a number of articles and conference presentations.

At issue for the current (year 8) research are the implications beyond regulatory frameworks. A diversity of expectations about the regulatory (and other) benefits of performance-based approaches have been set forth in the literature as summarized in the following table. As indicated above, the year 8 research will extend this analysis to consider more than regulatory implications of the performance-based approach. At a minimum, this research will provide a more systematic basis for discussing the societal implications of greater use of PBEE. This

research will also consider the societal implications of different choices that are made to disseminate and implement PBEE.

**Expectations for Performance-Based Regulatory Regimes.**

Criterion	Expectation <sup>a</sup>
<ul style="list-style-type: none"> <li>• <u>Effectiveness</u> in Reaching Regulatory Objectives</li> </ul>	<ul style="list-style-type: none"> <li>• <u>Increased</u>, but limited incentive to go beyond minimum performance objectives (Coglianese &amp; Lazar 2003 Gunningham &amp; Johnstone 1999).</li> </ul>
<ul style="list-style-type: none"> <li>• <u>Flexibility</u> in Means of Adhering to Regulation</li> </ul>	<ul style="list-style-type: none"> <li>• <u>Increased</u>, given ability to use alternate means to reach objectives (Project on Alternative Regulatory Approaches 1981 among others).</li> </ul>
<ul style="list-style-type: none"> <li>• <u>Innovation</u> Potential</li> </ul>	<ul style="list-style-type: none"> <li>• <u>Increased</u> incentives for innovation, but depends on industry structure and cost of innovation compared with current approaches (U.S. Congress. OTA 1995).</li> </ul>
<ul style="list-style-type: none"> <li>• <u>Consistency</u> in Application of Rules</li> </ul>	<ul style="list-style-type: none"> <li>• <u>Potential for inconsistencies</u> in interpretation of what is acceptable for which the standards and skills of inspectors are important (Gunningham &amp; Johnstone 1999).</li> </ul>
<ul style="list-style-type: none"> <li>• <u>Predictability</u> in Regulatory Expectations</li> </ul>	<ul style="list-style-type: none"> <li>• <u>May decrease</u> due to lack of understanding of what is a workable means for achieving desired ends; code of practice guidelines are useful in this respect (Foliente 2000; Gunningham &amp; Johnstone 1999).</li> </ul>
<ul style="list-style-type: none"> <li>• <u>Cost to:</u> <ul style="list-style-type: none"> <li>• <u>Government Regulators</u></li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• <u>Uncertain</u> -- Greater costs of developing rules and enforcement (U.S. Congress. OTA 1995; Project on Alternative Regulatory Approaches 1981), but not necessarily so for costs of developing rules (Gunningham &amp; Johnstone 1999).</li> </ul>
<ul style="list-style-type: none"> <li>• <u>Regulated Entities</u></li> </ul>	<ul style="list-style-type: none"> <li>• <u>Decreased or no change</u> in compliance costs (Project on Alternative Regulatory Approaches 1981), but some entities may choose to develop more costly alternative approaches (Coglianese, Nash &amp; Olmstead 2002).</li> </ul>
<ul style="list-style-type: none"> <li>• <u>Public Beneficiaries of Regulation</u></li> </ul>	<ul style="list-style-type: none"> <li>• <u>Decreased or no change</u> – not explicitly addressed in the literature; presumably benefit from lower costs to regulated entities and innovations spurred by performance-based approach.</li> </ul>
<ul style="list-style-type: none"> <li>• <u>Distributive Impacts</u> in Addressing Regulated Harms</li> </ul>	<ul style="list-style-type: none"> <li>• <u>Mixed</u> – Focuses attention on a given harm no matter where it is, but leaves potential for gaps in coverage of attention to that harm if performance is gauged on an area-wide basis through “hot spots” (U.S. Congress. OTA 1995).</li> </ul>
<ul style="list-style-type: none"> <li>• <u>Equity</u> in Treatment of Regulated Entities</li> </ul>	<ul style="list-style-type: none"> <li>• <u>Uncertain</u> -- Competitive differences may emerge due to large firms having advantage in developing alternative</li> </ul>

approaches (Project on Alternative Regulatory Approaches 1981) for heterogeneous industry. How rules are enforced will also affect equity.

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

The societal implications of performance-based regulation is topic of much interest to three groups:

1. International Council for Research and Innovation in Building and Construction (CIB) Task Group 37 addressing “Performance and Building Controls,”
2. the Inter-Jurisdictional Regulatory Collaboration Committee (IRCC) comprised of building regulatory officials from eight countries, and
3. the ATC 58 project on performance-based seismic design. The PI will continue to be involved with these forums, thereby providing important outlets for the proposed PEER research.

To date, these forums have only addressed societal implications of PBEE in general ways.

There is no specific dependency of this research on other PEER projects. This research relates to on-going research at MCEER addressing “societal resilience” and to on-going research at MAE addressing “societal consequences.” The PI for the PEER research will continue to maintain regular contact with relevant PIs working on these topics at MCEER and MAE.

**Plans for Year 9 if this project is expected to be continued**

It is anticipated that this project will continue into year 9. That extension will likely entail more detailed quantification, if possible, of costs and benefits. The feasibility of this, however, depends on the framework devised as part of the planned year 8 research.

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

None

**Expected milestones & Deliverables**

This is a new project that builds upon the research undertaken during years 6/7 addressing the regulatory system implications of performance-based approaches. The anticipated products from this research are a journal article about societal implications and a PEER technical research report.

The key milestones are as follows (revised due to late funding of the project):

- |                |   |
|----------------|---|
| March 15, 2005 | Review of existing commentary about potential societal implications of PBEE and performance-based regulation more generally.    |
| June 15, 2005  | Consideration of stakeholders for PBEE and related approaches with investigation of parallel examples of societal implications. |

Sept 30, 2005      Draw implications for efforts to implement PBEE methodologies with respect to potential societal benefits and costs.      Consideration of year 9 research directions.

<b>Project Title—ID Number</b>	<i>Implementation SFSI and Site Effect Models in PEER Methodology —1342004</i>		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	NSF
<b>Project Leader (boldface) and Other Team Members</b>	<b>Jonathan Stewart (UCLA/F)</b> , Ertugrul Taciroglu (UCLA/F), Christine Goulet (UCLA/GS), Edward H. Field (USGS/I), Caroline Wang (UCLA/US)		

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

### Project goals and objectives

Research conducted in Year 7 by the PI's identified several critical "gaps" within the PEER methodology with respect to the implementation of models for site effects and soil-foundation-structure interaction (SFSI) effects. The goal of Year 8 work is to fill three specific gaps related to the following subjects:

1. Utilization of site effect models within probabilistic seismic hazard analyses
2. Evaluation of seismic demand at the foundation level of structures given either a time history or response spectral representation of free-field demand
3. Improvement of spring and dashpot models representing the stiffness and damping of foundation-soil interaction

In Task 1 (site effect models), we are implementing the results of previous research on site effects (developed in the PEER Lifelines program and in Year 2-3 and 5-6 Core program research) into a modular, web-based, seismic hazard analysis platform being developed by the Southern California Earthquake Center (SCEC). This platform is known as OpenSHA (<http://www.opensha.org/>). The models that would be implemented describe site amplification as a function of shallow site descriptors (surface geology,  $V_{s-30}$ , etc.) and deep basin structure. Recommendations for incorporating site-specific ground response analyses into seismic hazard calculations would also be provided. By implementing those research results in OpenSHA, improved representations of site hazard will be possible, which will affect uniform hazard spectral ordinates and the epistemic uncertainty in the site hazard. Dr. Edward Field, who is the PI of the OpenSHA project for SCEC, has agreed to work with us at no cost on the implementation of the models and recommendations.

In Task 2 (foundation level seismic demand), we will fill an important gap in the specification of seismic demand for building structures. Existing models enable the evaluation of transfer function amplitudes representing (approximately) the ratio of the Fourier amplitude of foundation-level motions to free-field motions. Those models are functions of foundation size, frequency, and soil stiffness, and enable the estimation of Fourier amplitudes of foundation-level motions. There are two significant shortcomings to the existing models:

1. no guidance is currently available on the specification of Fourier phase, which precludes rigorous analysis of foundation-level time histories, and
2. existing guidelines on ratios of response spectra (RRS) for foundation/free-field motions, shown in Figure 1, are based on an assumption of zero phase shift and a limited investigation of the relationship between RRS and transfer function amplitude for zero phase shift.

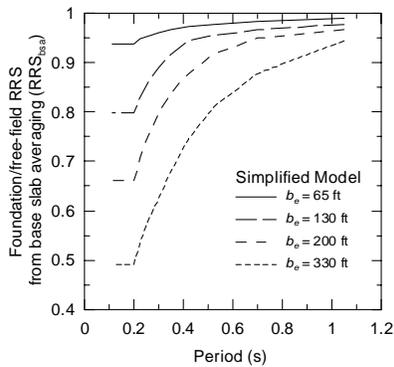


Figure 1- RRS guidelines proposed in FEMA-440 (2005)

In Task 3 (spring/dashpot models), we propose to work with Tara Hutchinson on several specific improvements that we feel are needed with the spring/dashpot models being developed for implementation in OpenSees. Specifically, we seek to enable coupling of the vertical and horizontal responses of shallow foundations and to develop frequency-dependent foundation stiffness/damping formulations for use in time history analyses.

#### Role of this project in supporting PEER's mission (vision)

This work will help enable implementation of the PEER methodology including the effects of site condition on ground motion, the effects of kinematic soil-structure interaction on seismic demand, and the effects of inertial soil-structure interaction on building response.

#### Methodology employed

Following the task list provided above, the following work is being undertaken:

**Task 1:** Working with Ned Field, we are programming Java applets for integration into the OpenSHA software. One applet will calculate the site hazard based on a  $V_{s-30}$ -based characterization of site condition. Another will use both  $V_{s-30}$  and basin parameters (basin depth and location of source with respect to basin). Others that may be considered will utilize NEHRP, Geotechnical, or surface geology site categories.

**Task 2:** For the phase shift/RRS issue, we are evaluating phase differences between foundation and free-field motions. We will attempt to identify frequency bands with small phase shift (typically low frequencies) and frequency bands with arbitrary phase shift (typically large frequencies), and the boundary frequencies separating those bands. Based on those observations, we will attempt to develop guidelines for evaluating foundation/free-field phase differences. Then, for a specified transfer function amplitude and the phase shift guidelines, we will utilize a large suite of recorded, free-field time histories to calculate compatible time histories for the foundation motion. We will then evaluate ratios of response spectra (RRS) for the foundation/free-field time histories. Based on previous experience documented in the FEMA-440 report, for some time histories we expect RRS to follow the transfer function amplitude up to frequencies as high as about 5 to 10 Hz. For others, RRS will be nearly unity regardless of period. We will attempt to relate the RRS/transfer function ratio to ground motion characteristics such as mean period as well as relevant site/source characteristics. Engineering models will be provided to estimate RRS given transfer function ordinates and the relevant ground motion/site/source characteristics.

**Task 3:** We are enhancing the existing macro-element (Winkler) models for shallow foundations. This effort is building upon analytical and experimental studies by Hutchinson et al. (PEER-2272002), and Kutter et al. (PEER-2262002). The enhanced model will incorporate the inherent coupling between the horizontal and vertical responses of shallow foundations. In particular, the model will properly simulate the lateral resistance as the foundation comes in and

out of contact with the soil due to vertical deformations. Our aim is to simulate this coupling from basic principles and avoid non-physical parametric approaches. Simulations with continuum finite element models will aid this development. We will validate and calibrate the model using available test data.

There are quite a number of analytically derived, frequency-dependent models of stiffness and damping for shallow foundations of various geometries, on layered soils. However, in their frequency-dependent form, these formulations cannot be readily used in nonlinear time-history analyses. We are investigating an iterative method based on least-squares approximations of the frequency dependent foundation stiffness and damping in the time-domain. Temporal variation of the stiffness and damping will be taken into account by considering windows of the time-history with sizes appropriately small to preserve accuracy.

#### **Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments**

Working in a collaborative group that includes researchers from Caltech and Stanford, we provided the IM characterization (hazard analysis and time history selection) for a hypothetical structure being considered in a benchmarking effort. The time history selection took into consideration the factors of magnitude, distance, site condition, and near-fault condition (or lack thereof), but also took into consideration a number of innovative features including:

1. the  $\varepsilon$  of the time histories, where  $\varepsilon$  is a measure of the extent to which the spectral ordinates from the time histories are unusual for their magnitude/distance and
2. the two-dimensional nature of horizontal ground motions, for use in 2D and 3D seismic response analyses of the benchmark structure.

We have also implemented soil spring and dashpot elements for the benchmark structure and have investigated the effect of soil parameter uncertainty on the median and standard deviation of EDPs.

#### **Other similar work being conducted within and outside PEER and how this project differs**

- The Task 1 work is synergistic with the OpenSHA model development being undertaken by SCEC and USGS. The proposed work complements that effort by implementing state-of-the-art site models into the platform.
- The Task 2 work is a follow-on to PI Stewart's previous participation in the ATC-55 project.
- The Task 3b work is an extension of previous work by E. Safak at the USGS. We will consult with Dr. Safak as we carry out this work.

#### **Plans for Year 9 if this project is expected to be continued**

A portion of Year 9 will likely be needed to complete Tasks 2 and 3. We also hope to implement the new models in additional benchmarking efforts in Years 9 and 10.

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

Not applicable

**Expected milestones & Deliverables**

- Posting of Applets to OpenSHA web page, with notification given to PEER for potential inclusion in *The PEER Review* newsletter.
- Development and dissemination of RRS and phase shift guidelines
- Development and validation of enhancements to existing spring models; implementation and documentation of these in OpenSees.
- Development of methods that enable the use of existing frequency-dependent foundation stiffness and damping formulations in nonlinear time-history analyses. Implementation and documentation in OpenSees.

<b>Project Title—ID Number</b>	<i>Performance of Shallow Foundations</i> — <b>1352004</b>		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	NSF
<b>Project Leader (boldface) and Other Team Members</b>	<b>Tara Hutchinson (UCI/F)</b> , Prishati Raychowdhury (UCI/GS) Barbara Chang (UCI/GS)		

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

### Project goals and objectives

Soil foundation interaction associated with heavily loaded shear walls during large seismic events may produce highly nonlinear behavior. Geotechnical components of the foundation are known to have a significant effect on the building response to seismic shaking. The nonlinearity of the soil may act as an energy dissipation mechanism, potentially reducing shaking demands exerted on the building. This nonlinearity, however, may result in permanent deformations that also cause damage to the building.

The goals of PEER researchers on this topic are to develop and test procedures to account for the foundation nonlinearity in performance based earthquake engineering. The primary goal of the research at UCI is to produce and test procedures for modeling shallow foundation nonlinearity using a beam-on-nonlinear-Winkler mesh (springs, dashpots and gap elements) to capture cyclic rocking, sliding, and vertical displacements. These procedures are being evaluated against centrifuge and one-g scale experimental data. A second goal of the UCI study is to test the effects of this foundation nonlinearity on structural systems, such as frame and shearwall systems.

### Role of this project in supporting PEER's mission (vision)

This project supports the PEER strategic plan by providing performance data, validation tests, and nonlinear models to advance the simulation capabilities of OpenSEES. In addition, understanding the behavior of shallow foundations is critical to development of performance based design procedures for buildings.

### Methodology employed

Our approach has been to use a Beam-on-Nonlinear-Winkler (BNWF) framework (e.g. using spring, dashpot, and gap elements) for modeling the nonlinear soil response. This allows us to capture the salient features of the rocking foundation, including distributed soil nonlinearity and uplifting of the foundation. The intent of subgrade type modeling has always been to strike a balance between theoretically more rigorous solutions and practicality and ease of use in routine geotechnical engineering practice. Therefore, the approach of using the BNWF model is directly applicable to many practical applications. Complementary numerical modeling is being conducted at UC Davis using a plasticity based 'macro-element' representation.

**Brief description of past year’s accomplishments and more detail on expected Year 8 accomplishments**

During the 7 research program, we worked closely with UCD and USC researchers using a broad range of shallow foundation experimental data sets to evaluate a Winkler-based modeling approach for capturing their cyclic rocking response. Experimental datasets used included those by Rosebrook and Kutter (2001), Gajan et al. (2002), ELSA (one-g) data, and New Zealand (one-g) (Bartlett and Weissing). Parameters were evaluated in terms of their ability to capture the moment-rotation, rotation-settlement response, lateral force-sliding response and energy dissipation.

During year 7, we also focused significant time on the design of a model frame-shearwall structure, which was tested at the end of year 7 on the UCD centrifuge. The model frame-shearwall structure was analyzed using a 2D representation within OpenSEES (Figure 1). Centrifuge tests consisted of two different types of structural systems, (i) a one bay frame and shearwall, and (ii) a two bay frame and shearwall (similar to Figure 1). Specimens were subjected to inertial-based slow cyclic loading, and dynamic base shaking using sinusoidal motions as well as earthquake motions. Photographs and preliminary results from these experiments are shown in Figure 2. Both systems observed significant ductility, attributed to both the fuse structural joints and the soil-foundation rocking allowed below the wall footing. During year 8, we are also working on implementing the Winkler spring generator (previously coded in TCL/tk by Harden), into C++. The base code for generating single springs properties is complete, and we are now working on the variable spring properties along the length of a typical footing. We plan to complete this implementation, for rocking wall footing spring models by the end of year 8 and prepare documented example uses of the code.

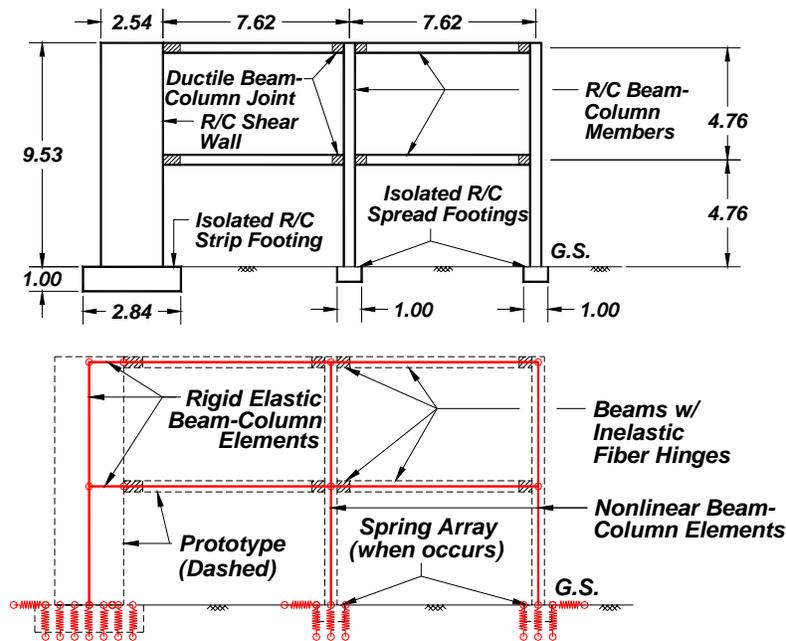


Figure 1 - Prototype frame-wall structure designed for centrifuge testing: (top) schematic and (bottom) idealized FE model.

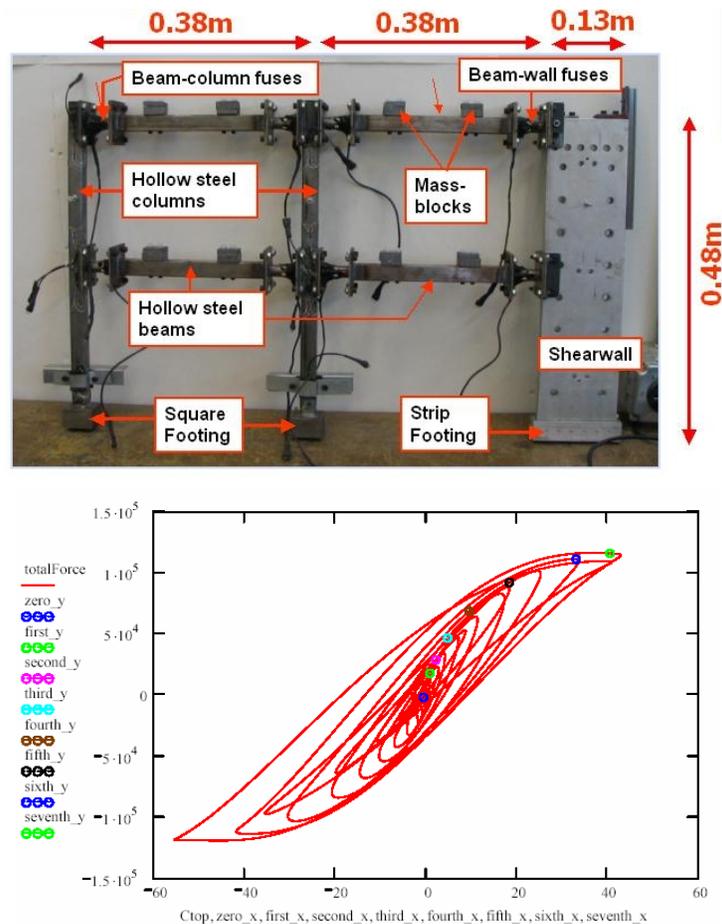


Figure 2 - (top) Schematic of two-bay frame-shearwall specimen ( $N=20$ ) and (bottom) preliminary force displacement response of the one-bay frame-shearwall model, under a dynamic base input cosine loading.

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

Within PEER, this work is closely coordinated with work by USC (Martin) and UCD (Kutter) and UCLA (Stewart). Work conducted at UCD includes providing experimental data and guidance for use of the data in analytical modeling. In addition, UCD is developing a complementary macro-element model. Work conducted at USC involves the oversight and integration of work performed at UCD and UCI. Work performed at USC also includes interfacing with practicing engineers in the US and Europe involved in implementation of nonlinear SSI into seismic design guidelines or codes. There also useful related work on this topic being conducted in France, Italy, and England. Work at UCLA involves extending the spring models and integrating the foundation modeling into the PEER PBEE framework.

Our numerical studies on this topic will be unique in that most studies either include nonlinearity of soil elements, or nonlinearity of structural components of the system. Both the testing and numerical simulations incorporate these two contributions and study system response.

**Plans for Year 9 if this project is expected to be continued**

1. Based on the centrifuge test results and accuracy of the model frame-shearwall structure, we expect further numerical modeling will be warranted. Once the numerical model is evaluated against centrifuge results, we would like to conduct additional parametric studies, using a suite of ground motions, and a broader range of structural and footing configurations, engaging different levels of inelastic behavior.
2. These results should be compared to current design practice for estimating inelastic displacement demands (e.g. FEMA 356/273, ICB 2003, ATC-40). These comparisons would help answer the question - how accurate are these simplified procedures when rocking is allowed at the foundation? Furthermore, the incompatibility of stiffness of the combined structural system (frame and shearwall) and particularly high FSv shearwalls, results in difficulties when using simple design methods (e.g. at the connection between the two systems).
3. The ultimate goal of this collaborative project is to provide PBEE recommendations for shallow foundations; this means that soil and structural uncertainty studies need to be conducted across a broad parameter space. Using soil property variability information (e.g. in provided in the study of Jones et al., 2002, PEER report 2002/16), foundation input parameters for use in the PEER methodology, considering the variability and distribution would provide valuable for researchers exercising the PEER methodology. For this study, these could be provided in the context of Winkler-based parameters (stiffness, strength, etc.), and determined using Monte Carlo simulations using the reliability toolbox in OpenSEES. This could easily be extended to deep foundations, using p-y springs.

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

Although we have consulted frequently with our project partner, Mark Moore, we are unaware of instances in practice where results are directly applied.

**Expected milestones & Deliverables**

We anticipate finalizing the data report on the model frame-shearwall structure in Spring 2005, with colleagues at UC Davis. We can then produce comparative experimental-numerical simulation results, considering the designed model with coupled nonlinear structure and nonlinear soil behavior over summer.

We also plan to complete the Winkler mesh generator implementation in C++ by the end of summer. During the Fall, we will prepare case examples using the code, and work to assure it is implemented in OpenSEES.

Regarding reporting of project results, so far we have completed: one synopsis paper for PEER, one status report (PEER report), one MS thesis (Harden 2003), a SEAOC conference paper and follow-on journal article (to Earthquake Spectra), and two joint papers with UCD/USC colleagues (to Soil Dynamics and Earthquake Engineering).

<b>Project Title—ID Number</b>	<i>Performance of Shallow Foundations</i> — <b>1352004</b>		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	NSF
<b>Project Leader (boldface) and Other Team Members</b>	<b>Bruce Kutter (UCD/F)</b> , Sivapalan Gajan (UCD/GS), Jeremy Thomas (UCD/GS), Jose Ugalde (UCD/US), Christopher Shibel (UCD/US)		

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

### Project goals and objectives

Soil foundation interaction associated with heavily loaded shear walls during large seismic events may produce highly nonlinear behavior. Geotechnical components of the foundation are known to have a significant effect on the building response to seismic shaking. The nonlinearity of the soil may act as an energy dissipation mechanism, potentially reducing shaking demands exerted on the building. This nonlinearity, however, may result in permanent deformations that also cause damage to the building.

The goals of this research are to develop and test procedures to account for the foundation nonlinearity in performance based earthquake engineering. The primary goal of the research at UC 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. A second goal of the researchers at Davis is to develop a coupled macro-element "constitutive model" to simulate the cyclic rotation, sliding, and settlement of a shallow foundation subject to combined moment, shear and axial loading.

The specific goals of this project in year 8 are:

1. To summarize basic and general procedures and guidelines for Engineers to account for foundation nonlinearity in performance based design.
2. To summarize centrifuge test data and the effects of various parameters on the performance of shallow foundations
3. To provide verified and calibrated capability (macro-element constitutive model) in OpenSEES to model the nonlinear behavior of shallow footings that are loaded into the nonlinear range.

### Role of this project in supporting PEER's mission (vision)

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 with particular focus on foundations for shear walls in non-ductile concrete frame buildings. This project directly supports the overall theme of performance based earthquake engineering. As the project also involves development of new elements for the OpenSees platform, it also supports that aspect of the PEER mission.

### Methodology employed

Centrifuge models of shear wall-foundation systems and frame-shear wall-foundation systems

are being tested in the 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 different heights above the foundation to provide different moment to shear load ratios as shown in the following figure. In other tests, model buildings are subject to base shaking using the shaking table mounted on the centrifuge. The data is being used to test, calibrate, and develop material models and new elements for OpenSees that will enable numerical simulation of nonlinear Soil-Structure Interaction. Results from each container are being posted at <http://cgm.engr.ucdavis.edu> for use by collaborators and others. The results are shared with other PEER researchers at UC Irvine, USC, and are available to other researchers.

#### Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments

The behavior of the wall-footing-soil system is analyzed in terms of the resultant of the vertical, horizontal, and moment load acting at the center of the base of the footing and the corresponding displacements (settlement, sliding and rotation). Fig. 1 shows the behavior of footing-soil interface for one test. The moment-rotation behavior is highly nonlinear and indicates a large amount of energy dissipation. Rocking of the footing progressively rounds the foundation soil, and this rounding causes a reduction in contact area between the footing and soil thereby causing a nonlinearity and stiffness reduction on the moment-rotation relationship. Permanent deformations beneath footing continue to accumulate with the number of cycles of loading, though the rate of accumulation of settlement decreases as the footing embeds itself.

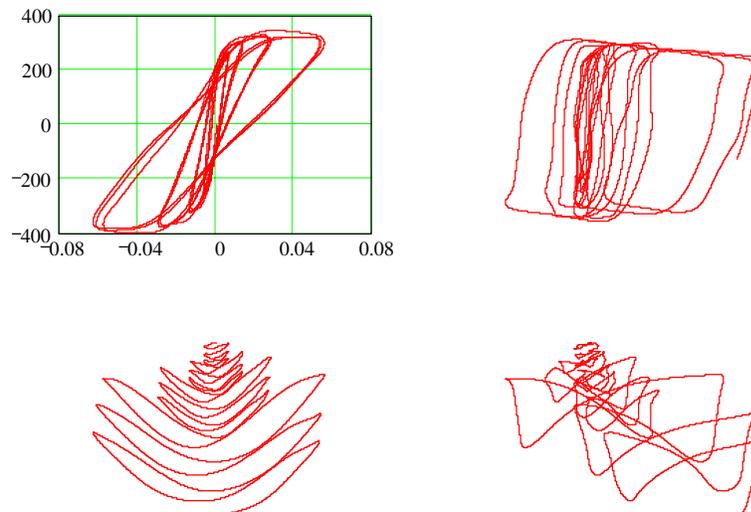


Figure - 1 Slow cyclic lateral push test; sand ( $D_r = 80\%$ ), footing length = 2.84 m, width = 0.65 m, embedment = 0.0m,  $FS = 6.7$ , lateral load height = 4.6m (forces and displacements are at the base center point of the footing)

Figure - 2. Schematic illustrating a range in possible behaviors for a shallow foundation subject to rotational loading. Curve 1 corresponds to a rigid foundation, Curve 2 to a footing that is on the verge of bearing capacity failure, and Curve 3 is for a footing with a factor of safety against bearing failure of about 4. Curve 1 results in cyclic uplift, Curve 3 results in excessive settlement, and Curve 2 shows reduced settlement per cycle and large hysteretic energy dissipation.

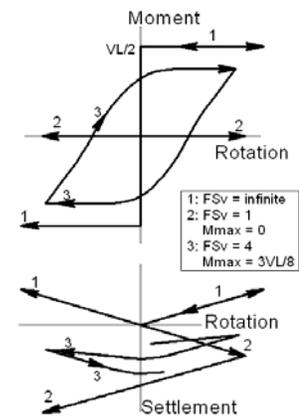


Figure 2 is a cartoon that illustrates the significant effect of factor of safety against bearing failure (FSv) on settlement, uplift and energy dissipation. In year 8 we are extending the parametric study to include footings of different shape and footings in intermediate soil types. We also performed a new unique model test of a soil-footing-shearwall-moment frame system on the centrifuge. This provides unique system level data that should enable direct observation of how footing behavior is propagated into demand on the building structure. Figure 3 shows a picture of a two-bay two story frame tested cyclically and dynamically in the centrifuge along with three UC Irvine PEER researchers.



Figure 3 - Moment frame – shear wall – foundation model, Prishati Raychowd, Tara Hutchinson, Barbara Chang (left to right). (Higher resolution photo available upon request.)

The contact element (macro model) has been successfully implemented in Opensees. It is verified that it works in Opensees for element level tests and a rigid shear wall supported by shallow foundation for moment loading. An improvement in the model, important for footings that slide and rock will be implemented in Opensees and the model is going to be used to simulate the behavior observed in the experiments for moment frame-shear wall – footing models.

**Other similar 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). Parametric studies will consider moment resisting frame (MRF) structures as well as coupled structural systems (MRF's and shear walls combined).

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.

A new project at UCLA (Jonathan Stewart, PI) is attempting to use the findings and developments at Davis and Irvine and implementing them in the context of performance based engineering.

**Plans for Year 9 if this project is expected to be continued**

Extend testing program to include different footing systems and geometries as needed to facilitate completion of the PEER mission. Document the software or increase capabilities of the material models and elements as necessary.

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

We have held a workshop in which we have discussed our results with several structural and geotechnical practicing engineers. Thus the results have been used to clarify the issues and mechanisms which require attention.

**Expected milestones & Deliverables**

1. One Masters thesis (June 2005) – Jeremy Thomas
2. One PhD thesis (June 2005) – Sivapalan Gajan
3. Final project summary report to PEER (Sept. 2005)

<b>Project Title—ID Number</b>	<i>Loss Modeling for Downtime, Deaths and Decision-Making — 1362004</i>		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	NSF
<b>Project Leader (boldface) and Other Team Members</b>	<b>James Beck (Caltech/F)</b> , Judith Mitrani-Reiser (Caltech/GS) Keith Porter (Caltech/F)		

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

### Project goals and objectives

The main goal of this work is to close the gaps that exist in the loss estimation module of the PEER performance-based earthquake engineering methodology. We would like to narrow, and eventually close these gaps in order to complete and package the PEER methodology. In support of this goal, we have the following more specific objectives:

- (a) coordinate a transfer of the EDP-to-DV Matlab toolbox, developed in our Year 7 benchmarking project, to Deierlein and his research team;
- (b) coordinate further development of the loss estimation toolbox with Miranda so that a single packaging of PEER's EDP-to-DV methodology results;
- (c) in coordination with Comerio, further develop the PEER methodology for EDP-to-DV = indirect losses arising from downtime;
- (d) further develop the PEER methodology for EDP-to-DV = deaths and injuries;
- (e) in coordination with May, Ince and Mezarios, begin developing a decision-analysis framework that uses the "3 Ds" (deaths, dollars, and downtime) as DVs but also allows the decision maker to account for his or her risk attitude.

### Role of this project in supporting PEER's mission (vision)

"PEER's mission is to develop and disseminate technology for design and construction of buildings and infrastructure to meet those diverse seismic performance objectives." The goal of our Year 8 project is to better identify these performance objectives and describe them more completely.

PEER's second generation PBEE methodology includes four steps of analysis: the hazard analysis, the structural analysis, the damage analysis, and the loss analysis. Our Year 8 project focuses on the last two steps. We will create probabilistic descriptions for two losses (decision variables) of interest: "deaths" and "downtime." In support of PEER's vision, this project will further develop the research that has been done in these two areas, and will better define PEER's seismic performance objectives. Ultimately, this project's results will aid decision makers.

### Methodology employed

We use the damage and loss analysis framework of PEER's second generation PBEE methodology that is documented in our Year 7 report.

**Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments**

This project is an extension of the Year 7 benchmarking study, in that it will make the EDP-to-DV MATLAB toolbox available to others in the PBEE community so that they may use it in their research projects. Also, this project will build a decision support system into the existing toolbox. Although some aspects of the proposed research are a direct consequence of our Year 7 work, it is also a cumulative effect of many years of research in damage and loss estimation supported by PEER.

