Pacific Earthquake Engineering Research Center

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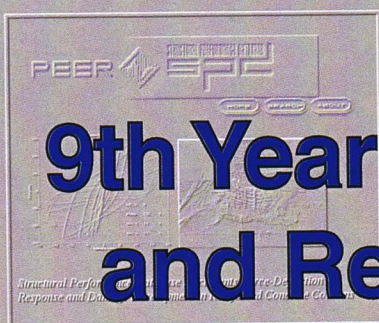
9th Year Progress Report and Renewal Proposal

Volume 2
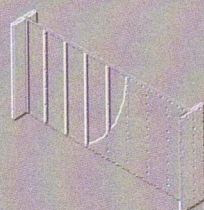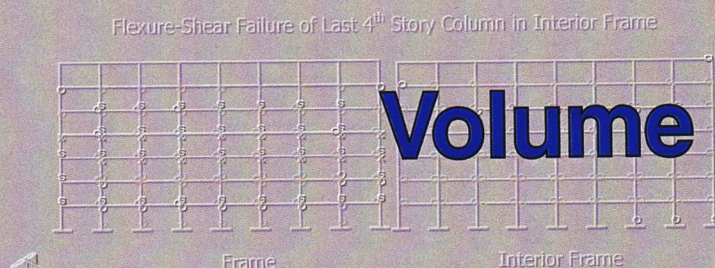
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Submission Date
May 2006
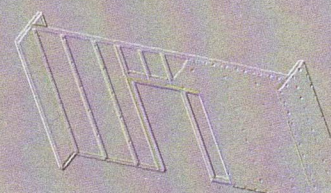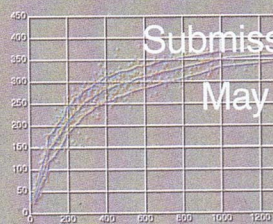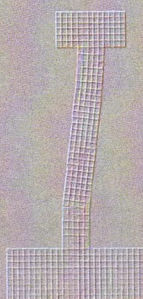
Thrust Area 1—Building Systems

Project Title—ID Number	Downtime Modeling and Consequences for Decision Variables - 1202005		
Start/End Dates	10/1/05 – 9/30/06	Funding Source	PEER-CA-Gen
Project Leader (boldface) and Other Team Members	**Mary Comerio** (UCB/F), Howard Blecher (UCB/GS), Gee Heckscher (Architectural Resources Group/I), Craig Comartin (Comartin Consulting/I), Charles Kircher (Comartin Consulting/I)		

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

Project goals and objectives

This project will complete the work on downtime modeling developed in Year 8, in coordination with Prof. Jim Beck at Cal Tech. In addition, we will apply the model to the U. C. Berkeley campus, in order to test the PEER loss modeling methodology.

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

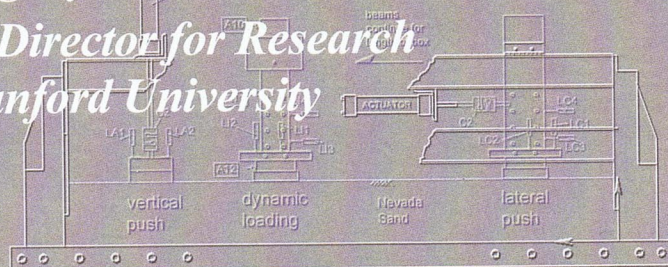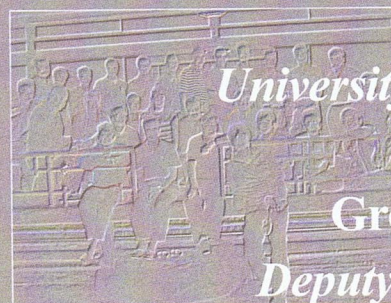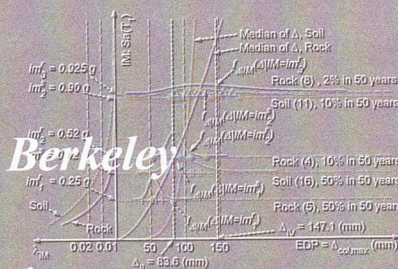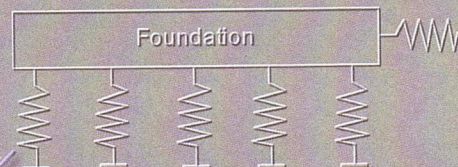This is part of the "packaging" effort to bring PEER performance based design methods into professional practice.

Methodology employed

Detailed case studies of downtime from past earthquakes have been used to provide data for the loss model developed at Cal Tech, and then input into a loss estimation for the UC Berkeley campus.

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

This is an outgrowth of the previous year's work, and an application of it. Comerio has published two articles: "Downtime Modeling For Risk Management" Safety and Reliability of Engineering Systems and Structures, G. Augusti, G.I. Schueller, M. Ciampoli (eds.) ICOSSAR 2005, Rome, June 2005; and "Estimating Downtime in Loss Modeling" Earthquake Spectra, Vol. 22, No. 2, May 2006. These articles outline the theory, methods, and data needs of downtime modeling issues.

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

This is similar to work underway to revise and improve the HAZUS loss estimating software, but the PEER methodology is building specific and will be adopted by Applied Technology Council for ATC 58. Our approach is not really similar to any other loss estimating methods.

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

The UC Berkeley Capital Projects Office has received funding for a computer-based loss modeling effort that is based on the Disaster Resistant University loss estimate (Comerio, 2000). Craig Comartin and Charles Kircher are developing the new loss estimate and my plan to work in coordination with that effort to revisit the estimates of downtime, based on my Year 9 PEER research.

Expected milestones & Deliverables

A fully developed downtime model will be completed with the Beck/Cal Tech team by October 06. As that is completed, we will test a computer based loss estimate for the campus, which will be completed and included as an example of a test of the PEER methodology.

Member company Benefits

REPAIR TIMES IN CASE STUDIES

Legend: ■ Repaired in 1-2yrs   ▨ Repaired in 2-10yrs   ☐ Demolished/Permanently Closed

Y-axis: Percent Repaired or Demolished/Permanently Closed (0 to 100)

X-axis categories: LA Single Family, LA Multi-Family, Stanford U., Berkeley U.
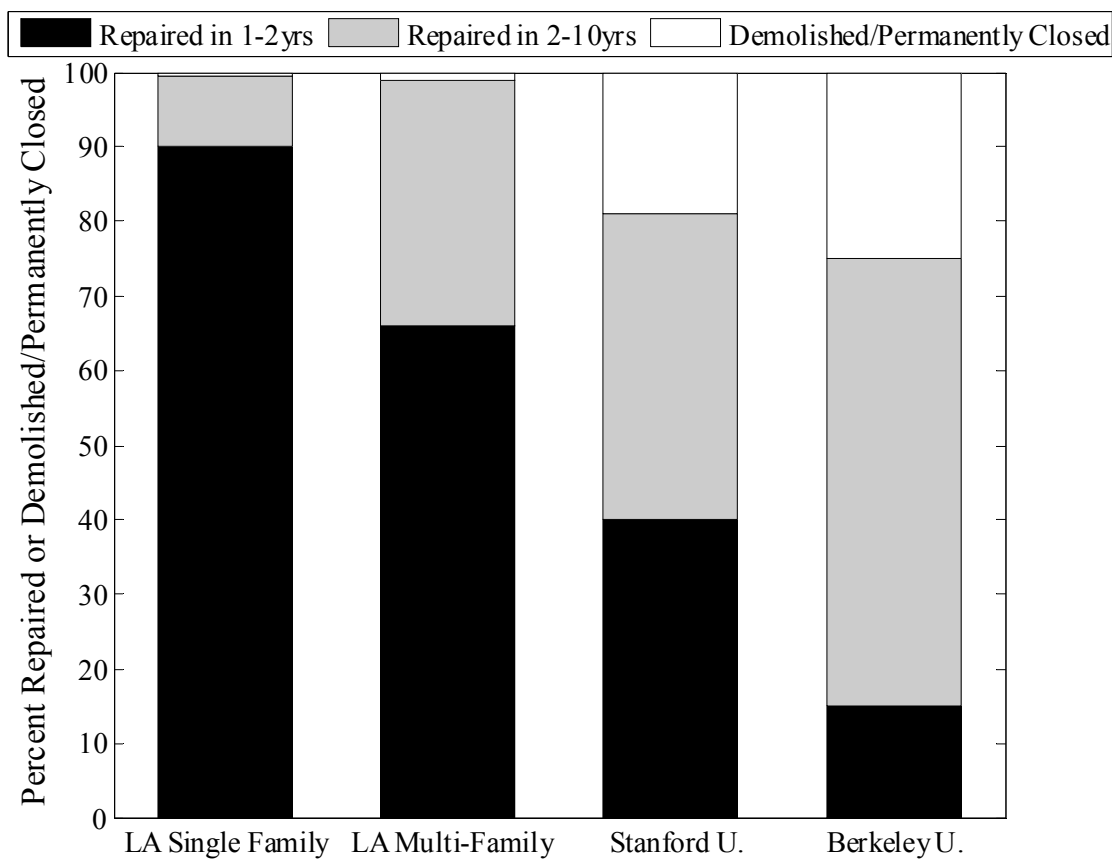
Project Title—ID Number	Facilitating the Use of the PEER PBEE: Methodology in Engineering Practice - **1292005**		
Start/End Dates	10/105 – 9/30/06	**Funding Source**	PEER-NSF
Project Leader (boldface) and Other Team Members	**Helmut Krawinkler** (Stanford/F), Farzin Zareian (Stanford/GS)		

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

Project goals and objectives

This project is an essential element 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. Its focus is on a simplified PBEE approach and on documentation of the PBEE methodology and its components.

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

The focus of the PEER research program on buildings during this year and next year is on the areas of: (a) benchmarking the PBEE methodology on code-conforming structures, (b) decision making based on anticipated performance, and (c) outreach and packaging the PBEE methodology. The focus of this project is on the second and third areas. Advantage is taken of the work performed in parallel in the benchmarking effort, and of the past work performed in the Van Nuys test bed study and in several other related projects.

Methodology employed

We have synthesized methods and tools developed by PEER researchers into a simple format that greatly facilitates the implementation of the PEER PBEE methodology in engineering practice. Much effort was devoted to the development of a graphical tool that facilitates Performance-Based Design (PBD) in engineering practice. This graphical tool is also capable of performing performance assessment in a simplified manner. The tool translates the deep yet complex equations used in probabilistic performance assessment into a graphical format that facilitates utilization in conceptual design decision making. An essential part of this tool is a database of IM-EDP response curves for generic structures. Such a database has been developed for generic moment-resisting frames and shear walls covering a large practical range of structural properties. As a side product, the sensitivity of different structural response parameters to variations of a number of structural parameter is evaluated and documented. Summary documents will be written that comprise the essentials of the complete performance assessment methodology, and additional user-oriented documents will be developed with 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 previous year's achievements, with emphasis on accomplishments during last year (Year 8)

During the last two years we have developed a simplified procedure for performance-based design and assessment that incorporates three domains: the *hazard domain*, the *structural domain*, and the *loss domain*, with an emphasis on the mean values of the ground motion intensity (IM), building response (EDP), and losses DVs (Figure below). This simple PBD procedure helps engineers make decisions on global structural parameters (e.g., base shear strength and period) and the choice of an effective structural system and material (e.g. steel moment-resisting frame or concrete shear wall), based on performance targets that are defined upfront (e.g., acceptable average monetary loss at discrete hazard level, and tolerable average annual probability of collapse). The simplicity of the proposed PBD approach and its semi-graphical presentation provide engineers with an insight about the contribution of different building subsystems to the building total loss.
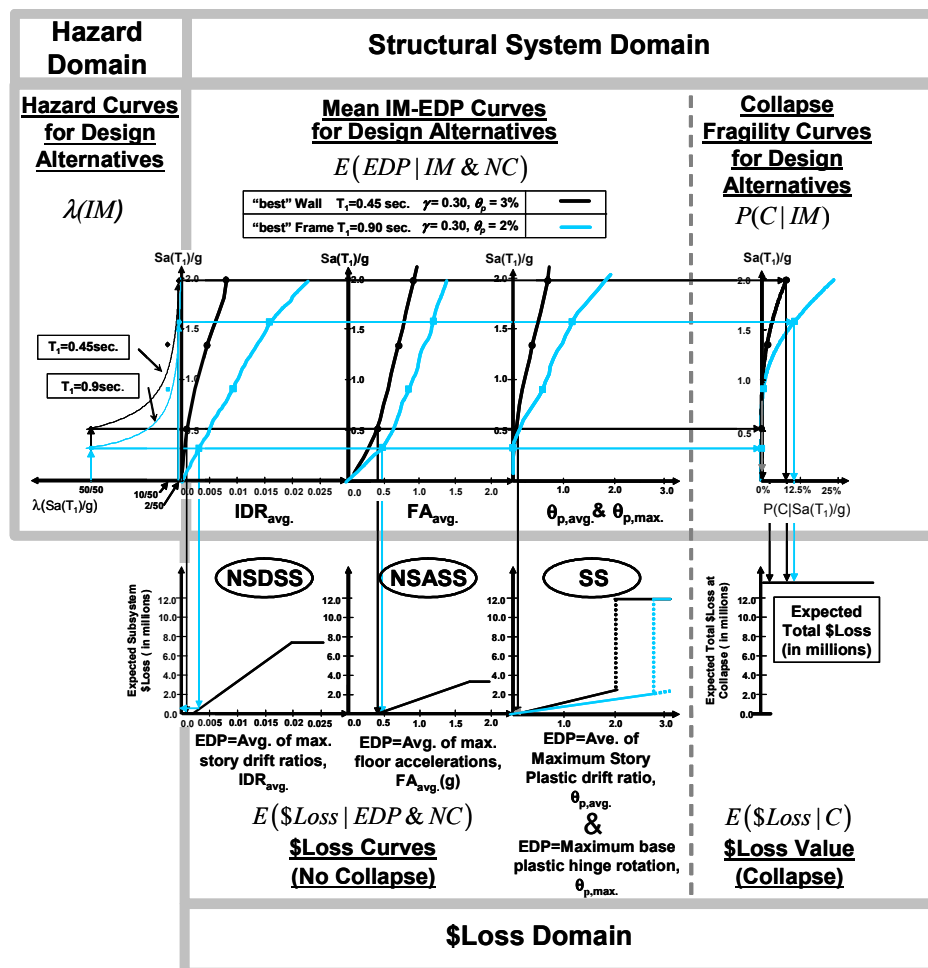
An additional advantage of this simplified PBD process is that it can be used as a performance assessment approach by reversing the flow of information from ground motion hazard to loss estimation. Special consideration is given to design for collapse prevention for the life span of

the structure. We have also developed a consistent way for incorporating different sources of uncertainty (*aleatory* and *epistemic*) in the proposed approach for collapse safety.

An essential backbone of the simplified PBD procedure is the information incorporated in the Structural System Domain in the form of mean IM-EDP curves and collapse fragility curves for various design alternatives. A comprehensive database of IM-EDP curves and collapse fragility curves for generic moment-resisting frames and shear walls covering a large practical range of structural parameters was developed during the past year. Sensitivity of various building response parameters to variation of these structural parameters was studied. The conclusions obtained from this sensitivity analysis provide insight about the effect of different structural parameters on building response. This is an essential ingredient needed for performing a conceptual performance-based design.

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

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.

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 9 and 10 activities. This project addresses this priority and will develop documents intended to encourage adoption of PBEE in engineering practice. Currently, the ATC-58 and ATC-63 projects incorporate components of the PEER methodology.