In Year 8, we will focus on establishing the probability that certain categories of facilities will be closed (not operational) and then focus on a probability distribution for downtime, given closure and various possible recovery strategies. We will also begin a study of a method for constructing a probability distribution on the number of deaths, given EDP. In this approach, we will study the practicality of using the results of previous PEER projects (e.g. Shoaf and Seligson, Yeo and Cornell) where a probability model for the number of deaths is conditional on local or global collapse. One difficulty is how to determine the fragilities for local and global collapse. We will investigate the use of the damage states of the RC structural components (e.g. severe and collapse) whose probabilities, given the appropriate EDP, can be determined, for example, by the beam and column fragilities functions from our previous research. For the decision-analysis framework, we propose to integrate the 3DVs (dollars, downtime and deaths) into a discounted total loss over a specified planning period and to examine the use of the “certainty equivalent” total dollar amount to account for the decision maker’s risk attitude (as in “Effect of Seismic Risk on Lifetime Property Values,” K.A. Porter, J.L. Beck, R.V. Shaikhutdinov, S.K. Au, K. Mizukoshi, M. Miyamura, H. Ishida, T. Moroi, Y. Tsukada and M. Masuda, *Earthquake Spectra*, November 2004). The Year 8 research will be published in PEER and Caltech technical reports and in conference and journal papers.

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

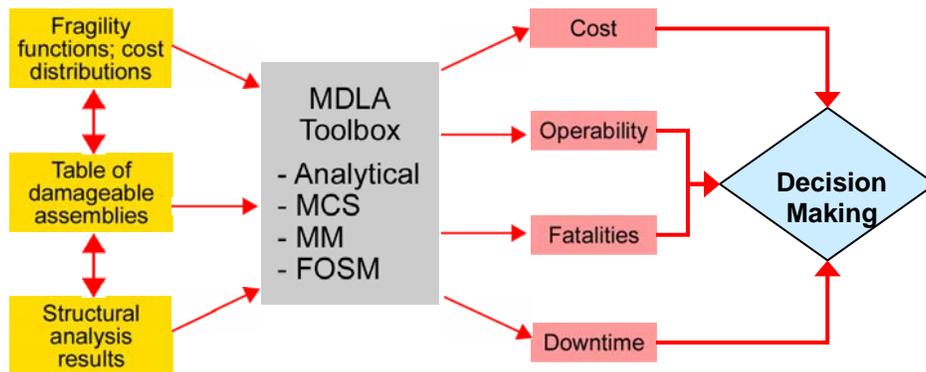
We are unaware of similar work being conducted outside of PEER. However, there are several research teams within PEER that are conducting research in similar areas as our group:

- Miranda & Aslani  
*These researchers at Stanford are also working on damage and loss analysis. They will be investigating story fragility functions and we will not. They will not be creating models for fatalities and downtime. Also, our toolbox development will continue to use Matlab.*
- Shoaf & Seligson  
*These researchers at Stanford have also worked on modeling fatalities, but did not fully develop a theory for estimating loss of life that can be integrated into PEER’s PBEE methodology.*
- Cornell & Yeo  
*These researchers at Stanford have also worked on modeling fatalities, but did not fully develop a theory for estimating loss of life that can be integrated into PEER’s PBEE methodology.*

- Comerio & Blecher  
*These researchers at Berkeley are also working on modeling downtime in a conceptual way and we will work with them to integrate their ideas into our loss analysis procedure.*

### Plans for Year 9 if this project is expected to be continued

In our Year 7 project, we developed software that could be used by other researchers and practicing engineers to estimate monetary losses. In Year 8, we are looking at losses other than monetary ones: fatalities and downtime. In a Year 9 project, we will extend our Year 8 work and then add the methods developed from our research, to our existing MATLAB Damage and Loss Analysis (MDLA) toolbox (see schematic below).



In addition to developing software, we may extend the modular PEER methodology to include other hazards in a Year 9 project. In fact, as the tenth year of the PEER Center approaches, it is critical to identify how the tools developed in PEER can be used in other areas of research (i.e., wind and blast engineering) and industry.

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

None that we are aware of.

### Expected milestones & Deliverables

31 Jan 2005: Transfer of Matlab toolbox for EDP-to-DV=repair costs, with documentation, to Deierlein and his research team.

28 Feb 2005: Completion with Miranda of a single packaging of PEER's methodology for damage and loss estimation from EDP-to-DV=repair costs, with supporting documentation.

31 Mar 2005: Completion of methodology to establish the probability that certain category of facilities will be closed (not operational).

30 Jun 2005: Completion of methodology to establish probability distribution for downtime, given closure and various possible recovery strategies.

31 Jul 2005: Report documenting EDP-to-DV=indirect losses from downtime.

30 Sep 2005: Report documenting initial methodology to establish probability distribution on the number of deaths, given EDP, using appropriate fragility functions for local and global collapse.

30 Sep 2005: Report documenting initial decision-analysis framework that uses the “3 Ds” (deaths, dollars, and downtime) as DVs but also allows the decision maker to account for his or her risk attitude.

<b>Project Title—ID Number</b>	<i>Benchmarking Performance of New RC Frame Buildings — 1382004</i>		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	NSF
<b>Project Leader (boldface) and Other Team Members</b>	<b>Greg Deierlein (Stanford/F)</b> , Curt Haselton (Stanford/GS), Paul Cordova (Stanford/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 assess the seismic performance provided by modern design provisions for reinforced-concrete buildings. By applying the PEER PBEE assessment methodology to a collection of building designs, the project will provide insight on how to extend the building-specific assessment methodology for individual buildings to assess building code provisions, which are used as the basis for design. Data from this research will serve a number of goals, including:

1. gauge whether design standards provide the expected performance across the range of building configurations permitted by design codes
2. contribute to establishing appropriate performance targets for performance-based design of new buildings,
3. provide a benchmark against which new innovative systems can be judged
4. provide data for improved building fragility models as input for loss simulations of large geographic regions
5. demonstrate the benefits of the PEER PBEE assessment method as compared to the current state-of-art in engineering practice (e.g., FEMA 356)

Beyond the primary objective to benchmark current design provisions, the project has two secondary objectives. First, by exercising the methodology and associated simulation/assessment tools, the project will contribute to the packaging of these tools as part of the technology transfer to practice. Second, by evaluating the impact of alternative design parameters on performance, the project will provide improved understanding to develop appropriate design criteria to relate provisions for minimum strength, stiffness and ductility of the structural system to the resulting performance.

### Role of this project in supporting PEER's mission (vision)

The goals and scope of this project are central to realizing the vision outlined in the strategic plan for Thrust Area (TA) I – Building Systems. Synthesis of the PBEE methodology components, models and criteria, which is necessary for this project, relates directly to the TA I need to package the PBEE methodology and make it accessible to the engineering community. The procedures and resulting data from the RC building benchmarking studies, resulting from this project, are a major unifying theme of the entire TA I research over years 8-10.

**Methodology employed**

The overall research strategy is to conduct an in-depth PBEE assessment of prototypical buildings designed according to the seismic provisions of the 2003 edition of the International Building Code (and the associated standards included by reference). Input and review from practicing engineers has been solicited in formulating strategies for developing the benchmark building designs for various building occupancies. This includes, for example, guidance on typical constraints faced in layout of framing bays, proportioning beams and columns, foundation design, and other items necessary to fulfill the minimum building code requirements. The study is focused on buildings in high-seismic regions, although through examination of the cause and effect relationships between various seismic design parameters (e.g., minimum strength, stiffness and toughness provisions), the benchmarking effort will provide information on buildings designed in regions of low to moderate seismicity. Moreover, based on comments raised during research coordination meetings, the Year 8 scope includes a review and assessment of the effect that changes in building code provisions from 1970 to the present have affected building performance.

The benchmark building designs are assessed using the PEER-PBEE approach, whereby the process is divided between ground motion hazard characterization (IM), structural response (IM-EDP), damage assessment (EDP-DM), and loss modeling (DM-DV). The structural response is being conducted through an incremented dynamic (time-history) analysis approach using OpenSees. The structural damage assessment is made using information developed both within and outside PEER on relationships between EDPs (primarily drift and inelastic deformations) and damage to the RC components. Damage to nonstructural components and loss models (DM-DV) is being provided by the collaboration with the Caltech research team.

**Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments**

Early in Year 7, the research team met with a number of practicing engineers to solicit guidance on typical RC moment frame building construction in the western US (occupancy, floor plans, height, framing layout, typical design considerations/constraints, etc.). From this, a detailed planning/scoping document was developed to outline:

1. key design, construction, and structural behavior considerations in the benchmark investigation,
2. details for implementing and applying the PBEE methodology to the benchmark buildings,
3. a matrix of descriptors for the initial benchmark building study.

A four-story benchmark RC building was developed, including comprehensive specification of the structural system and major nonstructural components and contents. Models, criteria and simulation tools were assembled and validated (in collaboration with researchers at Caltech and UCLA) to conduct the performance assessment, including detailed nonlinear simulation models in OpenSees.

Late in Year 7 and continuing into Year 8, a detailed assessment of the four-story building has been conducted. Shown in Figure 1 (see below) is an example of results from the OpenSees analyses to determine the peak inter-story drift ratio as a function of the site hazard (expressed in terms of spectral acceleration). Preliminary findings are that this building performs very well and exceeds the building-code expectations. As of this writing (March 2005) the investigation of the four-story building is near completion, and planning is underway for a systematic investigation of alternative structural configurations to investigate the range of building performance implied by current design standards.

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

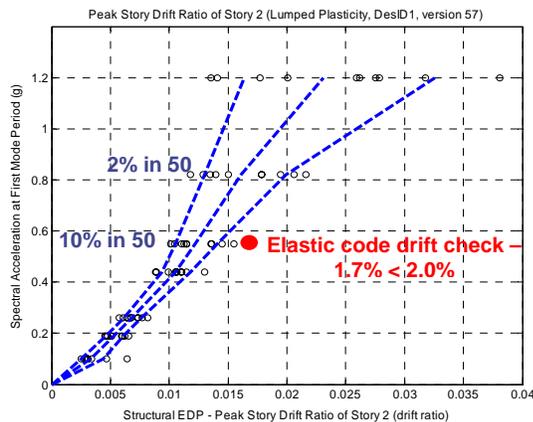


Figure 1- Incremental dynamic analysis results for four-story benchmark building

(articulation of performance metrics), Krawinkler (assessment and design methodology), Cornell (assessment methodology), Stewart (soil-structure interaction effects), Lehman/Lowes (damage assessment of RC components), Eberhard (simulation and performance of beam-columns), and others.

The initial benchmark study of the four story building has been conducted jointly between this project and two other TA 1 projects: Beck/Porter (Caltech) “*Loss Modeling for Downtime, Deaths and Decision-Making*” and Stewart (UCLA) “*Implementation SFSI and Site Effect Models in PEER Methodology*”. The Caltech group has been instrumental in the loss modeling aspects (EDP-DV) and the UCLA team has contributed to developing foundation models, site hazard data, and input ground motions for the time history analyses.

#### Plans for Year 9 if this project is expected to be continued

This project is a multi-year effort, which began in Year 7 and is expected to continue into Year 9. In Year 7, the project began with the detailed design and PBEE assessment of a 4-story code-complying RC moment-frame office building. This required considerable effort to assemble, check and validate procedures and models to conduct the benchmark study. During Year 8, the benchmarking effort is being generalized to represent the broader population of code-complying RC buildings, including buildings of differing heights, structural framing configurations (including wall-frame systems), and other design parameters. This study will, in effect, benchmark the performance of current building-code provisions for RC buildings. This is an

The PI is not aware of similar work of this type applied to reinforced concrete frames. The project shares some common aspects to a series of assessment studies of steel moment frame buildings conducted through the SAC joint venture; and these studies are being examined.

Synthesizing and “packaging” of the methodology and tools for this project is being done in collaboration with related PEER investigations, including: Beck/Porter (loss modeling); Miranda (loss modeling and non-structural components); May

ambitious effort that is expected to continue into Year 9. During the latter part of the project, we anticipate that the scope will emphasize the development and evaluation of alternative design provisions, which are of interest both to improve current building code requirements and provide the basis for performance-based *design* (as distinct from *assessment*).

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

The performance-assessment process and specific results from this benchmarking study are of direct interest to technical organizations involved in the development of building code provisions for seismic design. FEMA is supporting two such efforts that will affect engineering practice – one concerning the development of provisions for performance-based seismic design (ATC 58) and a second concerning the development of a rational procedure for substantiating seismic response parameters (e.g., R and Cd) of current building code provisions. The PI is involved in both of these projects, and his involvement is facilitating technology transfer of the procedures, technologies and data from the PEER research.

**Expected milestones & Deliverables**

This project is a multi-year effort, which began in Year 7 with the detailed design and PBEE assessment of a 4-story code-complying RC office building. The Year 7 effort has culminated in a technical report (April 2005, co-authored by the teams at Stanford, Caltech, and UCLA) on the benchmarking study. The following is a summary of future milestones and deliverables:

- Periodic Status Reports - status reports and other requested contributions to PEER quarter coordination meetings, PEER Annual Meetings, and meetings with outreach efforts to FEMA-ATC projects.
- Structural Modeling Guidelines – written guidelines to summarize OpenSees modeling techniques, assumptions and criteria to evaluate structural performance of code-complying buildings up through collapse (draft 6/2005).
- Detailed Planning Document on Strategy for Generalizing Results – documentation of research plan to generalize the benchmarking study to account for varying building configurations and design uncertainties. Plan to be presented and reviewed by TA I research team (6/2005).
- Final Project Report – anticipated for completion at end of Year 9 (9/2006).

<b>Project Title—ID Number</b>	<i>EDP-DM-DV Relationships for RC Components</i> — <b>1392004</b>		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	NSF
<b>Project Leader (boldface) and Other Team Members</b>	<b>Laura Lowes (UW/F)</b> , Peter Brown (UW/GS)		

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

### Project goals and objectives

The proposed research will develop EDP-DM-DV relationships for reinforced concrete structural components. Previous research by the PI and other PEER researchers (Miranda, Porter, Beck, Eberhard) has resulted in EDP-DM-DV relationships for several types of reinforced concrete components including columns, beams, slabs, slab-column connections, and older beam-column joints. Additional research is required to establish EDP-DM-DV relationships for other components. In Year 8, beam-column joints and structural walls designed in compliance with modern codes will be addressed. The effort to develop EDP-DM-DV relationships for beam-column joints builds directly on the PI's previous research activities (Year 4 and Year 7).

### Role of this project in supporting PEER's mission (vision)

The proposed research will develop EDP-DM-DV relationships for reinforced concrete structural components. These relationships define the likelihood of a component requiring a specific type of repair given a specific level of earthquake demand and can be extended to define the probability of component repair exceeding a specific dollar value and time limit, given a specific level of earthquake demand. As such, these relationships are required to enable application of the PEER PBEE methodology.

### Methodology employed

Development of the proposed component-specific EDP-DM-DV relationships relies heavily on review of previous experimental research to generate 1) an EDP-DM data set from which probabilistic EDP-DM models can be developed and 2) DM-DV relationships that link specific damage states with repair techniques that can be used to restore damaged components to pre-earthquake condition. Development of the proposed models relies also on application of standard statistical analysis methods.

The following research method will be employed to develop the proposed EDP-DM-DV relationships for the beam-column joint and structural wall components.

1. Review previous research results, design codes and building drawings to determine the design details that define "modern construction".
2. Review previous experimental research to generate EDP-DM data sets for components with design details that are characteristic of modern construction. Here it is assumed that EDPs will include maximum inter-story drift and number of load cycles with the addition of maximum joint strain for beam-column joints. Damage measures will include maximum concrete crack width and the extent of concrete cracking, the extent of concrete spalling and crushing, yielding of reinforcement, loss of strength and buckling

and fracture of reinforcing steel. In identifying and collecting damage data, the objective will be to include damage measures that trigger specific repair techniques.

3. Review previous research to develop relationships between sets of damage measures and repair techniques.
4. Use standard statistical analysis methods to develop probabilistic models linking EDPs with DMs and, ultimately, specific repair techniques. These models define the likelihood of a component requiring a specific type of repair given a specific level of earthquake demand.
5. Review standard cost estimating tables to generate unit cost and construction time data for specific repair methods. With this information the EDP-DM-DV relationships can be extended to define the likelihood of component repair costing a specific amount and requiring a specific construction time given a specific level of earthquake demand.

#### **Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments**

Year 7 research activities resulted in the development of EDP-DM-DV relationships defining the likelihood that an older beam-column joint would require a specific type of repair given a specific level of earthquake demand. Additionally, cost and downtime estimates were developed for each repair technique so that EDP-DM-DV relationships could be used to predict annualized loss. The results of this effort are reported in a M.S. thesis (Pagni, C. "Modeling of Structural Damage of Older Reinforced Concrete Components." *MS Thesis*. Seattle: University of Washington, 2000), a PEER Report (Pagni, C.A. and L.N. Lowes. *Predicting Earthquake Damage in Older Reinforced Concrete Beam-Column Joints*. PEER Report 2003/17. Berkeley: PEER, 2004) and a *Earthquake Spectra* paper (Pagni, C.A. and L.N. Lowes. "Empirical Models for Predicting Earthquake Damage and Repair Requirements for Older Reinforced Concrete Beam-Column Joints." *Earthquake Spectra*. Accepted for publication).

#### **Other similar work being conducted within and outside PEER and how this project differs**

Research to develop EDP-DM-DV relationships for structural components is being conducted within PEER; however, this research focuses on different types of components.

Research to develop earthquake damage-prediction models for tall buildings designed with structural wall system is being done by researchers at the MAEE center. However, this research does not focus on the development of component-specific damage models but instead focuses on prediction of building damage including structural and non-structural components.

#### **Plans for Year 9 if this project is expected to be continued**

The EDP-DM-DV models developed in Years 4, 7 and 8 used laboratory data and define relationships between **observed** EDPs and **observed** damage measures. Previous research, sponsored by PEER as well as other organizations, has resulted in moderately sophisticated models for use in predicting the response of beam-column joints, structural walls, beams, columns, slabs. In year 9, these models will be used to simulate laboratory tests and thereby develop data sets linking **predicted** EDPs with observed damage measures. Using these new data sets, EDP-DM-DV models can be developed that include uncertainty associated with modeling

error. These models provide a consistent approach for incorporation modeling uncertainty into the process of predicting the economic impact of earthquake loading; currently, modeling uncertainty is not included in prediction of economic impact.

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

**Expected milestones & Deliverables**

In developing EDP-DM-DV models for modern beam-column joints, milestones include the following:

1. Collect experimental data defining joint performance.
2. Use data and results of previous research to establish EDP-DM-DV relationships:

In developing EDP-DM-DV models for structural walls, milestones include the following:

1. Determine criteria to use for grouping wall specimens. It is expected that it will be necessary to group specimens by failure mode (flexure, flexure-shear and shear) and that it will be necessary to establish design parameters for use in predicting expected failure mode.
2. Defined damage measures. Damage measures may be different for different failure modes. Damage measures are assumed to be linked directly with specific repair methods.
3. Retrieve appropriate data sets from the literature and compute EDP-DM relationships.
4. Establish repair cost and repair time associated with each DM.

Project deliverables include EDP-DM-DV relationships for modern beam-column joints and structural walls.

<b>Project Title—ID Number</b>	<i>Validating Simulation of Deep Foundations and Lifelines Subjected to Lateral Spreading, and Collaboration on Bridge Abutments —2342004</i>		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	CA-Trans
<b>Project Leader (boldface) and Other Team Members</b>	<b>Scott Ashford (UCSD/F)</b> , Yohsuke Kawamata (UCSD/GS), Azadeh Bozorgzadeh (UCSD/GS), Teerawut Juirnarongrit (UCSD/PD)		

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

**Project goals and objectives**

The overall project goal is to utilize the full-scale data assess current methods for estimating the effect of lateral spreading on pile foundations and pipelines, and develop new procedures if necessary. Specifically, the objectives in Year 8 are to:

1. Model lateral spreading of blast experiment using seismic loading in OPENSEES.
2. Extend the results using OPENSEES to the ultimate loading condition.
3. Participate in payload experiments with already planned Caltrans experiments on bridge abutments and deep foundation to complement data from the Tokachi experiment.

**Role of this project in supporting PEER’s mission (vision)**

This one of a kind opportunity to participate in a full-scale test such as this will have a significant impact on PEER in a number of ways. Most importantly, it will provide our industrial partners with detailed performance evaluations of lifeline components subjected to lateral spreading. These evaluations will result in recommendations that can be applied in the very near future, leading to cost-effective design recommendations for pipelines and pile foundation in areas with a lateral spreading hazard. For PEER researchers, it will provide the first full-scale performance data on instrumented pile groups and pipeline subjected to lateral spreading. These results, in conjunction with previous and ongoing laboratory tests and data from past earthquakes, will significantly improve our understanding of the performance of lifelines subjected to lateral spreading. It is important to note that, not only are we collecting data ourselves, but we are also sharing and obtaining data from our Japanese counterparts that would otherwise be unavailable. Furthermore, the detailed data that we obtain will be vital to our assessment of our numerical modeling capabilities once OPENSEES is further developed. Finally, by participating in this international project, we are developing ties between PEER and Japanese researchers that can be utilized for additional collaborations in the future.

**Methodology employed**

We will use OPENSEES to model the results of the Tokachi experiments and assess the capabilities of OPENSEES. Once the numerical model is validated, we will conduct parametric study and attempt to extend the results to use for a wider range of application for piles and pipelines subjected to lateral spreading.

**Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments****Site Condition after blast-induced liquefaction at Tokachi Port, Japan**

Two full-scale experiments using controlled blasting were conducted in November and December 2001 in the Port of Tokachi on Hokkaido Island, Japan, to study the performance of lifeline facilities subjected to lateral spreading. This research project was the joint collaboration between the University of California, San Diego, (UCSD) and several Japanese organizations led by the Port and Airport Research Institute (PARI). The primary



objective of the test was to assess the performance of lifelines subjected to lateral spreading using controlled blasting. UC San Diego's participation in the test was funded by the PEER Lifelines Program with support from Caltrans, Pacific Gas & Electric and the California Energy Commission. The PEER Lifelines Program funded UC San Diego's participation in the test with support from Caltrans, Pacific Gas & Electric and the California Energy Commission.

In all, UCSD installed 6 test specimens. The pile specimens in the experiment program consisted of a single pile, a 4-pile group, and a 9-pile group. In addition, two natural gas pipelines and one electrical conduit were installed. All of them were extensively instrumented with strain gauges to measure the distribution of moment in the specimens during lateral spreading. Other instrumentation, including pore pressure transducers, GPS units, and slope inclinometers, were also installed to measure the degree of liquefaction as well as the movements of soil and lifelines. This data will allow us to compute the loading conditions during lateral spreading, as well as to assess the capabilities of our numerical models being developed within PEER. The objectives of this study is to conduct damage and performance assessments of those lifelines subjected to lateral spreading, as well as to evaluate loading conditions on the structures during lateral spreading. Currently, the final report on the experimental portion of the work as well as the evaluation of simplified p-y approach on piles subjected to lateral spreading for the Tokachi experiments is available at UCSD and will also be published as a PEER Report. All data from the experiment is also available on the web. In addition, a more rigorous approach using OPENSEES is currently being implemented to model the Tokachi experiments and the newly available data, as well as comparing the results to other lateral spreading experiments in the centrifuge and 1-g shake table.

The role of this research in Years 8-10 will be to validate OPENSEES and demonstrate the PEER methodology. In Year 8, the focus of the research will be to use OPENSEES to model the experiment and extend the results to the ultimate loading condition on the pipelines and pile foundations. In addition, participation is planned in Caltrans funded experimentation to be

carried out on large-scale bridge abutments at the Camp Elliott Field Station and pile foundations subjected to lateral spreading in the 5-m laminar soil box. The participation is anticipated to be the payload type experiment, taking full advantage of existing test plans.

The initial year of this project was funded by PEER Lifelines Program with \$610,000 in order to carry out both experiments in Japan. This was matched by over \$2.5 million by the Japanese to make the total effort over \$3 million. We are proposing that PEER Core continue funding the analysis portion of the project. For this effort in Year 8, we request funding on the order of \$67,000. This will continue to fund a PhD student (Yohsuke Kawamata) working on the project, fund participation of post-doctoral researcher Teerawut Juirnarongrit and PhD student Azadeh Bozorgzadeh on the payload experiments, and partially fund the PI (1-month for Professor Ashford). We look forward to much closer collaboration with UC Davis researchers beginning in Year 8. It is understood that PEER researchers at other Universities will be able to collaborate with us on the analyses within their existing funds, otherwise additional funding would be required.

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

The PI has conducted and is currently conducting research sponsored by Caltrans on the full-scale behavior of deep foundations in liquefied sand. These experiments also utilize controlled blasting to induce liquefaction. Though primarily focused on Cast-In-Drilled-Hole (CIDH) piles, these experiments also considered pile groups. This proposed research differs from these projects in two primary ways. First, in the previous research, only the soil in the immediate vicinity of the pile was liquefied and inertial loading was simulated used hydraulic actuators. In the Japan test, the soil was liquefied for a great distance around the piles, and loading was from lateral spreading soil. Secondly, the piles in the previous experiments had the free-head condition. In the proposed research, a pile cap was incorporated to test the fixed-head condition. The PI's are not aware of any ongoing full-scale field experimentation on the performance of pipelines subjected to lateral spreading.

**Plans for Year 9 if this project is expected to be continued**

In Year 9, we plan to continue the analysis work using OPENSEES to extend the results of the Tokachi experiments. We will attempt to use a more refined simulation (3D model) to gain better understanding of the behavior of piles subjected to lateral spreading in some specific issues where 2D modeling cannot explain, such as pile group effect, and effect of pile diameter. We will eventually make use of the analysis results in Year 9 to develop the design guideline for piles and pipelines subjected to lateral spreading.

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

None yet. Project is ongoing.

**Expected milestones & Deliverables**

Milestones:

- December 2004: OPENSEES model of Tokachi experiment using seismic loading.
- April 2005: Payload experiments to be finalized.
- June 2005: Payload experiments complete.

Deliverables:

- PEER Quarterly Reports

<b>Project Title—ID Number</b>	<i>Effect of Ground Deformations and Liquefaction on Bridges — 2392004</i>		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	CA-Trans
<b>Project Leader (boldface) and Other Team Members</b>	<b>Ross Boulanger (UCD/F)</b> , Scott Brandenberg (UCD/GS), Dongdong Chang (UCD/GS), Erik Malvick (UCD/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 support the Bridge Thrust Area's efforts regarding the simulation and performance of bridges subjected to liquefaction and lateral spreading hazards, with particular emphasis on supporting the continuing development of simulation tools, the validation of those simulation tools against physical data, and the further development of design procedures and guidelines.

**Role of this project in supporting PEER’s mission (vision)**

The project supports the PEER mission by providing the essential knowledge base and enabling tools for the Bridge Thrust Area's effort on demonstrating the PEER PBEE methodology for bridges subjected to liquefaction and lateral spreading hazards.

**Methodology employed**

The OpenSees simulation tools that we developed and are supporting include the p-y, t-z, and q-z spring materials that model nonliquefaction and liquefaction conditions. These spring materials interface with the Yang-Elgamal constitutive models for liquefiable soils.

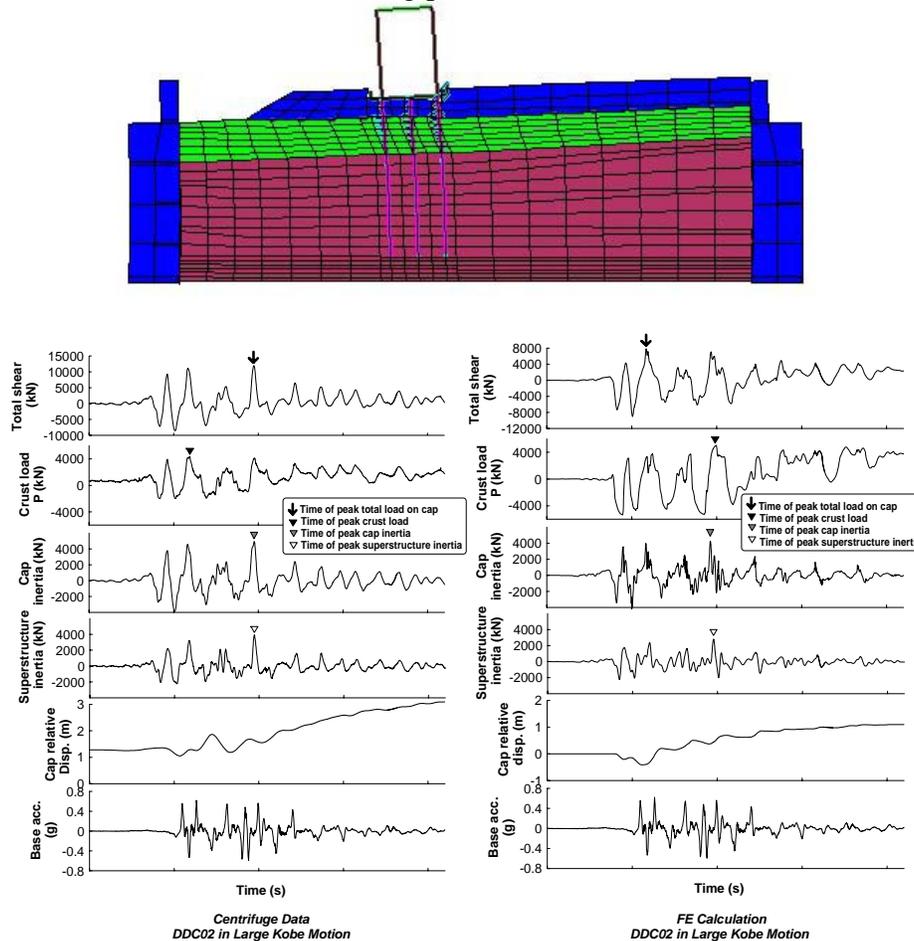
The validation of these simulation tools is being performed by comparison against dynamic centrifuge model test data that is archived at the UCD Center for Geotechnical Modeling. These centrifuge tests include single piles and pile groups, with and without superstructures, in level and sloping soil profiles, with and without nonliquefied surface layers. These validation exercises have identified various challenges in numerical modeling that had to be overcome, including the incorporation of model container effects and the inclusion of interface elements to model the localized shearing at the clay-sand interface.

The further development of pseudo-static design procedures and guidelines utilizes parametric analyses with the calibrated dynamic OpenSees models and the subsequent comparison of primary demand parameters that are computed using the dynamic and static procedures.

**Brief description of past year’s accomplishments and more detail on expected Year 8 accomplishments**

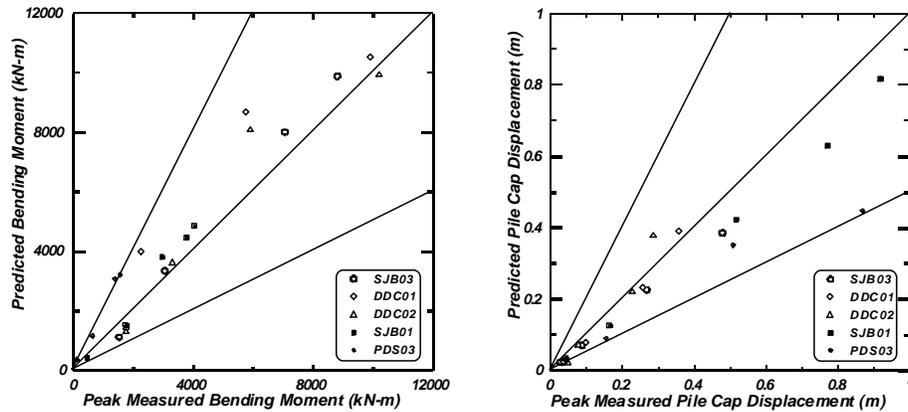
Nonlinear dynamic OpenSees analyses were used to model the responses of pile-supported structures in soil profiles that developed liquefaction and lateral spreading during earthquake shaking in centrifuge model tests, as depicted by the deformed FE mesh shown below. The centrifuge tests included a simple superstructure supported on a group of six piles. The soil

profile consisted of a gently sloping nonliquefied clay crust over liquefiable loose sand over dense sand. The FE models consisted of a two-dimensional model of the soil profile with a beam-column model of the structure and pile foundation that was attached to the soil profile by soil springs. Parametric studies were used to assess the influence of boundary conditions, the model container, and various other modeling parameters.



Comparisons of computed and recorded dynamic responses for a range of reasonable modeling parameters showed that the calculated responses could envelop the recorded responses. A baseline set of modeling parameters were chosen that produced reasonable agreement for the full set of centrifuge test data using this model configuration (eight cases). These calibrated OpenSees models were able to reasonably approximate the essential features of soil and structural response, as illustrated by the one example set of time series shown above.

Static design procedures and associated recommended guidelines were also developed and evaluated against the centrifuge test data. For example, the results below show computed versus recorded values for about 20 cases (five models, four earthquake motions for each model). The differences between computed and recorded responses arise primarily from the simplifications inherent to a static analysis of a seismic problem. These analyses and comparisons to centrifuge data support the development of design procedures and the characterization of the uncertainty in predicted responses.



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

This project complements other projects in the Bridge Thrust area. The projects by Kramer/Arduino and Bray/Martin are focused on demonstrating the PEER PBEE methodology against a baseline bridge, and thus their work will benefit from the continuing developments and validation efforts described herein. Ashford's work on the continuing interpretation of field blasting studies and Boulanger/Kutter's Lifelines project on pile pinning effects in bridge abutments are complemented by the studies described herein. These overall efforts further benefit and are coordinated with Elgamal's involvement in a US-Japan collaborative project with Dobry and Abdoun (MCEER) and NIED (Japan).