Expected milestones & Deliverables

The following products will be the deliverables of the Year 9 study:
- A set of short documents that will provide guidance in carrying out a performance assessment
- A comprehensive document summarizing the process and data for simplified approaches to performance assessment
- A comprehensive 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
- Interaction with ATC-63 in the utilization of the collapse fragility approach developed in this project and a previous PEER project.
- 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.

Member company Benefits

Project Title—**ID Number**	*Effect of Modeling uncertainty in loss estimation and on financial decision variables* - **1302005**
Start/End Dates	10/1/05 – 9/30/06	Funding Source	PEER-NSF
Project Leader (boldface) and Other Team Members	**Eduardo Miranda** (Stanford/F), Carlos M. Ramirez (Stanford/GS), Felix Cheong (UCB/US), Tim Schrotenboer (Calvin College/US)

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 fragility/loss information and tools that will enable practicing structural engineers to conduct loss assessments of buildings using PEER's performance-based loss estimation 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 computer tools to facilitate loss estimation calculations and delivering loss information to decision makers.

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

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 information and tools that will facilitate its adoption and that at the same time facilitates the visualization and interpretation of loss estimation results. The main objective of the project is development of such tools.

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. 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.

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

The toolbox will have two main components. The first one will permit the calculation of story fragility/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.. Main input to this toolbox will be on one hand the specification of performance groups present in each story, and on the other hand the damage state, EDP-sensitivity, fragility parameters and loss parameters for each performance group present in the story. The second one will conduct loss estimation calculations by using story fragility/loss functions; simulation results from OpenSees or another simulation tool; and seismic hazard curve at the site.

One of the main challenges of the proposed 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 is complementing existing experimental information with building performance data collected by structural engineers following the 1994 Northridge earthquake as part of the ATC-38 project (Database on the Performance of Structures Near Strong-Motion Recordings: 1994 Northridge, California, Earthquake). As part of the ATC-38 project, the Applied Technology Council developed and implemented a standardized procedure for systematically documenting the performance of buildings (both damaged and non-damaged) located in the vicinity (within 1000 feet) of strong-motion recording sites. The ATC-38 project involved the inspection of more than 500 buildings resulting in a statistically rigorous database of building characteristics and documented seismic performance which provides extremely valuable data to develop the proposed generic story loss functions. In addition to the ATC-38 data, 20 buildings that were inspected as part of the SAC project and that were located within 1,000 feet of a recording station will also be used. As part of a CSMIP-sponsored project these datasets were used to develop damage probability matrices and empirical fragility functions using ground motion parameters. In the proposed study structural motion based fragility functions are being 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 are treated as non-deterministic. Computer analysis tools were developed during Year 8 and the models were 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.

During Year 9 the development of empirical fragility functions will be finalized and a report explaining the methodology, data used, processed and final curves will be written to be published as a PEER report.

A small group of industry practitioners will be involved as an oversight committee during the development of the loss estimation toolbox. It is anticipated that during early stages of the development some portions of the code will be developed in Matlab, however the finish product will be a stand-alone product running in MS Excel which is a tool available and commonly used by structural engineers and other stakeholders. In particular, in is anticipated that interaction with ATC-58 project participant will take place. It is anticipated that the proposed 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 methodologies.
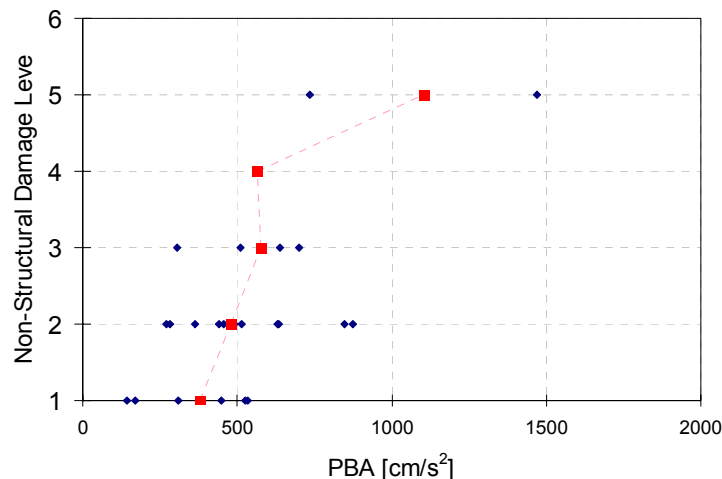
Example of empirical fragility function for acceleration sensitive nonstructural components.

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

The ATC-58 generated an example to illustrate the use of the loss estimation methodology. The proposed work differs from that effort in the sense that correlations between repairs and fragilities in that effort were neglected. The only correlations that were considered were those between response parameters of different floors. In the proposed approach all level of correlation are considered. Therefore, the proposed project compliments and provides improvements of this outside work.

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

Fragilities and damage methodologies were used by John Martin and Associates for implementing an automatic damage detection system for instrumented structures.

Expected milestones & Deliverables

There are three major milestones in the proposed research investigation:
1. Development of structural motion-seismic performance pairs from ATC-38 and CSMIP datasets. This involves first modeling each of the buildings and then computing peak responses on each story. Software tools were developed specifically for this purpose during Year 8 and a significant progress was made in processing each of the building. It is anticipated that this activity will be developed during Year 9.
2. Development of generic empirically-based fragility functions for nonstructural components. One will be for drift-sensitive components while the other one will be for acceleration-sensitive components.
3. Development, testing and calibration of the PEER loss estimation toolbox. It is anticipated that this activity will be initiated in Year 9, particularly the design of the user interface, and generation of expected annual losses and disaggregation of expected annual losses. The rest of the development and testing will be done in Year 10.

There will be three main deliverables from the proposed investigation:
1. A research report and papers documenting the development of the generic story loss functions;
2. 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
3. The Excel-based PEER loss estimation toolbox

Member company Benefits

Craig Comartin, CDComartin, Inc.

Project Title—ID Number	*IM and Ground Motion Selection for EDP Hazard Assessment -* **1312005**		
Start/End Dates	10/1/05 – 9/30/06	Funding Source	PEER-NSF
Project Leader (boldface) and Other Team Members	**Allin Cornell** (Stanford/F), Jack Baker (Stanford/GS), Polsak Tothong (Stanford/GS), Iunio Iervolino (U. of Naples/O)		

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

Project goals and objectives

This project is developing 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 are both scalar and vector schemes for IMs. For example, for first-mode dominated buildings the preferred scalar may well be inelastic spectral displacement, as used in the Van Nuys test bed, 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. (Epsilon is the standardized deviation of S_a from its predicted (median) value.) Far and near-source situations are being considered; the latter require extra care and/or modified IMs. The recommended procedures include (1) record selection and record processing such as scaling and/or "shaping", (2) number and kinds of Nonlinear Time History (NTH) analyses, and (3) suggested post-processing of response output. Fundamental engineering insights can 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 problem as well.

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

PEER's vision includes NTH analysis. This project provides (1) guidance on the input to those analyses and (2) the connection to the site hazard analysis that permits accurate and efficient computation of structural response (EDP) annual frequencies.

Methodology employed

From data bases of the results on multiple NTH analyses of multiple frame structures, we study the efficiency (i.e., variability in response prediction given an IM level), the sufficiency (i.e., sensitivity of the results to the selection of the record set, e.g., to their magnitudes), and the EDP-bias induced by record-scaling in order to understand and evaluate the pros and cons of different IMs.

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

The primary accomplishments of the project have been the thorough study of vector and advanced scalar IM's, including the role of epsilon in the effectiveness of Sa-based IMs and in the selection and scaling of records for NTH analysis. One specific accomplishment is the development of new approaches to record selection for non-linear analysis. These are based on

our findings of the role of "epsilon" as a characterizer of structural performance via its role as a proxy for spectral shape. Two alternative selection recommendations are given, their implications explored and their positive effectiveness demonstrated. One suggests selecting records primarily based on epsilon (rather than M or R). This suggestion has been implemented in the PEER building benchmark study. We show that when used with simple Sa(T1) (i.e., first-mode period Sa) as an IM it is efficient (reduces EDP|IM sigma), sufficient (avoids potential bias due to ignoring epsilon role), and avoids potential record scaling bias. The second selection procedure suggests selecting records (regardless of M, R or epsilon) that best match (not the UHS shape which is current – e.g., testbed - practice) but the "conditional expected spectral shape given Sa(T1) = x", where x is the ground motion level associated with the mean return period of the "stripe" of records being selected. In particular at large return periods this shape will match the UHS only at T1, and will lie below it elsewhere – falling off as T differs from T1. This approach has all the same beneficial properties as the first. Both lead to lower extreme responses and higher collapse fragility curves than the schemes used today (e.g., the test bed approach) and they avoid the need for more computationally intensive vector IM's.

Figure 1 shows the median spectra of four sets of records: (1) denoted AR is for an arbitrarily-selected set of records; (2) denoted MR-BR is for a set of records that have approximately the mean magnitude and distance from the PSHA disaggregation at this site for an S_a (0.8 sec) level of 1.6g (i.e., this mimics current best practice and the PEER testbed); (3) denoted ε-BR is for a set of records with approximately the same median ε from disaggregation (i.e., the first new method described above); and (4) denoted CMS-ε is for a set of records selected to match the conditional mean spectrum given this level of S_a(0.8sec). 0.8 sec is the first natural period of an example MDOF frame and the Sa level of 1.6g is approximately the median level at which collapse occurs. Figure 2 shows the global collapse fragility curve results from multiple NTH analyses. The more accurate new methods suggest a more robust structure than the other two cases. This can be anticipated by the shape of their spectra, which lie every (except at 0.8 sec) below the other two. The accuracy of these less conservative results is confirmed by vector-valued analysis (using Sa and epsilon as arguments).

All this work is based on "ordinary" records and makes important use of the Luis Ibarra-Helmut Krawinkler data base of generic frame structure IDA's to demonstrate our conclusions over a wide range of stories, periods, and backbones. Additional work has been conducted for near-source records and new methods of analysis are under development for this more complicated case.
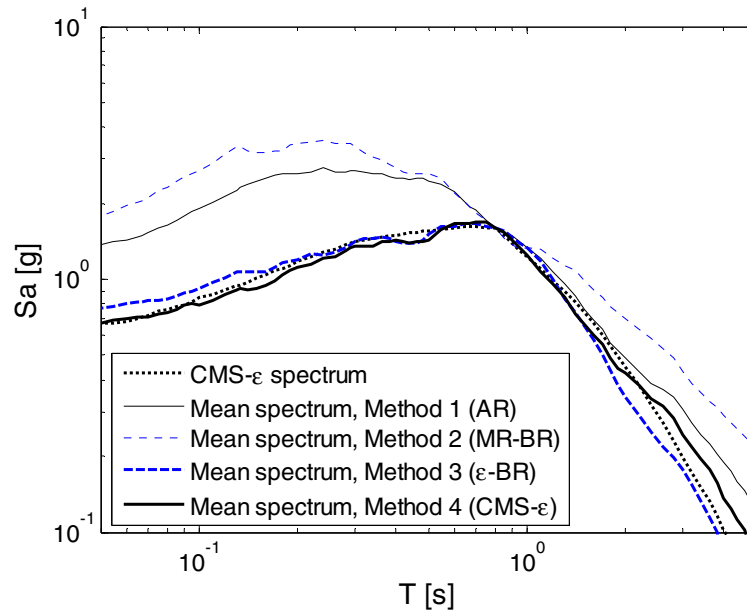
Figure 1 - The CMS-ε spectrum at Sa(0.8s)=1.6g (given $\bar{M}$ =6.4, $\bar{R}$ =11.5 km and $\bar{\varepsilon}$ =2.1) and the mean response spectra of record sets selected using each of the four proposed methods.
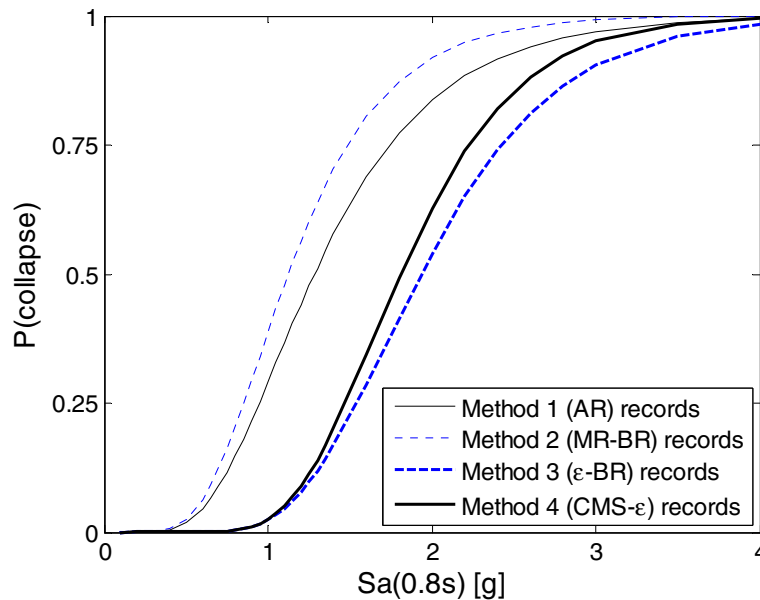
Figure 2 - Probability of collapse vs. Sa(T_1) (i.e., the collapse "fragility curve") using the four record-selection methods considered.

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

This project may be almost unique but it is receiving a great deal of attention. For example, researchers at USGS are now looking at our treatment of epsilon-induced difficulties with Sa as an IM.

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

We have been told informally that at least two firms have recognized now the issues induced by epsilon and are using our recommendations to avoid them when selecting and scaling records for their clients.

Expected milestones & Deliverables

1. Report on vector IM's and on the role of epsilon (Baker thesis). 2. Report on improved scalar IM's (Tothong thesis). 3. Report of summary recommendations for practice.

Member company Benefits

Better understanding and methods of ground motion selection and scaling for current and for future PBEE projects.

Project Title—**ID Number**	*Societal Implications of Performance-Based Earthquake Engineering* - **1332005**		
Start/End Dates	10/1/05 – 9/30/06	Funding Source	PEER-NSF
Project Leader (boldface) and Other Team Members	**Peter J. May** (UW/F), Chris Koski (UW/GS)		

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

Project goals and objectives

The goals of this continuing project from Year 8 are to:

- Characterize the societal implications of the use of performance-based approaches earthquake engineering assessment and design;
- Draw implications for efforts to implement PBEE methodologies.

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

This project fits into the PEER agenda of addressing implementation considerations and societal implications of PBEE.

Methodology employed

The project entails review of commentary about the societal benefits of PBEE, review of prior research concerning benefits of earthquake engineering innovations, and data collection and analysis of the adoption of analogous voluntary provisions.

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

This project is aimed at characterizing the societal implications of the use of performance-based approaches to engineering with particular attention to PBEE. The main goal is to draw implications for efforts to implement PBEE methodologies with respect to potential societal benefits and costs. The Year 8 project collected background material concerning various commentaries about PBEE. In searching for examples of successful societal adoption of regulatory innovations, we decided to focus attention on "green buildings" and the growing movement for adoption of the green building voluntary standards. We have collected documents about this movement and as part of the Year 9 project are collecting data about the factors that have led states to adopt the voluntary standards for public and other buildings. This should serve as a useful case study from which lessons can be drawn for PBEE. There has been much interest in this analog among the engineering community at the sessions where we have presented our findings to date.

The Year 9 work to date has sought to identify the lessons from the Green Buildings in seeking answers to key questions: (1) How did the guidelines move into general use? (2) What was involved in gaining acceptance of the voluntary standards? (3) What specific actions helped catapult these into prominence?

Thrust Area 1—Building Systems

A working paper on state adoption of green building requirements has been completed and submitted for publication. Table 1 shows the different state mandates that were adopted as of July 2005 that require adherence to green building standards for aspects of state construction.

Table 1. State Mandates for Green Buildings

Year[a]	State	Provisions	Governor (Party)	
		Executive Order Adoption		
2001	New York	New state projects – incentives to be green	Pataki	R
2002	New Jersey	New school designs	McGreevey	D
2003	Maine	New or expanded state buildings	Baldacci	D
2004	California	New and renovated state facilities	Schwarzenegger	R
2005	Arizona	All state-funded buildings	Napolitano	D
2005	Michigan	New state-funded buildings and major renovations	Granholm	D
2005	Colorado	All state buildings	Owens	R
2005	Rhode Island	All new, expanded, or renovated public buildings	Carcieri	R
		Legislative Adoption		
2001	Oregon	Sustainable tax credit for green buildings[b]	57-3; 26-3 [c]	D
2005	Washington	New state-funded buildings and major renovations	78-19; 32-16	D
2005	Maryland	New, major state capital projects	134-1; 47-0[c]	R
2005	Nevada	All state-funded state buildings, tax incentives	38-0; 19-0	R
2005	Pennsylvania	Incentives for new school construction	193-5; 50-0	D
2005	Arkansas	Encouragement for green design in state facilities	91-0; 35-0	R

Source: U.S. Green Building Council (2005) for state adoption and content.
Notes:
[a] States are ordered within categories of adoption by year and month of adoption.
[b] Governor Kulongoski (D) issued executive orders in 2003 and 2006 that set green-building goals for state buildings and schools with reference to the 2001 sustainability legislation.
[c] State legislative votes in state house and senate respectively; designation of party of the governor. Data collected from individual states.

We have undertaken analyses of a variety of factors that contribute to increased likelihood of adoption of state green building mandates. State actions in mandating these requirements are responsive to interest-group advocacy, the need for action, and bureaucratic considerations while resistant to interest-group opposition. The findings point to unique alignments and call attention to governors as environmental entrepreneurs. Unlike most environmental issues that involve visible and contentious debates, state requirements for green-buildings have been adopted with little controversy. Governors have been key players in exercising their administrative discretion in enacting green-building executive orders and in showing leadership in promoting green-building legislation. Table 2 elaborates on the role of governors in showing that they are responsive to the interest group pressures and cultural environments in deciding whether to endorse green building requirements.

Table 2. Political Context and Governors

Contingent Effect for [a]	Coefficient [b] (s.e.)	Original Effect [c]	Contingent Effect [d]
Interest group advocacy of stronger code provisions (Democratic governor)	.53** (.24)	.11	.22
Interest group opposition to stronger code provisions (Republican governor)	-2.51** (1.17)	-.24	-.40
Political culture – more moralistic government (Democratic governor)	.28** (.17)	-.01 (n.s.)	.27

Notes:

[a] Cells show relevant information about the influence of selected political variables for green building adoption conditioned on governors of a particular party (shown in parentheses) holding office at the time of the decision to adopt a green building provision.

[b] Logistic regression coefficient (standard error in parentheses) for the interaction of governor as a dummy variable and the relevant political variable. The coefficient is what is obtained when substituting the interaction term for the relevant political variable in the combined model that controls for energy demands, costs, and economic contexts.

[c] Effect of the original political variable as part of logistic modeling that controls for energy demands, costs, and economic contexts.

[d] Effect of the political variable conditioned on governor of the designated party. The effect is calculated in the same manner as the original effect, except taking into account the relevant party status of the governor.

The Year 9 effort will continue to develop a broader perspective on the societal implications of PBEE, drawing lessons from the Green Buildings and other relevant innovations. At a minimum, this research will provide a more systematic basis for discussing the societal implications of greater use of PBEE.

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 continues to be involved with these forums, thereby providing important outlets for the proposed PEER research.

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

The research has been of interest to some industry partners who are concerned about appropriate regulatory standards for "tall buildings" as evidenced by recent commentary and discussions in San Francisco and Los Angeles.

Expected milestones & Deliverables

Mar 31, 2006 Development of paper that analyzes variation in adoption of Green Building voluntary regulations at state levels, providing insights into adoption patterns of voluntary codes. [Completed]

June 30, 2006 Development of framework for characterizing the societal benefits and costs, at least in qualitative terms, of PBEE and performance-based regulation.

Sept 30, 2006 Draw implications for efforts to implement PBEE methodologies with respect to potential societal benefits and costs.

Member company Benefits

Consideration of broader societal perspectives of PBEE.

Thrust Area 1—Building Systems

Project Title—ID Number	Implementation of SFSI and site effect models in PEER methodology - 1342005		
Start/End Dates	10/1/05 – 9/30/06	Funding Source	PEER-NSF
Project Leader (boldface) and Other Team Members	**Jonathan Stewart** (UCLA/F), Ertugrul Taciroglu (UCLA/F), Christine Goulet (UCLA/GS), Rebecca A. Claasen (UCLA/US), Edward H. Field (USGS/I), Paolo Bazzurro (Air Worldwide/I)		

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

Project goals and objectives

The Year 7 project by the PIs consisted of a benchmark study of a code-compliant structure, which was carried out in collaboration with researchers at Stanford (Deierlein) and Caltech (Beck). During the course of that project, several critical "gaps" within the PEER methodology were identified with respect to the implementation of models for site effects and soil-foundation-structure interaction (SFSI) effects. Some of those issues were addressed during our Year 8 project, although not as many as we had originally anticipated because of roll-over of the Year 7 work into Year 8 (accordingly, some of our Year 8 work is rolling into Year 9). Our proposed Year 9 work is continuing to fill the gaps identified during the benchmark project and to package tools developed during previous years' work for application. Specific objectives include the following:

1. Integration of the results of site-specific ground response analyses (i.e., using appropriate equivalent-linear or nonlinear analysis) within probabilistic seismic hazard analyses (PSHA). Packaging of appropriate methods within OpenSHA.
2. Development and implementation of models to predict ground motion variations between the foundation level of buildings and the free-field (i.e., kinematic interaction models). The key technical issues to be addressed here are phase shift (equivalently expressed as coherency) of foundation/free-field motions and the development of simple models for the ratio of foundation/free-field response spectra (RRS).
3. Package of time history selection protocols into a database system already being developed by PEER staff as part of the NGA project. The key issue here is to ensure that critical information (search parameters) needed by engineers performing time history selection is available within the database.
4. Implementation and packaging in OpenSees of spring and dashpot models developed by co PI Taciroglu.
5. Assessment of previously developed foundation models. Key issues associated with this assessment include (a) identification of input parameters (and their uncertainties), (b) quantification of model variability (driven by both uncertainty in input parameters and the differing attributes of available foundation models), and (c) evaluation of model functionality (numerical stability) when models are utilized beneath multiple footings of a building structure. Work on this task will be closely related to a follow-on benchmark study that would likely involve a shear wall building. Accordingly, our work will be contingent on participation of other groups (Deierlein and Beck) and their schedules. Some of this work may occur in Year 10.

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. The major impact of our effort is to provide packaged tools for IM characterization, time history selection, and SFSI analysis (typically utilized in IM to EDP analyses).

Methodology employed

Scope items are discussed with reference to the specific goals/objectives described above.

Task 1: Implementing within OpenSHA routines that allow the results of 1D nonlinear geotechnical ground response analyses to be integrated into PSHA. The available routines that are being implemented were developed by Baturay and Stewart (2003) and Bazzurro and Cornell (2004). This work began in Year 8 and will be completed in Year 9. The programming of Java applets for use in the OpenSHA web-based software will be facilitated by Ned Field and his OpenSHA programming team.

Task 2: Our work on the phase shift/RRS issue will proceed as follows. We will begin by evaluating phase differences (coherency) 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. As noted previously, this was originally to be a Year 8 task. The work was pushed back to Year 9 because of rollover of Year 7 work into Year 8 and because of the supplemental tasks that have been added to Year 8 (see Tasks 1 and 3).

Task 3: Development of a user-interface within the NGA database to enable time history selection that accounts for parameters of interest (near-source parameters, epsilon, magnitude, distance, etc.). This work is collaborative with the NGA database manager on staff with PEER. Work on this task has actually begun in Year 8. Communications between this project team and the NGA project management have not always been optimal (our emails going unreturned, etc.), which has impeded timely progress on this work. Support and direction from PEER management will be needed.

Task 4: Implementation of soil-foundation interaction macroelement models into OpenSees. These models have already been developed through funding from Caltrans and PEER and have been validated for pile-foundations. The model will be validated for shallow foundations using centrifuge test data and relevant documentation will be provided.

Task 5: Foundation models have been developed with PEER support by a number of investigators (Kutter, Hutchinson, Taciroglu). This task involves an assessment of those models with respect to the issues outlined above (input parameters, model variability, model functionality). This model assessment work involves application of existing SFSI elements for wall foundations in a single shear wall/foundation system within a typical code-compliant building and in a centrifuge experiment (discussed in December 2005 and January 2006 meetings). Ongoing work is investigating the sensitivity of model predictions to non-physical model parameters.

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

We have completed the implementation of a nonlinear V_{s30}-based model for site effects into OpenSHA (now available in the attenuation relationship module under the title "Choi and Stewart" in www.opensha.org). An output example from this module is shown along with outputs from Abrahamson & Silva's 1997 attenuation results:
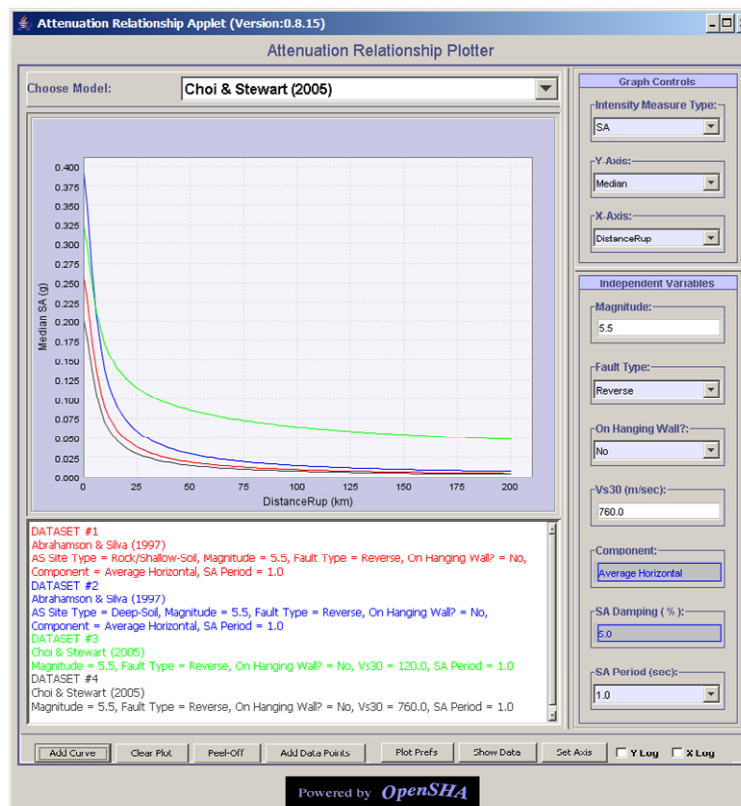
Thrust Area 1—Building Systems

In the area of SSI simulation, the following work has been completed:

(1) Using three-dimensional finite element simulations a coupled vertical-lateral macroelement response model for deep foundations was developed. A journal article in this topic is nearing completion.

(2) A prototypical macroelement model was developed for SSI in shallow foundations. Preliminary sensitivity studies have been completed of the foundation response to macroelement parameters, and model calibrations were performed using UC Davis centrifuge test results as a basis. This model currently provides an uncoupled lateral-vertical response of the soil-foundation system and was shown to be numerically robust under quasi-static, cyclic loading. Currently, we are developing calibrated finite element models of UC Davis tests. These models will aid us in developing coupled lateral-vertical versions of the macroelement models for shallow foundations.

(3) Preliminary studies were performed for converting impedance (frequency-domain) models of SSI into discrete time-domain filters using weighted least-squares techniques. These studies indicated that there is no universal weighting scheme and that the optimal values of the weighting parameters depend on the input ground motion. Automatic and adaptive procedures to determine optimal weighting parameters for a given ground motion are being considered.

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 natural follow-on to PI Stewart's previous participation in the ATC-55 project.

Task 3 will be completed in collaboration with the NGA group. We have initiated contact with Debra Bartling, the NGA IT manager, and we will have our first meeting with her at the end of November 2005.

The Task 4 work is an extension of the project that the PI and the Co-PI are completing for Caltrans. The implementation of the developed models in OpenSees is not only beneficial to the earthquake research community in general, but also for Caltrans engineers who might like to use OpenSees as a validation and analysis tool.

The Task 5 work is part of a collaborative effort with model developers within PEER (Tara Huitchinson and Bruce Kutter) as well as Gregg Deierlein and Helmut Krawinkler.

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

Site response models developed in earlier phases of work (Years 6–7) have been used by a number of consultants and also researchers across the U.S.

Thrust Area 1—Building Systems

Expected milestones & Deliverables

- Web-based Java applets for PSHA that include various site effect models
- Development and dissemination of RRS and phase shift guidelines
- Web-based time history selection tools integrated with NGA database
- New OpenSees models for deep/shallow foundation-soil interaction elements
- Documentation of foundation model assessment results

Member company Benefits

Project Title—**ID Number**	*Loss Modeling for Downtime, Deaths and Decision-Making –* **1362005**		
Start/End Dates	10/1/05 – 9/30/06	Funding Source	PEER-NSF
Project Leader (boldface) and Other Team Members	**James L. Beck** (Caltech/F), Judith Mitrani-Reiser (Caltech/GS), Keith Porter (Caltech/F), Gee Hecksher (Architectural Resources Group/I)		

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 continue to work towards closing the gaps that exist in the loss estimation module of the PEER performance-based earthquake engineering methodology. We aim to close these gaps by Year 10 in order to complete, document and package the PEER methodology. Specific objectives for Year 9 are:

(a) *Joint methodology document.* Prepare a joint document of PEER's loss estimation methodology with PI Miranda at Stanford which presents PEER's damage- and loss-analysis methodologies for the repair–cost decision variable.

(b) *Indirect loss associated with downtime.* In coordination with PI Comerio at UC Berkeley and BIP Hecksher, complete the PEER damage- and loss-analysis methodology for the decision variable of indirect losses arising from downtime, including the probability of building closure (thereby creating a *virtual building inspector*).

(c) *Decision-analysis performance metric.* In coordination with PIs May and Ince, work on the decision-analysis framework that uses the "3 Ds" (deaths, dollars, and downtime) as decision variables but also allows decision makers to account for their risk attitude.

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

PEER promotes and integrates the research of diverse scientists and engineers (earth sciences, engineering seismology, engineering, architecture, economics, and public policy) to create a practical methodology capable of estimating building and bridge performance in terms of interest to owners and society, namely, dollars, deaths, and downtime. The present research advances this mission in several ways.

(a) *Finalize building damage and loss analyses.* The joint methodology document will finalize the *EDP*-to-*DV* analysis and resolve any lingering questions of competing approaches within PEER.

(b) *Advance downtime modeling.* The indirect-loss research will advance, or finalize with consensus, probabilistic modeling of building closure and downtime and how to quantify the latter in financial terms.

(c) *Advance decision-making.* The decision-analysis framework will allow for the risk attitudes of decision-makers and will inform the decision-making stage of the PEER methodology, including addressing the cost of uncertainty.

(d) *Speed methodology dissemination.* By collaborating with ATC-58 researchers (e.g. Hecksher, Miranda and Porter), this research will be informed by practitioners' needs, will facilitate technology transfer from PEER to ATC-58 and then to practice.