### Plans for Year 9 if this project is expected to be continued

The parametric OpenSees analyses will be expanded over a broader range of conditions to study the relation between peak inertial loads in the presence of liquefaction versus in the absence of liquefaction. In common design methods, the inertial load is determined from a site spectra that does not include the effects of liquefaction, and thus the parametric study will provide guidance on how actual inertial loads compare to those estimated from design spectra. Second, the analyses will be extended to incorporate various levels of ductility in the structures, and then re-evaluate how inertial and lateral spreading loads combine when yielding in the structure in included, as well as how ductility demands in the superstructure are affected.

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

#### Expected milestones & Deliverables

We have arranged a meeting of OpenSees users who are modeling piles and liquefaction problems. This meeting will identify supporting simulation or productivity tools that would benefit PEER researchers, which we would then focus on. We will also meet with researchers dealing with transportation networks and identify their needs, and make plans to address them accordingly. Otherwise, our efforts will be focused on the parametric FE analyses, which are expected to be written up in the doctoral thesis of Dongdong Chang in mid 2006.

<b>Project Title—ID Number</b>	<i>PBEE Assessment and Design of Enhanced Bridge Piers for Near Field Effects</i> — <b>2402004</b>		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	CA-Trans
<b>Project Leader (boldface) and Other Team Members</b>	<b>Steve Mahin (UCB/F)</b> , Andres Espinoza (UCB/PD), Patxi Uriz (UCB/GS), Lukki Lam (UCB/GS), Junichi Saikai (UCB/GS)		

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

### Project goals and objectives

The overall goal of this study is to examine and assess various design concepts for enhancing the seismic performance of new bridge structures of the type being considered by PEER. Promising design details will be assessed through dynamic shaking table and/or quasi-static tests as well as through more extensive nonlinear dynamic analyses using the OpenSees computational framework. In particular, the potential for reducing residual displacements of bridges following severe earthquakes will be examined through the use of special plastic hinge regions containing combinations of unbonded prestressed and mild reinforcement. Other design approaches utilizing high performance concrete will be examined in concert with others working within the PEER Center. The results will be presented in a fashion that will support the development and assessment of the overall PEER PBEE methodology being devised by the Bridge and Transportation Thrust Area. The goal of this project would be to demonstrate physically and through PBEE the value of the PEER methodology for a specific application, and thereby accelerate the adoption of new bridge design technologies into practice.

### Role of this project in supporting PEER's mission (vision)

This project will develop and validate column design procedures and analytical models where columns will perform better than those using conventional design methods. This will reduce the amount of residual displacement in a bridge following an earthquake and degree of damage to the plastic hinge region. This will demonstrate the PEER methodology's ability to rationally evaluate the desirability of new technologies.

### Methodology employed

The primary goals of these continuing investigations are to:

1. demonstrate the viability of new design and construction strategies for mitigating the substantial residual displacements that tend to occur in modern bridges when large inelastic deformations occur during severe earthquake shaking,
2. use experimental data to help calibrate the confidence that can be placed in various analytical models and procedures, and
3. support the development of the PEER methodology as applied to bridge structures.

Residual displacements have an important impact on post-earthquake operability of bridge structures, and repair costs. In addition, opportunities will be pursued to support the work of others (Lehman, Kunnath, etc.) within PEER regarding other behavioral aspects that adversely affect overall performance, such as spalling, bar buckling and so on.

The initial thrust of this work has been focused on shaking table testing of a lightly reinforced bridge column specimen with unbonded post-tensioning. An identical companion specimen with conventional reinforced concrete was also tested. For the same input motions, both specimens achieved nearly identical peak displacements, but the partially prestressed column nearly recentered even though the conventional column had substantial residual displacement. However, the tests demonstrated that the partially prestressed column tended to concentrate damage in a short plastic hinge length and as such, the mild longitudinal reinforcement proved to be susceptible to catastrophic failures due to low cycle fatigue. Earlier analytical studies suggested this possibility, and that by debonding the mild reinforcement in the vicinity of the plastic hinge that a more robust connection can be achieved. A part of this year's activities, a set of 4 concrete columns will be constructed. One will resemble the partially prestressed column tested previously, but with a different degree of post-tensioning. One will be similar to the first but have the longitudinal mild reinforcement unbonded over a length of about  $2D$ . The third will be similar to the second, but have the extra confinement required from these columns provided by a steel jacket (which should make the column less likely to need repair following an earthquake). The last column will utilize fiber reinforced concrete near the plastic hinge region. The use of FRC is being studied analytically by Billington at Stanford as part of this project. Comparison of test results with one another and with numerical predictions will help understand the capabilities of these types of columns, and the accuracy of OpenSees in predicting response.



It is planned to work closely with other investigators working on this subject. For example, Dr. Billington is assessing DM/DV and EDP/DM relationships for bridge piers containing unbonded post-tensioned reinforcement and high performance, cement-based, ductile concrete. She will be using our results and has been supplying mix designs for construction. Dr. Stojadinovic is carrying out our extensive simulations to understand the contribution of various structural and ground motion characteristics to bridge fragilities, and further extending the PEER methodology as it applies to bridges. Marc Eberhard and Sashi Kunnath are working on improving OpenSees modeling capabilities, and we will work closely with them.



#### **Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments**

Two single-column specimens and one two-column model were tested in YR 7. Only one of these included partial prestressing, or other measures intended to improve performance. The results demonstrated the feasibility of the concepts being followed, but that the failure mode is quite abrupt once the failure limits for the performance-enhanced column are past. Thus, additional details are being studied in YR 8 to make the designs more robust. These include debonding of the longitudinal mild reinforcement in the plastic hinge region, adding a steel jacket over the plastic hinge region, changing the amount of prestress and using fiber reinforced concrete. These

will lead to more definitive guidelines for design. Additional work will be pursued in YR 9 examining system behavior.

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

Sarah Billington is examining in a companion PEER project the effect of re-centering columns on the overall performance of bridges. Some related research is underway at UC Reno using shape memory alloys for the longitudinal reinforcement, and at UofW using precast, post-tensioned columns. We will keep abreast of these efforts.

**Plans for Year 9 if this project is expected to be continued**

The work will continue to examine the effect of the performance-enhanced columns on actual, but simple bridge systems. Effects of continuity of the bridge deck over multiple columns, and different length columns are expected to substantially complicate behavior of both conventional and re-centering bridge systems. These differences need to be fully understood, and to have validated analytical models for making decisions on response.

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

Several instances of partially prestressed concrete columns have been found in Taiwan and in a few instances in the US.

**Expected milestones & Deliverables**

We expect to begin construction of the test specimens in March 2005, and begin testing as soon as the shaking table becomes available. As an alternative, we have developed a procedure for testing these specimens under bidirectional seismic motions through hybrid simulation. We will also explore options for using these columns for the bridge testbed structure identified for use during YR 8-10. A report on the experimental phase of the earlier work will be released in early summer 2005.

<b>Project Title—ID Number</b>	<i>Performance-Based Evaluation of Bridge on Liquefiable Soils Using OpenSees —2412004</i>		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	NSF
<b>Project Leader (boldface) and Other Team Members</b>	<b>Steve Kramer (UW/F), Pedro Arduino (UW/F), Hyung-Suk Shin (UW/GS)</b>		

*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 show that the PEER PBEE methodology, as expressed in the PEER framing equation, can be used with the OpenSees analytical tool to allow owners to make better decisions about seismic design and risk mitigation. The project will show how the OpenSees program can be used to develop EDP|IM fragility relationships for a bridge founded on liquefiable soils, and how those fragility curves can be used in the PEER PBEE framework to evaluate hazards for a complex soil-pile-structure system. The project will demonstrate the capabilities of OpenSees to (a) predict soil movements due to lateral spreading, (b) evaluate soil-pile-structure interaction in liquefiable soils, and (c) estimate the reliability of the performance predictions. The project will also demonstrate the capabilities of several important components of OpenSees.

**Role of this project in supporting PEER’s mission (vision)**

The project will show that the PEER PBEE methodology, as expressed in the PEER framing equation, can be used with the OpenSees analytical tool to allow owners to make better decisions about seismic design and risk mitigation. The project will show how the OpenSees program can be used to develop EDP|IM fragility relationships for a bridge founded on liquefiable soils, and how those fragility curves can be used in the PEER PBEE framework to evaluate hazards for a complex soil-pile-structure system. The project will demonstrate the capabilities of OpenSees to (a) predict soil movements due to lateral spreading, (b) evaluate soil-pile-structure interaction in liquefiable soils, and (c) estimate the reliability of the predictions. The project will also validate and demonstrate application of several important components of the OpenSees simulation platform.

**Methodology employed**

The performance of a bridge resting on favorable soil conditions is being evaluated by Stojadinovich and others. In this project, the same bridge will be assumed to lie in an area underlain by liquefiable soil conditions. The performance of the bridge will be evaluated in the PEER framework using the OpenSees analytical tool; in a parallel project, Bray and Martin will evaluate the performance of the bridge using simpler, empirical procedures.

Evaluation of the performance of the bridge will require development and testing of an OpenSees model of the bridge, its foundations, and the soils that support it. The model must be capable of computing the free-field response of the site, including pore pressure generation, redistribution, and dissipation in liquefiable soils along with the effects of those phenomena on the stiffness and strength of the soils, the interaction of the pile foundations with the liquefiable soils, including

the effects of pore pressure changes on that interaction, and the response of the above-ground portions of the structure.

The validated OpenSees model will then be used to investigate the dependence of appropriate EDPs on various IMs. This dependence will be studied first deterministically so that the investigators develop a good understanding of the mechanisms by which cyclic and permanent deformations develop in the soil, foundations, and structure, and the nature of the demands imposed on the structure and foundations by the response of the system to different input motions. Uncertainty in the EDP|IM relationship will then be investigated using relatively simple and computationally efficient methods such as the sensitivity analysis procedures implemented in OpenSees by Conte and the reliability module of Haukaas. EDP|IM fragility curves will also be investigated using Monte Carlo methods.

#### **Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments**

Since this is a relatively new project, work to date has involved meeting and discussing bridge and soil properties with other PEER investigators and development of trial soil profiles. The bridge has been selected by consensus agreement, and is based on a bridge designed and analyzed by Mark Ketchum in a previous PEER Lifelines project. At a recent PEER workshop, the PI was assigned the task of developing a suitable liquefiable soil profile for the evaluations to be conducted in this project and that of Bray. This task is nearly complete, and a report describing the proposed soil profile will be circulated to Bray, Martin, Boulanger, and other PEER investigators for review and comment. The profile will have liquefiable soils with a spatial trend in density so that one abutment of the bridge is underlain by soils that will liquefy in a 475-yr ground motion and the other end will liquefy in a stronger (longer return period) motion.

#### **Other similar work being conducted within and outside PEER and how this project differs**

The proposed project will have numerous interdependencies with other Year 8 projects over the anticipated three-year duration. For conciseness, the anticipated interdependencies are summarized in tabular form below.

Principal Investigator(s)	Needed Inputs	Provided Outputs
Boulanger	Updated p-y spring model, as appropriate, based on calibration against centrifuge model tests.  OpenSees p-y spring generator.	Results of OpenSees verification testing.

Bray Martin	Estimates of appropriate uncertainties involved in estimation of performance using simplified procedures.	OpenSees pile-soil interaction models for testing against simplified procedures.
Stojadinovich	Input on appropriate EDPs for structural damage due to liquefaction; insight into appropriate DMs and DVs for those EDPs.  OpenSees model for above-ground portions of bridge system.	EDP IM fragility curves for requested and appropriate EDPs.
Elgamal	Input on proper use of Elgamal constitutive model.	Results of OpenSees verification testing.
Boulangier	International perspectives, data on pile behavior in liquefied soils.	Results of OpenSees verification testing.

The project is most closely related to the project of Bray and Martin who will be evaluating the same bridge/foundation/soil system but using simpler, empirical procedures for soil and soil-foundation response. The results of these two projects will allow evaluation of the marginal benefits of performing detailed soil-foundation-structure interaction analyses using an advanced modeling tool like OpenSees.

We are unaware of similar work being conducted outside of PEER.

**Plans for Year 9 if this project is expected to be continued**

The project goals/objectives and methodology described in preceding sections of this document cannot be accomplished in Year 8. Therefore, a continuation of these activities into Year 9 is anticipated.

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

None to date.

**Expected milestones & Deliverables**

- Report describing soil profile to be analyzed (April 1, 2005)
- OpenSees free-field model (May 1, 2005)
- OpenSees complete model (June 1, 2005 pending receipt of structural model from Stojadinovich)

<b>Project Title—ID Number</b>	<i>Development of a Probabilistic Simplified Design Procedure for Assessing the Effects of Liquefaction and Lateral Spreading on Bridges —2422004</i>		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	CA-Trans
<b>Project Leader (boldface) and Other Team Members</b>	<b>Jonathan Bray (UCB/F)</b> , Christian Ledezma (UCB/GS), Norman A. Abrahamson (UCB/F)		

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

### Project goals and objectives

The primary objective of this research project is to develop a simplified design procedure for evaluating the effects of liquefaction and lateral spreading on bridges. This simplified design procedure must be developed to work within the PEER probabilistic performance-based engineering framework in that sources of uncertainty within each step should be incorporated properly. This project will translate pertinent PEER research findings into forms that can be adopted in practice as a probabilistic-based alternative to existing deterministic approaches. The project will attempt to demonstrate how the PEER methodology can be effectively used with simpler design-level analysis methods to make informed decisions.

### Role of this project in supporting PEER's mission (vision)

This project supports the PEER development and implementation of the Probabilistic-Based Earthquake Engineering methodology through the application and demonstration of the PEER methodology to the problem of evaluating the effects of liquefaction and lateral spreading on bridges.

A number of co-dependencies with other PEER research projects are noted the sections below. Hence, these will not be repeated here except our primary co-dependency with Professor Martin in his closely related research project.

Professor Geoff Martin is involved as a senior researcher on this project through a related PEER project (i.e. 2052004). Due to his expertise in this area and his previous extensive work in the area as evidenced by the many publications that he has co-authored as part of several research projects over the last decade, Professor Martin's insights and guidance will be invaluable. He helped develop the simplified methodology proposed by in the MCEER/ATC Joint Venture Document 49 (2003) "Recommended LRFD Guidelines for the Seismic Design of Highway Bridges."

### Methodology employed

This Year 8 project is planned as the first year of a three-year project to complete a development and demonstration project of the PEER probabilistic framework within the context of assessing the effects of liquefaction and lateral spreading on bridge foundations.

Mr. Christian Ledezma, a Ph.D. student researcher, will perform the primary work on this project. He will work under the supervision of Professor Bray. Professor Norm Abrahamson

will serve as a faculty associate to provide guidance and review on the implementation of aspects of the PEER probabilistic methodology. He has participated on many of the projects supervised by Professor Bray over the last decade and just recently initiated a study of probabilistic seismic slope displacement problems.

Professor Geoff Martin, who is funded separately on a related PEER project (2052004) will work as a senior researcher with Professor Bray and Mr. Ledezma, as he has extensive experience with the MCEER/ATC simplified deterministic design method that will serve as the initial basis for the new probabilistic procedure. Prof. Martin will work with us to ensure we understand and apply the MCEER/ATC design method with the necessary revisions for implementation within the PEER probabilistic framework. It will then be executed to see if it can be done and to identify key unresolved issues.

Revision of the MCEER/ATC simplified method will require that the Ph.D. student researcher, Mr. Ledezma, perform some simplified and advanced analysis to gain insight so that we can revise the procedure in a reasonable fashion. A number of simplifying assumptions were made in developing this practical design procedure and several of these assumptions warrant re-evaluation. These analyses will be performed using the simplified procedure delineated in MCEER/ATC-49 (2003) and with the OpenSees model developed by Professors Kramer and Arduino in a related project (2032004).

This project requires some physical model testing, due to the lack of available well-documented case histories to validate the existing simplified procedure and any proposed probabilistic simplified procedure. Without many detailed case histories, the UCD centrifuge studies (Boulanger 2012004) will be vitally important, but they are also complex in that they involve true liquefaction. The MCEER/ATC procedure is based on a linear-perfectly plastic response as a simple analogy for the complex phenomenon of liquefaction. The liquefied soil is modeled as a soft clay. It will be advantageous to perform some small-scale clay box model slope tests with model piles to collect data that compares directly to this simplified model to gain appropriate insight.

At Berkeley, we have recently performed two series of clay slope tests (Wartman, 1999 & Chen, 2004). We would add piles to slopes that we have shaken previously to develop a database that would help calibrate the methodology directly. If the methodology is based on the earth responding as a soft clay, then one should model it physically as a soft clay to get a direct one-to-one comparison, before trying to tie it to the more complex phenomenon of liquefaction.

However, the primary objective of this research project is to convert an appropriately revised MCEER/ATC methodology into one that can be exercised transparently through the PEER framework. Analytical and experimental work will be performed in a limited and focused manner to support this objective, without duplicating efforts by other PEER researchers.

**Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments**

This project builds upon the Years 3-5 and 7 projects on identification of efficient intensity measures for earthquake ground motions and development of a probabilistic method for estimating seismic slope displacements.

This research project will capitalize on the year 7 PEER work performed by Dr. Thalia Travararou who worked under the direction of Professor Bray at Berkeley. Travararou et al. (2004) developed a probabilistic methodology for assessing seismic slope displacements. This methodology is unique in that it includes the case in which combinations of parameters may lead to no seismic displacement, as well as cases where it will likely lead to significant displacement.

The relationships developed as part of this previous research are necessary to convert the MCEER/ATC methodology into a probabilistic framework. Instead of calculating displacement by difficult to characterize probabilistically parameters, such as the maximum seismic coefficient ( $k_{max}$ ), which is a function of many factors, the Travararou et al. (2004) method uses a commonly available ground motion intensity parameter, i.e. the spectral acceleration at a degraded slope period. Use of  $S_a(1.5T_s)$  as opposed to  $k_{max}$  is important if one wants to incorporate this procedure within the PEER framework (i.e.  $S_a$  is a common IM; attenuation relationships and hazard curves are available for  $S_a$ , but not for  $k_{max}$ ). The method also requires the slope parameters  $k_y$  and  $T_s$ .

#### **Other similar work being conducted within and outside PEER and how this project differs**

Similar work by the PI is not being conducted within PEER or outside of PEER.

#### **Plans for Year 9 if this project is expected to be continued**

Year 9 plans are discussed in the section entitled “Methodology Employed.” A preliminary exercise of the PEER methodology as applied to the lateral spreading of ground affecting pile foundations will be completed in Year 8, but additional work will be required to incorporate the uncertainty properly, to critically review and revise the analytical procedure employed, and to develop the insight required for this application.

#### **Describe any instances where you are aware that your results have been used in industry**

None at this time.

#### **Expected milestones & Deliverables**

The primary deliverable for this project will take the form of a technical report that will summarize the research methods used and present the probabilistic simplified design procedure for evaluating the effects of liquefaction and lateral spreading on bridges. The goal is to demonstrate the use of the PEER methodology through its application to this problem.

The basic framework for PEER’s performance-based earthquake engineering efforts requires explicit consideration of uncertainties in the seismological, geotechnical, structural, and economic analyses required for comprehensive performance-based seismic evaluation. The reliability of performance predictions will be improved by any reductions in the uncertainties of

the parameters used as input to these analyses. Significant uncertainties exist in each of these areas, but perhaps none are as significant as the uncertainties in earthquake ground motions and the dramatic response of soils that are potentially liquefiable.

The following tasks will be completed as part of this three-year research project:

1. Review of previous and ongoing PEER research related to this problem, such as that performed by through the projects mentioned above as well as additional projects by Professor Ray Seed on probabilistic-based estimates of liquefaction triggering and lateral spreading and fundamental work by Professors Elgamal and Jeremic. Additionally, it will be necessary to review the work of Professor Stojadinovic on bridge performance. The goal is to ensure awareness of PEER's recent relevant research efforts in both geotechnical and structural earthquake engineering.
2. Review and apply the current MCEER/ATC-49 simplified design procedure to the proposed standard bridge designs and ground conditions developed by the PEER Thrust Area 2 team. This effort will be performed in close collaboration with Professor Martin, as he is intimately familiar with these procedures. Available case histories that provide insight will be re-examined in an attempt to validate the proposed method. In addition, a review of other relevant work completed by investigators not involved in the MCEER/ATC-49 project will be performed. This effort would be greatly aided by the sharing of the literature review performed by PEER investigators, such as Professor Boulanger, who have already devoted much effort in this area of research.
3. Perform advanced analyses to gain insight so that the simplifying assumptions made in developing the MCEER/ATC-49 practical design procedure can be re-evaluated. These analyses will be performed using the simplified procedure discussed above as well as with the OpenSees model developed by Professors Kramer and Arduino in a related project (2032004). Professor Martin's experience with applying FLAC to this problem will also be invaluable.
4. Implement the slightly revised MCEER/ATC-49 (and hopefully somewhat validated) simplified design methodology in the PEER probabilistic framework by systematically addresses the uncertainties involved in each step. As we implement each step of the simplified design procedure, Professor Martin will be consulted for insight and judgment. The procedure will follow the framework established by Professor Stojadinovic in his demonstration project for the baseline bridge structure (2092004).
5. Perform three 1-g small-scale clay slope model experiments on the small shaking table in Davis Hall to repeat three experiments already performed with the exception that the new experiments will have instrumented small-scale piles installed in the slopes. The data developed through these experiments will provide additional insight and confidence in the simplified design procedure, which cannot be directly compared to the centrifuge tests with liquefiable soil.
6. Perform additional analyses as required to refine and validate the proposed simplified probabilistic design procedure. This activity will also take advantage of insights gained from related studies by Professors Kramer and Arduino, which explore the sensitivity of the results of the OpenSees analyses, and by Professor Boulanger, which provide centrifuge

experiments of bridges undergoing liquefaction and lateral spreading. Professor Martin will participate in refining the methodology.

7. Prepare a report that documents the work completed and importantly demonstrates how the design method can be implemented in practice. Project output reporting will be through a PEER report and conference and journal publications.

<b>Project Title—ID Number</b>	<i>Development of a Probabilistic Simplified Design Procedure for Assessing the Effects of Liquefaction and Lateral Spreading on Bridges —2432004</i>		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	CA-Trans
<b>Project Leader (boldface) and Other Team Members</b>	<b>Geoff Martin (USC/F)</b>		

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

**Project goals and objectives**

The primary objective of this research project is to develop a simplified design procedure for evaluating the effects of liquefaction and lateral spreading on bridges. This simplified design procedure must be developed to work within the PEER probabilistic performance-based engineering framework in that sources of uncertainty within each step should be incorporated properly. This project will translate pertinent PEER research findings into forms that can be adopted in practice as a probabilistic-based alternative to existing deterministic approaches. This project will attempt to demonstrate how the PEER methodology can be effectively used with simpler design-level analysis methods to make informed decisions.

**Role of this project in supporting PEER’s mission (vision)**

This project supports the PEER development and implementation of the Probabilistic-Based Earthquake Engineering methodology through the application and demonstration of the PEER methodology to the problem of evaluating the effects of liquefaction and lateral spreading on bridges.

**Methodology employed**

This Year 8 Project is planned as the first year of a three-year project to complete a development and demonstration project of the PEER probabilistic framework within the context of assessing the effects of liquefaction and lateral spreading on bridge foundations.

The PI, Geoffrey Martin, will provide technical support and review to the Year 8 research project to be conducted at U.C. Berkeley. This project (2042004-PI Professor Bray) will focus on the implementation of the MCEER/ATC-49 simplified design procedure for the evaluation of liquefaction induced lateral spread on bridge pile foundations (originally developed under the direction of the PI) within the PEER probabilistic framework.

Assumptions used in the simplified procedure will be examined and re-evaluated, and comparisons made with the Open Sees model developed by Professor Kramer and Ardino in a related project (2003-2004), U.C. Davis centrifuge studies conducted by Professor Boutanger (2012004) will also be used to provide essential calibration data for the model. Additional physical model tests using a small U.C. Berkeley shake table will also be used to provide insight to the simplified approach.

The scope of probabilistic studies are described in the work statement for Project 2042004 (Professor Bray).

**Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments**

Not Applicable

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

Not Applicable

**Plans for Year 9 if this project is expected to be continued**

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

Not Applicable

**Expected milestones & Deliverables**

Specific details of the Milestones and Deliverables are described in the work statement for Project 2042004 (Professor Bray). A summary is provided below:

The primary deliverable for this project will take the form of a technical report that will summarize the research methods used and present the probabilistic simplified decision procedure for evaluating the effects of liquefaction and lateral spreading on bridges. The goal is to demonstrate the use of the PEER methodology through its application to this problem.

The following tasks will be completed as part of this three-year project:

1. Review of previous and ongoing PEER research related to this problem.
2. Review and apply the current MCEER/ATC-49 simplified design procedure to the proposed standard bridge designs and ground conditions developed by the PEER Thrust Area 2 team.
3. Perform advanced analyses to gain insight so that simplified assumptions made in developing the MCEER/ATC-49 practical design procedure can be re-evaluated.
4. Implement the slightly revised MCEER/ATC-49 (and hopefully somewhat validated) simplified design methodology in the PEER probabilistic framework.
5. Perform three 1-g small-scale clay slope model experiments on the small shaking table in Davis Hall.
6. Perform additional analyses as required to refine and validate the proposed simplified probabilistic design procedure.
7. Prepare a report that documents the work completed and importantly demonstrates how the design method can be implemented in practice.

<b>Project Title—ID Number</b>	<i>PBEE Procedures Report for Bridges and Benchmarking Performance of RC Bridges —2442004</i>		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	CA-Trans
<b>Project Leader (boldface) and Other Team Members</b>	<b>Bozidar Stojadinovic (UCB/F)</b> , Kevin Mackie (UCB/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 project is to apply the tools for probabilistic performance assessment of highway overpass bridges. Such tools enable assessment of bridge performance in terms of the potential for bridge collapse in an earthquake, cost of repair of such a bridge after an earthquake, and the ability of the bridge to carry a given level of traffic load after an earthquake. The intended users of such tools are bridge engineers and highway system maintenance and emergency management professionals.

The objective of this project is to perform an example application of the PEER methodology to a baseline highway overpass bridge and document it. In other words, the objective is to push through the entire PEER integral, demonstrate how it works in practice and show where it is possible to make a difference. The intended users of the results of this study are: 1) PEER researchers working to enhance performance of bridges in geotechnical and structural engineering domains; and 2) Caltrans engineers who want to implement the PEER methodology in their design process.

**Role of this project in supporting PEER’s mission (vision)**

The result of this project will benefit PEER industry partners involved in bridge design and highway network maintenance and risk assessment because it will give them a tool to estimate performance of highway overpass bridges. This tool may be integrated into high-level applications that assess the performance of highway networks enabling emergency scenario planning and decision making at the level of an urban region.

This project, together with project 214, is at the core of the Trust Area 2. An array of structural (202, 207, 208, 210 and 213) and geotechnical (201, 203, 204, 205, and 206) engineering projects aimed at enhancing the performance of bridges in earthquakes will use this baseline bridge to demonstrate the enhancements they develop. The baseline bridge models and the PEER methodology implementation will be develop in this project. In Trust Area 3, this project will provide the fragility curves needed by projects 339 and 340.

**Methodology employed**

The fragility curves developed by the PIs in PEER projects 318 and 539 are used as input in the PEER integral to derive the result for the chosen testbed bridge.

**Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments**

Referring to the milestones listed below, milestones 1, 2, 3, 7 and 9 have been completed. Deliverable 1 has been completed and delivered.

Bridge Type 11 from PEER Lifeline Report 6D01 "Influence of Design Ground Motion Level on Highway Bridge Costs" by Dr. Mark Ketchum, Vivian Chang (OPAC Consulting Engineers, Inc.) and Thomas Shantz (Caltrans) has been adopted as the testbed bridge. A tool for computing the PEER integral both analytically (using Matlab) and graphically has been developed.

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

A project on the development of a risk-based methodology for assessing seismic performance of highway systems (REDARS) is conducted by MCEER under the leadership of Dr. Stu Warner with TRB funding. The differences with respect to this project 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 for the specific bridges considered, while the REDARS project uses simplified bridge models or empirical fragility curves; (2) REDARS project has a significantly wider aim, while this project is focused on rational evaluation of bridge post-earthquake operational state, repair time and cost, and aftershock collapse risk for specific baseline bridges. Interaction with other earthquake centers is ongoing: PEER project 334 will be used to continue work on a joint tri-center project that will build on our work in this area.

**Plans for Year 9 if this project is expected to be continued**

If continued, the testbed bridge developed in this project and analyzed with respect to the repair cost ratio decision variable will be analyzed further to develop the decision variables related to the remaining ability of the bridge to carry traffic loading.

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

Dr. Mark Ketchum of OPAC Inc. has been involved in the implementation of the damage and cost fragilities for this project. He has found PEER methodology quite interesting and on the way of adopting it in his own practice. Caltrans engineers are looking at this project to determine if they would consider adopting PEER methodology in their work.

**Expected milestones & Deliverables**

The milestones for this project are:

1. In cooperation with Caltrans and other design engineers select a baseline bridge design that includes abutments and structural joints.
2. In cooperation with Trust area 1 researchers and Caltrans select a set of ground motions with associated IM hazard values.
3. Develop an OpenSees model for the baseline bridge assuming good soil under the bridge and includes the abutments.

4. Compute the EDP-IM relations. Use Sa(T1) as the primary IM.
5. Using PEER Structural Element Database and concurrent Trust Area 2 projects, develop DM-EDP relations.
6. Compute DM-EDP-IM relations.
7. Using an estimate of repair cost developed in cooperation with Caltrans, compute relevant DV-DM relations in terms of repair cost ratio.
8. Complete the DV-DM-EDP-IM fragility computations.
9. Develop a report and example software applications to use the PEER methodology.
10. Help implement more sophisticated soil movement related hazard and EDP-IM models developed by other Trust Area 2 researchers.
11. Help implement more sophisticated enhanced performance element models and DM-EDP relations developed by other Trust Area 2 researchers.
12. Prepare fragility curves for traffic function loss models and DV-DM relations developed by other Trust Area 4 researchers.

The deliverables of this project are:

1. Matlab software that integrates the IM-EDP-DM-DV chain for performance assessment of overpass bridges.
2. A short report summarizing the implementation of the PEER methodology to bridges.
3. Quarterly and annual reports.
4. Final project report.

<b>Project Title—ID Number</b>	<i>Relating EDP's in RC Bridges to Damage and Decision Metrics</i> —2452004		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	NSF
<b>Project Leader (boldface) and Other Team Members</b>	<b>Marc Eberhard (UW/F), Michael Berry (UW/GS)</b>		

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

### Project goals and objectives

The overall goal of this project is to relate Engineering Demand Parameters (EDPs) to Damage Measures (DMs) and Decision Variables (DVs) for reinforced concrete bridges. Specific objectives that support this goal are:

1. finalize and disseminate recommendations for using OpenSEES to simulate column performance and estimate EDPs.
2. finalize and disseminate recommendations for using strains computed with OpenSEES to estimate the likelihood of column cover spalling, bar buckling and longitudinal bar rupture.
3. provide simulation support for Lehman and Stanton bar buckling experiments, and for implementing and evaluating the Kunnath steel stress-strain model.
4. develop methodologies to use OpenSEES to estimate a general set of EDPs, DMs and DVs for reinforced concrete bridges.

### Role of this project in supporting PEER's mission (vision)

The accuracy of the PEER methodology depends on the accuracy of the individual components. Column damage is one of the most common types of damage in bridges and buildings.

During Year 8 and Year 9, we will be expanding the range of DMs and DVs to consider other types of damage and systems. This expansion is critical to the successful implementation of PEER's research results.

### Methodology employed

The description of the project methodology is organized in four sections, according to the project objectives listed earlier.

### OpenSEES Simulation of Force-Deformation Relationships for RC Columns

Mike Berry, a PhD student at the University of Washington, is nearly finished developing recommendations for using OpenSEES to model reinforced concrete columns whose behavior is primarily flexural. Based on comparisons of calculated and measured monotonic behavior, he has developed recommendations to discretize column cross-sections, model reinforced concrete stress-strain relationships, model reinforcing steel stress-strain relationships, and integrate the

beam-column element. He is currently finalizing recommendations for setting parameters that affect the cyclic behavior of RC columns.

These modeling recommendations, along with those of other researchers, need to be collected, vetted and documented. We are finalizing our recommendations, and organizing a workshop on column modeling to gather a wider range of recommendations and to reach a consensus on “best practices”. The workshop will take place in May 2005, shortly after the annual meeting but before the NSF PEER site review on May 19-20. Preliminary, informal discussions during the annual meeting will help make the workshop efficient and productive.

The outcome of the workshop and the follow-up work will be a set of modeling recommendations for columns, which will be made available on the PEER website.

#### OpenSEES Simulation of RC Column Damage

Mike Berry is also developing a strain-based damage model, but it cannot be completed until there is consensus on the modeling methodology for columns, because the calculated strains vary with the modeling methodology. Following the column workshop, the strain-based damage models will be finalized and disseminated. Such models are needed for several other PEER projects, such as Stojadinovic’s analyses of the baseline bridges, developed based on the work of Ketchum.

#### Simulation Support and Coordination

Three other PEER projects are considering (in part) flexural damage progression in reinforced concrete columns. The experimental work performed by Lehman and Stanton, the analytical work performed by Kunnath, and the analyses of baseline bridge by Stojadinovic need to be coordinated with the standard column methodology. The results also need to be checked with the data in the PEER performance database. We will provide simulation support for the Lehman and Stanton experimental work. We will also compare the Kunnath model with the performance data in the column database. We will coordinate with Stojadinovic to ensure that EDP calculations and EDP-DM relationships are consistent among the projects.

#### General Set of Damage Measures and Decision Variables

So far, much progress has been made in modeling the flexural performance of reinforced concrete columns in bridges. Much less attention has been paid to other types of damage (e.g., residual displacements, unseating, joints) that have important consequences for bridges. We will develop a preliminary set of damage measures and relationships to decision variables that are important to bridges (e.g., closure, downtime, repair cost). During year 8, we will focus on assembling and packaging previous work (e.g., Lehman/Stanton/Lowes, Porter, DesRoches), developing an expert consensus where little data is available, and identifying strategies for improving the estimates of EDPs and DM-DV relationships.

### Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments

Mike Berry has already developed and published (*ASCE Structural Journal*, July 2005) a practical model for predicting the likelihood of cover spalling and bar buckling in RC columns based on drift ratio and key column characteristics. For a typical spiral-reinforced column, Figure 1 shows the required transverse reinforcement ratio needed to obtain a probability of bar buckling of 10%, as a function of the drift imposed on the column and the axial-load ratio.

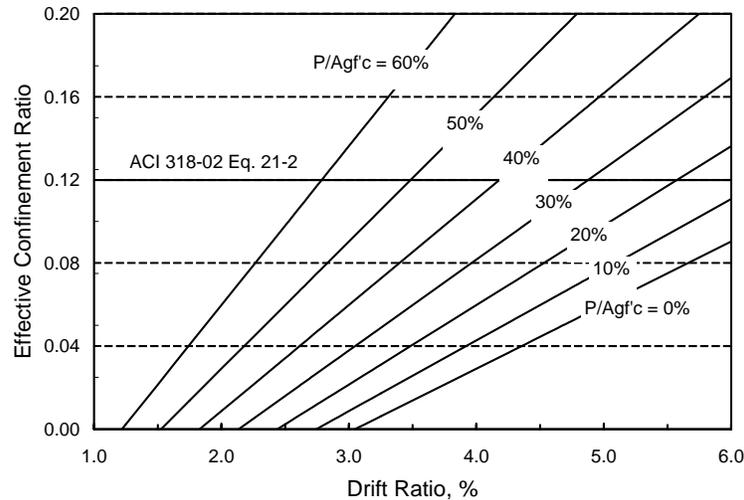


Figure 1- Transverse Reinforcement Requirements for a Spiral Reinforced Column

During the current year, recommendations are being finalized for modeling RC columns with OpenSEES. The types of bridge damage is also being widened to include elements other than columns.

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

To my knowledge, little work has been done on systematically evaluating the accuracy of OpenSEES using column data. In contrast, the Tri-Center Collaborative research has done some work on developing a general set of EDPs.

### Plans for Year 9 if this project is expected to be continued

During Year 9, we plan on considering a wide variety of damage measures for bridges, such as vertical and horizontal residual displacements, column shear failure, joint cracking, and abutment damage.

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

The Washington State Department of Transportation is considering using precast component in bridge bents. Our results have made it possible for WSDOT to consider new systems by explicitly considering likelihood of damage.

**Expected milestones & Deliverables**

Mid May: Workshop on Best Practices in Modeling RC Columns with OpenSEES

May 31: Submit informal report on column modeling recommendations

July 15<sup>th</sup>: Preliminary recommendations for general set of EDP-DM-DV relationship for bridges

Sep 30<sup>th</sup>: Submit formal PEER research report on modeling of RC columns with OpenSEES.

<b>Project Title—ID Number</b>	<i>Benchmarking Enhanced Performance of Post-Tensioned RC Piers with Ductile Materials</i> — <b>2462004</b>		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	NSF
<b>Project Leader (boldface) and Other Team Members</b>	<b>Sarah Billington (Stanford/F)</b> , Won Lee (Stanford/GS)		

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

### Project goals and objectives

The overall goal of this study is to demonstrate how the PEER PBEE methodology can accelerate the adoption of new bridge design technologies by quantitatively assessing the performance enhancement provided by these technologies. We will be demonstrating the application of the PBEE methodology while also identifying where in the process the uncertainties have the most impact on the final assessment. The demonstration will be performed on a baseline bridge also studied by other researchers in PEER's Thrust 2 area, to facilitate comparisons of performance assessment. The technologies investigated here apply to the design of bridge piers and will focus on unbonded vertical post-tensioning for self-centering, segmentally precast concrete, and high performance fiber-reinforced concrete materials for localized regions of a structure. IM-EDP and EDP-DM relationships will be developed analytically using a combination of OpenSEES modeling and where necessary, more advanced finite element (continuum) modeling. All models have been or will be calibrated against recent cyclic experiments on enhanced-performance bridge piers.

### Role of this project in supporting PEER's mission (vision)

Through this project, we will demonstrate how the PEER PBEE methodology can be applied to assess quantitatively new structural systems for structural concrete bridges, which employ post-tensioning, rapid construction techniques and new high-performance materials. This research will offer a comparison of enhanced performance systems with traditional systems studied by other PEER researchers. The extent to which reductions in post-earthquake residual displacements and concrete spalling as well as increased construction time contribute to improved performance of the bridge and its role in the highway network (considering for example bridge functionality and restoration time as decision metrics) will be assessed.

### Methodology employed

The enhanced performance system investigated here is that of unbonded post-tensioned (UBPT) bridge piers. This system is self-centering and provides the advantage of reduced residual displacements after a seismic event. This system can be applied to current cast-in-place construction or can incorporate many innovations for further enhanced performance. Innovations include the use of precast concrete for construction efficiency and improved concrete durability, and the use of damage-tolerant fiber-reinforced concrete in hinge regions for added hysteretic energy dissipation and reduced spalling. A combination of standard and innovative versions of the UBPT bridge pier system will be investigated here and it is envisioned that investigation of the many versions will continue beyond Year 8.

To demonstrate the application of the PEER PBEE Methodology to the assessment of new technologies, we will develop IM-EDP-DM-DV relationships for a baseline bridge that will be studied by several researchers in Thrust Area 2. The IM-EDP and EDP-DM relationships will be developed analytically, as there is not enough experimental data on the enhanced performance systems to create experimentally-based fragility relationships. However all analytical models will be calibrated with the available cyclic and seismic data available from UBPT bridge pier experiments. Furthermore, agreement among other Thrust 2 researchers on modeling approaches and parameters will be sought. Fragility curves representing the EDP-DM relationships will be developed using first order second moment (FOSM) methods. DM-DV relationships will be estimated for this demonstration project and will be modified in future years as more information from designers and contractors becomes available for repair costs of these new systems. The initial focus in Year 8 will be on DVs related to repair costs and to post-earthquake residual strength (vertical and lateral).

With a heavy reliance on simulation to assess enhanced performance bridge piers, model calibration and validation against experiments is essential. As stated above, the modeling approaches used here will be calibrated with recent cyclic and seismic experiments on UBPT bridge piers using models of varying complexity from simple macro-models to detailed finite element analyses. An example of a simulation of an experiment on UBPT bridge piers is shown in Figure 1. The varying levels of complexity in modeling are necessary to understand the global and local performance and to assess the ability of these models to be used as design tools in the future. Furthermore, several simple experiments are being considered by PI Mahin in a related project to investigate further different design details, materials and construction methods for enhanced performance piers. Collaboration between that project and this will greatly benefit the outcome of the PBEE assessment of enhanced performance piers.

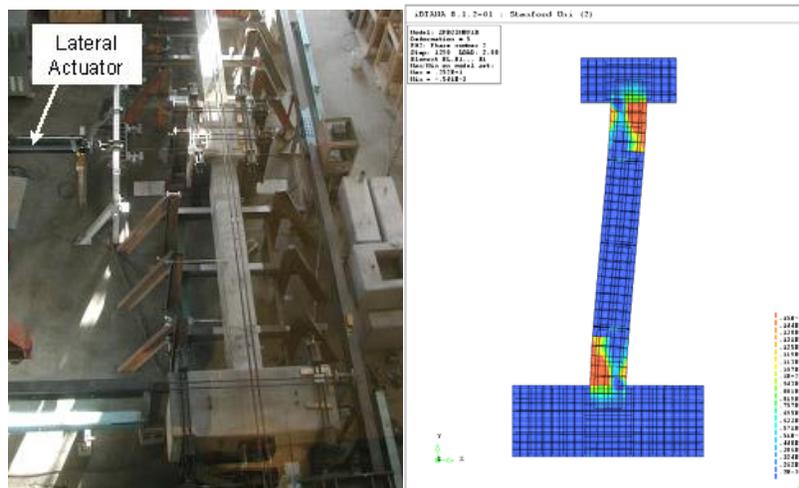


Figure 1 - Test set-up for large-scale experiments on UBPT bridge piers (left) and the tensile strain distribution in a specimen under cyclic lateral load (right) from a nonlinear finite element analysis

**Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments**

Our progress to date includes:

- Conducted detailed analysis of large-scale experiments on unbonded post-tensioned bridge piers and identified appropriate DMs.
- Calibrated finite element analysis approaches with large-scale experimental results
- Identified damage measures (DMs) and engineering demand parameters (EDPs) for enhanced performance.
- Developed fragility information using analytical models of designs of precast segmental post-tensioned bridge piers following CalTrans specifications where possible. The pier designs were for an overpass that PI Stojadinovic had studied previously for traditional reinforced concrete systems.
- Began developing IM-EDP relationships for enhanced performance piers.
- Expected Year 8 accomplishments:
- Verification of simulation methods in OpenSees of unbonded post-tensioned bridge piers with ductile cement-based materials, including implementation of material model in OpenSees.
- Development of IM-EDP-DM relationships for enhanced performance bridge pier system using recently selected Thrust Area 2 baseline bridge. These will be developed using the OpenSees platform.
- Comparison of results of enhanced performance system to those of traditional system.

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

Within PEER, a similar step-by-step approach for demonstrating the PBEE methodology has been carried out by PI Stojadinovic for a traditional reinforced concrete highway bridge. The project proposed here will follow closely behind Stojadinovic's project – to facilitate the comparison of traditional and new structural systems. PI Mahin is also investigating enhanced performance bridge piers with an emphasis on experimental studies, offering further opportunities for collaboration with the project proposed herein.

The PI has conducted analytical work related to UBPT bridge piers through prior research and has investigated such enhanced performance systems (that included using damage-tolerant fiber-reinforced concrete in hinge regions) through cyclic experiments and some simulation work through an NSF Career project. While other experimental work related to UBPT bridge piers is or has been conducted in Japan (Ikeda) as well as at The University of California at San Diego (Priestley and Seible), the PI is not aware of other researchers conducting detailed simulation work related to UBPT bridge piers. Macro-modeling has been conducted for other self-centering construction practices such as the hybrid frame (PRESSS System – modeling by Cheok for instance). Finally, PEER researchers Eberhard and Stanton are currently working on a project for the Washington DOT related to investigating precast construction for bridge decks and substructures to be used in seismic regions. A goal of this project is to identify potentially promising precast systems for the Washington DOT.

**Plans for Year 9 if this project is expected to be continued**

1. More detailed development of DM-DV relationships

2. Investigation of alternate combinations of UBPT, precast techniques and high performance concrete materials for PBEE demonstration and enhanced performance assessment.
3. Experimental shake-table testing in collaboration with PI Mahin in particular for incorporating damage-tolerant fiber-reinforced concrete materials into bridge piers. These materials have never been tested dynamically. Further validation of alternate combinations of new technologies (above) for enhanced performance piers
4. Incorporation of advantages of rapid construction technique into new technology assessment

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

The PI is not aware of any direct use of her results related to seismic design in industry. However companies have expressed interest in using unbonded post-tensioned bridge pier systems for upcoming projects. Additionally, there has also been company interest on applications of the damage-tolerant fiber-reinforced concrete materials (e.g. LaFarge, Kuraray Co., Ltd.). The PI is currently collaborating on research with LaFarge.

**Expected milestones & Deliverables**

A comparison of an enhanced-performance system to a traditional system using the baseline bridge adopted by Thrust Area 2 in Year 8. This comparison will cover the various areas of the PEER PBEE methodology:

1. IM/EDP relationships
2. EDP/DM relationships
3. Identification of appropriate DVs and initial estimations for DM/DV relationships.

This comparison will be prepared as a report beginning in Year 8 and will be completed in Year 9. The report will assess the behavior and performance of the enhanced performance system in comparison to the traditional system, as well as provide a detailed summary of the procedures used in performing the assessment.

<b>Project Title—ID Number</b>	<i>Performance Assessment of Reinforcing Bar Anchorage and Buckling Effects in RC Piers — 2472004</i>		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	NSF
<b>Project Leader (boldface) and Other Team Members</b>	<b>Dawn Lehman (UW/F)</b> , John Stanton (UW/F), Dylan Freytag (UW/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 this research project is to quantitatively study parameters that influence the occurrence of bar buckling in bridge components and to develop data to validate and calibrate models. Study of previous research results suggests that bar buckling is influenced by the response of the longitudinal steel, which is in turn affected by the strain history, the type of steel, and the lateral restraint on the bar, which is typically provided by the transverse reinforcement and the cover. Most previous research studies have focused on the longitudinal steel response and have resulted in models which modify the steel constitutive law to account for bar buckling. However, experimental research shows that neglecting the influence of the lateral restraint limits the applicability of these models. In this study, the restraint and other salient parameters will be considered explicitly using experimental research methods. The projects will result in reliable experimental data for supporting the development and validation of bar buckling damage and simulation models (in development by others within the PEER research community).

### Role of this project in supporting PEER's mission (vision)

Within the field of bridge engineering, a primary mission of the PEER is to develop tools and technologies to enable practicing engineers and transportation agencies to conduct performance-based earthquake engineering in a reliable manner. The seismic performance of bridges depends on the response of and damage to the columns. Previous research indicates that columns which sustain buckling of the longitudinal bars are not repairable and replacement of part, or all, of the column is required (Elkin et al. 2001) which indicates its importance in performance assessment. However, previous studies have not resulted in models that reliably predict bar buckling. In conjunction with other PEER research, this project will result in these much needed models, including damage models (Eberhard) as well as models to predict system performance (Kunnath).

### Methodology employed

Initiation of bar buckling is a critical event in the response history of a column, because it usually leads to the fracture of the spiral at the peak of the buckled region. Experiments designed to explicitly study the effects of salient column parameters on bar buckling are needed because the event is difficult to observe and, in most previous experiments, no special instrumentation has been used to detect it. The study discussed herein was developed to specifically study the parameters the influence bar buckling. A specific portion of the research will be devoted to developing special instrumentation for the detection and monitoring of bar buckling. The experimental data will be analyzed and compared with the digital video and photographs. The

results from the data analysis will be used to evaluate the existing bar buckling models. The research will be conducted in collaboration with other PEER researchers who will assist in finalizing the experimental program by sharing their research findings related to bar buckling. Upon completion of the experiments, the data will be used to make advances in the available models for bar buckling.

#### **Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments**

The overall research program is multi-phased and includes:

- Review and analysis of previous data and damage models (Year 7)
- Development of Instrumentation to Monitor Bar Buckling (Year 7)
- Test Series 1: Lateral Restraint Mechanisms (Year 7/8)
- Test Series 2: Displacement History and Other Salient Parameters (Year 8)
- Data Analysis and Distribution (Year 8)
- Model Evaluation and Modification (Year 8)

During the first phase of the Year 7 research, previous experimental and analytical research results were gathered, studied, and evaluated. From these studies, the following parameters were deemed most influential:

- (a) Drift History
- (b) Spiral Reinforcement Spacing and Size
- (c) Cover Dimensions and Material Properties
- (d) Material Properties of Longitudinal Reinforcement
- (e) Axial Load.

Previous researchers have emphasized the importance of drift history and axial load ratio on the onset of bar buckling (e.g., Kunnath et al. 1997, Kowalsky and Moyer 2001). In some cases, researchers have used experimental and/or analytical techniques to study bar buckling on isolated bars (e.g., Gil-Martin et al. 2005). However, these studies consider bar buckling between two ties or spirals and do not properly consider the impact of the lateral restraint along the length of the buckled bars. Study of column tests indicates that in columns meeting modern seismic code specifications, bars buckle over more than one tie spacing, as shown in Figure 1 (e.g., Lehman and Moehle 1998, Calderone et al. 1999). In addition the cover may function to temporarily restrain the bar. For example, columns constructed using engineered cementitious composite materials within the plastic hinge zone have delayed spalling of the cover which delays or prevents bar buckling (e.g. Saiidi 2005).



*Figure 1 Bar Buckling*

To study the parameters that influence bar buckling, one-third scale models of full-size bridge columns (20-inch diameter circular columns with No. 5 longitudinal reinforcing bars) will be tested. Currently, concrete-filled tube columns of similar dimensions are being tested by Professors Lehman and Roeder (shown in Figure 2) and the research team will use this testing apparatus for these column tests. During testing, photographs and digital video will be taken. Data will be gathered including loads, displacements, average segment curvatures, and bar strain, as well as data from the instrumentation specially developed to monitor the bar buckling. The instrumentation will be concentrated on the region of the column where bar buckling is expected. The time markers on the electronic data and the video will be coordinated so that the visual observations of column damage can be correlated with the measured data.

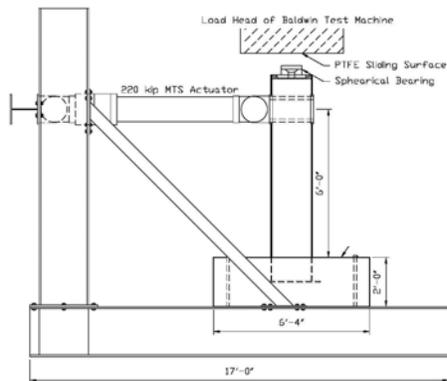


Figure 2 Test Apparatus

After completion of Test Series I and evaluation of the data, the research team will provide the data to Professors Kunnath and Eberhard for analysis. The three research teams will gather to discuss their findings and to develop a second test series. It is expected that at least one pair of the specimens will study drift history where the specified histories will be developed specifically to study or verify proposed models and hypotheses on the manner in which bar buckling is influenced by the strain history. This technique was used by Moyer and Kowalsky (2001) and proved beneficial in improving the understanding of, in that case, the

influence of the tensile strain demand on the onset of bar buckling. Once formulated, the second series of specimens will be constructed and tested.

The final phase of the research project will combine the findings from Test Series I and II. First, the experimental data will be analyzed and compared with the digital video and photographs. The results from the data analysis will be used to evaluate the existing bar buckling models. Finally, the experimental findings will be used to make advances in the available models for bar buckling.

#### **Other similar work being conducted within and outside PEER and how this project differs**

Previous researchers, within and outside of PEER, have developed models to predict the occurrence of bar buckling (e.g., Eberhard, Pantazopoulou, Bayrak and Sheikh). Experimental programs have identified approximately the onset of bar buckling (e.g., Lehman and Moehle, Henry and Mahin, Eberhard and Stanton). However the experimental research programs have not been developed to specifically study the parameters that influence bar buckling, in particular the restraint provided by the cover concrete and the transverse reinforcement. This study will provide a much needed understanding of and a reliable experimental data set for the influence of salient column parameters on the onset and occurrence of bar buckling. The research results will be useful to PEER researchers to calibrate and validate performance and simulation models, and to bridge engineers to predict bar buckling.

#### **Plans for Year 9 if this project is expected to be continued**

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

### **Expected milestones & Deliverables**

The research will provide reliable bar buckling data for PEER and other researchers, better understanding of the phenomenon and improved damage models for bar buckling. More specifically, the project may provide:

- Practical guidelines outlining the range of application, and the limits, of existing bar buckling models
- Improved understanding of the mechanism of bar buckling
- Local data to support the development of advanced bar buckling models for performance-based assessment and design
- Improvements to existing damage models for bar buckling and cross section fatigue

The research program is a continuation of the Year-7 effort. The specific Year-8 research milestones include:

- Coordination meetings with PEER researchers (two meetings are proposed ~ one at the start of Year 8 and a second after completing Test Series I)
- Generation of experimental data for validation and calibration of performance and analytical models.
- Improvement of a practical performance model to predict bar buckling

The program deliverables include a critical evaluation of existing performance and analytical models for bar buckling, a set of reliable experimental bar buckling data including column performance and data, and an improved performance model for bar buckling.

<b>Project Title—ID Number</b>	<i>Transportation Network Design Following a Large Metropolitan Earthquake —2502004a</i>		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	CA-Trans
<b>Project Leader (boldface) and Other Team Members</b>	<b>Yue Yue Fan (UCD/F)</b> , Changzheng Liu (UCD/GS), Lydia Kan (UCD/US)		

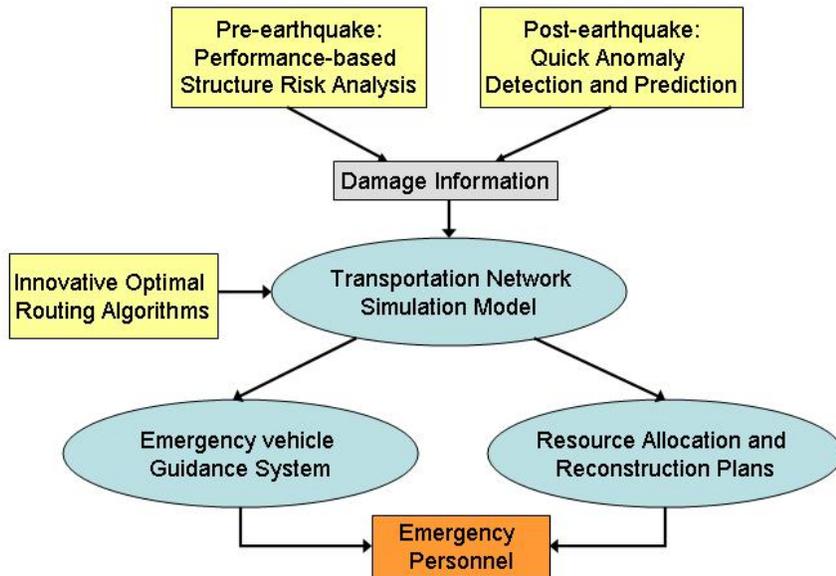
*F=faculty; GS=graduate student; US=undergraduate student; PD=post-doc; I=industrial collaborator; O=other*

**Project goals and objectives**

To ensure a high level of reliability for continued operation of the transportation system following an earthquake.

**Role of this project in supporting PEER’s mission (vision)**

The project links the performance-based seismic risk analysis of individual structures to the overall performance of the entire transportation network. It integrates multi-disciplinary topics (including structure engineering, transportation engineering, probability theory and stochastic processes, and operations research) to help disaster mitigation planning and to achieve better social-economic outcomes.



**Methodology employed**

The major part of this research is to develop an optimization model, in which the objective is set to be

1. minimum total time delay between critical facilities following earthquakes, or
2. maximum reliability of travel time between critical facilities, or
3. maximum level of connectivity between critical facilities.

The constraints include limited recourses for retrofitting or reconstruction, and the relationships describing network dynamics. This model can be considered as an integration of network design

problem and stochastic path-finding problem. A picture showing the overall framework of this project is below. The spatially distributed network data and results will be maintained and represented using geographic information systems. The San Francisco Bay Area is used as the test-bed.

**Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments**

In our previous work on seismic risk analysis of highway networks for PEER and other sponsors, we developed models for assessing the total economic loss due to transportation network disruption caused by given earthquake scenario. We focused on travel time as the network performance measure, and converted time to its monetary value based on a regional survey. Our previous work for PEER has allowed us to incrementally and substantially improve our initial efforts, first by modifying network flow models to account for how reduced level of service on the network suppresses demand for transportation services, and most recently by estimating the economic value of trips foregone when demand for travel is reduced.

Our previous work on the economic loss assessment provides the basic information need to complete standard cost benefit analyses with respect to allocating resources for disaster mitigation. Our long term goal is to determine which mitigation projects should be undertaken. In the next three years, we propose to study how to allocate given resources in order to improve the overall reliability of transportation network and how to route emergency vehicles in order to improve the efficiency of emergency response, subject to seismic risks and (by extension) other disasters. The reliability measure will include all three of the aforementioned definitions.

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

This work will produce results that can be incorporated into the MCEER/FHWA REDARS model. Current risk analysis packages such as HASUZ developed by the National Institute of Building Sciences (NIBS) for Federal Emergency Management Agency (FEMA) and the MCEER/FHWA REDARS (Risks from Earthquake Damage to Roadway Systems) only provide estimation on the loss caused by earthquakes, but do not have a module for optimizing mitigation and emergency response plans, which are in fact the overarching goal of seismic risk research.

**Plans for Year 9 if this project is expected to be continued**

In year 8, our focus is on mathematical modeling and numerical implementation. In Year 9, we plan to integrate the optimization model into geographic information systems, so that the projects results can be better understood and utilized outside of network analysts, particularly by relevant social scientists and policy makers. In the next two years, we also plan to integrate the optimization model to the current version of REDARS model, so that the entire procedure from risk analysis to optimal decision making on disaster mitigation and emergency response can be automated.

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

Our previous collaborative work with ImageCat and Stu Werner on REDARS model has been used for consulting work on seismic risk analysis.

**Expected milestones & Deliverables**

In the end of year 8, we expect to have a mathematical model and feasible numeric methods for optimal vehicle routing and network design in given earthquake scenarios. In Year 9&10, we expect to integrate the proposed optimization model into GIS and REDARS and automate the entire analysis procedure. Annual report on the project progress will be submitted and the software developed by our project team will be made available immediately to PEER and other public agencies and researchers.

<b>Project Title—ID Number</b>	<i>Implications on PBEE Assessment on Bridge Design Standards and Practice — 2522004</i>		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	CA-Trans 18081
<b>Project Leader (boldface) and Other Team Members</b>	<b>Mark Ketchum (OPAC Engineers/F)</b> , Kwong Cheng (OPAC/I) Vivian Chang (OPAC/I) Francis Drouillard (OPAC/I) Eric Lin (OPAC/I)		

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

**Project goals and objectives**

Provide input and feedback to PEER bridge researchers on current practice in bridge engineering design and construction, and on professional implications of proposed new technologies.

**Role of this project in supporting PEER’s mission (vision)**

Assuring that the PEER bridge focus researchers provide technologies, tools, etc. that are applicable to bridge engineering design and construction practice.

**Methodology employed**

Review, consultation, testing, provision of design examples.

**Brief description of past year’s accomplishments and more detail on expected Year 8 accomplishments**

Provided a portfolio of bridge designs for potential application as demonstration projects of PEER methodology, provided consultation on an incremental path from simple to complex structures.

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

The primary practice of the PI is bridge engineering design, evaluation, and construction support. Academic research is a regular but not significant part of the work mix. Currently providing seismic evaluation of the SFPUC Dumbarton pipeline bridge, construction support on the 1100 ft span Hoover Dam Bypass arch bridge, etc.

**Plans for Year 9 if this project is expected to be continued**

Provide input and feedback to PEER bridge researchers on current practice in bridge engineering design and construction, and on professional implications of proposed new technologies.

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

I am responsible for design of the Berkeley I-80 pedestrian / bicycle arch bridge, the Carquinez Strait bridge, and others.

**Expected milestones & Deliverables**

Bridge Demonstration type Selection, February 2005

<b>Project Title—ID Number</b>	<i>Tri-Center Collaboration on Geographically Distributed Systems — 2532004</i>		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	CA-Trans
<b>Project Leader (boldface) and Other Team Members</b>	<b>Jack Moehle (UCB/F)</b>		

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

**Project goals and objectives**

The goal is to enhance PEER research in geographically distributed networks by strategic planning and collaboration with other earthquake centers.

**Role of this project in supporting PEER’s mission (vision)**

This project will improve capabilities in modeling geographically distributed networks and will enable simulation of performance of those networks. In so doing, PEER will be able to (a) measure performance of a network and (b) identify impacts of individual component performance on the overall system. Both of these outcomes support PEER’s mission in PBEE.

**Methodology employed**

PEER has established a joint coordination committee hired a consultant (Dr. Ron Eguchi) to assist in strategic planning and program management. PEER also supports various workshops, including participation of PEER researchers as needed.

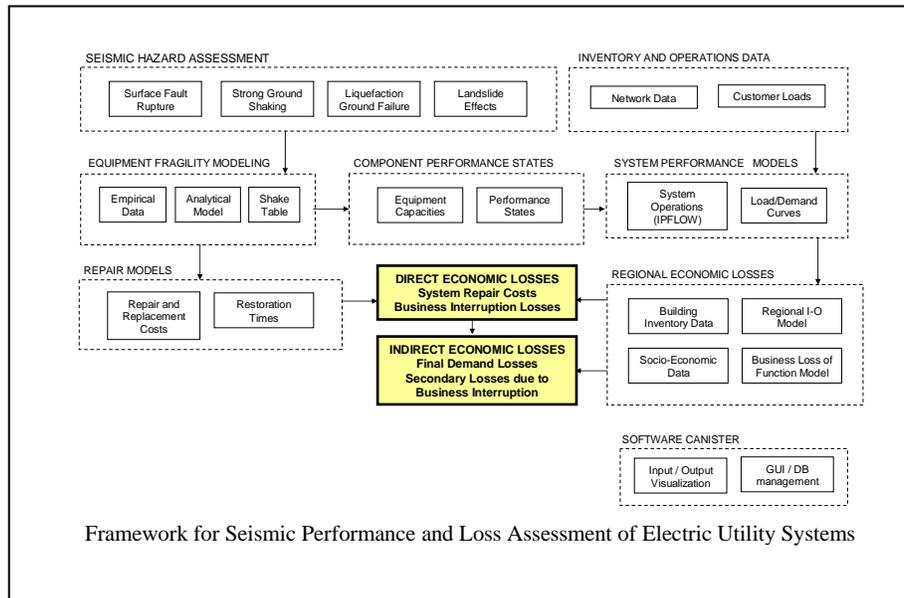
**Brief description of past year’s accomplishments and more detail on expected Year 8 accomplishments**

This is an ongoing project involving joints strategic planning activity with MCEER and MAE aimed at defining the areas of mutual interest and collaboration related to research in geographically distributed networks. We jointly formed a Tri-Center Coordinating Committee on Network Systems (TC<sup>3</sup>NS) to manage on-going research collaborations between the centers. Members are the Directors from each center (M. Bruneau, J. Moehle, A. Elnashai, Acting Director), the Deputy Directors (G. Deierlein, A. Filiatrault), the Technical Director of the MCEER-FHWA program (I. Buckle), and a representative of the PEER-Lifelines program.

Important developments include:

- Report summarizing ongoing activities and strategic planning concept, illustrated for one component of distributed systems in the accompanying figure.
- The *Transportation Seismic Risk Assessment Workshop (San Pedro, CA., June 23-25, 2003*, bringing together tri-center researchers and transportation officials (representing end users and stakeholders) to discuss the development and application of seismic risk assessment (SRA) technologies for geographically distributed transportation systems.

- *Tri-Center Annual Meeting on Geographically Distributed Systems (Las Vegas, NV, Dec. 11-12, 2003)*, bringing together about 60 investigators, business and industry partners, and representatives of transportation and utility agencies to: Coordinate research on bridge fragility relations; Prioritize research needs on transportation system performance; Define the current status and user/researcher needs to conduct seismic risk analyses of electric utility components and systems; and Examine opportunities to improve seismic risk assessment of geographically distributed systems by tri-center research to improve characterization of seismic hazards (strong ground motions and ground deformations).



- In 2004-2005, coordinated research funding in areas related to bridge fragility development and distributed transportation networks research in support of the FHWA simulation program REDARS.

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

This project coordinates work being done in PEER, MAE, and MCEER.

#### Plans for Year 9 if this project is expected to be continued

This project will continue into Year 9 with the same general plan, but will be revised in view of changes to FHWA and Caltrans funding initiatives.

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

Results from this collaboration are being used by Caltrans as it develops a model to study the expected performance of a northern Bay Area transportation corridor.

**Expected milestones & Deliverables**

Various research reports by PEER-funded researchers.

<b>Project Title—ID Number</b>	<i>1D Simulation Analysis and Surface Fault Check —1C02d</i>		
<b>Start/End Dates</b>	7/19/04—8/31/04	<b>Budget/ Funding Source</b>	Caltrans
<b>Project Leader (boldface) and Other Team Members</b>	<b>Paul Somerville (URS/I), Robert Graves (URS/I), Nancy Collins (URS/I), Hong Kie Thio (URS/I)</b>		

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

### Project goals and objectives

The objective of this report is to summarize and analyze the results of the 1D simulations done by these three groups (PEA, UNR, URS). The purpose of the analyses is to aid in the identification of those aspects of the simulations that may provide a reliable basis for addressing the scaling issues that are needed to guide the development of empirical models in the NGA-E Project. The issues are:

1. Magnitude scaling
2. and 3. Distance scaling (not addressed directly in this report)
4. Period scaling
5. Directivity scaling
6. Static stress drop scaling
7. Buried / shallow rupture scaling
8. Hanging wall / foot wall scaling

### Role of this project in supporting PEER's mission (vision)

This project is in support of the NGA-E Project, whose goal is to develop a next generation of ground motion attenuation relations for use in industry.

### Methodology employed

The simulations described in this report were generated following the Draft Plan for 1-D Rock Motion Simulation dated July 11, 2003 (Abrahamson and Chiou, 2003). The simulations were performed by Walt Silva at Pacific Engineering and Analysis (PEA), Yuehua Zeng at the University of Nevada at Reno (UNR), and Robert Graves, Arben Pitarka and Nancy Collins (URS Corporation Pasadena). The NGA Program developed guidelines for validating the simulation procedures entitled "Validation Guidelines for Numerical Simulation of Ground Motion on Rock Conditions," dated July 10, 2003 (Abrahamson and Chiou, 2003). The six events included in the validation program are: 1971 Imperial Valley, 1989 Loma Prieta, 1992 Landers, 1994 Northridge, 1995 Kobe, and 1999 Kocaeli.

Much work was devoted to confirming that the geometrical parameters used in the three sets of simulations were correctly identified and used consistently in the analysis. These parameters include fault orientations, hypocenter locations, and station locations.