Methodology employed

Caltech is approaching the issue of building downtime by considering both building closure (red-tagging) and building inoperability, since a building that is green-tagged may not be operational. The Applied Technology Council's *Procedures for Post-earthquake Safety Evaluation of Buildings* document (ATC-20, 1989 and 1995) offers guidelines for rapid and detailed building evaluations after seismic events. We use the available structural performance data from simulations (EDP's from nonlinear structural analysis and DMs from fragility functions) in accordance with these guidelines to create an event tree, shown in Figure 1 below, whose branches provide the probabilities of a building being green-, yellow- or red-tagged. Based on ATC guidelines, a building is unsafe to inhabit if it receives a red-tag (which may have been initially a yellow-tag). Conditional on the closure of a building, we can establish a probability distribution for building downtime based on mobilization time (time to inspect, acquire building permits, acquire financial means, etc.) and the repair durations of the damaged building assemblies. The repair strategy is owner-dependent, but we will provide an envelope of repair durations based on slow- and fast-track strategies for the repair work.
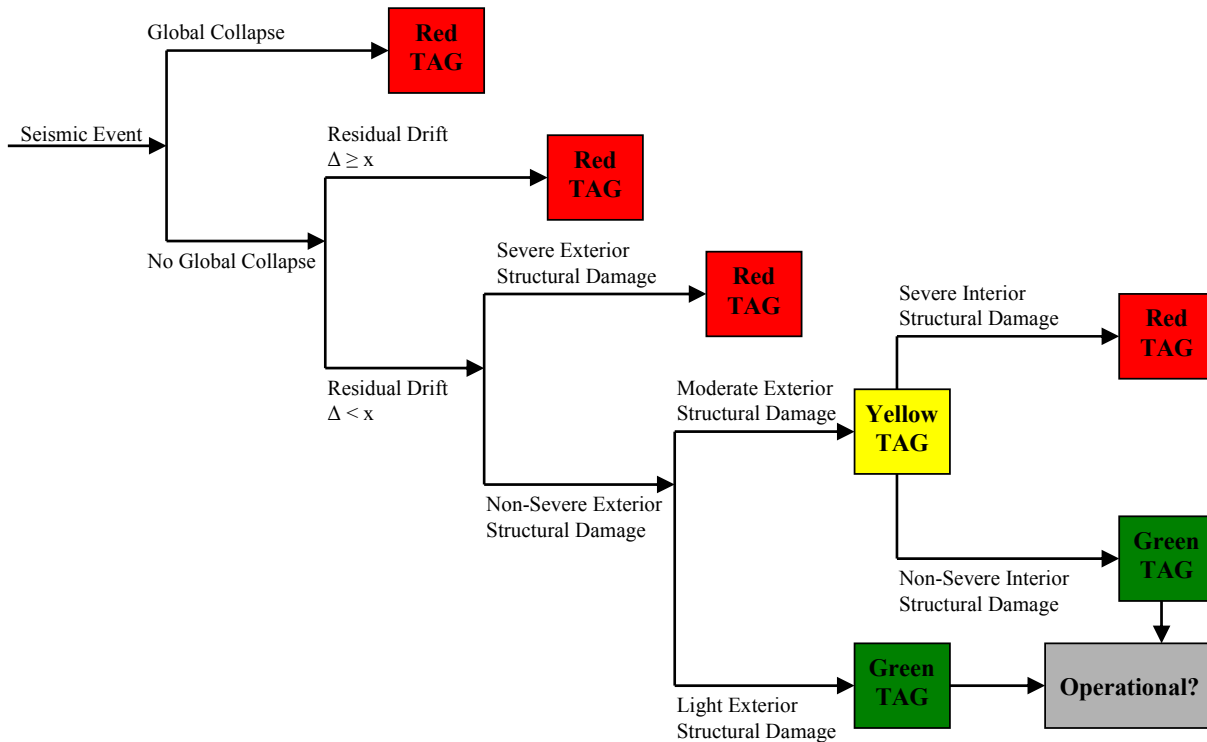
Figure 1 - Caltech model for building closure

A building can receive a green tag but still be inoperable because of severe damage of its nonstructural components and equipment. The Caltech downtime model currently includes all nonstructural components, equipment and occupancy-specific systems for which there are existing fragility functions (i.e., wallboard partitions, raised access flooring, suspended ceilings, glazing, elevators, domestic water, fire response, etc.) and that are considered critical for building operability by ATC (ATC-20 1989, ATC-20 1995, ATC-58 2005) and other researchers (e.g. Porter et al. 1993). As in the case of building closure, conditional on building inoperability,

we can establish a probability distribution for building downtime based on mobilization time and the repair durations of the damaged building assemblies.

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

In the previous year, Caltech has completed the damage and loss analysis of the benchmark building. The Caltech, Stanford, and UCLA research teams submitted two papers to 8NCEE and will give a joint oral presentation at the conference. Also, the MATLAB loss estimation toolbox is complete and now available (contact Judy Mitrani-Reiser: judith@caltech.edu). Various PEER researchers and industrial collaborators interested in loss modeling have met several times to discuss the similarities and differences in their approaches for the PEER methodology. The outcome of this meeting was a consensus that the PEER approaches can be adopted as tools for assisting engineers, architects, building owners, and city officials in design-related decisions. Caltech also developed a preliminary model for building closure and building inoperability, and is finalizing it in Year 9.

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

ATC-58 workers this year are advancing from a 25% draft of their analysis methodology. They appear not yet to have begun to address fatalities or downtime. There is no indication that they will address decision-making through formal decision analysis.

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

(a) *The Kajima Corporation* of Japan has developed a PBEE-like methodology, partly in collaboration with Caltech.
(b) *John A. Martin Associates* has developed loss-estimation software for CSMIP that relies in part on fragility functions developed by Caltech researchers.
(c) *The California Earthquake Authority* is reviewing its seismic retrofit incentive program using products of Caltech's PBEE research.
(d) *Commercial Internet users* have accessed the Caltech-produced PEER Testbeds webpage more 4,000 times per month as late as November 2005. Two of the most-popular documents downloaded were Porter's 2003 PEER Methodology Overview and the 2002 Caltech documents of the methodology for performing and depicting sensitivity studies.

Expected milestones & Deliverables

31 Mar 06: Completion of methodology to establish the probability that certain category of facilities will not be operational.
30 June 06: Completion of methodology to establish probability distribution for downtime, given closure and the recovery strategy.
31 July 06: Completion with Miranda of documentation of PEER's methodology for damage and loss estimation: EDP to DV=repair costs.
31 Aug 06: Report documenting EDP-to-DV=indirect losses from downtime.

30 Sep 06: 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.

Member company Benefits

Architectural Resources Group (Hecksher's company) will gain early access to and influence over the downtime methodology.

Project Title—**ID Number**	*Benchmarking Performance of New RC Frame Buildings -* **1382005**		
Start/End Dates	10/1/05 – 9/30/06	Funding Source	PEER-NSF
Project Leader (boldface) and Other Team Members	**Greg Deierlein** (Stanford/F), Curt Haselton (Stanford/GS), Abbie Liel (Stanford/GS), Sarah Lange (UCD/US)		

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 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: (a) gage whether design standards provide the expected performance across the range of building configurations permitted by design codes, (b) contribute to establishing appropriate performance targets for performance-based design of new buildings, (c) provide a benchmark against which new innovative systems can be judged, (d) provide data for improved building fragility models as input for loss simulations of large geographic regions, and (e) demonstrate the benefits of the PEER PBEE assessment method as compared to the current state-of-art in engineering practice (e.g., FEMA 356). A related objective is to compare the collapse safety of modern (2003) buildings with ones designed according to the 1967 UBC code, which are viewed as seismically deficient according to modern codes.

Beyond the primary objective to benchmark current design provisions, the project will contribute to the packaging of these tools as part of the technology transfer to practice. Additionally, 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 relates directly to the TA I need to package the PBEE methodology and make it accessible to the engineering community. The procedures and data from the RC building benchmarking studies are an integral part of the major unifying theme of the 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 primarily focused on new buildings in high-seismic regions, although the project is examining how various design parameters, including changes in building code provisions from 1970 to the present, can affect building performance.

The benchmark building designs are assessed using the PEER-PBEE approach, where the structural response is evaluated through nonlinear time history analysis 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 previous year's achievements, with emphasis on accomplishments during last year (Year 8)

In prior years, detailed plans were developed to outline (a) key design, construction, and structural behavior considerations in the benchmark investigation, (b) details for implementing and applying the PBEE methodology to the benchmark buildings, (c) 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.

A detailed assessment of the four-story index building has been completed. Shown in Figure 1 (see below) is an example of the incremental dynamic analysis results OpenSees analyses to determine the peak interstory 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 has collapse safety consistent with building-code expectations. Research is currently underway on a systematic investigation of alternative structural configurations.
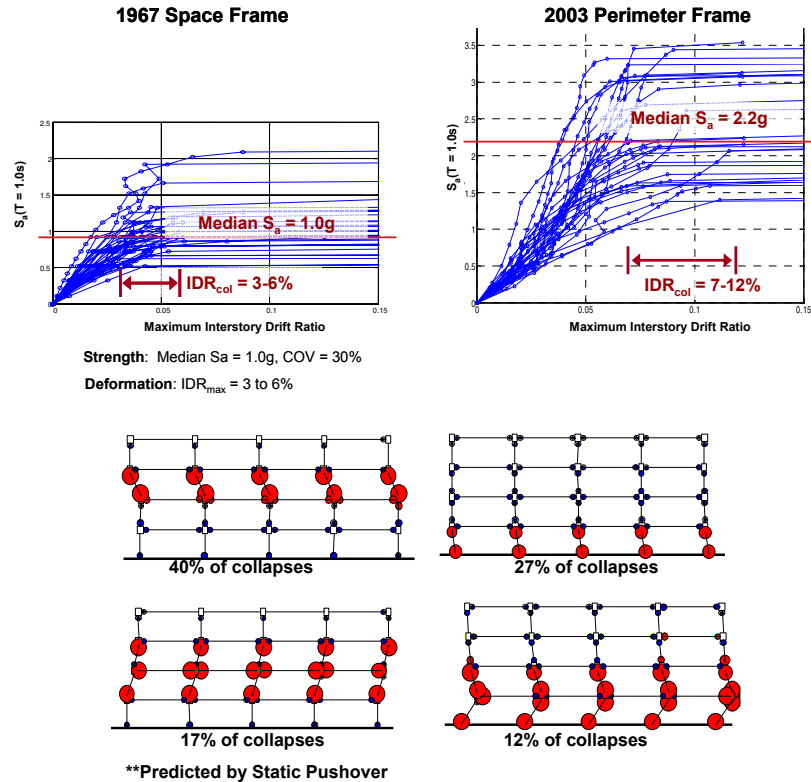
Figure 1 – Incremental dynamic analysis results for four-story benchmark building

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

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 (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.

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 (ATC 63) 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. Results of this research have also been show-cased in a technical seminar on the performance assessment of RC buildings that was jointly sponsored by PEER and EERI in 2006.

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 (completed in April 2006, 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 (6/2006).
- 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).

Member company Benefits

This study is serving to refine and implement the PBEE methodology that is of interest to PEER's Business and Industry Partners who are involved in the seismic design and evaluation of buildings and in building code development.

Project Title—ID Number	Database and Simulation Models for RC Structural Components - 1402005		
Start/End Dates	10/1/05 – 9/30/06	Funding Source	PEER-NSF
Project Leader (boldface) and Other Team Members	**Laura Lowes** (UW/F), Nilanjan Mitra (UW/GS)		

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

Project goals and objectives

The research will develop a comprehensive report to support modeling of reinforced concrete beam-column joints for performance-based earthquake engineering. A web-based, searchable database will be developed to provide easy access to experimental data characterizing the seismic behavior of RC components. Data will include geometric and material properties as well as damage data and load-deformation response data.

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

PBEE requires prediction of component and system damage for multiple performance levels. This requires accurate response prediction models as well as accurate damage prediction models. Ready access to component data will enable engineers and researchers to develop and evaluate models used for PBEE.

Methodology employed

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

Year 8 research activities resulted in the development of EDP-DM-DV relationships defining the likelihood that various RC components (modern beam-column joints and structural walls) would require a specific type of repair given a specific level of earthquake demand. The results of this effort are reported in a M.S. thesis (Brown, P. "Modeling of Structural Damage in Reinforced Concrete Components." *MS Thesis*. Seattle: University of Washington, 2000) and an *Earthquake Spectra* paper (Brown, P. and L.N. Lowes. "Empirical Models for Predicting Earthquake Damage and Repair Requirements for Modern Reinforced Concrete Beam-Column Joints." *Earthquake Spectra*. In review).

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

The PI is unaware of similar efforts outside of PEER.

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

Expected milestones & Deliverables

Milestones for the project include the following:

- With respect to development of the database: (i) contacting researchers to request electronic response data, (ii) accumulating non-digital response data,(iii) assembling response data, (iv) verifying material, geometric, etc. data for each test, (v) publishing data to a website.
- With respect to documentation of response-prediction models: (i) develop elastic-effective stiffness models for modern joints and document these for older joints, (ii) develop additional calibration parameters for moment-rotation models for older and modern joints and document these models, (iii) document additional joint models developed at PEER
- With respect to documentation of performance-prediction models: (i) develop fragility functions for exterior joints, (ii) document fragility functions for interior joints.
- With respect to demonstrating application of models: (i) assemble and document example analyses accomplished previously using the OpenSees platform.

Deliverables include (1) a searchable website

Member company Benefits

Access to experimental data characterizing the seismic performance of RC components.

Project Title—**ID Number**	*Performance-based Design of Soil-Foundation Interface in Buildings* - **1412005a**		
Start/End Dates	10/1/05 – 9/30/06	Funding Source	PEER-NSF
Project Leader (boldface) and Other Team Members	**Tara Hutchinson** (UCI/F), 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

Seismic loading on a building with shear walls can potentially cause the foundations of the shear walls to rock. Current building codes discourage designs that allow rocking. For existing buildings, however, it is often very expensive to retrofit foundations to prevent rocking. Furthermore, it has been suggested that building performance might actually be enhanced if rocking is allowed because rocking could reduce seismic demands on a building and dissipate energy in hysteresis at the foundation soil interface. Although previous work has focused on shear walls, results should be applicable to shallow foundations for building and bridge columns as well.

The ultimate goal of this project is to develop the necessary tools to predict rotations and translations at the soil – shallow foundation interface and to allow engineers to assess, through quantitative analysis, the trade off between the benefits (energy dissipation and isolation) and the detriments (e.g., permanent and cyclic settlement and/or tilt) associated with foundation nonlinearity.

The objectives of this work in Year 9 are to:

(1) Refine and finish a BNWF foundation model implementation in OpenSees, assuring it reasonably captures foundation nonlinearity; moment-rotation, shear-sliding, and axial-settlement behavior. This includes documenting the model for use by others and testing the model convergence and sensitivity to input parameters. In addition, it includes clearly identifying and quantifying all empirical model parameters, presenting these guidelines for their quantification, evaluating the sensitivity of the results to engineering assumptions inherent in these parameters, and delineating boundaries beyond which application of these models is not appropriate.
(2) Complete data analysis from the frame-wall-foundation model centrifuge tests and archive data report with UC Davis.
(3) Develop and document a process for using the models to extract a basic engineering foundation interface model for wall or column footings

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.

Centrifuge testing with UC Davis has been conducted on two different wall-frame-foundation models to develop a database for evaluating the models. In addition, UC Davis has an extensive database of isolated footing-wall models, considering different factors of safety, embedment moment/shear ratios, and soil conditions for model evaluation.