The analysis approach followed that devised by Norm Abrahamson and shown at previous NGA Workshops. The results were analyzed by removing a simple distance-dependent model from the simulations for each event in the distance range of 1 – 100 km. The simple model has the form:  $\ln SA = c1 + c2 \ln \text{sqrt}(R2 + c3)$

For strike-slip, the model was fit to event SD and for reverse, to event RG. The resulting residuals are then analyzed for the various source effects listed above. Comparison of the amplitudes of individual events is done by reference to the amplitudes of the M 7 event. As an additional reference, the residuals from the Sadigh et al. (1997) model are shown in some of the figures.

This report includes 27 figures that describe the principal results for the average horizontal component. These figures are selected from a much larger set of approximately 300 figures that are contained in an accompanying CD ROM. The larger set of figures includes results for the strike-normal and strike-parallel components in addition to the average horizontal component, results for multiple distance ranges, and plots of residuals to which simple quadratic curves were fit. Most of the 27 figures in the report contain these quadratic curves, and not the residuals from which they were derived. In some cases, the quadratic curves are a crude approximation to the residuals, and it is important to examine the residual plots to get a full representation of the simulation results. The accompanying CD ROM also contains an Excel worksheet with the coefficients for the quadratic equation fit to each set of residuals. The form of the equation is  $y = c_0 + c_1x + c_2x^2$ . There is one line in the table for each of the 9 periods on a plot. Each line contains the plot outline number as given in Table 4, plot file name, period, and the coefficients c0, c1, and c2 for the equation.

**Brief description of past year’s accomplishments and more detail on expected Year 8 accomplishments**

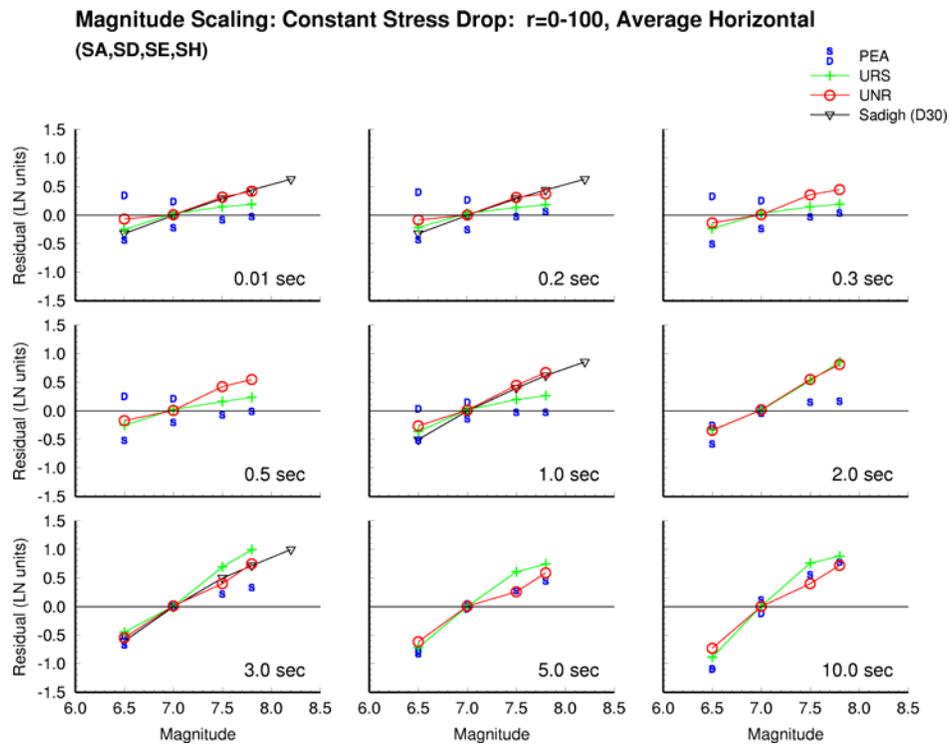


Figure 1- Magnitude scaling of spectral acceleration for strike-slip earthquakes assuming constant stress drop scaling, normalized at M 7

**Sample Results: Strike-slip constant stress drop (Figure 1).** At periods of 1 second and less, the UNR simulations show magnitude scaling similar to the Sadigh et al (1997) model for  $M > 7$ , while the PEA and URS simulations show less scaling than the Sadigh model, and approach magnitude saturation. At periods longer than 1 second, the scaling of all three simulations is closer to the Sadigh model.

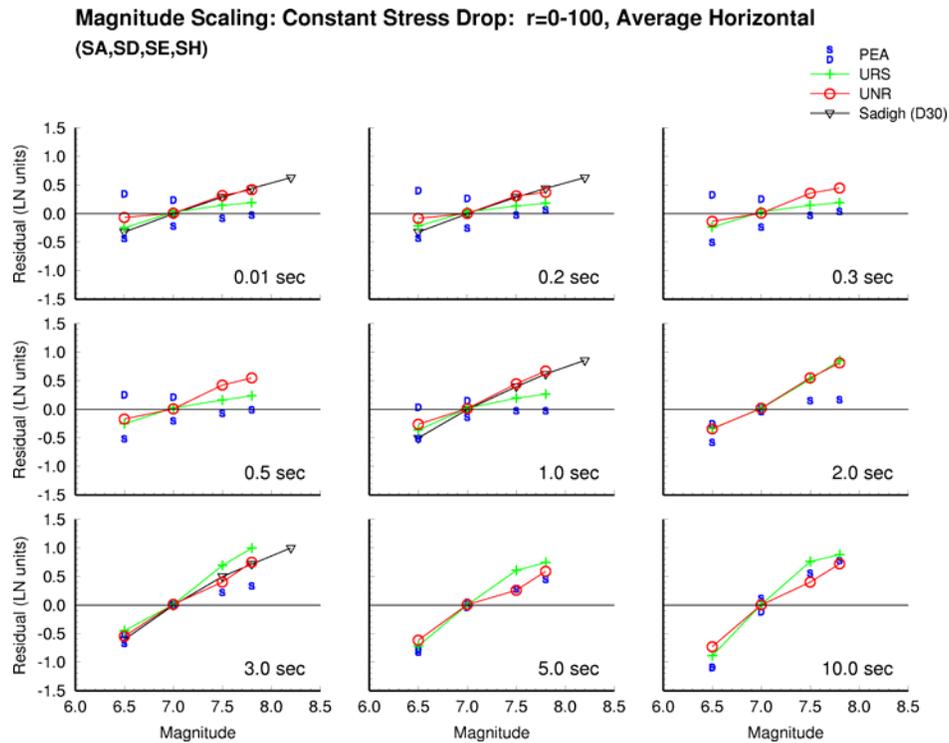


Figure 2- Magnitude scaling of spectral acceleration for strike-slip earthquakes assuming L model scaling (Hanks and Bakun, 2002), normalized at M 7

**Strike-slip L model (Figure 2).** Overall, magnitude scaling is stronger for the L model than for the constant stress drop model. The PEA simulations oversaturate at all periods for M 8.2, due to the use of constant slip velocity, but the other two simulations do not. The URS simulations have scaling similar to Sadigh for periods up to 1 second, and stronger scaling for periods longer than 1 second. The UNR simulations have scaling that is stronger than Sadigh at all periods, and have no saturation.

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

None

**Plans for Year 9 if this project is expected to be continued**

None

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

The NGA-E ground motion models will become the standard set of crustal earthquake models that are used in seismic hazard analyses in the western United States.

**Expected milestones & Deliverables**

<b>Project Title—ID Number</b>	<i>Surface Fault Rupture Design Model: Hazard Model Inputs — 1J01</i>		
<b>Start/End Dates</b>	3/1/02—3/31/04	<b>Budget/ Funding Source</b>	Caltrans
<b>Project Leader (boldface) and Other Team Members</b>	<b>Schwartz (USGS/)</b> , Dawson, T. (Consultant/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 1J project series is the development of design-oriented conditional probability models for estimating fault rupture hazard within either a deterministic or probabilistic framework.

Task 1J01 provides 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, Izmit, and others (Figure 1). These relevant inputs are: 1) a “mapping accuracy model” probability density function comparing the location of pre-rupture mapped fault traces and the actual surface rupture; 2) a “secondary fault rupture model” probability density function; and 3) quantifying effects of variable surface material (soil, rock, sediments) on rupture width and complexity. Model sensitivities are examined, and refinements are made in light of these findings and input from the technical coordination panel and project review panel.

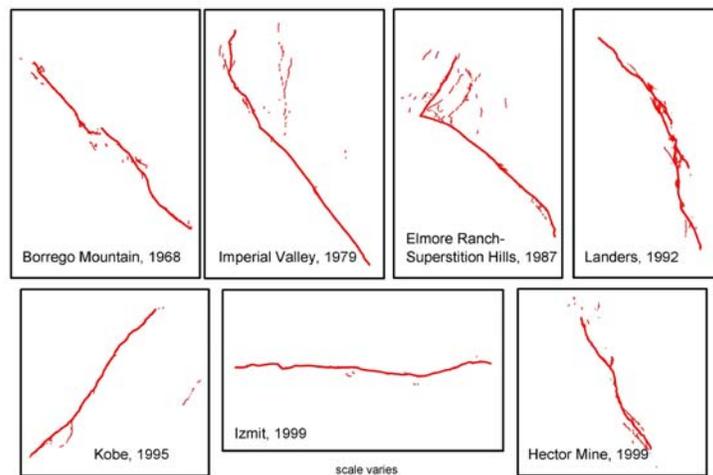


Figure 1 - Traces of faults used in analysis

**Role of this project in supporting PEER’s mission (vision)**

The result of this project provides a methodology to assess the fault rupture hazard for engineering design.

**Methodology employed**

Task 1J01 utilizes the active fault data and expertise of the US Geological Survey to develop a set of input parameters to fault rupture hazard calculations using both published and unpublished

data from major surface ruptures. These include variability of the amount 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 provide the basis for developing the methodology for fault hazard calculations.

This methodology is an extension of the probabilistic fault displacement hazard assessments used for the proposed Yucca Mountain high-level nuclear waste repository in Nevada and for the Wasatch Fault in central Utah. These studies analyzed normal-fault displacements while the 1J01 project is primarily focused on strike-slip fault displacements in regions of differing mapping quality. We have found that the actual distribution of displacements about a previously mapped fault reflects the accuracy of fault mapping and the complexity of the mapped trace. These factors were not considered explicitly in previous studies.

**Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments**

Accomplishments include:

1. Revisions of data and analysis: The data, analyses, and a test case example will be presented to the project technical review committee during Spring 2005. The technical review committee will review the methods, analysis, and results of the project. Following this review, the basic data as well as analysis will be revised based on the committee's suggestions.

2. Preparation of digital data for distribution: A major project component is the digital data compiled in the GIS. These are being compiled in a way that will allow other users to reproduce project results as well as modify the analyses for specific needs. Metadata is required for each of the GIS shapefiles, as well as explanatory text to accompany the digital data files. The digital fault rupture data are being prepared for distribution as a PEER technical report and for a broader distribution as online USGS and CGS Open-File reports.

3. Preparation of final technical reports: A final technical report summarizing the methods and results of the analysis is in preparation. This includes descriptions of the surface rupture data and GIS data as well as the results of the analysis and an example test applied to a fault in California.

4. Thrust faulting input: As originally envisioned, this project proposed the PFDHA could be extended to include thrust faults. While limited high-quality data exist for thrust fault surface ruptures, the available thrust fault observations will be integrated into the GIS database and developed for inclusion into the Probabilistic Fault Displacement Hazard Analysis database.

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

Similar work is not being conducted within PEER and we are not aware of significant work of this type being conducted outside of PEER.

**Plans for Year 9 if this project is expected to be continued**

Project work will be completed during Year 8.

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

The methodology developed by this project will be applied during 2005 to fault offset and design evaluations at locations where the BART system crosses the Hayward, Concord, and Calaveras faults.

**Expected milestones & Deliverables**

<b>Project Title—ID Number</b>	<i>Next Generation Attenuation (NGA) Models, WUS Shallow Crustal Earthquake— 1L01</i>		
<b>Start/End Dates</b>	10/1/04— 9/30/05	<b>Budget/ Funding Source</b>	Caltrans
<b>Project Leader (boldface) and Other Team Members</b>	<b>Maurice Power (Geomatrix/I)</b> , Norman Abrahamson (PG&E/I), Gail Atkinson (Carleton Univ/O), David Boore (USGS/O), Yousef Bozorgnia (PEER/F) Kenneth Campbell (ABS/I) Brian Chiou (Caltrans/I) I.M. Idriss (UC Davis/I) Walter Silva (Pacific Eng/I) Robert Youngs (Geomatrix/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 project is to develop Next Generation Attenuation (NGA) relationships for shallow crustal earthquakes in the western United States. Five attenuation relationship developer teams (Norman Abrahamson and Walter Silva; David Boore and Gail Atkinson; Brian Chiou and Robert Youngs; Kenneth Campbell and Yousef Bozorgnia; and I.M. Idriss) are developing separate sets of NGA relationships through a process that includes interaction among the developer teams and with other researchers, development of an upgraded strong motion data base, and utilization of related research results on strong ground motion.

**Role of this project in supporting PEER’s mission (vision)**

A critical element of Performance-Based Seismic Design is the estimation of the seismic ground motion to which a structure may be subjected, including the uncertainty in the ground motion. The NGA provides improved relationships for estimating ground motion as a function of the characteristics of the seismic source, source-to-site travel path, and the local soil or rock conditions.

**Methodology employed**

The NGA project is jointly sponsored and conducted by PEER Lifelines Program (PEER-LL), U.S. Geological Survey (USGS) and Southern California Earthquake Center (SCEC), with each organization actively participating in different components of the project. The methodology framework for the NGA project includes five attenuation relationships developer teams developing their own sets of NGA relationships in a process that is interactive and systematic and provides improved resources for development and review of attenuation relationships. The project includes:

1. major expansion and upgrading of the PEER strong-motion data base to provide the strong motion data and supporting information needed for the development of attenuation relationships;
2. application of research results from PEER-LL, USGS, SCEC, California Geological Survey (CGS), and other organizations to provide physical constraints on factors influencing ground motions;
3. development of improved statistical methods for analyzing ground motion data; and

4. a series of workshops, working group meetings, and meetings of the developers to present and review the data base, supporting research results, and attenuation relationships.

Research tasks and corresponding working groups supporting NGA relationship development are summarized in Table 1.

*Table 1. Technical Tasks and Related Working Groups for NGA Program*

<b>Tasks</b>	<b>Working Groups(s)</b>
<u>Task 1</u> : Dataset Development, Validation of Record Processing, and Evaluation of Fling Step Removal Procedures	WG#1a Record Processing WG#1b Fling Step Removal Procedure WG#2 Ground Motion Dataset WG#4 Source/Path Effects WG#5 Site Effects
<u>Task 2</u> : 1-D Rock Simulations and Validation of Simulation Procedures	WG#3 Validation of 1-D Rock Simulation Procedures WG#4 Source/Path Effects
<u>Task 3</u> : 3-D Simulations of Basin Effects	WG#4 Source/Path Effects WG#5 Site Effects
<u>Task 4</u> : Evaluation of Alternative Source/Path Predictor Variables	WG#4 Source/Path Effects
<u>Task 5</u> : Evaluation of Site Classification Schemes and Site Effects	WG#5 Site Effects
<u>Task 6</u> : Evaluation of Site Response Analysis Procedures and Development of Site Amplification Factors	WG#5 Site Effects
<u>Task 7</u> : Development of Statistical Methods and Tools for NGA Applications	WG#6 Statistical Modeling of Data

#### **Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments**

The project accomplishments in Year 7 are summarized as follows:

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

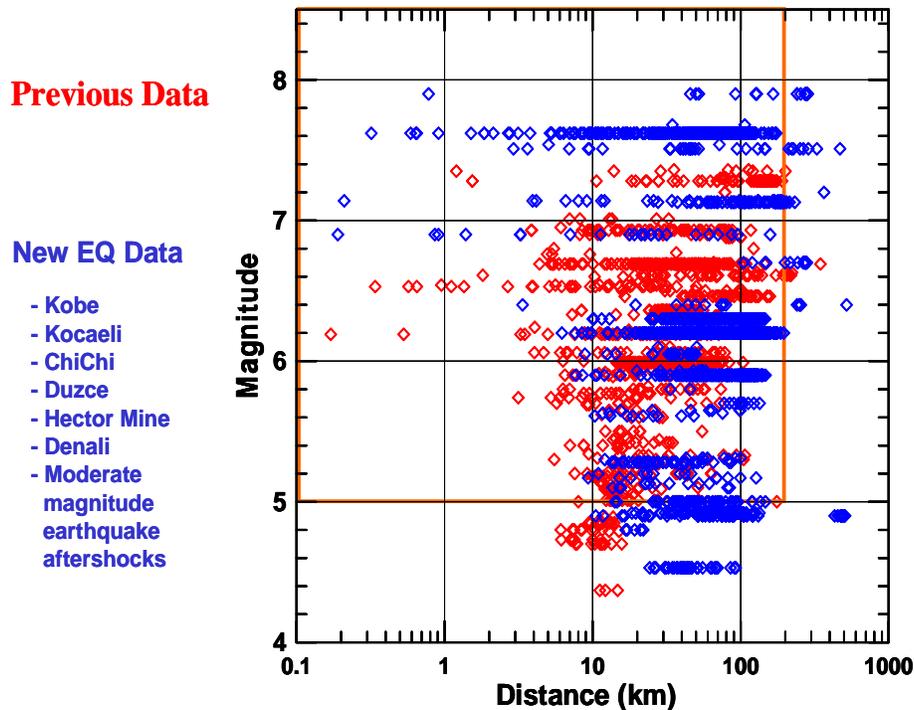


Figure 1 - Magnitude–Distance Distribution of NGA Data Base

2. Selected research and synthesis of current and previous research has developed findings from the following projects:
  - a. rock motion simulation;
  - b. basin response simulations;
  - c. site response simulations;
  - d. attenuation at moderate distances;
  - e. effects of rupture directivity on ground motions;
  - f. and synthesis of empirical studies on site response.
  
3. During Year 7, four workshops were held following a kickoff meeting and two workshops in Year 6. These workshops, each attended by approximately 40 to 45 researchers and stakeholders in the NGA project, have facilitated review of interim results for the project. Preliminary results for effects modeled in NGA relationships were presented by the five NGA relationship developer teams at Workshop #6 in July 2004. Presentations from the workshops have been placed on the PEER web site. In addition to the workshops, a number of meetings of NGA working groups and of the NGA attenuation relationship developers have been held for project review and interaction.

During Year 8, one workshop was held in December 2004, and workshops are planned for April and July 2005. The Year 8 Workshops are to present complete results of attenuation relationship development for external review by researchers engaged in ground motion development and related research and by potential users of the developed relationships (stakeholders). Meetings

of the NGA attenuation relationship developer teams have been held and additional meetings are planned to discuss issues and perform internal review of results.

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

The NGA project is unique in providing a focused effort to utilize the latest scientific knowledge and research results, a comprehensive ground motion data base, and advanced statistical analysis methods to develop a next generation of ground motion attenuation relationships for western U.S. shallow crustal earthquakes.

**Plans for Year 9 if this project is expected to be continued**

During Year 9, a review of the NGA relationships by the U.S. Geological Survey is planned. Following this review, revisions in the relationships will be made as needed, final reports will be prepared, and articles will be prepared for publication. Each attenuation relationship developer team will document their results in a report. In addition, a synthesis report will be prepared summarizing the overall project methodology, highlighting the key issues and bases for developing the relationships, and comparing the relationships with each other and with previously developed relationships. The comparisons will include examples of ground motion response spectra developed using deterministic and probabilistic seismic hazard analysis methods.

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

Because the attenuation relationships are still under development, they are not yet in use in industry. It is expected that preliminary versions of the relationships will be used by industry for comparative analysis by Summer 2005 and the final relationships will be in widespread use in 2006.

**Expected milestones & Deliverables**

Remaining milestones in Years 8 and 9 include two project workshops, publication of preliminary NGA relationships, and publication of final NGA relationships after final review. Project deliverables include five sets of attenuation relationships and reports documenting them individually and collectively. In addition, the greatly expanded, improved and well-documented ground motion data base that has been developed as a principal resource in NGA relationship development will essentially become the updated PEER web-based ground motion data base.

This database will be widely used in industry and research as a source of ground motion records for use in the seismic analysis of structures.

<b>Project Title—ID Number</b>	<i>D. Boore participation with NGA modeling— 1L03b</i>		
<b>Start/End Dates</b>	3/1/03— 6/30/05	<b>Budget/ Funding Source</b>	PG&E/CEC
<b>Project Leader (boldface) and Other Team Members</b>	<b>D. Boore (USGS/I)</b>		

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

**Project goals and objectives**

Develop ground-motion prediction equations. This sub-award is for David Boore’s contributions to the Next Generation Attenuation Model (NGA). See also description for project 1L01.

**Role of this project in supporting PEER’s mission (vision)**

See description for project 1L01

**Methodology employed**

See description for project 1L01

**Brief description of past year’s accomplishments and more detail on expected Year 8 accomplishments**

See description for project 1L01

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

See description for project 1L01

**Plans for Year 9 if this project is expected to be continued**

See description for project 1L01

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

See description for project 1L01

**Expected milestones & Deliverables**

See description for project 1L01

<b>Project Title—ID Number</b>	<i>Checking and Augmentation of NGA Database —1L09</i>		
<b>Start/End Dates</b>	5/1/03—6/30/04	<b>Budget/ Funding Source</b>	PG&E/CEC
<b>Project Leader (boldface) and Other Team Members</b>	<b>Nancy Collins (URS/I), Paul Somerville (URS/I), Hong Kie Thio (URS/I), Robert Graves (URS/I), Carla Willis (URS/I)</b>		

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

### Project goals and objectives

Review the NGA empirical database including earthquake source parameters, station distance and directivity parameters, orientation of recorded components, and station locations and other items as may be deemed pertinent. Add to the database depth to Vs isosurfaces; basin outlines at the ground surface; other basin parameters that more fully describe the geometric relation of source, basin, and site; and a flag indicating shallow vs deep asperities of fault models. Calculate residuals of 3D basin simulations with respect to the Abrahamson and Silva (1997) model. Add data from USGS processed data to the database including PGA and sampling interval from Volume 1 files and PGA, PGV, PGD, and filter information from Volume 2 files. Create summary tables of simulations results from the three modeling groups.

### Role of this project in supporting PEER's mission (vision)

This project supports the development of NGA attenuation relations which will be used widely in engineering practice to develop seismic design criteria.

### Methodology employed

See description of accomplishments below.

### Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments

We have reviewed the magnitudes and source parameters of major earthquakes in the database and documented references used. Finite fault models have been checked in detail for 13 earthquakes including four earthquakes with multiple segments (Landers, Kocaeli, Hector Mine (Fig 1), and Denali). Fault models and source parameters for an additional six earthquakes have been reviewed by literature search. Results have been documented by updating Excel spreadsheets created by the original researchers and providing notes with references.

The formula used for calculation of closest distances has been checked. Component orientations entered in the database were checked against those in the COSMOS database and any discrepancies noted on the appropriate Excel spreadsheets. We have added basin depth information to the "flat file" that had been created by Brian Chiou to summarize a number of tables developed by Pacific Engineering and Analysis (PEA).

The "flat file" was updated with data from 333 three-component Volume 1 time histories representing 40 earthquakes and 354 three-component Volume 2 time histories representing 41 earthquakes.

A table of results of simulations done by the three modeling groups (Pacific Engineering and Analysis, University of Nevada Reno and URS Corporation) was created.

For all work, reports were written and suggestions for additional tasks that need to be addressed were made.

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

**Plans for Year 9 if this project is expected to be continued**

Further checking of the component orientation will be done as well as any further checking that is required.

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

When completed, the NGA ground motion models will be used widely in industry.

**Expected milestones & Deliverables**

Formal reports have been written and updated data bases provided to PEER.

<b>Project Title—ID Number</b>	<i>NGA Amplification— 1L11</i>		
<b>Start/End Dates</b>	12/26/04-12/31/05	<b>Budget/ Funding Source</b>	Caltrans
<b>Project Leader (boldface) and Other Team Members</b>	<b>Silva (PE&amp;A/F)</b>		

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

### Project goals and objectives

- a) Extend current  $V_S(30m)$  amplification factors to higher and lower ground motion levels. Specifically, peak accelerations (NEHRPB) of 1.0, 1.25, 1.50, and 0.01g will be added for all factors and both nonlinear models (EPRI and Peninsular Range). Three more soil categories will be added corresponding to  $V_S(30m)$  averages of 400m/sec and 900m/sec as well as a soft profile ( $V_S(30m) \approx 200m/sec$ ) with nonlinear properties corresponding to Imperial Valley type soils. The current soft profile is highly nonlinear and corresponds to Bay mud which contains limited zones of Old Bay Clay and Bay mud. It is appropriate for the San Francisco Bay margin: Humboldt, California; Kobe, Japan fill and marine clay soils (e.g. Port Island); Lotung, Taiwan etc. It is not appropriate for the more linear soft soil sites such as Imperial Valley, which have clayey soil throughout the profile resulting in surprisingly linear response.
- b) Develop separate Geomatrix Category  $V_S(30m)$  correlations for Taiwan and all other regions since Taiwan appears to have a distinct bias. We will use our profile database which has many more Geomatrix Category assignments and  $V_S(30m)$  measurements than strong motion sites. This will be updated with additional Kobe, Japan SASW data received from Rob Kayen as well as the California strong motion site SASW data of Rob Kayen, for those sites which are confirmed to be adjacent to strong motion sites. We will also update the Anchorage area  $V_S(30m)$  assignments with available NEHRP category maps, resolve inconsistencies in our  $V_S(30m)$  assignments with those of reviewers Jon Stewart and Brian Chiou, add several missing Taiwan  $V_S(30m)$  measurements, address inconsistencies in Little Skull Mountain earthquake site categories, and complete our update of Z1 (Z 1.5) inconsistencies using available measurements (includes a number of Kobe earthquake recording sites).

### Role of this project in supporting PEER's mission (vision)

Amplification factors will be used in the PEER NGA project to guide development of empirical site amplification coefficients.

### Methodology employed

**Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments**

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

NONE

**Plans for Year 9 if this project is expected to be continued**

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

**Expected milestones & Deliverables**

Work completed and final report delivered in June, 05.

<b>Project Title—ID Number</b>	<i>Benchmarking of Nonlinear Geotechnical Ground Response Analysis Procedures —2G02</i>		
<b>Start/End Dates</b>	7/1/04—6/30/05	<b>Budget/ Funding Source</b>	Caltrans
<b>Project Leader (boldface) and Other Team Members</b>	<b>Jonathan P. Stewart (UCLA/F)</b> , Annie O. Kwok (UCLA/GS), Youssef Hashash (UIUC/F), Neven Matasovic (Geosyntec /I), Robert Pyke (TAGAssoft/I), Zhiliang Wang (Geomatrix/I), Zhaohui Yang (UCSD/PD), Walter Silva (Pacific Engineering/I)		

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

### Project goals and objectives

This project consists of a benchmarking study of nonlinear ground response analysis procedures. The project has two principal objectives:

1. Identify the conditions for which nonlinear geotechnical modeling should be performed in lieu of more approximate equivalent-linear modeling.
2. Provide clear guidelines for the use of several nonlinear geotechnical models, with particular emphasis on the selection of input parameters. By following the guidelines for input parameter selection, users of the nonlinear codes should be able to obtain stable and unbiased median estimates of site amplification as well as reasonable levels of variability when model parameters and input motions are simultaneously varied over their distributions.

### Role of this project in supporting PEER's mission (vision)

The project supports the evaluation of intensity measures (IMs), with particular emphasis on the use of nonlinear ground response analyses to evaluate site effects on ground motions and their IMs.

### Methodology employed

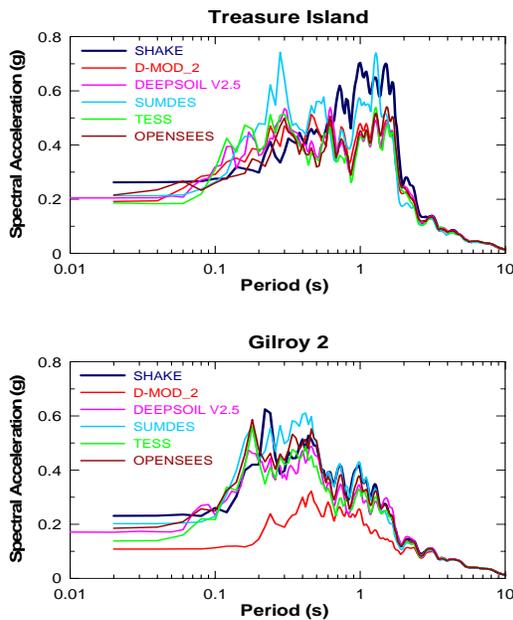
The project involves a broad array of researchers and practitioners working collaboratively. These individuals are divided into three groups. One group consists of the Management team (PI Stewart, graduate student Annie Kwok, Tom Shantz, Brian Chiou, and Yousef Bozorgnia). The second group is referred to as the “developers,” and consists of researchers that have developed nonlinear ground response analysis codes. The third group is referred to as the “advisory panel,” and consists of engineers and researchers who have significant experience with ground response analyses. By engaging the advisory panel throughout the duration of the project, we are soliciting recommendations to help guide the project to ensure that it will produce useful results.

<b>Code</b>	<b>Developer</b>	<b>Advisory Panel</b>
DEEPSOIL	Hashash, Y	Chang, Susan
D-MOD_2	Matasovic, N.	Idriss, I.M.
TESS	Pyke, R.	Kramer, Steven
SUMDES	Wang, Z.L.	Makdisi, Faiz
OPENSEES	Yang, Z.	Martin, Geoff
		Mehia, Lelio
		Silva, Walter
		Sun, Joseph

*The developers and advisory panel members are listed above.*

The project scope includes the following tasks:

1. Model parameter identification: Identify all parameters used in each nonlinear constitutive model under consideration. All model parameters should be identified as “fixed” or “free” parameters. Fixed parameters are those that would not be adjusted as part of a validation exercise. Most parameters would fall into this category. Free parameters are those for which recommended values might be established on the basis of validation exercises. Possible examples of free parameter include the frequencies used in the evaluation of Raleigh damping or the multiplier on static shear strength to obtain the ultimate dynamic shear strength of the nonlinear backbone curve.
2. Parameter selection protocols: Develop preliminary protocols for the selection of all model parameters used in each code. These protocols are prepared by the code developers.
3. Code use exercise: PI Stewart and graduate student Kwok implement each of the nonlinear codes for a set of example sites using the parameter selection protocols developed in (2). Reports are prepared for each code documenting difficulties encountered in running the codes and in selecting model parameters. Recommendations are made in the reports for how the codes and/or the users guides can be improved. Developers also run analyses for the same sites, to facilitate comparisons to Stewart/Kwok results. Developers indicate how they wish to modify their codes or users manuals in response to comments from Stewart/Kwok. A comparison of the results obtained from the nonlinear analysis codes with those obtained from an equivalent-linear code is provided in the figure below.



4. Model verification - element behavior: Simple strain histories are applied to the soil elements in the nonlinear codes to check issues like unload-reload behavior, small strain reversals, etc. Intent is to check for numerical errors in the implementation of nonlinear models in the codes.
5. Model verification - very small strain (visco-elastic) conditions: Verify the accuracy of the wave propagation component of the models by solving problems involving fixed soil parameters and simple site layering.
6. Model verification - small to moderate strain conditions: Verify the nonlinear analyses using ground motions recorded in vertical arrays without liquefaction. The strains spanned by this data set are expected to vary from small to moderate.
7. Model verification - large strain conditions: Verify the nonlinear analyses using available centrifuge test data.
8. Parametric uncertainty studies - various strain ranges:
  - a. For vertical array sites, randomize the appropriate parameters of the nonlinear soil models to represent appropriate (and pre-selected) ranges of shear wave velocity ( $V_s$ ) profiles, modulus reduction curves ( $G/G_{max}$ ), and soil damping curves ( $\beta$ ). Input

- motions will consist of recorded downhole motions (producing small to moderate strains) and synthetic waveforms (producing large strains). Evaluate the parametric variability of the results to identify the input parameters to which the results are most sensitive.
- b. For vertical array sites, fix the parameters of the nonlinear soil model that control  $V_s$ ,  $G/G_{max}$ , and  $\beta$ , and select an appropriate range for other model parameters, such as a viscous damping term. The parametric variability of the results will be evaluated.
9. Parametric studies involving selected codes: Perform analyses targeted at identifying the benefits of nonlinear ground response analyses relative to equivalent linear.

#### **Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments**

We have completed Tasks 1-3 above and have mapped out a detailed plan for Task 4. By the end of the first year of project funding, we hope to complete verification work up through Task 6. The remaining work indicated above will be performed in the second year of the project.

#### **Other similar work being conducted within and outside PEER and how this project differs**

There have been previous benchmarking studies such as VELACS, but little has come out of them in terms of the follow-up required to resolve user concerns. The multi-investigator, collaborative nature of this project is unique; we do not believe that any similar effort is being undertaken at present.

#### **Plans for Year 9 if this project is expected to be continued**

Not applicable

#### **Describe any instances where you are aware that your results have been used in industry**

The 2G01 and 2G02 project series will benefit practice by providing guidelines on how to perform nonlinear ground response analyses and under what conditions such analyses are beneficial with respect to equivalent linear methods as well as more approximate techniques such as amplification factors. The 2G01 results have found their way into Caltrans guidelines for site response analysis (Roblee, personal communication). Since 2G02 remains in progress, the results have been implemented to date (to our knowledge).