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

BNWF Model Implementation, Testing, Sensitivity Evaluation and Documentation

The UC Irvine implementation involves use of a number of independent nonlinear springs at the base of the shear wall or column. This model has been tested on a number of isolated wall-footing model experiments conducted by UC Davis and has worked well for large amplitude rotations on fairly strong soils (see Figure, SSG03#2c test, with FSv = 11.5). However, for softer foundation soils and for small amplitude rotations, the model underestimates settlements observed in the centrifuge tests. We are evaluating existing axial load-settlement curves from centrifuge experiments and plan to use these to refine the backbone curves for shallow footings on softer/looser soils to correct this shortcoming. Datasets from SSG02 and 03 series tests include datasets on medium sands, which are ideal for this purpose. After regressing through the test datasets backbone curves, the existing qzMaterial model may be modified to account for the softer initial axial load-settlement backbone curve observed in these centrifuge tests.
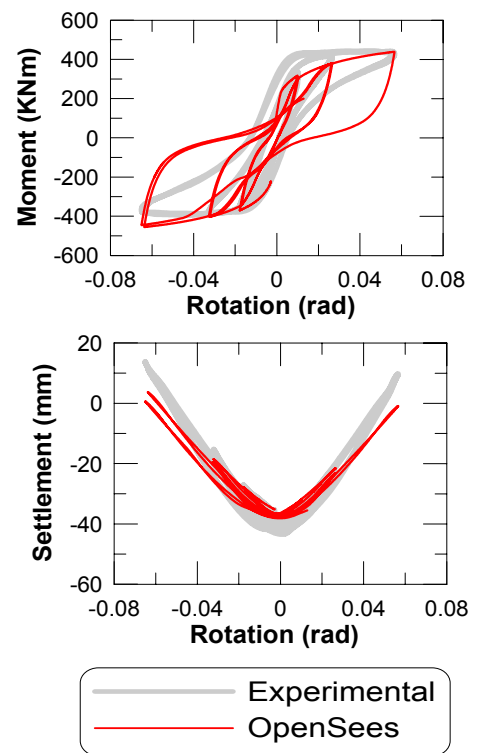
To test the sensitivity of the model, we participated in a case study building evaluation with UC Davis, led by UCLA. The shearwall-footing portion of an example 4 story building was modeled and is being used to study the sensitivity of response to derived input and model parameters. We find from this study that Rayleigh damping and mesh discretization have the most pronounced affect on the models response. We plan to further evaluate the model sensitivity for other case

buildings, and other ground motions. For example, one additional case study is a model of the wall-frame-foundation structure tested on the centrifuge. Here we considered five different base conditions in the modeling: (i) fixed base, (ii) elastic base with no sliding, (iii) elastic base with sliding allowed, (iv) nonlinear base with no sliding, and (v) nonlinear base with sliding allowed. We considered 10 ground motions applied to the model and a range of FSv (3, 5, 7, 10). Results show that FSv has a significant affect on the response of the building (on floor acceleration, drift, moment and shear). The capacity curves as expected also show the dramatic difference in stiffness, period, yield point, etc. for the different foundation cases.

Model Frame-Wall-Foundation Centrifuge Test Data Analysis

We have conducted a series of tests with UC Davis where one and two-bay frame structures were attached to shearwalls and supported by square and strip footings. These models were subjected to slow cyclic lateral loading and dynamic base excitation (sinusoidal and earthquake motion). A unique feature of the models was the use of designed plastic hinges at the beam-column joints. This was intended to model the energy dissipation within the superstructure. The models were heavily instrumented, with nearly 70 sensors on the two-bay model and therefore the data processing is a significant task. Preliminary findings show that the desirable yielding and nonlinear behavior of the beam-column joints is occurring during the experiments. Energy is also dissipated by rocking, sliding, and settlement of the footings. However, we observe highly asymmetric hysteretic loops for both structures, due to the asymmetry of the lateral force resisting system. The figure below shows the percentage of energy dissipated by the footings E_F divided by the total energy dissipated (by footings and beam-column fuses) $S E_{(F-B)}$ in % versus the drift ratio (%). This preliminary data shows that even at low drift ratios, the footings can provide a good portion of the total dissipated energy (as much as 35% of the total). For higher drift ratios, one would expect the portion of energy dissipated due to the yielding of the joints to be more substantial, which is observed for the static push test data.
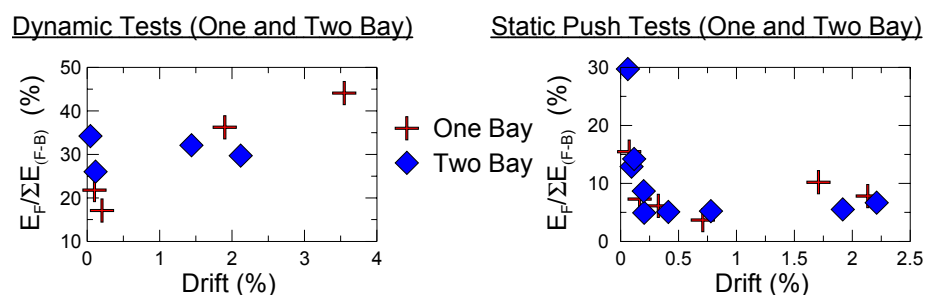
Other similar work being conducted within and outside PEER and how this project differs

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. A new project at UCLA (Stewart) is

attempting to use the findings and developments at Davis and Irvine and implementing them in the context of 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.

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. Data report on frame-wall-foundation tests in collaboration with UC Davis – Summer 2006.
2. BNWF mesh implementation (including code examples, documentation, and sensitivity studies) in C++ - Fall 2006.
3. PhD dissertations: Chang and Raychowdhury, expected 2007

Member company Benefits

We have engaged significantly with Mark Moore of Rutherford and Chekene on this work.

Project Title—**ID Number**	*Performance-based Design of Soil-Foundation Interface in Buildings* - **1412005b**
Start/End Dates	10/1/05 – 11/30/06 Funding Source PEER-NSF
Project Leader (boldface) and Other Team Members	**Bruce L. Kutter** (UCD/F), Sivapalan Gajan (UCD/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 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 9 are:

1. To summarize centrifuge test data and the effects of various parameters on the performance of shallow foundations
2. 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 previous year's achievements, with emphasis on accomplishments during last year (Year 8)

SUMMARIZING CENTRIFUGE TEST DATA

Seven series of centrifuge experiments, including about 60 shear wall-footing models, have been conducted at UC Davis. The eighth test series included nonlinear frame structures supported by shear wall-shallow foundations. The effects of parameters such as vertical static factor of safety, depth of embedment, applied moment to shear ratio, footing geometry and soil type will be systematically analyzed and summarized in the final report. Data reports for completed tests are already in the project website. The data from test series 8 are available to collaborating PEER researchers at USC and UCI.

DEVELOPMENT OF MACRO-ELEMENT MODEL

We have coded a single-element constitutive model (macro-element model) to simulate the foundation-soil interface behavior in C++. Footing and the soil beneath the footing were considered as a single element. By keeping track of the shape of the soil surface beneath the footing, maximum past pressure and settlement experienced by the soil, and the location of the contact area of the footing with soil, the nonlinear cyclic load-displacement behavior of the footing-soil system was modeled. We have used bounding surface plasticity theory to capture the coupling effect of combined vertical-shear-moment (V-H-M) loading. The major model parameters are: friction angle, vertical stiffness and the rebounding ratio of soil. An example measured and predicted moment, rotation, lateral force and sliding displacement for a shear wall footing are presented in the figure below.
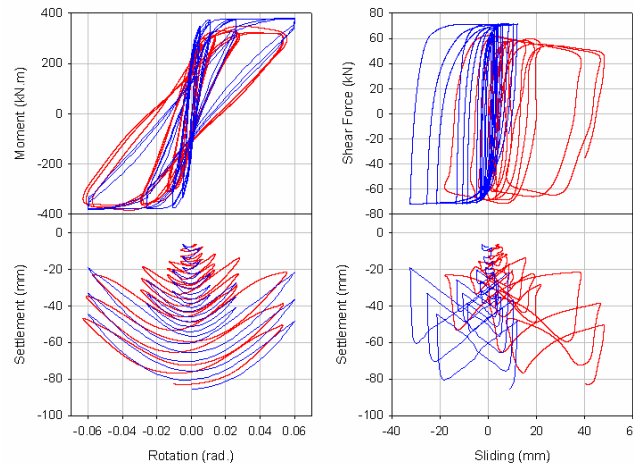
Figure 1 - Comparison of predicted and calculated moment, rotation, horizontal load, sliding, and settlement of a centrifuge model of a building shear wall.

IMPLEMENTATION OF MACRO-ELEMENT MODEL IN OPENSEES

The macro-element model has been implemented in OpenSees in Year 8. We run the model in OpenSees to simulate the footing-soil interface behavior for a rigid shear wall structure. One student (George Hu) has completed his MS thesis in UC Davis using our model in OpenSees. We have done simulations and compared to the simulations form UCI and USC for a shear wall structure.

SENSITIVITY ANALYSIS

We will run OpenSees parameter studies with the nonlinear shear wall footing element and with a moment frame attached (vary the FS of footing, effective height of building, footing embedment, frame stiffness, fraction of inertial frame load transferred to shear wall, ground motions). We will provide recommendations on how the new footing element in OpenSees can be used in a probabilistic PBEE framework. This will include analysis of propagation of the uncertainties in field measurements of soil properties to uncertainties in the new constitutive model parameters and finally into the demands placed on the building.

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.

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

Ph.D. thesis (June 2006 – Sivapalan Gajan)
Final project summary report to PEER (Sept. 2006)

Member company Benefits

Project Title—**ID Number**	*Performance-based Design of Soil-Foundation Interface in Buildings* - **1412005c**		
Start/End Dates	10/1/05 – 9/30/06	Funding Source	PEER-NSF
Project Leader (boldface) and Other Team Members	**Jonathan Stewart** (UCLA/F), Ertugrul Taciroglu (UCLA/F), Payman Tehrani (UCLA/GS)		

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

Project goals and objectives

Work with Topic Area Leader Helmut Krawinkler to coordinate foundation modeling activities of PEER researchers Kutter/Gavin (funded separately), Hutchinson/Prishati (funded separately), and Taciroglu. Goal of the work is to have alternative foundation modeling routines implemented into OpenSees that provide reasonable results for benchmark buildings.

Specific goals include identifying non-physical parameters used in the SSI models, evaluating the sensitivity of the results to reasonable range of those non-physical parameters, and developing guidelines for users on the selection of those non-physical parameters.

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

The major impact of our effort is to provide packaged tools in OPENSEES for SFSI analysis (typically utilized in IM to EDP analyses) that are sufficiently well documented and robust that they can be used with confidence by users other than the developers of the tools .

Methodology employed

This work principally involves coordinating the activities of SFSI model developers, who are funded separately. This is being done through a series of coordination meetings. Two meetings have been held to date, one at Stanford in December 2005, the second at the PEER annual meeting (January 2006), and the third is scheduled for May 2006.

These meetings are used to share results and reach consensus on the work that is needed to reach the project objectives.

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

See report for the 1342005 project.

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

See report for the 1342005 project.

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

See report for the 1342005 project.

Expected milestones & Deliverables

Web page posted as of January 2006 (http://www.christinegoulet.com/files.htm)
Web page updated as needed following meetings
OpenSees modules for foundation models by end of project period.

Member company Benefits

Thrust Area 2—Bridge and Transportation Systems

Project Title—ID Number	*Effect of Ground Deformations and Liquefaction on Bridges -* **2392005**		
Start/End Dates	10/1/05—9/30/06	Funding Source	PEER-CA State Transp. Fund
Project Leader (boldface) and Other Team Members	**Ross W Boulanger** (UCD/F), Alicia Ambrosini (UCD/US), Alex Kan (UCD/US), Dongdong Chang (UCD/GS)		

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

Project goals and objectives

The objective of this project has been to support the Bridge Thrust Area's efforts regarding the simulation and performance of bridges subject 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 continuing development of design procedures and guidelines.

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

This project supports PEER's mission by further developing the knowledge base and enabling technologies necessary for Thrust Area II's application of the PBEE methodology to bridge and transportation systems.

Methodology employed

The project involved: (1) continued support and enhancement of various nonlinear soil spring material models, (2) systematic comparisons of FE models that used the 4-node porous solid, 4-node quad u-p, and 9-node quad u-p elements against centrifuge data, and (3) expanded parametric analyses using the calibrated FE models to address issues in the simplified design procedures being utilized in the test bed and bridge fragility projects.

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

Different FE models have been evaluated against the experimental data from two dynamic centrifuge model tests. Each centrifuge model had a pile-supported structure embedded in soil profile that developed lateral spreading during strong shaking. The deformed FE mesh for one of these models is shown below.
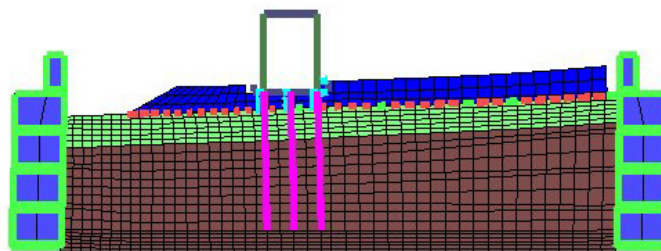
Each centrifuge model had been shaken by a series of four earthquake motions, such that there were a total of eight cases to analyze. The input parameters for the two models were essentially

identical except for small differences in the thickness of each soil layer, the fundamental period of the supported superstructure, and the undrained shear strength of the clay crust layer. Analyses have been completed using the 4-node porous solid and 4-node u-p quad elements in OpenSees, while work is ongoing with the 9-node u-p quad elements. The computed responses are compared to the measured responses in terms of acceleration time series, excess pore water pressures, displacements, bending moments, and lateral loads on the pile foundation. The computed time series are compared to measured quantities of the some of the key quantities in the figure below for the two different structural models during a large "Kobe" input motion. The computed and recorded responses are in reasonably good agreement for this and the other cases.
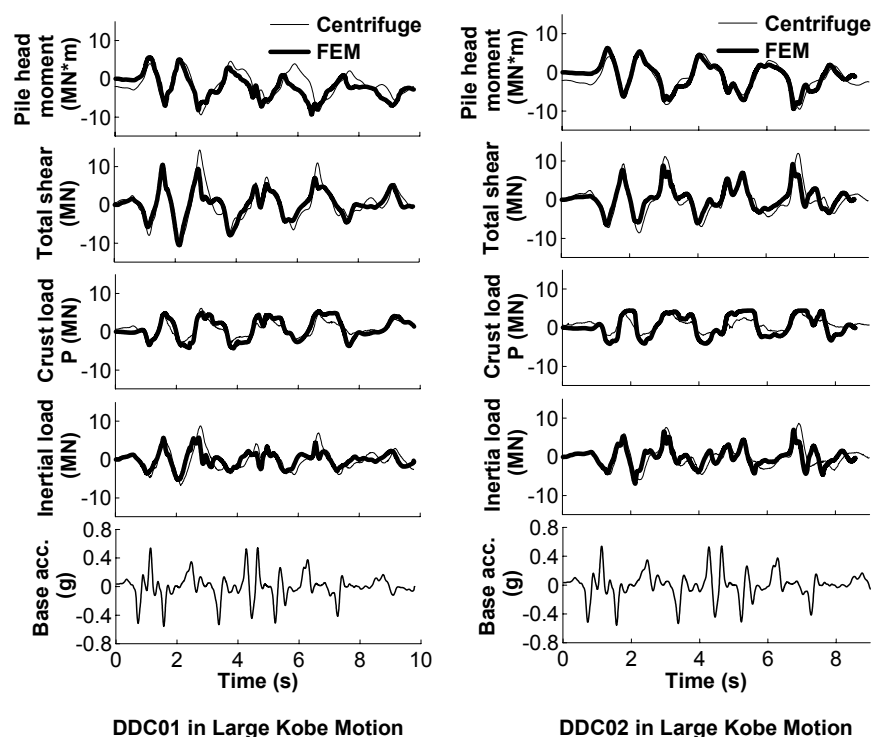
DDC01 in Large Kobe Motion   DDC02 in Large Kobe Motion

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

This project complements related projects in the Bridge Thrust area. The projects by Kramer/Arduino and Bray/Martin are focused on demonstrating the application of the PEER PBEE methodology against a baseline bridge, and thus their work benefits from the continuing developments and validation efforts described herein. Brandenberg's work on fragility relations will directly use the design procedure he developed during his doctoral studies, and it will benefit from any updates/revisions that are derived from the parametric studies herein and the improvements in the efficiency tools. Boulanger/Kutter's Lifelines project on pile pinning effects in bridge abutments is ending, but any subsequent continuation of this work will benefit from the studies described herein. These overall efforts further benefit and are coordinated with Elgamal's involvement in a US-Japan collaborative project that involves Dobry and Abdoun (MCEER) and NIED researchers from Japan.