#### **Expected milestones & Deliverables**

Major meetings of all project participants include the following:

- Meeting #1 – September 21, 2004: Introduction to project. Discussion of model parameters. Agreement on first task being code usage exercise
- Meeting #2 – February 15 2005: Reviewed results of code usage exercise. Planned validation effort
- Meeting #3 – Summer 2005: Review results of validation exercise, plan parametric studies

- Meeting #4 – Winter/Spring 2006: Discuss results of parametric studies and final project deliverables.

Deliverables include a project web page (below), final report, journal papers and conference presentations.

<http://cee.ea.ucla.edu/faculty/jstewart/groundmotions/PEER2G02/index.htm>

<b>Project Title—ID Number</b>	<i>Benchmarking of Nonlinear Geotechnical Ground Response Analysis Procedures— 2G02a</i>		
<b>Start/End Dates</b>	7/1/04—6/30/06	<b>Budget/ Funding Source</b>	Caltrans
<b>Project Leader (boldface) and Other Team Members</b>	<b>Silva (PE&amp;A/I)</b>		

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

### Project goals and objectives

The project objective is to evaluate five different nonlinear site response simulation methodologies using both recorded and simulated motions. In particular, guidelines will be developed for each methodology describing how simulation parameters may be uniquely developed from typically available site specific as well as generic static and dynamic material properties. The guidelines will also include implementation manuals with sufficient detail to permit easy used by geotechnical engineers.

### Role of this project in supporting PEER's mission (vision)

The project is intended to evaluate various nonlinear site response methodologies and develop guidelines for their implementation in developing site-specific design motions. The results are intended for direct utilization by industry.

### Methodology employed

The guidelines will be produced by the code developer with validation exercises performed by the principal investigator. The code developers will participate as consultants as follows:

1. Youssef Hashash, University of Illinois
2. Neven Matasovic, GeoSyntec Consultants
3. Robert Pyke, TAGAssoft, Engineering Portal Ltd
4. Zhiliang Wang, Geomatrix consultants, Inc.
5. Zhaohui Yang, University of California, San Diego

### Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments

Two workshops with the code developers have taken place. The workshops were to define calibration exercises.

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

### Plans for Year 9 if this project is expected to be continued

This is a two year project, more workshops are planned to present/discuss additional validation exercise and code implementation guidelines.

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

**Expected milestones & Deliverables**

For each nonlinear methodology, implementation guidelines and validation results will be included as a final report and made available on the PEER web site. Validation results will be published in a industry journal.

<b>Project Title—ID Number</b>	<i>Archiving &amp; Web Dissemination of Geotechnical Data II—2L02a</i>		
<b>Start/End Dates</b>	3/31/04—6/30/04	<b>Budget/ Funding Source</b>	PG&E/CEC
<b>Project Leader (boldface) and Other Team Members</b>	<b>Carl Stepp (COSMOS/F), Jennifer Swift (USC)</b> , Jean Benoit (UNH), Loren Turner (Caltrans), Joe Futrelle (UI NCSA), John Bobbitt (POSC), Dan Ponti (USGS)		

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

### Project goals and objectives

Develop a Pilot system for archiving and web dissemination of geotechnical data and plan and conduct a workshop to review and obtain input and consensus of the geotechnical community.

### Role of this project in supporting PEER's mission (vision)

This project supports PEER Lifelines research. It is focused on integrating distributed geotechnical databases and developing optimal methods for data archiving, transfer and dissemination that serve researchers, practitioners, private companies and public agencies that use geotechnical data.

### Methodology employed

The project methodology integrated in a highly coordinated project the participation of IT researchers, geotechnical database providers, and geotechnical practitioners to establish a baseline understanding of geo-professional practice for generating, using, archiving, and disseminating geotechnical data and information. Results of the baseline survey were used to:

1. identify users and providers of geotechnical data,
2. identify priorities for types of geotechnical data and information use,
3. determine the lifecycle of geotechnical data,
4. determine the patterns of use of geotechnical data, and
5. identify the functional requirements for a web-based geotechnical data dissemination system linking multiple database archives to a web enabled user interface.

Evaluation of the baseline results was used to define:

1. the scope of a data dictionary and geotechnical data exchange schema that would serve the needs of the geotechnical data user community for archiving and exchange of geotechnical data, and
2. to define and develop a web-based geotechnical virtual data system architecture that would provide seamless access to geotechnical databases of multiple providers.

### Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments

Year-7 focused on development of the XML data exchange schema, the completion of the data

dictionary, and the completion of GVDC harvester system. Year-8 focused on:

1. Complete of data mapping and XML translators for two of the four databases linked to the Pilot GVDC – USGS, and PG&E;
2. Developing on-the-fly query results display downloading of XML into Excel and ASCII/XML formats;
3. Completion of linking with three of the four Pilot System databases;
4. Updating the JAVA back-end;
5. Upgrading administrative JSP pages, and;
6. Development of the user interface web-page in order to provide for ease of user access to the VDC;
7. Develop a professional web page design for the user interface. The Project adopted the XML schema to implement the VDC. In order to implement the schema it was necessary to prepare translators that map each of the data providers' data into the XML schema.

A workshop was held on June 21-23, 2004 to obtain review and input from the broad geotechnical professional community. The final project report was completed in December 2004. Editing and publication of the June 21-23 workshop proceedings will be completed in Year-9.

#### **Other similar work being conducted within and outside PEER and how this project differs**

Work related to elements of the pilot virtual geotechnical data center is being done by a number of groups:

1. A geotechnical database to support seismic hazard mapping is under development by the California Geological Survey (CGS), [creal@consrv.ca.gov](mailto:creal@consrv.ca.gov). The CGS collaborated with this project to link the Geohazards Database to the Pilot GVDC.
2. The ROSRINE Geotechnical Engineering Database and Website, <http://geoinfo.usc.edu/rosrine>.
3. The USGS is developing a geologic site database and data acquisition for stratigraphic model development, [dpointi@usgs.gov](mailto:dpointi@usgs.gov). The USGS collaborated with the this project to link the USGS geologic site database to the Pilot GVDC.
4. An integrated geotechnical Database, Kobe Jibankun, for seismic hazard studies is under development at Kobe University, [ytgeotec@kobe-u-ac.jp](mailto:ytgeotec@kobe-u-ac.jp).
5. The Federal Highway Administration has developed a web-enabled deep foundation load test database, [carl.ealy@fhwa.dot.gov](mailto:carl.ealy@fhwa.dot.gov). The Federal Highway Administration collaborated with this project to hold the workshop: "National Geotechnical Management: Archiving and WEB Dissemination of Geotechnical Data", <http://www.cosmos-eq/pilot.study>.
6. The National Geotechnical Experimentation Sites Database currently can be accessed by the web, <http://www.unh.edu/nges>.

These single databases are or will be, web-accessible. None however, link multiple databases in a virtual system that can be accessed simultaneously from a single user interface.

#### **Plans for Year 9 if this project is expected to be continued**

Plans for Year-9 are to:

1. Modify the COSMOS-PEER LL Pilot GVDC XML Schema as recommended by the June 21 – 23 workshop participants and modify server-side and client-side COSMOS/PEER-LL Pilot GVDC system architecture to support updated versions of the COSMOS/PEER-LL Pilot XML Schema.
2. Expand the Pilot GVDC Dictionary Standard to include velocity logs, laboratory geotechnical data, and insitu geotechnical soundings.
3. Develop a business plan for a GVDC with multiple geographically distributed sister sites that can serve the needs of geotechnical community for cost effective and efficient access to archived geotechnical data.

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

The University of Missouri at Rolla, the Missouri Geological Survey, and the Illinois Geological Survey has been granted permission to use the COSMOS-PEER LL Pilot GVDC data dictionary and XML data exchange schema products to develop a "sister GVDC site".

**Expected milestones & Deliverables**

Proceedings of the workshop “National Geotechnical Management: Archiving and WEB Dissemination of Geotechnical Data” will be published in May 2005.

<b>Project Title—ID Number</b>	<i>Modification of the COSMOS-PEER LL Pilot GVDC &amp; Imp—2L03</i>		
<b>Start/End Dates</b>	10/1/04—12/31/05	<b>Budget/ Funding Source</b>	Caltrans
<b>Project Leader (boldface) and Other Team Members</b>	<b>Carl Stepp (COSMOS/F), Jennifer Swift (USC/F), Jean Benoit (UNH/F), Loren Turner (Caltrans), John Bobbitt (POSC), Dan Ponti (USGS), Charles Real (CGS)</b>		

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

**Project goals and objectives**

1. Modify the COSMOS/PEER-LL Pilot GVDC XML Schema as recommended by the June 21–23 workshop participants and modify server-side and client-side COSMOS/PEER-LL Pilot GVDC system architecture, to support updated versions of the COSMOS/PEER-LL Pilot XML Schema.
2. Expand the Pilot GVDC Dictionary Standard to include velocity logs, laboratory geotechnical data, and insitu geotechnical soundings.
3. Develop a business plan for a GVDC with multiple geographically distributed sister sites that can serve the needs of geotechnical community for cost effective and efficient access to archived geotechnical data.

**Role of this project in supporting PEER’s mission (vision)**

This project supports 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 that serves researchers, practitioners, private companies and public agencies that use geotechnical data.

**Methodology employed**

The Project is being implemented under the direction of the Principal Investigator. Two working groups are implementing the technical tasks. Working Group 1 has primary responsibility for implementing Task 1. Jennifer Swift and Loren Turner are co-leaders of this working group. Working Group 2 has primary responsibility for implementing Task 2. Jean Benoit and John Bobbitt are co-leaders of this working group. Working Group Leaders have responsibility for the implementation of the technical work required to complete the tasks assigned to them. They coordinate their work within the Project by telephone conferences and electronic mail and in Project Integration meetings and coordinate with relevant activities external to the Project as needed to ensure the quality and completeness of their work products. Three Project integration meetings will be held during the Project performance period to ensure within project coordination of the technical work and for the purpose of evaluating the quality and completeness of subtask work products. The Project will produce four deliverables: the expanded data dictionary standard, the revised and expanded Pilot GVDC system, the Project final report, including a Users Guideline, and a long-term M&O Plan. The users guideline will be developed and included as an appendix of the Final Report and the M&O Plan will be delivered as a separate report.

**Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments**

A pilot system for web dissemination of geotechnical data collected and archived by various agencies and organization, the COSMOS/PEER LL GVDC, was completed in Year-7. The Project final report, "Archiving and Web Dissemination of Geotechnical Data: Development of a Pilot Geotechnical Virtual Data Center", was completed and submitted to PEER LL in December 2004. Review and input from the broad community of geotechnical data users and providers was obtained in a workshop held on June 21-23, 2004, which was co-sponsored by the Federal Highway Administration and included known domestic and international organizations concerned with archiving and web dissemination of geotechnical data. Workshop participants developed recommendations for continued development of the Pilot COSMOS-PEER LL GVDC. The statement of work for Project 2L03, which will be implemented during Years-8 & 9, was developed to implement these recommendations. The recommendations are grouped into three task areas:

1. Modify the COSMOS/PEER-LL Pilot GVDC XML Schema as recommended by the June 21 – 23 workshop participants and modify server-side and client-side COSMOS/PEER-LL Pilot GVDC system architecture, to support updated versions of the COSMOS/PEER-LL Pilot XML Schema.
2. Expand the Pilot GVDC Dictionary Standard to include velocity logs, laboratory geotechnical data, and insitu geotechnical soundings.
3. Develop a business plan for a GVDC with multiple geographically distributed sister sites that can serve the needs of geotechnical community for cost effective and efficient access to archived geotechnical data.

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

Work related to elements this project is being done by several organizations:

1. The Association of Geotechnical and Geoenvironmental Specialists (AGS) maintains an operational geotechnical data dictionary, AGS ML, and web-based geotechnical data dissemination site. Project 2L03 has established coordination with AGS and will work with AGS to achieve compatibility with the AGS ML schema.
2. The Commonwealth Scientific and Industrial Research Organization (CSIRO) Australia has developed a geotechnical data exchange schema, XMML, which is similar to the XML schema that has been adopted for this project, but is more general and is AGS GML compliant. We plan to establish coordination with CISRO and achieve compatibility with the XMML schema to the extent possible.
3. The FHWA working with the University of Florida has proposed to develop a GML compliant standard XML data interchange schema for geotechnical data. This proposed effort would repeat some tasks that were performed in COSMOS-PEER LL Project 2L02. We are currently reviewing the FHWA/UF proposal and will attempt to coordinate and collaborate to the extent achievable.

**Plans for Year 9 if this project is expected to be continued**

The project implementation is scheduled to continue through the December 31, 2005. Year-9 activities will consist of completing the final project reports.

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

The University of Missouri at Rolla, the Missouri Geological Survey, and the Illinois Geological Survey has been granted permission to use the COSMOS-PEER LL Pilot GVDC data dictionary and XML data exchange schema products to develop a "sister GVDC site".

**Expected milestones & Deliverables**

Tentative key project milestones are as follows:

- 04/21/05 – Workshop on data dictionary expansion
- 05/15/05 – Deliver expanded data dictionary
- 10/17/05 – Deliver draft final Project Report and draft Users Guideline
- 10/17/05 – Deliver draft long-term maintenance and operation plan
- 12/04/05 – Deliver final Project Report and Users Guideline
- 12/04/05 – Deliver final plan for long-term maintenance and operation of the GVDC

<b>Project Title—ID Number</b>	<i>Using the Downhole Freestanding Shear Device to Characterize the Dynamic Properties of Bay Mud Sites with Non-linear Seismic Response — 2P01</i>		
<b>Start/End Dates</b>	12/1/04—11/30/05	<b>Budget/ Funding Source</b>	PEER Lifelines USGS external match
<b>Project Leader (boldface) and Other Team Members</b>	<b>Micahel Riemer (UCB/F)</b>		

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

### Project goals and objectives

The primary objective of this newly awarded grant is to apply a new tool (the Downhole Freestanding Shear Device, or “DFSD”, developed through Caltrans funded research) to measure the non-linear stress-strain behavior of soft soils around the S.F. Bay margin. This will provide valuable site-specific data for use in evaluating likely site response at these locations, as well as validating the efficacy of the new method. In addition, the data obtained will allow direct comparison between laboratory and field measurements of these key properties, supporting evaluation of the degree of disturbance introduced by the traditional sampling/lab testing approach.

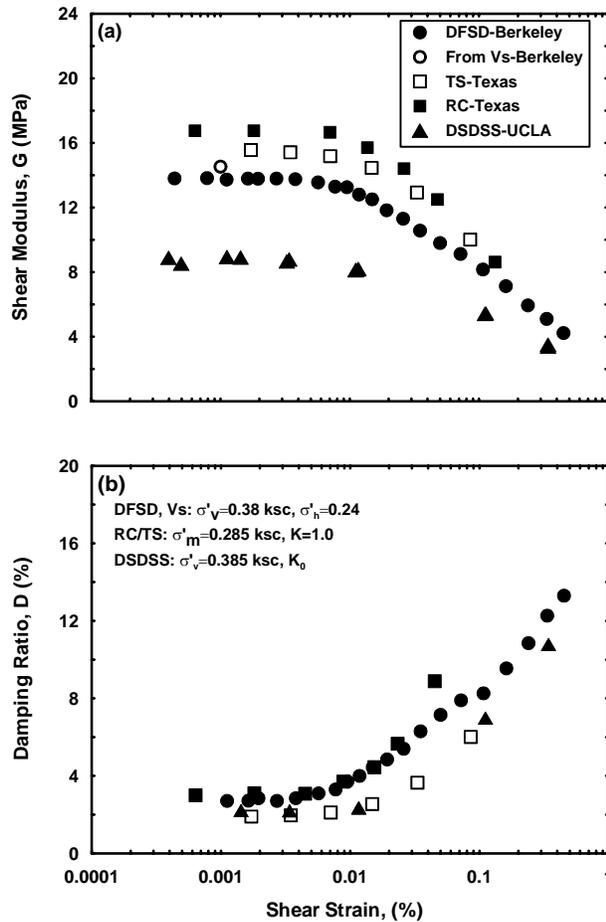
### Role of this project in supporting PEER’s mission (vision)

Predicting the seismic response of any structure depends on accurate assessment of the likely ground motions. On soft soil deposits, these motions are heavily influenced by the soil’s dynamic properties, including the dynamic stiffness and damping characteristics. This project supports improved ground motion estimates through both direct measurement, and better understanding of likely disturbance effects on laboratory measurements. This in turn will reduce the uncertainties on critical inputs to the performance-based designs of key structures built on deep, soft soil deposits around the San Francisco Bay Area.

### Methodology employed

The project will be measuring dynamic properties at up to eight sites around the S.F. Bay margin, over which the soil conditions may vary significantly. The primary advantage of this new device is its capability of making such measurements of stiffness and damping *in situ*, and over a wide range of shear strains. This allows for direct characterization of soft soil deposits at multiple depths, without subjecting the soil to the disturbance (and consequent change in properties) attributed to the sampling, stress relief, transport, and other procedures associated with conventional laboratory testing.

The capabilities of the DFSD are illustrated in the following figure, which shows the variation of shear stiffness as measured by the device compared with similar measurements made at two of the premier laboratories for such testing. In addition to the good agreement with both the velocity data and the results from UT, it is also clear that the DFSD provided data across the entire strain range of interest.



**Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments**

This project was not supported by PEER in Year 7.

In addition to the field testing using the DFSD at these soft soil sites, high-quality Shelby tube samples will also be obtained, and these will be tested in the laboratory. This will provide data for direct comparison between the methods, and should provide greater confidence in the *in situ* data, as well as a valuable look at potential effects of sampling disturbance as a function of both sample depth and soil index parameters.

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

Related work in assessing regional amplification factors are usually limited by assuming generic dynamic properties for a particular geologic unit. It has been clearly demonstrated, however, that Bay Mud properties vary substantially from one are of the

bay to another, so this project will be supplying site specific amplification information for a range of sites, thereby providing a more realistic picture of the variation of ground motion amplification for a given scenario event, or probabilistic analysis.

**Plans for Year 9 if this project is expected to be continued**

Additional sites would be tested as part of Year 9 efforts.

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

As this is a newly developed tool, just now being applied to fieldwork, the results have not yet been implemented in industry.

**Expected milestones & Deliverables**

March- June 2005	Test at initial 2 sites, modifications likely required to DFSD
May 2005	Progress Report
July – Sept. 2005	Testing at remaining sites, Initiate lab testing for comparison
October 2005	Compilation of results, synthesis of data
November 2005	Annual report

<b>Project Title—ID Number</b>	<i>Inertial &amp; Kinematic Load Combinations on Pile Foundations in Liquefying and Laterally Spreading Ground —3F03</i>		
<b>Start/End Dates</b>	4/1/04—6/30/04	<b>Budget/ Funding Source</b>	Caltrans
<b>Project Leader (boldface) and Other Team Members</b>	<b>Ross Boulanger (UCD/F), Bruce Kutter (UCD/F), Dongdong Chang (UCD/GS), Umit Gulerce (UCD/GS), Scott Brandenburg (UCD/GS)</b>		

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

### Project goals and objectives

The objective of the proposed research is to evaluate and advance the design methodologies for pile foundations in abutments or slopes subject to liquefaction-induced lateral spreading. The design methodology being investigated builds upon current practices that iteratively couple the separate analyses of lateral spreading and pile foundation response. This methodology has not been evaluated against case histories, physical models, or advanced FEM analyses, and so there remain important questions as to its limitations and capabilities.

### Role of this project in supporting PEER's mission (vision)

This project supports the Bridge Thrust area by providing the necessary experimental validation and knowledge base for the projects that will be demonstrating the PBEE methodology for bridges that are subject to liquefaction and lateral spreading hazards.

### Methodology employed

Dynamic centrifuge model tests will be used to quantify the physical mechanisms that control pile pinning effects on bridge abutments and provide the data to evaluate analysis methodologies against. The design methodologies in use at Caltrans and advocated in the NCHRP 472 guidelines for evaluating pile pinning effects will be evaluated against the experimental data. Dynamic FE analyses will be calibrated against the experimental data as well, and used in parametric studies to cover a broader range of conditions than covered by the experiments alone.

### Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments

The first dynamic centrifuge model test was designed, constructed, and tested. The model consisted of two dry coarse sand abutments facing each other across a channel in the middle. The abutments were underlain by a layer of loose sand, and then dense sand. One abutment had a row of six piles at the head of the slope, while the other did not have any piles in it.

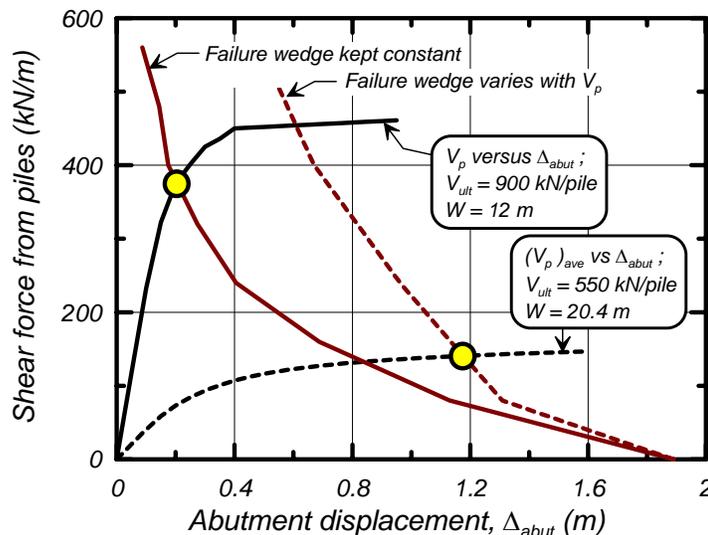
The photograph below shows the model as it is being dissected following testing.



Four separate improvements to the NCHRP 472 methodology were derived and implemented. These four changes were shown to be necessary for the design methodology to be able to reasonably agree with the observations of abutment deformations, with and without piles, in the first centrifuge test. The four modifications were:

- Explicit accounting for the effect that pile pinning forces have on the critical slope failure surface.
- Recognizing that the compatibility condition between pile pinning forces and sliding block deformations must account for the fact that the pile pinning forces increase from near zero at the start of shaking and then increase as the abutment displaces. In the NCHRP 472 procedure, this can be accomplished by determining compatibility with the displacement-averaged pile restraining force.
- Inclusion of approximately one-half of the side slope masses in the total mass that the pile and bridge restraining forces act against.
- Recognizing that internal deformations of the abutment mass can reduce the fixity of the pile above the liquefied layer, which reduces the available shear resistance from the pile foundations.

The figure below illustrates the cumulative effect of these four modifications when applied to the first centrifuge model (photo shown above). The bullet point at 0.2 m of abutment displacement is what a designer could obtain following current guidelines, while the bullet point at 1.2 m of displacement is what a designer would obtain using the recommended modifications. As the observed slope displacement in the first centrifuge test was about 1.2 m in the piled abutment, it is clear that the suggested modifications are necessary for the methodology to reasonably agree with the observed model performance.



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

RPI has indicated that they also have started performing dynamic centrifuge model tests to study pile pinning effects. We will be in contact to compare findings and coordinate future tests.

**Plans for Year 9 if this project is expected to be continued**

Complete the remaining two centrifuge tests. Evaluate the modified design methodology against the combined data set. Perform the FE analyses.

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

Findings were just presented at the US-Japan workshop in March, at which Caltrans representatives who utilize this general technique were participating.

**Expected milestones & Deliverables**

The proposed project is expected to contribute to simplified design procedures for designing pile foundations and bridge abutments in areas of liquefaction and laterally spreading ground. Each centrifuge tests will be individually documented in a standard "data report" at the Center for Geotechnical Modeling, which provides a permanent public online archive from which the other researchers can obtain full experimental records. A final report will be prepared that evaluates the design methodology proposed in NCHRP 472 against the centrifuge model tests. The final report and three centrifuge test data reports will all be submitted by May 30, 2006.

<b>Project Title—ID Number</b>	<i>Input Motions for Earthquake Simulator Testing of Electric Substation Equipment—408</i>		
<b>Start/End Dates</b>	5/1/00—6/30/05	<b>Budget/ Funding Source</b>	PG&E/CEC
<b>Project Leader (boldface) and Other Team Members</b>	<b>Fenves (UCB/F)</b>		

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

**Project goals and objectives**

The main objective of the study was to develop a set of earthquake ground strong motion time histories suitable for seismic qualification testing of electrical substation equipment in accordance with the IEEE 693-1997 standard. Although the study’s objective deals with shake table testing of a particular class of equipment, many of the issues investigated are equally relevant to the dynamic testing of other types of equipment and components. This study was motivated by a desire to introduce a standard set of input motions in three orthogonal directions, and thus achieve more consistency in earthquake simulator testing. The project is focused on developing an input strong motion based on a record of actual earthquake with a time-domain spectral matching procedure, so the spectrum-compatible strong motion time history would preserve the non-stationary behavior of the real record. Figure 1 shows the elastic response spectra of the proposed strong motion time history (TestQke4IEEE) for qualification testing of electrical equipment closely matching the IEEE 693 required response spectra.

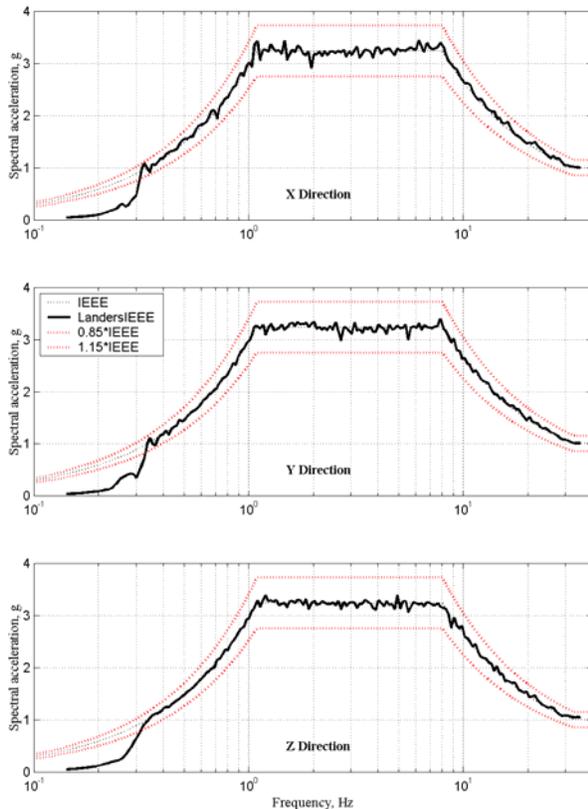


Figure 1- IEEE-compatible Landers (TestQke4IEEE) at 2% damping (1/24 octave resolution)

A selection of 35 three-component historic records from 18 earthquakes was analyzed and the records were cross-compared based on use several parameters. From the analysis the best candidate for the input strong motion was selected and modified by adding non-stationary wavelets to the signal. The resulting strong motion time history preserves the non-stationary behavior of the real earthquake record while its response spectra envelope the IEEE target response spectra in a broad range of natural frequencies as required by the standard. The resulting strong motion time history is intended for use by testing facilities, and will be considered for inclusion in a future revision to IEEE 693.

Additional requirements on the input motion generation and the IEEE seismic qualification procedure are recommended. The requirements are proposed for inclusion in the new version of the IEEE 693 standard.

**Role of this project in supporting PEER's mission (vision)****Methodology employed**

The scope of the work was achieved by means of a comprehensive theoretical study and some experimental study on an earthquake simulator performance with no specimen attached.

**Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments**

The main objective of the study was achieved and a three-component set of earthquake ground motion time histories suitable for seismic qualification of electrical substation equipment in accordance with the IEEE 693-1997 standard (IEEE, 1998) was developed. The strong motion time histories in three principal directions of testing are available for download from the Westcoast Subcommittee's web site: [www.westcoastsubcommittee.com/ieee693/qualified.php](http://www.westcoastsubcommittee.com/ieee693/qualified.php)

Along with the set of strong motion time histories, the study provides specifications for spectral matching procedure and extended requirements on the IEEE-compatible time history. The recommendations on requirements for test response spectrum (TRS) are also provided. The specifications and requirements are summarized in 'Specification for Input Motion Used in Earthquake Simulator Testing Under IEEE 693' in Appendix C of the project's report and is available on the PEER's web-site: [http://peer.berkeley.edu/lifelines/Task408\\_411/Task408.html](http://peer.berkeley.edu/lifelines/Task408_411/Task408.html). Matlab (The MathWorks, 2001) codes developed in the study form another set of the study's deliverables. The set consists of implementations of the filtering procedure and of the high cycle counting procedure in single degree of freedom system response. The codes are available at the Westcoast Subcommittee's web site provided above.

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

Shakhzod M. Takhirov, Gregory L. Fenves, Eric Fujisaki. 'Seismic Qualification and Fragility Testing of Line Break 550 kV Disconnect Switches'.

**Plans for Year 9 if this project is expected to be continued****Describe any instances where you are aware that your results have been used in industry**

The test strong motion time history (TestQke4IEEE) was used during a companion experimental study on seismic qualification of a 500-kV disconnect switch: Shakhzod M. Takhirov, Gregory L. Fenves, Eric Fujisaki. 'Seismic Qualification and Fragility Testing of Line Break 550 kV Disconnect Switches'. The newly developed requirements on the time history testing procedure have been included in the current draft version of the IEEE 693 document.

**Expected milestones & Deliverables**

The project deliverables benefit the industry by providing newly developed requirements and a strong motion time history for seismic qualification testing of electrical equipment in accordance with IEEE 693.

<b>Project Title—ID Number</b>	<i>Seismic Qualification and Fragility Testing of 500 kV Disconnect Switches—411</i>		
<b>Start/End Dates</b>	8/1/02—6/30/04	<b>Budget/ Funding Source</b>	PG&E/CEC
<b>Project Leader (boldface) and Other Team Members</b>	<b>Gregory Fenves (UCB/F)</b> , Shakhzod Takhirov (EERC/O), Don Clyde (EERC/O)		

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

**Project goals and objectives**

The objective of the study is to conduct seismic qualification and fragility testing of a single pole of 550-kV porcelain disconnect switch shown in Fig.1. Due clearance limitations above the shaking table the switch with the main blade in open position could not be tested in a typical field installation; therefore, several switch configurations were developed for testing. The 550-kV disconnect switch is tested in three configurations: mounted on typical 14 ft tall supports, mounted on a short 4-in spacer to simulate flexibility of the top plates of the supports, and rigidly fixed to the earthquake simulation platform. In the two latter configurations the switch is tested with the main blade in open and closed positions, and these configurations are used for seismic qualification testing of the open-blade switch (shown in Fig. 2) and in the experimental study for amplification factor estimation.



Figure 1 550-kV switch in the closed position mounted on supports



Figure 2 550-kV switch in the open position mounted without the tall supports.

Tri-axial tests of a single pole of the porcelain disconnect switch mounted on elevated supports are conducted by means of IEEE-compatible time history to determine its dynamic properties and to qualify the switch to the high Performance Level. A feasibility of seismic qualification

testing of tall electrical equipment with supports removed by introduction of an amplification factor due to the supports is also studied experimentally. Tri-axial time history tests of a single pole of porcelain disconnect switch mounted without the tall supports on the simulator platform is conducted to determine the dynamic properties of the pole and to evaluate its seismic response. A seismic qualification test for the switch in open blade position on the earthquake simulator platform (mounted without the tall supports) by means of use the amplification factor is performed.

In addition, the main objective of the study includes static and dynamic testing of switch components (the tall supporting legs and the insulator posts) and a study of feasibility to replace the blade with an equivalent shorter blade or a concentrated mass for seismic qualification testing of tall electrical equipment that cannot accommodate clearance above the table. The component testing also includes static cantilever tests on insulator posts to determine failure modes and equivalent cantilever loads in failure for the ceramic insulators used in the switch.

#### **Role of this project in supporting PEER's mission (vision)**

Assessment of seismic vulnerability of high voltage substation equipment and development of seismically reinforced designs.

#### **Methodology employed**

The seismic qualification testing and associated experimental study of the 550-kV switch was conducted by means of earthquake simulator. The experimental study on the switch components was consisted of low-level pull-back, free-vibration, and cantilever strength tests. The latter testing was conducted for porcelain posts only.

#### **Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments**

The disconnect switch preserved its major functions up to the highest levels of PL testing conducted in this project, without any major damage. Some anomalies occurred during the test were insignificant and minor. The restoration work did not involve any installation of new parts: the parts impacted out from their original positions were simply repositioned back in place. Therefore, the disconnect switch complied with seismic qualification criteria for PL testing, up to the level conducted in the project. Although the TRS achieved in the test program technically does not satisfy the new recommended specification for IEEE 693 (developed in a companion theoretical study: Task408) for qualification to the High Seismic PL, the deficiencies in the TRS are limited to frequency ranges not close to the important modal frequencies of the equipment. Although the TRS came close to satisfying the new recommended input motion specifications for IEEE 693, the rigid insulator post in the PL test was loaded to a level 37% beyond the rated cantilever strength assigned to this model of insulator by the manufacturer. Fracture of the porcelain insulator post did not occur during the PL test because the actual strength of the installed insulator exceeded the rated cantilever strength by over 40%. This outcome highlights the conservatism associated with insulator cantilever strength ratings.

The disconnect switch mounted on 4-in spacer with main blade in the open position and grounding blade in closed position preserved its major functions after the 1.17g target pga testing without major damage. Therefore, the disconnect switch complies with IEEE 693 criteria for PL seismic qualification testing at the Moderate Seismic Qualification Level, using the new recommended input motion specifications for IEEE 693 (developed in the companion theoretical study: Task408). In order to qualify the switch to the High Seismic Qualification Level, allowable stresses in critical elements are reviewed. Demand to capacity ratios for porcelain insulators were found to exceed allowable values by about 60%, assuming that a 1.83 amplification factor is used.

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

The qualification testing used a strong motion time history for the IEEE 693 that was developed in a companion theoretical study entitled ‘Ground Motions for Earthquake Simulator Qualification of Electrical Substation Equipment’ by Shakhzod M. Takhirov, Gregory L. Fenves, Eric Fujisaki, Don Clyde.

**Plans for Year 9 if this project is expected to be continued**

Both numerical and experimental studies should be conducted to develop a reliable procedure for estimation of the amplification factor. Such procedures or guidelines are needed in order to streamline the qualification procedure, particularly for large equipment that cannot be practically tested on their supports, and also for equipment that may be supported on several different types of support structures. In addition, the consideration of alternative methods of testing, possibly using substitute support structures which are intended to provide the same equipment response as a full-scale structure, would be valuable.

Further material studies on porcelain insulator acceptance criteria are needed. IEEE 693 acceptance criteria for qualification require a factor of safety of 2.0 and 1.0 against the “ultimate strength” of the insulator, respectively for the RRS and PL. The current practice of most utilities, manufacturers or consulting engineers is to use the rated cantilever strength as the ultimate strength of the insulator. As highlighted in the tests conducted in this project, the rated cantilever strengths of insulators are frequently set at levels representing a guaranteed minimum breaking strength. Alternative definitions of ultimate strength should be explored for use when designing for extreme events such as a large earthquake.

Differences between the stiffness of porcelain insulators in tension and compression should be investigated further. Investigations should include further tests on multiple-section insulators, porcelain material studies and tests, and collaboration with insulator manufacturers. The differences observed in this project may be significant enough to influence the outcome of qualification tests.

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

Since the disconnect switch tested represents a very common design of the 500-kV switch used by utilities, the results of qualification testing are very important for assessing the vulnerability of a electrical power transmission system during strong earthquakes.

**Expected milestones & Deliverables**

The seismic qualification testing of the 550-kV disconnect switch assessed its vulnerability and demonstrated its adequate performance during strong earthquakes

<b>Project Title—ID Number</b>	<i>Database of Seismic Parameters of Equipment in Substations—413</i>		
<b>Start/End Dates</b>	3/1/03—3/31/04	<b>Budget/ Funding Source</b>	PG&E
<b>Project Leader (boldface) and Other Team Members</b>	<b>D. Ostrom (D. Ostrom Consulting/I)</b>		

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

**Project goals and objectives**

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

**Role of this project in supporting PEER’s mission (vision)**

Reducing earthquake risk to electric utility systems.

**Methodology employed**

Monte Carlo simulation for system risk assessment.

**Brief description of past year’s accomplishments and more detail on expected Year 8 accomplishments**

- Documentation of substation equipment performance data base.
- Documentation of substation equipment installation and connectivity data base.
- Creation of hypothetical electrical system and its equipment data documentation
- Sample simulation run and data results of a hypothetical electrical system to a single earthquake scenario

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

This work is an extension and documentation of the SERAs that were done on SCE in 1990 and 1998 and EBMUD in 1993.

**Plans for Year 9 if this project is expected to be continued**

- Develop more complete equipment performance data and improve the loading metrics on which the electrical system performance is based.
- Develop system performance metrics

- Develop Return-to-service algorithms
- Combine MCEER system “return to service” work with PEER “system performance” work and conduct full SERA on hypothetical system.

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

No System Earthquake Risk Assessment (SERA) of the nature that is contained in this work has been done on an electrical system since this project was completed. This work is that documentation and extension of previous work that was done at Southern California Edison in the 1990s.

**Expected milestones & Deliverables**

Development of a comprehensive procedure for compiling seismic performance data of electric substation equipment that is tied to a network-based earthquake loss estimation methodology will enable accurate and standardized estimates of potential losses to electrical systems in earthquakes and set priorities for equipment upgrades and replacements.

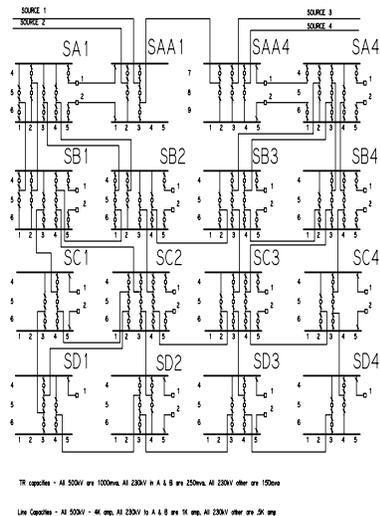


Figure 4-1 – Hypothetical System Single Line Drawing.

<b>Project Title—ID Number</b>	<i>PEER Analysis Platform for Demand Simulation — 4102004</i>		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	CA-Gen 19900
<b>Project Leader (boldface) and Other Team Members</b>	<b>Gregory Fenves (UCB/F), Frank McKenna (UCB/PD) Filip C. Filippou (UCB/F) Silvia Mazzoni (UCB/PD)</b>		

*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 design, develop, implement, and utilize OpenSees (the Open System for Earthquake Engineering Simulation), a software framework for simulation of structural and geotechnical systems. The open-source software is an important enabling technology within PEER because it allows integration of the results of research in structural performance modeling, geotechnical modeling of soils and foundations, computational methods, and advanced information technologies, such as databases and visualization. The objective of this project is to continue the development of the simulation technology. A major thrust is adapting the recent models developed for OpenSees for parallel and distributed computing. This will enable larger problems to be analyzed. This project also provides the user and developer support for many other PEER projects that are utilizing OpenSees in their research. We continue to hold workshops for both users and developers, and meet regularly with the PEER participants involved with OpenSees to assist in their research and projects.

**Role of this project in supporting PEER’s mission (vision)**

Simulation systems for engineering demand parameters (EDP) and also damage measures (DM) is central to PEER’s PBEE methodology. OpenSees is the primary software used for conducting advanced simulations of structural and geotechnical systems. It serves as means of communication within (and outside) PEER by allowing researchers access to a wide variety of community-developed models. With the advent of NEES, this is extended to community data and computational resources. The software is critical to the conduct of the PEER benchmark studies in Year 8, and the lessons-learned in the testbed projects are being incorporated into the models and simulation methods.

**Methodology employed**

The project has three major components. The first component is the continued development and maintenance of the software architecture. OpenSees is designed and implemented as an object-oriented framework. This means that it is a, now large, set of modules (called classes) that represent the data and operators on data needed for modeling and simulation. The classes are then used to develop simulation applications in a flexible and extensible manner. The extensions for parallel and distributed computing are included in this component, using the underlying distributed memory model in OpenSees.

The second component of the project involves graduate student research to extend and improve the framework. The research is a combination of engineering and computer science topics. In Year 8, we are working on two areas. One is a general approach to representing parameters in models. This is an important extension because it will allow general handling of response

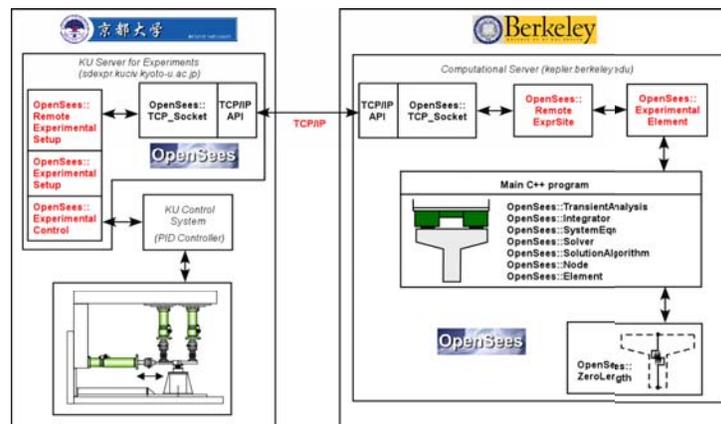
sensitivity computation (much of which has been implemented) for reliability computation, system identification, and optimization. Parameter representation requires careful software design because it introduces data structures and inter-module communication that is very different than for solving equations of motion. The second topic is extensions for multi-physics. The motivation is to solve porous flow and liquefaction problems and also some formulations of composite structural members require different types of degrees-of-freedom. It will involve new data structures, partitioning, and software features for applying different solvers to partitions of equations. Both the parameterization and multi-physics must be introduced into OpenSees in a way that is scalable for multiple processors.

The third component of the project is providing support for OpenSees users and developers, primarily working on PEER projects. This is an important investment in resources so that PEER researchers can effectively utilize and extend OpenSees. Also included in this component is continual updating of the documentation and holding workshops.

### Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments

In Year 7, Version 1.6.2 was released with improvements in the nonlinear beam column elements, recorders, a Krylov solver, and new sensitivity calculations. A number of scripts were developed to assist PEER researchers with solving large, highly nonlinear problems. The new Krylov solver has been very successful for systems with softening and degradation.

As an example of the flexibility of OpenSees, a visiting post-doctoral scholar from Japan worked closely with this project to extend OpenSees for hybrid computation-experimental simulation. This involved new classes of software classes to represent experimental setups, controllers, and processing. At an abstract level, an experimental specimen with its controller and data acquisition acts as an element within OpenSees. Distributed hybrid simulation is accomplished using exactly the same software design as distributed processing is used in OpenSees. To demonstrate the OpenSees extensions and application and distributed pseudo-dynamic test was conducted between Berkeley and Kyoto, as illustrated in the figure below. A journal paper has been submitted on this component of the project.



The plans for Year 8 are described in the previous section.

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

Although there has been much good research on modeling and simulation of structural and geotechnical systems, OpenSees continues to be a unique integrative project that integrates the results of the research into a common software framework. The flexible, object-oriented design makes this unique aspect possible.

This project is central to nearly all the projects in Thrust Area 4, and it is a critical enabling technology used by many other projects in the buildings and bridges thrust areas. OpenSees incorporates software deliverables from other projects involved with development, provides software interfaces for projects that add capability, or is the simulation tool used by other projects. OpenSees will be the simulation engine for the planned modules implemented the PBEE methodology.

**Plans for Year 9 if this project is expected to be continued**

As part of the strategic plan, in Year 9, we will focus on release of Version 2.0, which will include the multi-physic and parameterization. It will also provide much more capability for parallel and distributed processing. Streamlined modules will be adapted for specific PBEE applications.

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

We have had several inquiries from software development firms about utilizing OpenSees. The software is apparently widely used around the world by researchers as evidenced by Google hits and the number of OpenSees websites, particularly in Asia.

**Expected milestones & Deliverables**

In Year 8, we will provide software updates, particularly with the new features for parameterization and the initial work on multi-physics. As more models are adapted for parallel processing (not all developers have done this), there will be increased capability for large-scale simulations. PEER researchers will continue receive support in using OpenSees, developing features, and adding new capability to the repository.

<b>Project Title—ID Number</b>	<i>Reliability of Soil-Structure-Foundation Systems — 4132004</i>		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	CA-Trans
<b>Project Leader (boldface) and Other Team Members</b>	<b>Joel Conte (UCSD /F)</b> , Lauren Stuart (UCSD /US), Joe Letizio (UCSD /US), Yuyi Zhang (UCSD /GS), Quan Gu (UCSD /GS), Michele Barbato (UCSD /GS)		

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

### Project goals and objectives

- Extension of sensitivity and reliability framework in OpenSees to analyze Soil-Structure-Foundation (SSF) systems.
- Definition of seismic input and ground motion intensity measure(s) (IM) for large SSFI models.
- Integration of finite element sensitivity and reliability analysis with the PEER-PBEE methodology.

Application of sensitivity and reliability analysis tools to some simple generic soil-structure-foundation systems of the bridge and building types.

### Role of this project in supporting PEER's mission (vision)

This project contributes advanced analytical tools to enable finite element response sensitivity and reliability analysis of soil-foundation-structure interaction (SFSI) systems based on state-of-the-art computational mechanics models of each system component. Such tools are needed in the PEER PBEE methodology.

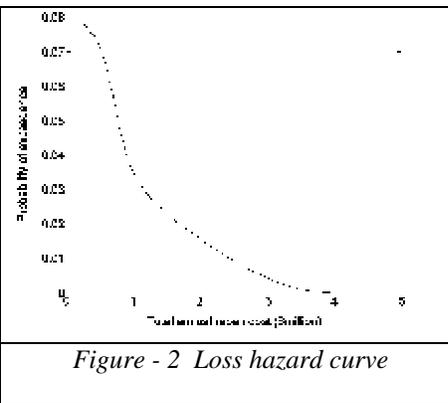
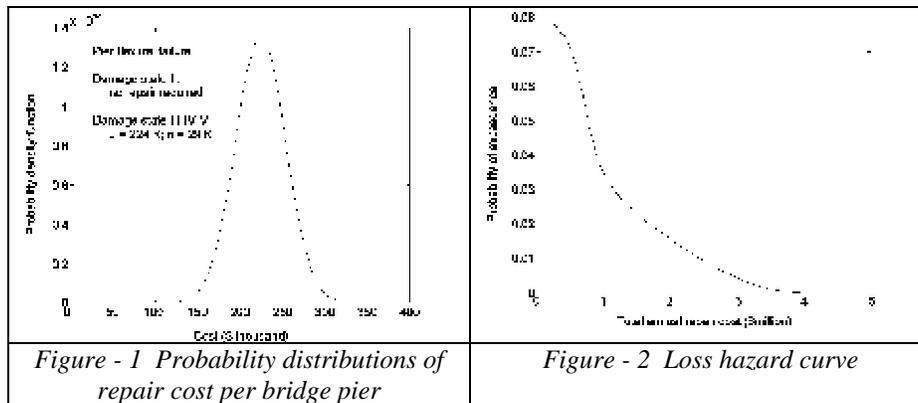
### Methodology employed

This project consists of developing and/or integrating analytical tools for stochastic ground motion modeling, finite element response sensitivity analysis, and reliability analysis in order to propagate basic sources of uncertainty related to earthquake loading and material (structural and soil) properties through nonlinear seismic response analysis of SFSI systems.

### Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments

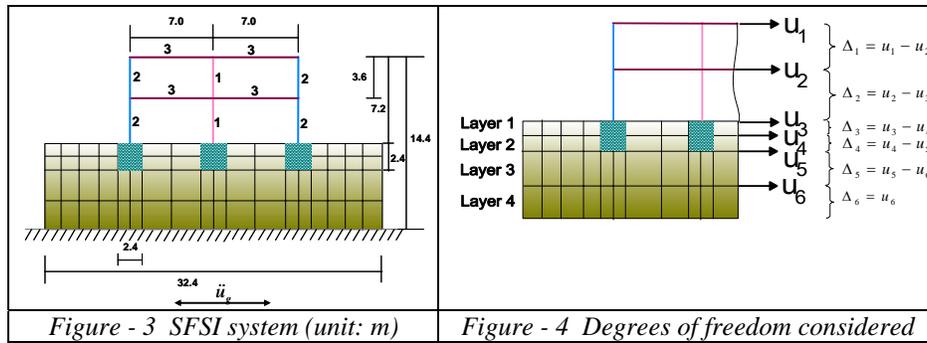
The various analytical steps of the PEER PBEE methodology (probabilistic seismic hazard analysis, probabilistic demand analysis, probabilistic capacity analysis, reliability analysis, and probabilistic loss analysis) were applied to the Humboldt Bay Middle Channel (HBMC) Bridge based on a 2-D, advanced, nonlinear finite element model of the bridge-foundation-soil system developed in OpenSees. An improved mechanics-based model of R/C piers with lap-spliced longitudinal reinforcement near their base was developed, calibrated with experimental data, and implemented in the OpenSees FE model of the HBMC Bridge. Fragility curves for the bridge piers were computed based on this lap-spliced pier model used as predictive capacity model and experimental data on lap-spliced columns. In collaboration with engineers from LAN Engineering, our business & industry partner, probability distributions of repair costs for various

discrete damage-states considered were developed based on real-world cost data. As an illustration, Fig. 1 shows the probability distributions of the repair cost for one bridge pier at the four discrete damage-states considered (II-yielding; III-peak capacity; IV-full formation of failure mechanism; V-strength degradation/collapse). This probabilistic information on repair costs was then used to generate the loss hazard curve (see Fig. 2) using a global Monte Carlo simulation procedure from the ground motion intensity measure (IM) to the engineering demand parameters (EDPs), to the damage measures (DMs), to the repair cost of each damaged component, and to the total repair cost for the whole bridge.



In closing the loop on the application of the PEER PBEE methodology to the HBMC Bridge testbed, a number of simplifications, approximations and compromises were made. In Year 8, the effects of these simplifications on the robustness of the PBEE methodology will be systematically investigated by decreasing the level of these simplifications as much as possible.

On a parallel track, significant progress has been made in the development of analytical tools for finite element response sensitivity and reliability analysis of SFSI systems. Consistent/algorithmic tangent moduli were derived for a multi-yield-surface plasticity model used extensively to model pressure independent soil materials (clay type). These consistent tangent moduli were needed to develop finite element response sensitivity algorithms (for 2D quadrilateral plane strain elements) for geomaterials based on the Direct Differentiation Method (DDM). These algorithms were successfully added to the sensitivity framework in OpenSees (developed by Prof. Der Kiureghian and co-workers). Modeling and analysis options in OpenSees to study the response of SFSI systems have been extended to enable response sensitivity computation, including (i) zero-length elements (useful to model expansion/abutment joints), (ii) section aggregation, (iii) nodal and integration point recorders, (iv) transformation constraints, and (v) stage analysis (e.g., gravity first applied statically, then earthquake load applied dynamically). The OpenSees framework has been extended to allow for parameterization of soil material properties in finite element models of soil systems composed of multiple types of soil materials. Demonstration applications of response sensitivity analysis of SFSI systems are being developed (see Figs. 3, 4, and 5). For example, Fig. 5 shows the normalized sensitivities of the 2<sup>nd</sup> floor



interstory drift (response to an earthquake) to various material (concrete, reinforcing steel, soil layers) properties, thus allowing to evaluate the relative importance of these parameters. Other extensions of the sensitivity framework to include 3-D displacement-based and force-based beam-column elements are currently being implemented in OpenSees. The sensitivity framework will also need to be streamlined for increased computational efficiency. For example, in its current version, it does not take advantage of the already factorized tangent stiffness matrix at convergence of the response calculation when computing response sensitivities. Significant gains in computational efficiency are expected.

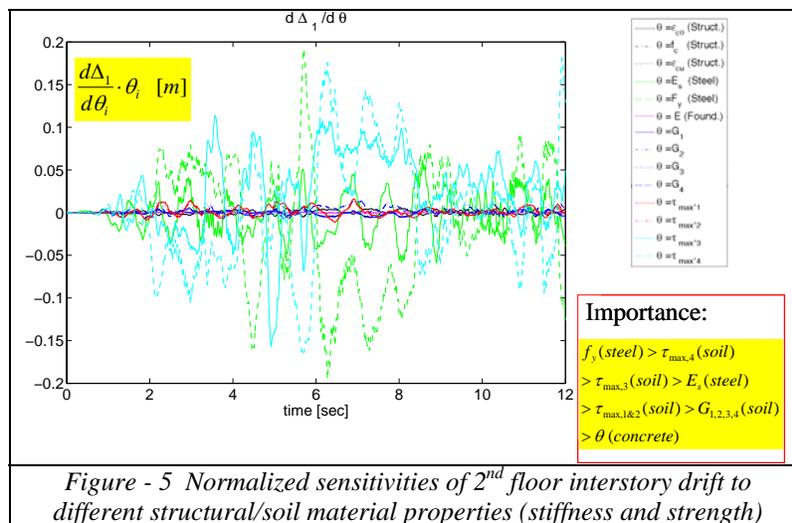


Figure - 5 Normalized sensitivities of 2<sup>nd</sup> floor interstory drift to different structural/soil material properties (stiffness and strength)

Probabilistic push-over analysis and time-variant reliability analysis of SFSI systems will make use of the response sensitivity algorithms developed and may also require the implementation of new computational optimization algorithms/packages in OpenSees for robust solution of the nonlinear, high-dimensional constrained optimization problems to be solved in order to compute mean out-crossing rates of uncertain SFSI systems subjected to stochastic earthquake loading. A discretized nonstationary ((in amplitude and frequency content) stochastic earthquake ground motion model (already developed by the PI in previous research) calibrated to actual earthquake ground motions and parameterized in terms of seismological variables (M and R) will possibly be implemented in OpenSees to complement the current capabilities implemented by Der Kiureghian and co-workers. Demonstration applications of the new computational modules for reliability analysis of SFSI systems will be developed and made available to users of OpenSees.

**Other similar 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 software STRUREL) and the Technical University of Denmark (PROBAN software). To my knowledge, none of this software is under an objected-oriented platform, or aimed specifically at soil-foundation-structure systems and seismic reliability problems. In this sense, the options available in OpenSees for finite element response sensitivity and reliability analyses of SFSI systems are unique.

**Plans for Year 9 if this project is expected to be continued**

- Extend OpenSees framework for response sensitivity and reliability analyses of SFSI systems to high-performance computing (to enable treatment of 3-D large-scale problems).
- Develop and/or implement in OpenSees hybrid methods of reliability analysis such as the combination of FORM and sub-set simulation.
- Development of optimum performance-based earthquake engineering methodologies and supporting software framework to minimize for example life cycle costs.
- Development of simplified methods and design guidelines for the practical use of PBEE in structural engineering practice.

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

Other PEER Researchers such as Prof. Steve Kramer (Univ. of Washington) and Prof. Boza Stojadinovic (U.C. Berkeley) have expressed interest in using the tools developed as part of this project. We will assist them in using these tools.

**Expected milestones & Deliverables**

Theoretical and Users manuals of analytical tools for response sensitivity and reliability analyses of SFSI systems in OpenSees.

<b>Project Title—ID Number</b>	<i>Reliability of Degrading Systems</i> — <b>4142004</b>		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	CA-Trans
<b>Project Leader (boldface) and Other Team Members</b>	<b>Armen Der Kiureghian (UCB/F)</b> , Kazuya Fujimura (UCB/GS)		

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

### Project goals and objectives

Project goals/objectives for Year 8 are:

Complete the development, refinement and implementation in OpenSees of a robust algorithm for reliability analysis of inelastic structures under stochastic loading. The aim is to compute the mean up-crossing rate and first-passage probability of structural response quantities for a stochastic definition of the earthquake ground motion. In the context of the PEER Framework formula, the first-passage probability provides the distribution of an EDP for a given IM. The computation is based on a tail-equivalent linearization method.

Apply the tail-equivalent linearization method to stochastic dynamic analysis of PEER test-bed structures, including the I880 viaduct and a selected building structure.

Extend the existing reliability methods in OpenSees for application to structures having non-ductile failure modes. Considering the non-differentiable nature of the response of such structures, non-gradient based methods, including various efficient simulation methods, will be developed and implemented in OpenSees.

### Role of this project in supporting PEER's mission (vision)

This project supports the PEER mission of performance-based earthquake engineering by providing an alternative means for computing the conditional distribution of EDPs (engineering demand parameters) for given IM (intensity measure). Presently this distribution is computed by incremental dynamic analysis using a selected set of scaled ground motions. The solution is not invariant of the selected ground motions or the scaling method. The alternative being developed would allow determination of this distribution for a stochastic definition of the ground motion, avoiding the need for selecting or scaling ground motions or time-history dynamic analysis.

### Methodology employed

The methodology is based on the first-order reliability method (FORM). For a given EDP, at each selected threshold, an equivalent linear system is defined which has equal probability in the tail of the distribution. The equivalent linear system is then used to compute the first-passage probability for the selected threshold. By varying the threshold and, thereby, the equivalent linear system, a series of first-passage probabilities are obtained which collectively define the probability distribution of the maximum of the EDP during the excitation. This distribution is a key ingredient in the PEER performance-based earthquake engineering approach. In the development of this methodology, a series of approximations are employed in order to reduce the

amount of computation and to achieve convergence. A lot of our work has dealt with developing and testing these approximate methods and algorithms.

**Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments**

The main accomplishment of Year 7 was the development of efficient algorithms for computing the first-passage probability for the stochastic response of inelastic structures. The first-passage event is described as a series-system problem with the components representing instantaneous exceedance events. Each instantaneous event is solved by FORM. Ordinarily this would require finding many design points, each involving several dynamic response and sensitivity calculations. However, we were able to develop methods and accurate approximations to drastically reduce the required number of computations. Use has been made of the fundamental properties of dynamic systems and the characteristics of stationary and non-stationary processes.

During the present year we have formalized this methodology by introducing the tail-equivalent linearization method. In contrast to the standard equivalent linearization method which defines the equivalent linear system by minimizing a mean-square error, we define the equivalent linear system by requiring that the tail probabilities of the nonlinear and linear systems be equal in first-order approximation. This linearization method gives much more accurate results for small exceedance probabilities than the standard equivalent linearization method.

As an example, Figure 1 shows the I880 test-bed structure together with the instantaneous and first-passage probability distributions for the transverse displacement at node 15005. The model for this structure was developed by PEER researchers at UC Davis.

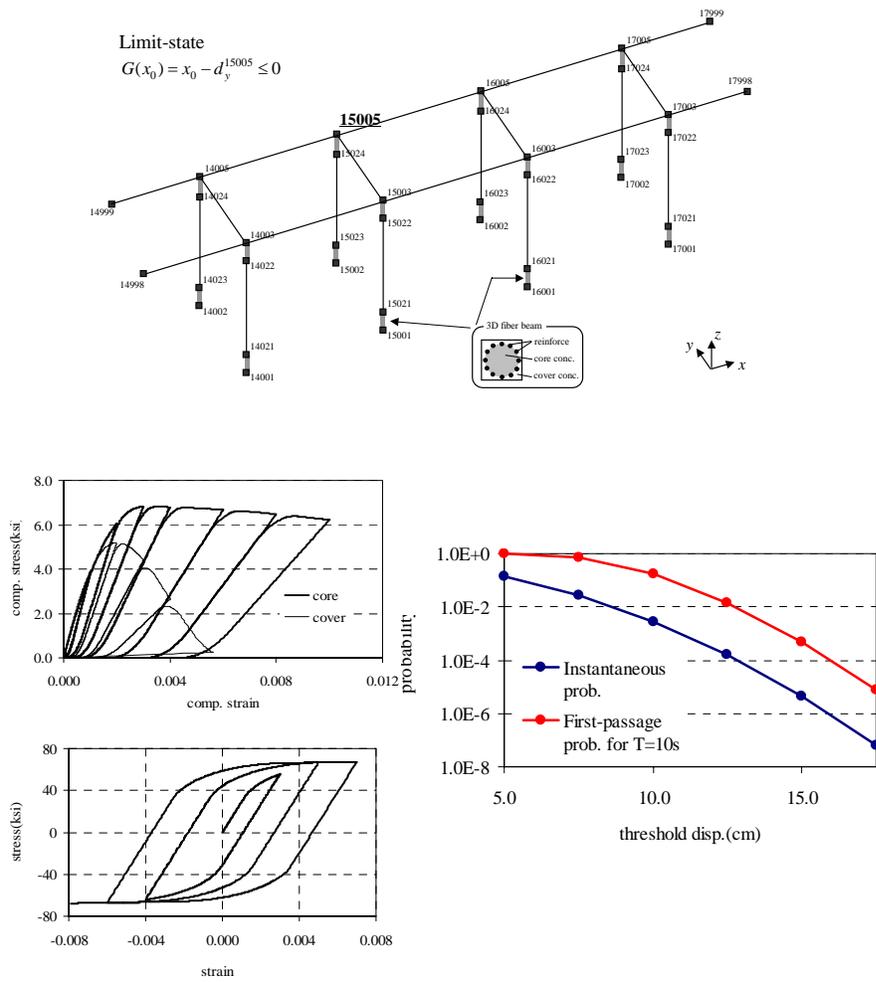


Figure 1 - Application to I880 Test-bed: finite element model (top), concrete and reinforcing material models (left), probability distributions for instantaneous exceedance and first-passage for transverse displacement at node 15005 under a stochastic ground motion as obtained by the tail-equivalent linearization method.

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

As mentioned above, many PEER researchers use incremental dynamic analysis with scaled ground motions to approximately compute the distribution of EDP for given IM. Our project offers an alternative to this approach. Outside PEER, we are aware of several investigators who are pursuing the use of FORM to solve nonlinear stochastic dynamic problems. However, we believe our idea of the tail-equivalent linearization method is unique and a major advancement of this methodology.

**Plans for Year 9 if this project is expected to be continued**

The issue of degrading and non-ductile systems is an open one. Even deterministic dynamic analysis of such systems is problematic. We are pursuing a number of ideas at this time, including an appropriate tail-equivalent linearization method. We hope to be able to continue our study of such systems in year 9.

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

We are not aware that the results of this research have been used by the industry at this time.

**Expected milestones & Deliverables**

June 2005: Implementation of tail-equivalent linearization method in OpenSees.

August 2005: Development of comprehensive example applications.

October 2005: Preliminary results for stochastic dynamic analysis of degrading and non-ductile systems.

<b>Project Title—ID Number</b>	<i>Modeling and Simulation of Degrading Shear Behavior in RC —</i> <b>4212004</b>		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	CA-Trans
<b>Project Leader (boldface) and Other Team Members</b>	<b>Filip Filippou (UCB/F), Afsin Saritas (UCB/GS)</b>		

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

### **Project goals and objectives**

Simulate the hysteretic behavior of shear critical structural elements such as poorly reinforced columns and shear walls.

### **Role of this project in supporting PEER's mission (vision)**

The project supports the element library of OpenSees, which in turn is a fundamental tool in performance-based evaluations of structural systems.

### **Methodology employed**

Force formulation for beam element with Timoshenko assumption on section deformations, plastic-damage model for concrete, uniaxial steel model.

### **Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments**

Completed model for metallic shear link devices  
Completed 2d concrete constitutive damage model

### **Other similar work being conducted within and outside PEER and how this project differs**

Not aware of similar work within PEER; the work follows earlier studies by a researcher team from University of Rome, but is more general and suitable for large scale simulations.

### **Plans for Year 9 if this project is expected to be continued**

Introduce the effect of confinement through 3d extension of concrete constitutive model, introduce effect of bond-slip.

### **Describe any instances where you are aware that your results have been used in industry**

OpenSees and its beam-column elements are starting to be used in industry.

### **Expected milestones & Deliverables**

Beam-column element with P-V-M interaction capability for RC structures, Dec 2005  
Correlation studies with available experimental results, Dec 2005.

<b>Project Title—ID Number</b>	<i>Simulation and Performance Models for Cyclic Degradation Effects in RC Bridge Columns — 4232004</i>		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	CA-Trans
<b>Project Leader (boldface) and Other Team Members</b>	<b>Sashi Kunnath (UCD/F)</b> , Jon Mohle (UCD/GS) YeongAe Heo (UCD/GS) Yihai Bao (UCD/GS)		

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

### Project goals and objectives

The primary goal of this project is the development, validation and calibration of phenomenological material models for reinforcing bars in RC members that incorporate bar buckling and low-cycle fatigue. These material models are being developed in the context of fiber-based nonlinear beam-column elements currently implemented in OpenSees. A parallel objective is the development and implementation of damage modeling schemes for use in performance assessment of RC structures.

### Role of this project in supporting PEER's mission (vision)

The vision of this project is to contribute to a collaborative PEER effort to simulate degrading behavior of RC structures thereby enabling the prediction of post-yield damage states through collapse.

The implementation of damage models in OpenSees will enable the generation of damage measures conditioned on the defined demand variables. The prediction of performance (or damage) states is central to the overall PEER performance-based methodology.

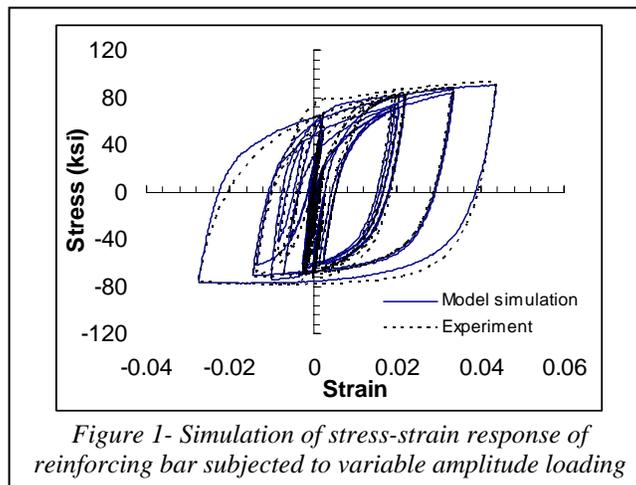
### Methodology employed

The proposed developments are analytical and will comprise the extension and refinement of existing constitutive models. The model development will include calibration/validation for the range of conditions encountered in practice (reinforcing bars in conforming and non-conforming columns, bridge piers, and wall piers), with consideration of characterizing uncertainties. The work is expected to extend into the development and use of "damage models or indices" as both input to the bar buckling models and output for damage assessment.

**Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments**

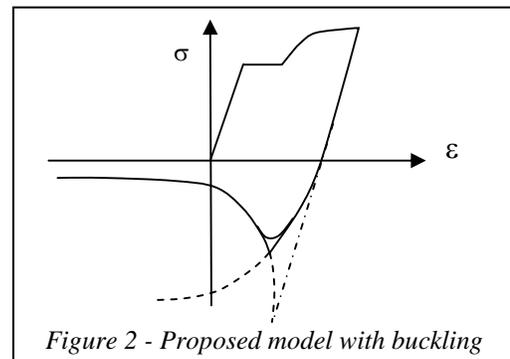
### 1. Development of a New Base Material Model for Steel

The base model development is now complete and has been validated with numerous experiments. A sample simulation of the stress-strain response of a reinforcing bar subjected to random cyclic loading is shown in Figure 1.



### 2. Incorporation of Buckling

A preliminary implementation based on a variation of the model proposed by Gomes and Appleton (1996) was pursued. The original Gomes-Appleton model was found to consistently under-predict the buckled compressive stress. Additionally, the stress strain curve makes an abrupt change in direction resulting in numerical instabilities at the turning point. A transition curve was added to smooth the change from non-buckled to buckled behavior. The resulting change in the stress-strain curve on the compression side is shown conceptually in Figure 2.