Thrust Area 2—Bridge and Transportation Systems

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

The design guidance developed from this and related projects have been utilized by engineers within Caltrans and private firms in California.

Expected milestones & Deliverable

We expect to complete the systematic evaluation of alternative FE models and the main body of parametric analyses by the end of this year. The results will be summarized in a final report and journal papers.

Thrust Area 2—Bridge and Transportation Systems

Project Title—ID Number	PBEE Assessment and Design of Enhanced Bridge Piers for Near Field Effects - 2402005		
Start/End Dates	10/1/05—9/30/06	Funding Source	PEER-CA State Transp. Fund
Project Leader (boldface) and Other Team Members	**Stephen Mahin** (UCB/F), Hyungil Jeong (UCB/GS), Junichi Sakai (Public Works Research Institute, Japan/PD), Andres Espinoza (UCB/GS), Gita Dombrowski (Portland State Univ/US)		

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 though 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 capabilities of OpenSees and of the PEER methodology's 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 from shaking table tests of for conventional and improved column designs 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 re-centered 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. As part of the Year 8 activities, a set of 4 concrete columns have been constructed and tested. One resembled the partially prestressed column tested previously, but with the ground motion record amplitudes adjusted to better represent design criteria. The second specimen was similar to the first but with the longitudinal mild reinforcement unbonded over a length of about 2D. The third was similar to the second, but the level of post-tensioning was increased. The fourth specimen was similar to the second, but with the extra confinement required for these columns provided by a steel jacket (which makes the column less likely to need repair following an earthquake). These tests were completed towards the end of Year 8 and the results are being analyzed during Year 9.

It was intended that one of the columns utilized an Engineered Cementitous Composite (ECC) instead of concrete. A PEER intern working with Prof. Billington at Stanford worked with another intern at Berkeley to assess the feasibility of using the ECC material. A wide range of concrete cylinders having different degrees of spiral confinement were prepared and cast using conventional concrete, ECC and a hybrid multi-scale concrete. The ECC test results were disappointing, indicating significant constructability problems, and inconsistent test results. During Year 8 we are working to assess improved methods for constructing columns with high performance concrete, with special emphasis on the hybrid concrete composite materials. However, the focus of the work is on improving analytical models of the column behavior, which to date is considered inadequate in terms of assessing residual displacement and local damage, and developing and demonstrating the adequacy of design methods using conventional concrete. 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 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.

Thrust Area 2—Bridge and Transportation Systems

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

As noted above, 4 columns using the proposed self-centering technology were constructed and tested on the Berkeley shaking table. These results substantiate the ability of these partially prestressed concrete columns to achieve displacements similar to those developed by conventional bridge columns, but to have residual displacements substantially smaller. It was found that unbonding of the mild reinforcement in the plastic hinge region softens the column and results in slightly larger lateral displacements. By increasing the amount of post-tensioning, stiffness is increased to desirable levels, and residual displacements are very small, even for large earthquakes. However, during the maximum considered earthquake shaking, the amount of spalling and the degree of bar buckling is increased with larger post-tensioning forces. It was found that a partially prestressed concrete column with unbonded post-tensioning and mild reinforcement (in the plastic hinge region) which has the plastic hinge region confined by a steel jacket has similar or smaller displacements compared to a conventional reinforced concrete column, has residual displacements less than 0.5% when the peak displacement ductilities exceeded 10 (this is less than a tenth of what was retained by a similar RC column), and very little visible damage is apparent following even the maximum considered events.

To date, analyses using OpenSees and other programs have been able to predict the peak lateral displacements of the test specimens fairly well. However, prediction of post peak response, and in particular the residual displacements, has been poor. Thus, we are continuing to work on this issue in conjunction with others (Eberhard, Billington, Filippou, etc.).

The disappointing results of the feasibility tests with the ECC material resulted in a decision not to build a full test specimen constructed with ECC. However, additional work on cylinders and in the construction of a small-scale pilot test specimen is planned for the remainder of Year 9.
The main thrust of Year 9 is to learn from the results of the 4 tests conducted in Year 8 and design, construct and test a small bridge system that employs the self-centering columns. This is based on a specimen using conventional columns that was tested in Year 7. The new specimen is in construction and will be tested during the summer 2006. The specimen includes columns with steel jackets that confine the plastic hinge region at the top and bottom of the columns. The structural system employed is such that the specimen develops frame action in the longitudinal direction and plastic hinging would be expected at the top and bottom of the specimens, and that the specimen would exhibit primarily cantilever action in the transverse direction. The two columns are different in length (by D/2) so that the specimen will develop a small amount of torsional response as well. This data will help demonstrate the capabilities of this concept for bridge systems, and be extremely helpful in assessing models for use in OpenSees for predicting post peak responses.

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

Prof. Billington is examining in a companion PEER project the effect of self-centering columns on the overall performance of bridges. Some related research is underway at UC Reno using prestressed precise columns (with no mild reinforcement) and use of shape memory alloys for the longitudinal reinforcement to help reduce the residual displacements of columns. At the University of Washington, Profs. Eberhard, Stanton and others are exploring the use of precast, post-tensioned columns. In Japan, there is a significant effort related to shaking table testing of

conventional concrete columns being begun by PWRI, E-Defense, and the Tokyo Institute of Technology. We will keep abreast of these and other related efforts.

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 & Deliverable

We expect to begin construction of the two self-centering column test specimen in Spring 2006 and test it during the Summer 2006. We will carryout additional work on the high performance concrete materials during the Summer 2006. The analytical research using OpenSees is continuous. A report on the first two specimens tested is in final stages of preparation and will be released as a PEER report soon. A report on the results of the next four specimens and the two column specimen will be part of the thesis of graduate student H. Jeong, expected to be completed in Year 10. A series of papers on the findings of the research have and are continuing to be prepared and published.

Project Title—**ID Number**	*Performance-Based Evaluation of Bridge on Liquefiable Soils Using OpenSees* - **2412005**
Start/End Dates	10/1/05—9/30/06 Funding Source PEER-NSF
Project Leader (boldface) and Other Team Members	**Steve Kramer** (UW/F), Pedro Arduino (UW/F), Hyung-Suk Shin (UW/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 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 evaluate performance of an existing structure located on poor soils. It will illustrate the interaction between structural and geotechnical damage mechanisms. In combination with the project of Bray and Martin, this project will demonstrate the benefits associated with detailed response analyses in terms of identifying damage mechanisms, soil-structure interaction effects on performance, and reduction of model uncertainty.

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 requires 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 is being used to investigate the dependence of appropriate EDPs on various IMs. This dependence is being studied first deterministically to 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 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 previous year's achievements, with emphasis on accomplishments during last year (Year 8)

Much of the work to date has centered upon building and testing of an OpenSees model of the bridge, foundations, and soil deposit. Several iterations of soil geometry and material properties have been required to identify a soil profile that is amenable to analysis using the OpenSees approach and the empirical approach of Bray and Martin. The structural model was implemented with the assistance of Kevin Mackie. An OpenSees model was developed and tested using the equivalent pier concept of foundation modeling (i.e. modeling pile groups as a single shaft with appropriate material properties). The model was subjected to a series of ground motions representing four return periods (figure below shows relative efficiencies of different IMs). Further discussion with the other investigators and with Caltrans engineers led to the decision to model the pile foundations individually (at least individual rows in the two-dimensional model). A new mesh adopting this approach has been developed and is being tested at this time. This model will be previewed at the May 4 project meeting, and then used for multiple analyses.

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

The project has numerous interdependencies with other Year 9 projects. For conciseness, the interdependencies are summarized in tabular form below.

Principal Investigator(s)	Needed Inputs	Provided Outputs
Bray Martin	Estimates of appropriate uncertainties involved in estimation of performance using simplified procedures.	OpenSees pile-soil interaction models for testing against simplified procedures.
Stojadinovic	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.

The project is most closely related to the project of Bray and Martin who are 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.

Expected milestones & Deliverable

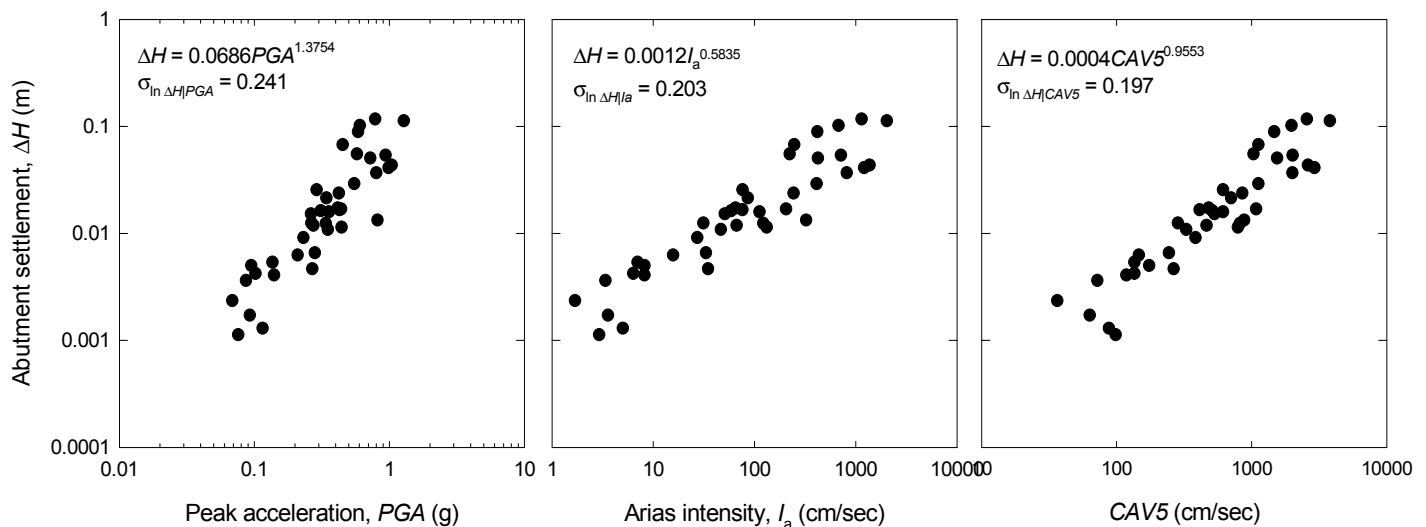OpenSees complete model with individual piles: May 4, 2006
OpenSees analyses with suite of ground motions: June 30, 2006
OpenSees sensitivity analyses: July 31, 2006
Identification of most significant geotechnical/foundation parameters: August 30, 2006
Investigation of effects of geotechnical uncertainties on EDPs: September 30, 2006

Member company Benefits

Panel 1: $\Delta H = 0.0686 PGA^{1.3754}$, $\sigma_{\ln \Delta H | PGA} = 0.241$; y-axis: Abutment settlement, ΔH (m); x-axis: Peak acceleration, PGA (g)

Panel 2: $\Delta H = 0.0012 I_a^{0.5835}$, $\sigma_{\ln \Delta H | Ia} = 0.203$; x-axis: Arias intensity, I_a (cm/sec)

Panel 3: $\Delta H = 0.0004 CAV5^{0.9553}$, $\sigma_{\ln \Delta H | CAV5} = 0.197$; x-axis: $CAV5$ (cm/sec)

Project Title—**ID Number**	*Development of a Probabilistic Simplified Design Procedure for Assessing the Effects of Liquefaction and Lateral Spreading on Bridges* - **2422005**		
Start/End Dates	10/1/05—9/30/06	Funding Source	PEER-CA State Transp. Fund
Project Leader (boldface) and Other Team Members	**Jonathan Bray** (UCB/F), 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 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). 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" that this project is applying in a probabilistic format. Due to his expertise in this area and his previous extensive work in the area as evidenced by his numerous publications on this topic, Professor Martin's insights and guidance is proving invaluable.

Methodology employed

This Year 9 project is the second 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. Candidate Graduate Student Researcher, is performing the primary work on this project. He will work under the supervision of Professor Bray. Professor Norm Abrahamson serves 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 recently initiated a study of probabilistic seismic slope displacement problems.

Professor Geoff Martin, who is funded separately on a related PEER project (2052004) works 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 works 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 requires 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). Without many detailed case histories, the UCD centrifuge studies (Boulanger 2012004) will be vitally important in evaluating the results of the analyses and in judging the appropriateness of the many assumptions involved in the simplified procedure.

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 will be performed in a limited and focused manner to support this objective, without duplicating efforts by other PEER researchers.

This research project capitalizes on the Year 7 PEER work performed by Dr. Thalia Travasarou who worked under the direction of Professor Bray at Berkeley. Travasarou 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 Travasarou 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.

This research also takes advantage of the PEER-Lifelines program research results of Professor Seed on probabilistic liquefaction triggering procedures (principally with O. Cetin and R. Moss) and probabilistic lateral spreading (with A. Faris and R. Kayen). It utilizes the probabilistic

performance-based earthquake engineering methodology developed by Dr. K. Mackie and Prof. B. Stojadinovic of U.C. Berkeley.

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

This project builds upon the Years 3-5 and 7 PEER projects on identification of efficient intensity measures for earthquake ground motions and development of a probabilistic method for estimating seismic slope displacements. It builds as well upon the first year of this three year project, which is Year 8

This research project capitalized on the Year 7 PEER work performed by Dr. Thalia Travasarou who worked under the direction of Professor Bray at Berkeley. Travasarou 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 Travasarou 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.

In Year 8 (the first year of this project), accomplishments include:
1. Developing the foundation design for the bridge design example that will be analyzed by a group of PEER researchers.
2. Worked with the Univ. of Washington researchers to refine the soil profile to be used in the bridge design example.
3. Completed preliminary evaluation of the MCEER/ATC simplified methodology for evaluating the effects of piles in restraining liquefaction-induced lateral spreading.
4. Integrated the Seed et al. (2003) probabilistic liquefaction-triggering procedure and the Travasarou et al. (2004) probabilistic seismic displacement procedure into the deterministic MCEER/ATC simplified methodology and included a probabilistic assessment of the ground motion Intensity Measure. Example results are shown in Figure 1 below.
5. Hosted a one-day workshop on key aspects of the soil-foundation-pile-structure interaction parts of the liquefaction-induced lateral spreading effects on bridge pile foundation problem.

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.

Expected milestones & Deliverable

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 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.
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 the simplifying 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 by systematically addresses the uncertainties involved in each step.
5. Perform additional analyses as required to refine and validate the proposed simplified probabilistic design procedure.
6. Prepare a report that documents the work completed and importantly demonstrates how the design method can be implemented in practice.
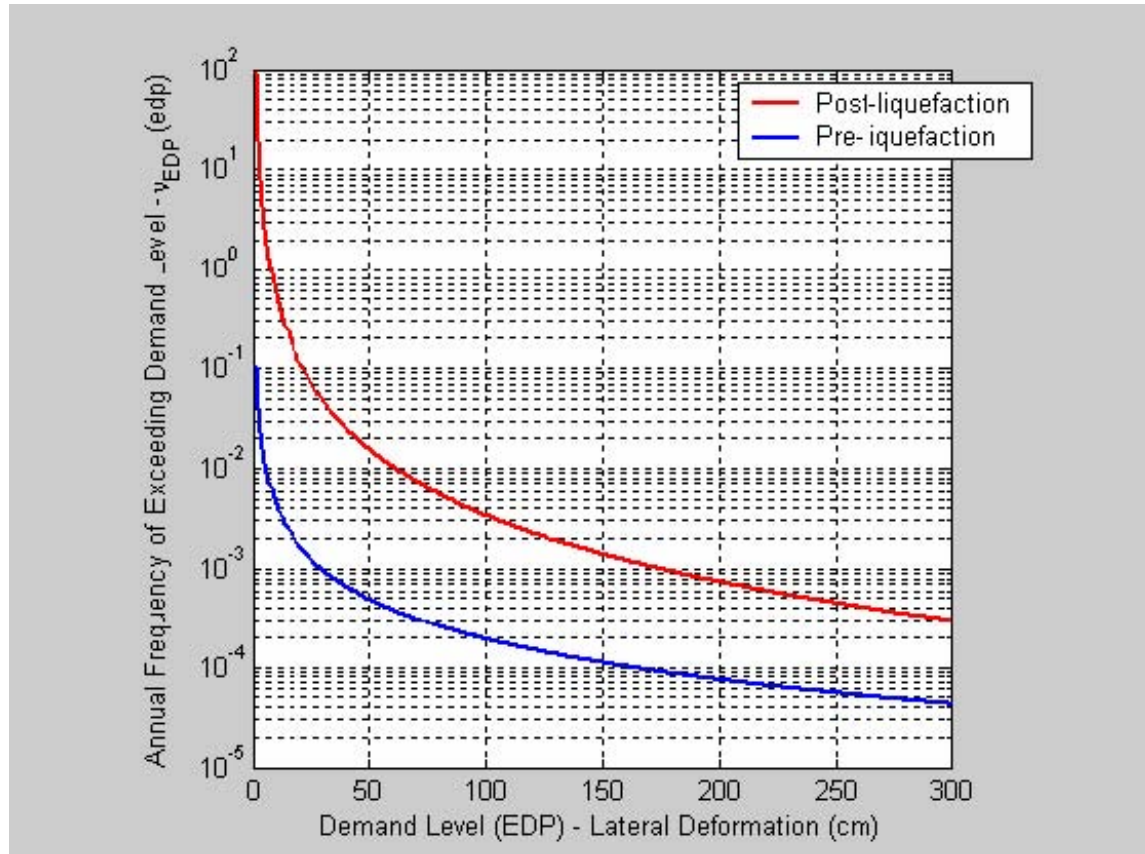
Member company Benefits

Figure 1 - Probabilistic Displacements of Design Bridge Example Using Mackie and Stojadinovic (2005) Approach with Travasarou et al. (2004) Seismic Displacement Procedure. Note that the occurrence of liquefaction changes the demand significantly at a specified hazard level.

Project Title—ID Number	PBEE Procedures Report for Bridges and Benchmarking Performance of RC Bridges - 2442005		
Start/End Dates	10/1/05—9/30/06	Funding Source	PEER-CA State Transp. Fund
Project Leader (boldface) and Other Team Members	**Bozidar Stojadinovic** (UCB/F), Kevin Mackie (UCB/PD), Vesna Majstorovic (UCB/GS), John-Michael Wong (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 demonstrate how to use the PEER tools for probabilistic seismic performance assessment to highway overpass bridge structures. 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.

This project has two objectives. The first objective is to complete the benchmarking of the PEER PBEE procedure to the bridge test-bed developed in PEER project 2004209. This PBEE procedure was successfully applied up to the DM level. Repair cost data will be collected in order to extend the PBEE procedure to the DV level. The second objective is to complete the PBEE procedure report as it applies to bridges, and to provide support for other researchers working in the PEER bridge group on the test-bed bridge models to enable them to complete their portions of the PEER procedures report.

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)

This project is at the core of the Trust Area 2. An array of structural and geotechnical engineering projects aimed at enhancing the performance of bridges in earthquakes will use the test-bed baseline bridge models, developed and maintained in this project, to demonstrate the enhancements they develop.

This project will continue to serve as the liaison project to the MCEER and MAE center. The October 13 and 14, 2005 Tri-Center Bridge Workshop represents a formal result of the ongoing cooperation between the PEER, MAE and MCEER bridge researchers.

Furthermore, this project continues the ongoing cooperation with Caltrans. A PEER Lifelines project 9A01 has been initiated based on this cooperation.

Methodology employed

The fragility curves developed by the PIs in PEER projects 318, 539, 209 and 213 are used as input in the PEER integral to derive the result for the chosen testbed bridge.

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

Results from work performed in Years 3 and 4 on project 312 "Seismic Demands for Performance-Based Design of Bridges", in Year 5 and 6 on project 318 "Bridge Fragility and Post-Earthquake Capacity", in Year 7 on project 538 "Performance Assessment of Highway Overpasses", and in Year 8 on project 209 "PEER Methodology Application to a Baseline Highway Overpass Bridge" is utilized in this project.

The principal results used from the Year 8 project is the prototype testbed bridge Type 11 (with long columns) and Type 1 (with short columns). The OpenSees models for these bridges have been developed in the modular fashion enabling other researchers to use them easily.

Reporting on project output will be conducted using a project reports, Trust Area meetings and a project web page. This web page will: 1. provide other PEER researchers with the updated status of this PEER projects; 2. enable exchange of data and software with other PEER researchers; and 3. provide the outreach to similar work conducted by the other two Earthquake Engineering Centers. In addition to this web page, conventional quarterly and annual repots will be prepared.

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.

The MAE center project on fragility assessment of bridges is lead by Prof. Reggie DesRoches. This project is similar, however the MAE project addresses the typical East Coast bridges. The MAE project has gone further in terms of assessing possible retrofit strategies and providing fragility curves for the retrofitted bridges. It has, also, a visual interface called MAE-VIZ developed by the MAE center. However, this project is ahead of the MAE project in terms of the complex soil-bridge modeling, consideration of soil-structure interaction and consideration of bridge repair cost and traffic capacity losses.

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.

Thrust Area 2—Bridge and Transportation Systems

Expected milestones & Deliverable

The milestones for this project are:
1. Maintain the test-bed bridge OpenSees models developed in Year 8.
2. In cooperation with Bridge Trust Area researchers Professors Arduino and Kramer merge the bridge model with the soil model.
3. Conduct a probabilistic seismic demand analysis using the combined bridge-soil model for firm soil.
4. Conduct a probabilistic seismic demand analysis using the combined bridge-soil model for liquefiable soil.
5. In cooperation with Dr. Mark Ketchum develop a number of repair scenarios consistent with damage to the test-bed bridge at different levels of earthquake ground motion intensity.
6. In cooperation with Caltrans and independent estimators, conduct a survey to generate data on repair cost for the test-bed bridge repair scenarios.
7. In cooperation with PEER Buildings group develop an estimate of the remaining gravity load carrying capacity of the bridge based on the amount of residual displacement to generate data for an estimate of the remaining traffic load capacity of the test-bed bridge.
8. Use the IM-EDP models that include soil-structure effects, the EDP-DM models developed by Prof., Eberhardt, and the repair cost data to develop bridge repair cost fragility data.
9. Use the IM-EDP models that include soil-structure effects, the EDP-DM models developed by Prof., Eberhardt, and the repair cost data to develop bridge traffic capacity loss data.
10. Prepare fragility curves for traffic function loss models and DV-DM relations developed by other Trust Area 4 researchers.
11. Complete the report and the examples on the use of PEER PBEE methodology.

The deliverables of this project are:
1. Documentation on the combined soil-bridge model.
2. Bridge repair cost fragility curves.
3. Bridge traffic capacity loss curves.
4. Quarterly and annual repots.
5. Final project report.

The scope of the project is defined by its milestones listed below. The project time line is:
1. January 15, 2005: milestone 1, 2, and deliverable 1.
2. April 1, 2006 milestones 3, 4.
3. June 1, 2006 milestones 5, 6, 7.
4. September 1, 2006 milestone 8,9,10, and deliverable 2 and 3.
5. October 1, 2006 milestones 11 and deliverable 4.

Member company Benefits

Typical California Highway Overpass Bridges

Elevation
Scale: 1"=30'-0"

Type 11   **Type 1**
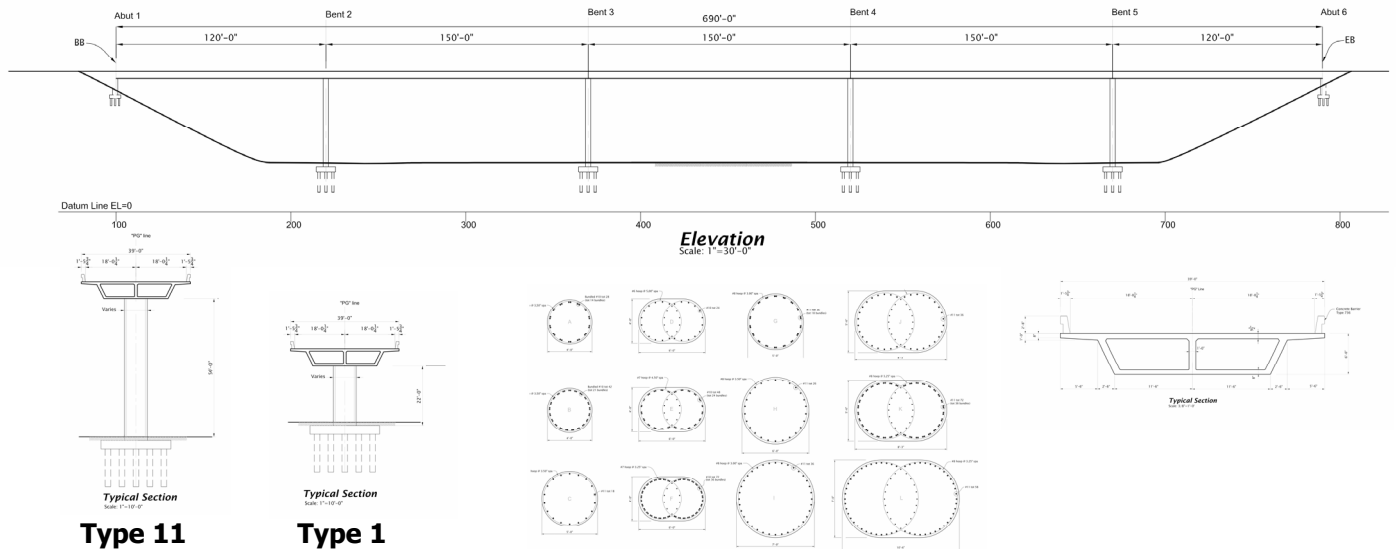
Project Title—ID Number	*Relating EDPs in RC Bridges to Damage and Decision Metrics -* **2452005**		
Start/End Dates	10/1/05—9/30/06	Funding Source	PEER-NSF
Project Leader (boldface) and Other Team Members	**Marc Eberhard** (UW/F), Michael P. Berry (UW/GS), David Tayabji (UW/GS)		

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 project is to relate Engineering Demand Parameters (EDPs) to Damage Measures (DMs) and Decision Variables (DVs) for reinforced concrete bridges.

The specific objectives are to

1. Evaluate and calibrate the OpenSees column modeling strategies using the PEER Structural Performance Database, and for complex loading conditions, including varying axial loads, bi-directional loading and shaking-table experiments.

2. Calibrate and evaluate the benefits/drawbacks of implementing new material models for the cyclic response of reinforcing bars (Mohl-Kunnath) and concrete (Mitra-Berry-Lowes).

3. Provide simulation support for PEER bar buckling experiments (Lehman-Stanton)

4. Coordinate WSDOT, FHWA and PEER-sponsored modeling (Mahin, Billington) on the development of post-tensioned systems for bridge columns.

5. Assist Stojadinovic on the development of methodologies to estimate a general set of EDPs, DMs and DVs for reinforced concrete bridges.

6. Continue to maintain and (if possible) expand the Structural Performance Database, which provides column data for nearly 500 columns.

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

The successful application of the PEER methodology depends (among other things) on the development and calibration of tools and methodologies to predict the force-displacement response, damage development and damage consequences for key structural elements. Column damage is one of the most common and most important types of damage in bridges and buildings.

Methodology employed

The research description is organized into six sections, according to the project objectives listed in the preceding section.

Column Modeling

The spread-plasticity and lumped-plasticity column models have been evaluated and calibrated using the detailed response measurements from Lehman-Moehle column tests, and using the larger set of column tests documented in the PEER Structural Performance Database (Berry-Eberhard). During Year 9, the modeling strategies will be evaluated and calibrated using cyclic tests of columns with bi-directional loading and/or variable axial loads (e.g., Xiao), and tests of column on the shaking table (e.g., Mahin and Sakai).

On the practical side, Berry, Lehman and Lowes will submit a manuscript on the plastic-hinge modeling of bridge columns in April, 2006. Elwood (UBC) and Eberhard wrote a PEER research digest, which evaluates the current FEMA recommendations for estimating column effective stiffness and which recommends a new methodology. A key plot from the digest appears below.
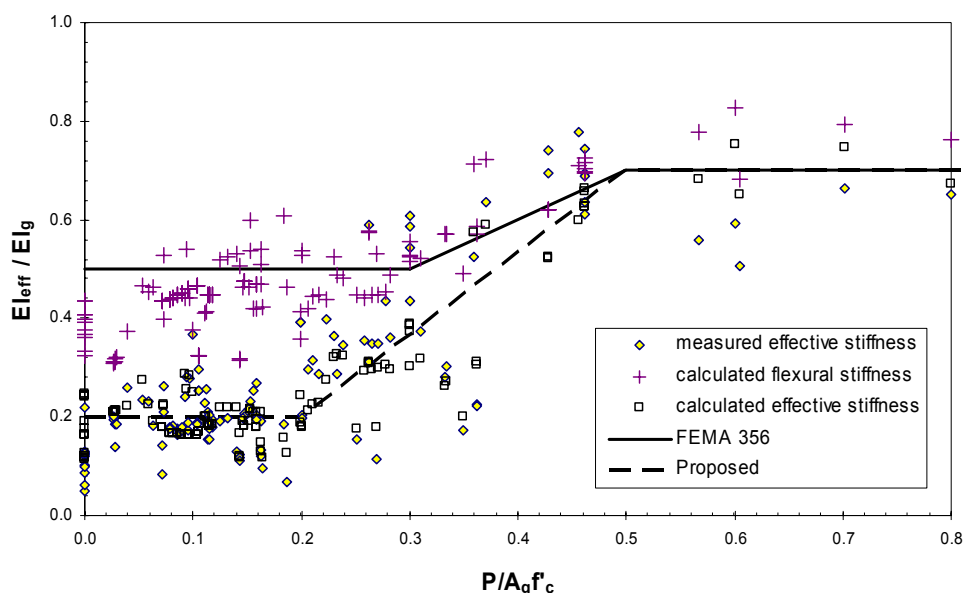

Figure: Comparison of calculated and measured effective stiffnesses

Evaluation and Calibration of New Material Models

The accuracy of estimates of column behavior will be improved by evaluating and calibrating two new material models. The Mohl-Kunnath reinforcing bar model, which was recently added to OpenSees, will be calibrated (using the performance database) to improve force-deflection estimates (especially stiffness and strength degradation) and predictions of bar buckling. The Mitra-Lowes concrete model (concrete04) will be modified to improve the accuracy of the reloading branches, which will likely lead to better estimates of residual displacements. These improved estimates are critical to the implementation of the PEER methodology for bridges, in which residual displacement is a key damage measure. This measure is particularly important in evaluating the merits of post-tensioned column construction, such as Billington and Mahin are doing.