A new material model under the UniaxialMaterial class in OpenSees has been implemented as follows:

uniaxialMaterial ΡεΒαρωιτηΒυγκλινηανδΦατιγη

ΞΤαγ Ξφψ Ξφυ ΞΕ ΞΕση Ξεση Ξευλτ Ξδια Ξσλενδερνεσσ <Ξπ1> <Ξπ2> <Ξπ3>

By assigning a slenderness = 0.0, buckling will be ignored. The last three parameters are optional and the user can resort to using default values. Part of the current ongoing work involves calibrating these parameters and developing guidelines for assigning appropriate values based on section and material data.

### 3. Validation of Model

To evaluate the effectiveness of the new reinforcing bar model, the cyclic response of a reinforced concrete bridge column was simulated and compared to available experimental data. The column considered in the validation study represents a bridge pier that was tested by El-Bahy et al. (1999). The observed and simulated response of the column to constant-amplitude low-cycle fatigue loading is shown in Figure 3.

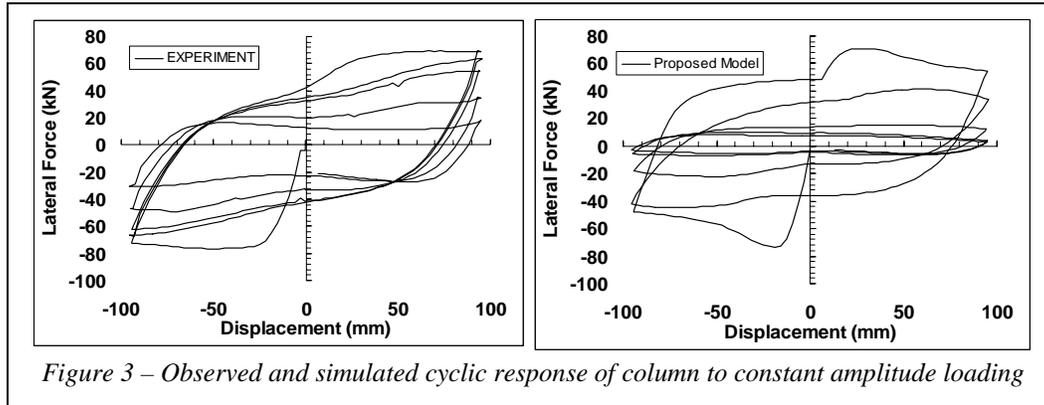


Figure 3 – Observed and simulated cyclic response of column to constant amplitude loading

### 4. Ongoing Work

The current implementation of bar buckling assumes the reinforcing bar to form plastic hinges at the ends and the mid-point of the bar region across a single hoop spacing. In reality, the buckling will occur across several hoop spaces. Studies are underway to investigate an energy-based formulation to estimate the span-to-depth ratio of the buckled profile.

Extensive parametric studies are also underway to identify the critical parameters needed to define the material model. Existing models of low-cycle fatigue failure of reinforcing bars are also being investigated. These models will be incorporated as damage models to aid in performance assessment studies. Ultimately, as suggested by the title of the proposed material model, the new model will incorporate both buckling and low-cycle fatigue effects and serve as a material model and a damage model.

### References

- El-Bahy, A., Kunnath, S.K., Stone, W.C. and Taylor, A.W. (1999). Cumulative Seismic Damage of Circular Bridge Columns: Benchmark and Low-Cycle Fatigue Tests. *ACI Structural Journal*, Vol.96, No.4.
- Gomes, A. and Appleton, J. (1997). Nonlinear Cyclic Stress-Strain Relationship of Reinforcing Bars including Buckling. *Engineering Structures*. 19 (10), 822-826

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

Known efforts outside PEER have focused on the following:

- Development of macro-models which treat cyclic degradation in an equivalent sense using hysteretic force-deformation models.
- Calibration of fiber-based beam-column elements

However, none of these efforts consider advanced material models to characterize buckling and low-cycle fatigue fracture of reinforcing bars. The tasks to be completed in the proposed project

will advance the state of the art in modeling degrading RC behavior in the context of fiber-based elements. It will also enhance our ability to quantify damage measures for use in PBEE

**Plans for Year 9 if this project is expected to be continued**

The model will be enhanced, refined and re-validated following the experimental tests to be conducted this year by Lehman and co-workers at Washington. Additional damage measures, as identified during the course of this year's effort, will also be completed in Year 9.

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

None

**Expected milestones & Deliverables**

- Develop a new phenomenological model for predicting buckling and low-cycle fatigue failure of reinforcing bars
- Calibrate and validate model with experimental data
- Investigate appropriate damage models for performance assessment of RC components within context of fiber model
- Document OpenSees implementation
- Prepare final report

<b>Project Title—ID Number</b>	<i>Abutment and Deep Foundation Modeling and Simulation</i> — <b>4242004</b>		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	CA-Trans
<b>Project Leader (boldface) and Other Team Members</b>	<b>Ahmed Elgamal (UCSD/F)</b> , Jinchi Lu (UCSD/GS), Linjun Yan (UCSD/GS), Zhaohui Yang (UCSD/PD)		

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

**Project goals and objectives**

- Develop detailed 3D OpenSees computational models for simulation of large-scale soil-structure-interaction systems, based on experiments recently performed within PEER and elsewhere (e.g., UCSD).
- Further refinement and improvement of existing soil models and numerical procedures implemented in OpenSees.
- Continue to provide support for geotechnical simulation capabilities for the PEER platform OpenSees.

**Role of this project in supporting PEER’s mission (vision)**

The geotechnical simulation capabilities developed are important components in the PEER computational framework OpenSees for Performance-Based Earthquake Engineering (PBEE) applications. These capabilities are being verified and utilized by PEER researchers in conducting computational simulations such as the Humboldt Bay Bridge testbed. In the Y8 project, these simulation capabilities are further calibrated/verified using large-scale testing data sets.

Dr. Yang continues to prepare documentation and provide support for geotechnical engineering users of OpenSees.

**Methodology employed**

The PEER computational program, OpenSees, is employed as the main research platform.

**Brief description of past year’s accomplishments and more detail on expected Year 8 accomplishments**

This is a continuation of our prior efforts in developing advanced soil constitutive models and numerical procedures for geotechnical earthquake engineering simulations. In Year 7, two plane-strain and two 3D solid-fluid fully coupled elements for modeling soil liquefaction response were implemented in OpenSees. These elements will be used in the Year-8 project.

Also in Year 7, a large-scale OpenSees 3D model of the Humboldt Bay Bridge was employed to study the presence of abutments on the dynamic response characteristics of a bridge-soil system (Fig. 1). Appropriate transmitting boundaries were included to allow radiation of seismic waves.

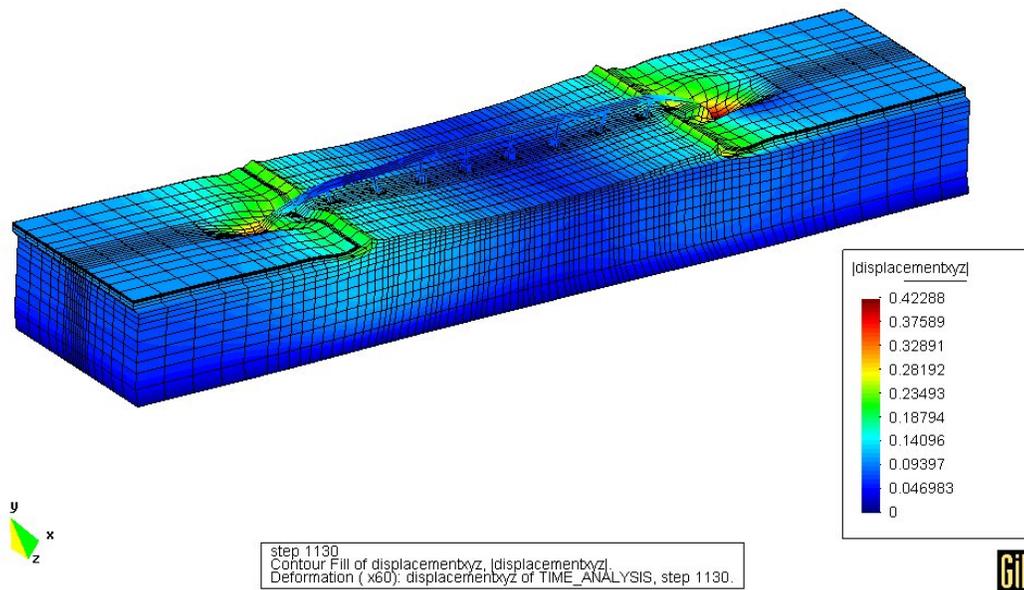


Figure - 1. Deformed shape of OpenSees 3D bridge-foundation-ground model subjected to base excitation.

The Year-8 project includes the following specific tasks:

1. Develop large scale 3D simulation models for Bridge Abutment Systems, coordinating with Prof. Ashford's experimental research on Abutments.
2. Develop large scale 3D simulation models for pile-soil interaction simulations, calibrated using data from the PEER lifelines large-scale liquefaction experiments in Japan.
3. Develop Graphical User Interface (GUI) for static/dynamic analysis of Large Diameter Shaft Foundations (see Fig. 2. for a preliminary version).

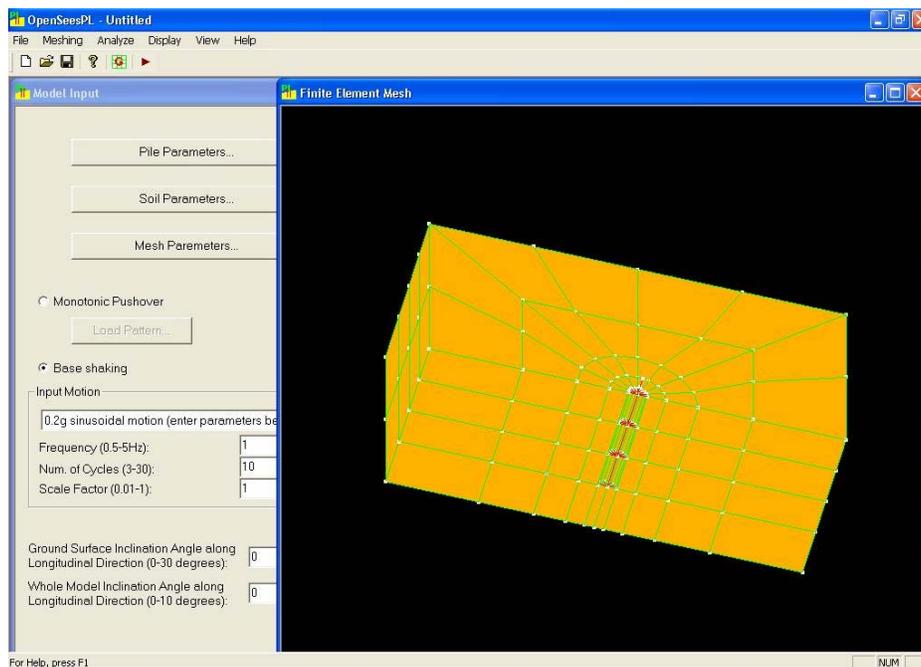


Figure - 2. Example GUI for pile-soil-interaction simulation (<http://cyclic.ucsd.edu/openseespl/>)

4. Further refine soil constitutive model and numerical analysis procedures. Coordinate with Prof. Boris Jeremic (UCD) in comparative studies of our UP and his UPU formulations.

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

Large-scale 3D computer simulation of seismic wave propagation and nonlinear site response effects are only at the very early stage of development. Related work is being conducted at Carnegie Mellon Univ. for linear and mildly nonlinear scenarios. A main goal of this project is to more accurately model soil-structural interaction response ranging from linear to highly nonlinear scenarios (e.g., liquefaction).

**Plans for Year 9 if this project is expected to be continued**

- Further develop the Year 8 3D simulation efforts, and employ for analyses of relevance to practice.
- Further develop the Graphical User Interface (GUI), extending its range of options and capabilities, based on feedback from practice.

**Describe any instances where you are aware that your results have been used in industry****Expected milestones & Deliverables**

12/15/04: Develop large scale 3D simulation models for pile-soil interaction analyses, calibrated using data from the PEER lifelines large-scale liquefaction experiments in Japan.

12/15/04: Further refine soil constitutive model and numerical analysis procedures.

2/1/05: Develop initial version of Graphical User Interface (GUI) for static/dynamic analysis of Large Diameter Shaft Foundations.

4/1/05: Coordinate with Prof. Boris Jeremic (UCD) in comparative studies of our UP and his UPU formulations (based on his feedback).

8/1/05: Develop large scale 3D simulation models for Bridge Abutment Systems, coordinating with experimental research efforts at UCSD on Abutments.

<b>Project Title—ID Number</b>	<i>Simulation of Structural Collapse — 4252004</i>		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	CA-Gen
<b>Project Leader (boldface) and Other Team Members</b>	<b>Khalid Mosalam (UCB/F)</b> , Mohamed Talaat (UCB/GS)		

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

### Project goals and objectives

Model the initiation and progression of collapse in reinforced concrete framed structures

### Role of this project in supporting PEER's mission (vision)

Allowing realistic prediction of potential collapse limit state and identifying the mode and extent of system collapse. For existing structures, such modeling can enable sound assessment of life-safety hazard and estimation of expected losses to life in the event of an earthquake. For new and retrofitted construction, collapse-capable simulations can lead proper design of new RC frames structures against the undesired limit state of collapse

### Methodology employed

Identification of generic system representative of old non-ductile construction, newer ductile construction, and retrofitted construction.

Implementation and validation of proposed material models to better capture the degrading behavior at extreme events (bar buckling, concrete crushing).

Validation and calibration of enhanced material models for component failure predictions.

Implementing a numerically robust shear-axial interaction model, calibrated to results from ongoing experimental programs. This includes the development of a post-failure deterioration rule and criteria to trigger the removal of failed columns.

Implementation of a robust element elimination technique(s).

### Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments

#### 2. Tasks:

- Identification of a ductile waffle-slab system subject to flexural- and shear-dominated collapse. Experimental data is recorded and available until imminent collapse.
- Investigating the role of existing concrete and bond-slip models on cyclic behavior.
- Investigating the adequacy of the OpenSees' fiber element for simulating flexure-dominated collapse.
- Preliminary Investigation of the use of shear-axial limit-state model for identifying drift at axial failure.

- Implementation and verification of a uniaxial concrete material model which accounts for confinement by hoops and jackets, that is capable of predicting and reporting compatible lateral strains. Current implementation defines monotonic behavior (see comparison Figure in Appendix A), cyclic behavior is being implemented. The implemented model in OpenSees in its monotonic version follows the formulation presented in [Binici, 2005].
- Development of analytical model for bar buckling.

Findings (see Figures in Appendix B):

- Successful identification of failure modes in simple systems.
- Existing concrete compressive model underestimates cyclic degradation.
- Bond-slip effect needed for accurate post-peak hysteretic behavior.
- Bar buckling is a major source of discrepancy in capacity at collapse.

Better understanding and possible improvements needed to avoid numerical convergence problems for shear-axial limit-state elements.

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

**RC Frame Validation Tests—5252002 (PI: Moehle)**

This project is of direct relevance to the current research. We are closely collaborating with the researchers of this project and are making full use of the previous study documented in the following PhD dissertation. The main difference is that the focus in the current project is on implementation and numerical robustness in addition to the experimental validation.

K.J. Elwood, "Shake Table Tests and Analytical Studies on the Gravity Load Collapse of Reinforced Concrete Frames," Ph.D. Dissertation, Department of Civil and Env. Eng., Univ. of Cal., Berkeley, 2002.

**Database and Acceptance Criteria for Column Tests—5282002 (PI: Eberhard)**

This project aims at developing and calibrating tools and models for assessing and predicting the seismic performance of ductile and non-ductile RC columns. Its experimental findings will be used in validating the component failure models

**Plans for Year 9 if this project is expected to be continued**

It is anticipated to plan for extensions to non-framed or non-planar RC structures including walls and three-dimensional systems.

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

None

**Expected milestones & Deliverables**

- Implemented classes and algorithms into OpenSees that enable the analysis of collapsing structures.
- Manual to use newly-developed capabilities.
- Verification examples.

<b>Project Title—ID Number</b>	<i>Geomechanics Simulations Tools for PBEE — 4262004</i>		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	CA-Trans
<b>Project Leader (boldface) and Other Team Members</b>	<b>Boris Jeremic (UCD/F)</b> , Zhao Cheng (UCD/GS), Matthias Preisig (UCD/GS), Kallol Sett (UCD/GS), Wai Ching Sun (UCD/US)		

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

### Project goals and objectives

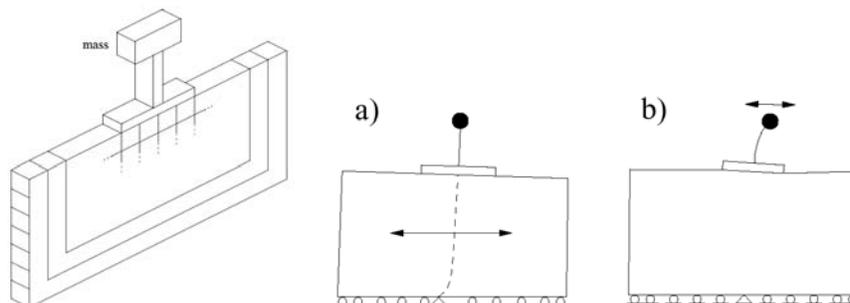
This project has a number of goals and objectives, all related to reliable computational tools treating soil component of Performance Based Design process.

In particular work since last October has been focused on (a) verification and validation study for fully coupled u-p-U formulation for saturated soils during dynamic loading, (b) study of seismic input method for finite size finite element models, (c) incorporation of nonuniformity and probability of soil properties into elastic-plastic computations with OpenSees, and (d) development of parallel version of OpenSees that will be able to maximize used of distributed computational resources for inelastic computations.

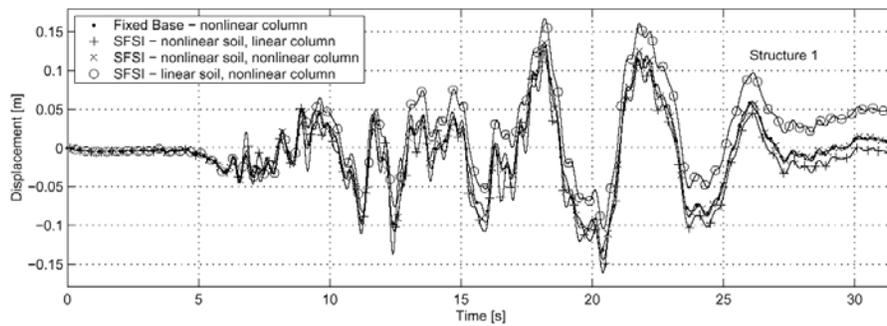
**Coupled Formulation:** This part of project is currently organizing physical test data in order to provide set of validation experiments to be used for validation. Verification was finished (comparison with available closed form solutions) and it was show that the formulation and implementation can model and simulate fully coupled behavior of soils with pore fluid for both slow processes (like consolidation) and fast processes (like earthquake loading of soil-foundation-structure systems). One student is finishing master thesis on this subject by the end of spring quarter and we envision production of a number of papers from this work.

**Seismic input for finite size finite elemen models:** This part of project deals with consistent methodology for applying seismic wave propagating from hypocenter to the soil-foundation-structure (SFS) system being simulated. A so called Domain Reduction Method (developed by Prof. Bielak) was used as a starting point. The main work was in developing stability and accuracy criteria for seismic waves propagating through elastic-plastic soil and affecting inelastic structures.

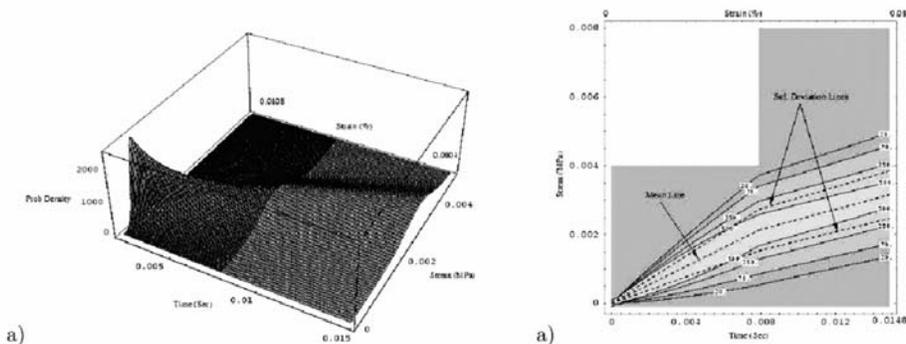
For example following figure show simplified 2D model (a number of 1D and 3D models was also analyzed) that were used for this study.



In particular the first figure shows a 2D DRM model with soil and structure on top, while the second one shows the first and the second modes of the SFS system obtained from the analysis. The extensive study (a number of papers are forthcoming) shows, among other things comparisons of behavior of structure only and SFS systems to different earthquakes. For example following figure show one such comparison for which the fully inelastic (nonlinear) treatment of soil and column resulted in larger deformations then non-SFS case or any of the elastic simplifications.



Probabilistic elasto-plasticity of soils: The problem of nonuniformity of soil and stochastic nature of soil properties is tackled in a general, way allowing for large covariances (above 20%) in properties to be taken into consideration. For example the following figure shows response (probability density function) of 1D, elastic-perfectly plastic soil conforming to stochastic Drucker Prager material model, with given variation in elastic modulus and friction angle.



Both surface plot and contour lines are shown.

Development of parallel version of OpenSees for inelastic computations will maximize use of distributed computational resources and allow for large, realistic models to be analyzed and simulated in reasonable time.

Current work is on verifying initial implementation which takes into account initial domain decomposition and subsequent redistributions (dynamic computational load balancing).

**Role of this project in supporting PEER's mission (vision)**

All three focus areas of this project are supporting PEER's mission in the area of simulation tools.

Coupled formulation and implementation makes it possible to analyze fully coupled soil prior (solid phase saturated) and during liquefaction (heavy fluid phase). This is important for assessing effects of liquefaction on SFS systems in consistent way using rational mechanics tools and implementations.

Appropriate modeling of seismic input is very important in order to have verifiable numerical simulations of earthquakes and their effects on SFS behavior. It is particularly important to make sure that there is no trapping of seismic energy in finite size model and the model is properly constructed (mesh size) and the appropriate time stepping is used (for elastic-plastic soil and inelastic structure behavior).

Stochastic treatment of elastic-plasticity of soil is at the core of PEER's vision. Our current work will allow for any (general) probabilistic description of soil properties (any number of them) to be taken into account in appropriate way and propagated through simulations toward the probabilistic estimate of performance of SFS systems during earthquakes.

High performance parallel computations will allow estimates of performance (numerically) for realistic models of real SFS systems.

**Methodology employed**

Formulations are based on rational mechanics as much as possible. This is important in order to have verifiable set of numerical tools that can then be validated using physical models (from within PEER or outside).

Accompanying implementations into OpenSees are based on state of the art techniques.

**Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments**

Current work is a continuation of work from previous years, and as such shows steady progress. Coupled formulation and implementation are going through verification (done) and validation (in progress) stages.

Seismic input using DRM was developed in previous years and this time we study fine details of stability and accuracy of seismic wave propagation (numerically) in elastic-plastic soils. Probabilistic treatment of elastic-plastic soils is new focus area and is actually quite novel in general area of computational geomechanics (and I might add, on wider scale too).

Initial parallel version of OpenSees was tested late last Summer and current work is on verifying dynamic computational load balancing algorithm that will make possible maximizing use of distributed computational resources.

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

A somewhat different coupled formulation (u-p) is being pursued by UCSD group. Our work is complementary as it is intended to extend the coupled analysis to liquefaction phase, by employing a more general u-p-U formulation which can be used follow fluid (heavy fluid, a mixture of soils and fluid in liquefied state) displacements and loads on SFS system.

Seismic input has apparently been pursued by UCSD group (as reported last year during PEER annual meeting) but the PI has not seen that implementation and cannot comment. Similar work has also being reported by other researchers from UCB on a non—PEER project but again PI has not seen implementation, verification of validation of that either. The only other group working in this area is a group from Carnegie Mellon Univ. and we follow them closely and collaborate.

Stochastic treatment of material properties is being pursued by both UCB group (Prof. der Kiureghian) and by a group from UCSD (Prof. Conte) but our approach is different in that is more general. It is PIs understanding that current approach implemented into OpenSees dealing with sensitivity is based on the perturbation method, which expand a random variable with respect to its mean value by Taylor series. The perturbation method has the disadvantage that the Taylor series expansion permits only small deviations from the mean. Hence the applicability of perturbation method is restricted to problems where  $COV < 20\%$ . It is noted in literature that for soils COV's are rarely less than 20% and in most cases the variation is much larger.

Parallel algorithm developed by the UCD CompGeomech group is designed to maximize use of distributed computational resources during inelastic simulations. This is in contrast with current implementation at UCB that does one static domain decomposition prior to inelastic computations and can results in computational imbalance and decrease in computational performance. Our work is done in collaboration with UCB.

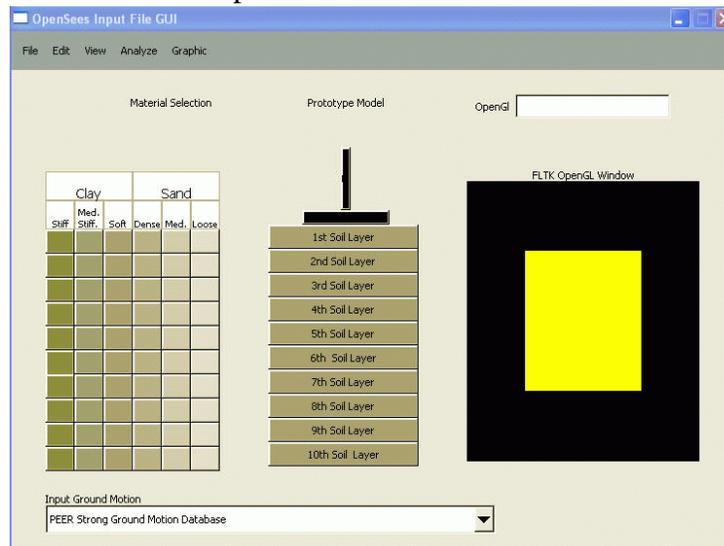
**Plans for Year 9 if this project is expected to be continued**

All four focus areas will be continued in year 9 and merged into a number of Performance Based Design Simulation examples.

- Coupled formulation will be by that time validated against available test data and realistic model of SFS systems can (will) be simulated for effects of liquefaction. These simulations will be 3D and as realistic as possible thus allowing for real predictions as opposed to sometimes used backcalculations approach.
- Seismic input will be expanded to large bridge systems and effects of variations in soil conditions on bridge behavior will be investigated.

- Stochastic elasto-plasticity will at this time focus on 1D (seismic) wave propagation. The goal is to use develop simulation tool that will mimic look and feel of program shake but comprising the stochastic behavior of soils.
- High performance formulation and implementation for inelastic computations in OpenSees will be undergoing further tests and tuning up for performance. Our development platform (local parallel computer GeoWulf) will continue to be used, but ports to large national parallel supercomputers (Seaborg at LBL and Datastat at SDSC) are in works as well and will be pursued in year 9.
- The crystallization of last few years of UCD CompGeomech work on OpenSees platform will be in the development of Performance Based Design Simulation tools. For example, one such tool, in development stage is shown in Figure below.

The goal is to allow practicing engineers to experiment with effects of soil layering on the dynamic response of structure on top.



The choice of soil for each layer, choice of column cross section, choice of input ground motions are simplified and made intuitive enough, while details of underlying finite element model (including mesh, elastic plastic material models for soils, beam column model for the structure, foundation model, seismic input...) are kept away from users view. Best available models will be used for underlying OpenSees computational engine, but the idea is to get users away from computational issues (which we take care of!) and let them investigate the physics of the problem. This will allow users (practicing engineers, researchers, students) to focus on achieving desired performance objectives while changing designs and not spend time dealing with underlying computational, discretization and algorithmic issues.

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

Recent discussion with Po Lam, a principal at Earth Mechanics Inc. indicate that they do use our recent work PEER related work on behavior of piles in layered soils, and behavior of piles in pile groups. Discussions with Caltrans (Tom Shantz, Saad El-Azazy) also indicate that our publications are used, but more importantly, they start do use OpenSees. Planning is underway to organize a workshop/seminar (initially one, by next year a series of) on geotechnical/structural capabilities of OpenSees relevant to their work.

**Expected milestones & Deliverables**

Work is progressing well, and it is expected that the following deliverables will be available in noted time frame:

- Fully verified and validated coupled formulation with liquefaction capabilities (modeling of heavy mixture of soil and fluid during liquefaction phase) should be available by late Summer or early Fall,
- Verified and validated seismic input computational tools with accuracy and stability criteria clearly spelled out, will be available by early Summer,
- Constitutive probabilistic elasto-plasticity with initial work on up scaling to 1D seismic wave propagation problems will be available by the end of Summer or early Fall,
- High performance, parallel version of OpenSees is available now, we are conducting portability tests and cleaning up the source code, performance tuning will be performed during Summer/Fall time frame
- Performance Based Design simulation tools are in constant development, first such tool (described above) will be ready by early summer and then, depending on PEER needs other tools will be designed and programmed.

<b>Project Title—ID Number</b>	<i>RC Frame Validation Tests — 4282004</i>		
<b>Start/End Dates</b>	10/1/04—9/30/05	<b>Budget/ Funding Source</b>	CA-Gen
<b>Project Leader (boldface) and Other Team Members</b>	<b>Jack Moehle (UCB/F)</b> , Tony Yang (UCB/G), Wassim Ghannoum (UCB/G), Yoon Bong Shin (UCB/G), Lauren Kuntz (UCB/US), Kyle Chatman (UCB/US), Indra Wijaya Wong (UCB/US), Zhongjie Chen (UCB/US)		

*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 and models for nonlinear response, component failure mechanisms, and internal force redistribution as collapse occurs in a building frame representative of older concrete construction.

### Role of this project in supporting PEER's mission (vision)

This project supports the PEER strategic plan by providing performance data, validation tests, and nonlinear models to advance the simulation capabilities of OpenSees. Performance data and simulation are central to the PEER mission of developing performance-based earthquake engineering methodologies.

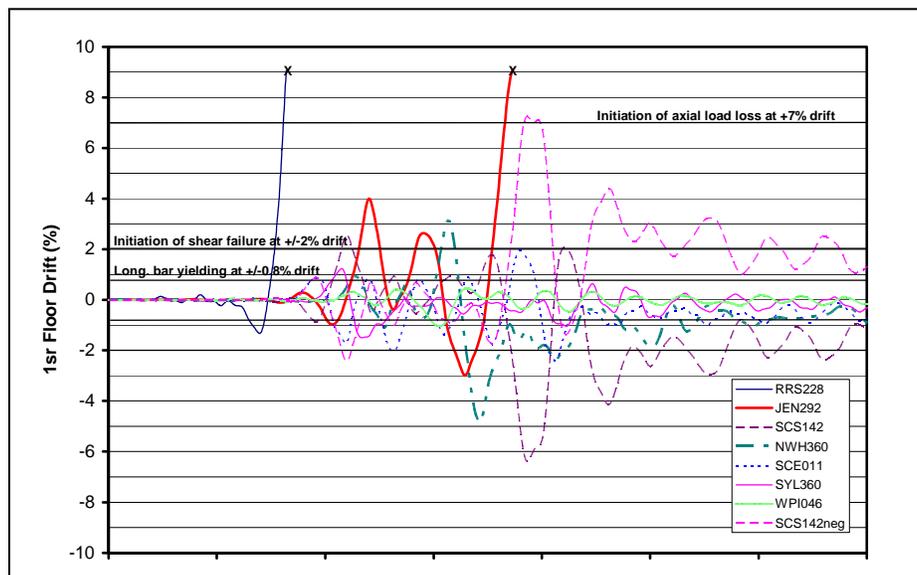
### Methodology employed

This project is conducting analyses and experiments on the nonlinear dynamic response of components and substructures sustaining shear and axial load failures. These tests provide validation data for simulation models being developed in OpenSees. Additional work includes development of mechanical models for shear and axial failure and implementation of those models in OpenSees.

### Brief description of past year's accomplishments and more detail on expected Year 8 accomplishments

We previously have completed pseudo-static and dynamic shaking table tests of specimens sustaining shear and axial-load failures, and implemented models in OpenSees for shear and axial load failure. Additional details can be found at <http://peer.berkeley.edu/%7Eelwood/research/dissertation.htm>.

We are planning experiments on the shaking table (specimens are under construction in the laboratory at the time of this writing). In preparation for those tests, we have conducted nonlinear collapse analyses, including one study in which three-story building models were subjected to several nearby ground motions recorded during the 1994 Northridge earthquake. As shown in the figure, a wide range of results was obtained for this single earthquake, depending on where the record was recorded. Shake table tests will help validate the models and results.



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

Researchers in Japan and Taiwan have carried out similar work, and we have arranged an extensive collaboration with leading researchers in both countries for the next two years. Within PEER, we are collaborating with developers in OpenSees to ensure optimal development of analytical models and simulation modules. A companion project in PEER (PI Mosalam) will collaborate in developing analytical models.

#### Plans for Year 9 if this project is expected to be continued

We anticipate completing earthquake simulator tests during Year 8. We propose to continue work in this general direction with emphasis on the development of nonlinear models/simulation strategies for systems with strength degradation.

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

Our results have been used by Degenkolb and Rutherford & Chekene for assessment of collapse potential of existing buildings.

#### Expected milestones & Deliverables

1. Complete shaking table tests on single-story specimens (May 2005).
2. Complete shaking table tests on multi-story specimens (June 2005).

**PEER YEAR 8**  
**PROGRESS REPORT**

**SECTION C**

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