Thrust Area 2—Bridge and Transportation Systems

Simulation Support for Bar-Buckling Study

The bar buckling study (Lehman and Stanton) needs to be closely coordinated with the development of column modeling recommendations. During Year 9, we will conduct analyses in support of this project, and will ensure that the lessons learned are incorporated into the modeling recommendations.

Post-Tensioned Bridge Columns in Seismic Regions

As part of a WSDOT-sponsored project, Stanton and I are developing precast bent systems that can be constructed rapidly and that have adequate seismic performance. Self-righting systems are an important component of our work. In communicating our results with WSDOT, we are adopting many of the tools, language and concepts of the PEER performance-based methodology.

During Year 9 (and beyond, if funded), we will coordinate these activities with those of Mahin and Billington on self-righting reinforced concrete bridge systems, and will take advantage of synergies between 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 assist Professor Stojadinovic in developing a preliminary set of damage measures and relationships to decision variables that are important to bridges (e.g., closure, downtime, repair cost). During Year 9, 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.

Maintain and Expand Performance Database
As new data becomes available, the database is being updated and expanded.

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

During Year 8, we developed and calibrated strategies for modeling column force-displacement response (related to EDMs) and damage progression (related to DMs) using both distributed-plasticity and lumped-plasticity modeling strategies.
These modeling strategies have been implemented by a series of other PEER project, including the bridge testbed (Mackie and Stojadinovic)

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

To my knowledge, no other work has been done on systematically evaluating the accuracy of OpenSees modeling strategies using column data, either within or outside of PEER.

Thrust Area 2—Bridge and Transportation Systems

This project needs to be coordinated with many other current PEER projects, including:

- Lehman and Stanton experimental study on bar buckling

- Kunnath project development of bar buckling model

- Lowes modification of Concrete04

- Mahin and Billington projects on self-righting bridge bent systems

- Stojadinovic project on general EDP-DM-DV relationships.

This project will also take advantage of previous PEER projects, including Lehman, Stanton and Lowes studies on joint vulnerability, Porter study on DM-DV relationships, and column testing projects (e.g., Xiao).

Expected milestones & Deliverable

April 1st:, 2006: Elwood and Eberhard submitted PEER research digest

April 15th, 2006: Berry, working with Lehman and Lowes, will submit manuscript describing the development of a new plastic-hinge model and its application to estimating likelihood of column damage.

June 30th, 2006: Participate (with Stojadinovic) in workshop with Washington State DOT on DM-DV relationships.

Sept 30th, 2006 Submit formal PEER research report on modeling of RC columns with OpenSees

Member company Benefits

The development of a general set of EDP-DM-DV relationships for bridges is critical to applying the PEER methodology in practice, and in demonstrating its value to Caltrans and other bridge agencies.

The use of the PEER methodology in discussions with WSDOT and Caltrans will demonstrate the practical implementation of the methodology in developing and evaluating new systems.

Project Title—**ID Number**	*Benchmarking Enhanced Performance of Post-Tensioned RC Piers with Ductile Materials* - **2462005**		
Start/End Dates	10/1/05—9/30/06	Funding Source	PEER-NSF
Project Leader (boldface) and Other Team Members	**Sarah Billington** (Stanford/F), Won Lee (Stanford /GS), PEER Summer Intern (Stanford /US)		

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 are being calibrated again recent cyclic and seismic experiments on reinforced concrete and enhanced-performance bridge piers.

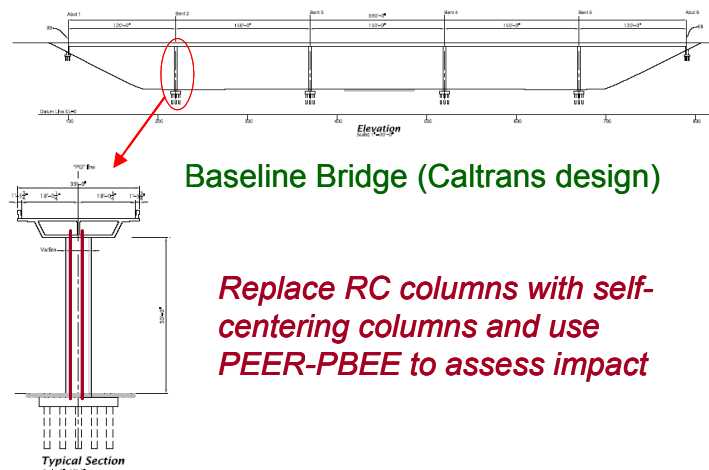**Role of this project in supporting PEER's mission (vision)**

Through this project, we are demonstrating how the PEER PBEE methodology can be applied to assess quantitatively new structural systems for structural concrete bridges, which employ post-tensioning, jacketing techniques and the application of new high-performance materials in localized regions. This research will offer a comparison of enhanced performance systems with traditional systems studied by our group as well as other PEER researchers who are using different techniques for various steps in the PBEE framework. The extent to which reductions in post-earthquake residual displacements, concrete spalling, and bar buckling contribute to improved performance of the bridge and its role in the highway network (considering for example bridge functionality, repair cost and restoration time as decision metrics) are being 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 steel jackets for added confinement, damage-tolerant fiber-reinforced concrete in hinge regions for added hysteretic energy dissipation and reduced spalling. The use UPBT in bridge piers is being conducted first and compared with traditional systems. Innovative versions of the UBPT bridge pier system will then be investigated.

To demonstrate the application of the PEER PBEE Methodology to the assessment of new technologies, we are developing IM-EDP-DM-DV relationships for a baseline bridge that is being studied by several researchers in Thrust Area 2. For the systems utilizing the ductile fiber-reinforced concrete materials, the EDP-DM relationships are being developed analytically, as there is not enough experimental data on the enhanced performance systems to create experimentally-based fragility relationships. The experimentally-based fragility relationships developed by PI Eberhard are being used for the EDP-DM relationships for the traditional concrete and the UBPT piers that do not incorporate ductile fiber-reinforced concrete. All analytical models being developed to complete these analyses are being calibrated with available cyclic and seismic data for UBPT bridge pier experiments. In some cases, modifications to models for traditional bridge piers are being made (e.g. modification of a concrete model to capture residual displacements). Additional or more detailed model development from other Thrust 2 researchers is underway and will be incorporated into our analyses as recommendations are available. The IM-EDP relationships are being developed using incremental dynamic analyses. Modeling uncertainty will be incorporated using the FOSM method. Fragility curves representing the EDP-DM relationships are being developed using finite element analyses in conjunction with reliability methods.

Baseline Bridge (Caltrans design)

Replace RC columns with self-centering columns and use PEER-PBEE to assess impact

DM-DV relationships have estimated using HAZUS for a relative comparison between traditional reinforced concrete piers and UBPT piers. Consultation with maintenance engineers at Caltrans and cost estimators being carried out by PEER collaborators will be used to improve the accuracy of absolute values used in the DM-DV relationships.

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 continue to be calibrated with recent cyclic and seismic experiments on UBPT bridge piers, structural elements using damage-tolerant fiber-reinforced concrete and traditional reinforced concrete (for capturing residual displacements). Models for of varying complexity from simple macro-models to detailed finite element analyses are being used. 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. Furthermore, several simple experiments are being designed in collaboration with PI Mahin to investigate design details, materials and construction methods for enhanced performance piers using ductile

fiber reinforced concrete. The purpose of the experiments is to serve as pilot studies for a larger-scale shake table test in the future.

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

We developed a model of a UBPT bridge pier for the baseline bridge and used it to analyze the bridge in comparison with a traditional bridge. We completed a demonstration of the framing equation (the four steps from IM to DV) for traditional bridge piers and UBPT using several simplified models (e.g. HAZUS data for DM-DV). It was found that at hazard levels above a 2% in 50 year hazard, the UBPT columns displayed excellent behavior, with peak drifts similar to those of the RC columns but with significantly reduced residual displacements (roughly 35% of those of RC columns). Furthermore the anticipated downtime for a bridge with a UBPT pier was less than 1 day whereas for the bridge with an RC column, the downtime would be 29 days. At hazard levels of 2%, 10% and 50% in 50 years, the UBPT and traditional RC piers are expected to behave similarly according to the PBEE analyses.

During the summer, PI Mahin and PI Billington each had a PEER REU student and together they worked on setting up experiments to record the stress-strain response of confined ductile fiber-reinforced concrete.

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. We will compare our results for a traditional bridge with theirs as we performed some of the steps using different methods (e.g. IDA for the IM-EDP step vs. the "cloud" approach). PI Mahin is also investigating enhanced performance bridge piers with an emphasis on experimental studies, offering further opportunities for collaboration. We collaborated on simple material tests of ductile fiber-reinforced concrete over the summer (see section 4) and collaboration on the application of this material to enhanced-performance bridge piers is continuing in Year 9.

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) and the University of Nevada at Reno (Saiidi and Sanders), 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.

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 Caltrans has recently called for proposals to investigate the development of a segmentally precast bridge pier system that could be a direct competitor to traditional reinforced concrete in seismic regions. This is the exact topic of the PIs previous research for non-seismic regions as well as more recent research on segmentally precast bridge piers for seismic regions using UBPT. Additionally, there has also been company interest on applications of the damage-tolerant fiber-reinforced concrete materials (e.g. LaFarge, Kuraray Co., Ltd.).

Expected milestones & Deliverable

A comparison of a variety of enhanced-performance systems to a traditional system using the baseline bridge adopted by Thrust Area 2 will be conducted. This will include several refinements to the analyses performed in Year 8. This comparison will cover the entire PEER PBEE Methodology. Analysis will also be conducted on the effect of using differing approaches in the various steps of the PBEE Methodology. Finally, a constitutive model to capture residual displacements in concrete (currently not possible in OpenSees) and one to capture the tensile strain-hardening and unique reversed cyclic loading response of ductile fiber-reinforced concrete will be created and validated for use in OpenSees.

Member company Benefits

A complete demonstration of the application of PEER-PBEE for the systematic assessment of a new technology and new materials for highway bridge design.

Thrust Area 2—Bridge and Transportation Systems

Project Title—**ID Number**	*Performance Assessment of Reinforcing Bar Anchorage and Buckling Effects in RC Piers* **- 2472005**
Start/End Dates	10/1/05—9/30/06 — Funding Source — PEER-NSF
Project Leader (boldface) and Other Team Members	**Dawn Lehman** (UW/F), John Stanton (UW/F), Dylan Freytag (UWGS), Amanda Jellin (UW/UG), Malena Foster (UW/UG), Ian Patterson (UW/UG), Shawn Roberge (UW/UG)

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 be used by other PEER researchers to develop and calibrate appropriate simulation (Kunnath) and damage (Eberhard) models. The specific Year-8 research project objectives include:
- Generation of experimental data for validation and calibration of performance and analytical models.
- Improvement of a practical performance model to predict bar buckling
- Meet the needs of those conducting the analytical (Kunnath) and Performance (Eberhard) simulation including coordination and exchange meetings

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

Study of experimental and analytical research results suggests that bar buckling is influenced by the response of the longitudinal steel, which is in turn affected by the strain history and the type of steel, and the lateral restraint on the bar, 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 shown 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 results in reliable experimental data for supporting the development and validation of bar buckling damage and simulation models (in development by others).

Methodology employed

The experimental program has two goals, which require two separate test series. The first is to generate experimental data from which the stiffness of the circular hoops can be obtained. Modeling is still necessary, if for no other reason than the fact that a finite number of tests will have to be conducted and at model scale. However, such tests will provide physical data against which to calibrate analytical or numerical models of an isolated bar restrained against lateral movement by a flexible support. This model represents a small part of the entire column system, but it is the most critical part.

The tie stiffness tests were conducted on specially designed specimens, shown in Figure 1. A short segment of a circular column is cast with longitudinal bars and individual, welded, hoops. The #5 longitudinal bars were placed evenly around the perimeter. The hoops were spaced at 8" along the column length to allow room for the test equipment. A hook was placed under the

spiral and pulled radially by a center-hole ram supported by a steel bridge over the hoop being tested, as shown in Figure 1 to simulate a single longitudinal bar pushing radially outwards against the hoop. The load and displacement of the hook were measured to assess the spiral stiffness. The three primary variables tested were (a) the bar size, (b) the presence of cover, and (c) the bond along the hoop.

Figure 1 - Hoop stiffness test specimens.

A pilot test series was conducted. Observations during the pilot tests already reveal some useful findings. First, the hoop experiences bending as well as tension, and the curvature is much larger at the hook than elsewhere. The local curvature is, in fact, defined by the diameter of the hook, which should be the same as that of a typical longitudinal bar if the conditions in a complete column test are to be replicated faithfully. The curvature diminishes with distance from the hook, and changes sign between the hook and the point of contact with the concrete core. A plastic hinge occurs at the hook while the average strain in the hoop is still relatively low. This suggests that the criterion for hoop failure in a complete column should be based on combined tension and bending at a buckling longitudinal bar rather than on pure tension fracture of the hoop due to uniform lateral expansion of the concrete core. In this sense, initiating of longitudinal buckling is indeed the event that sets in motion the process of column failure.

The second goal is to produce test data on complete columns subjected to cyclic lateral loads. These tests represent the whole column system, and will differ from others conducted in the past in that bar buckling will be the primary focus of the study. Special instrumentation was developed to ensure detection of the initiation of bar buckling, and load histories will be selected to determine as precisely as possible the effect of load history.

The experimental study on complete columns includes eight specimens at 1/3 scale. In an effort to capture buckling of the longitudinal reinforcement, two methods of measuring displacements will be used in conjunction with strain gages placed on both the longitudinal bars and the spiral. First, a set of string potentiometers will be attached to the longitudinal bars and another to the body of the column at three locations above the top of the footing as shown in Fig. 2. The differences between the readings of the pairs of instruments will give the displacement of the bar relative to the column at each level. Second, digital photogrammetry will be used to capture column
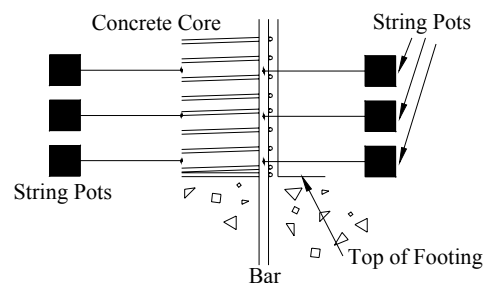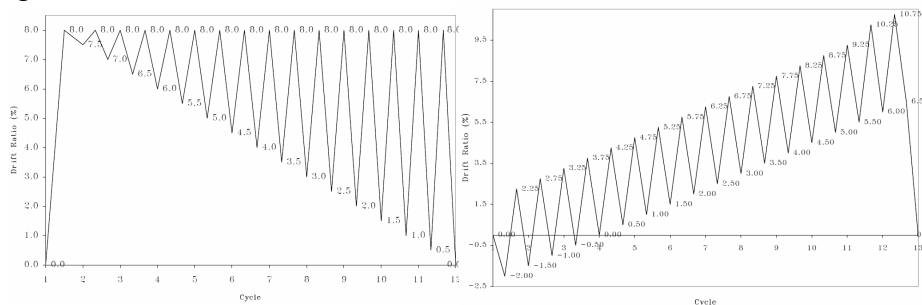

Figure 2

displacement, concrete bulging and, eventually, buckling of longitudinal bars as shown. Three cameras set up with overlapping fields of view (FOV) will record digital images simultaneously to piece together 3-dimensional displacement information about the column as concrete damage (cracking, spalling, bar buckling) progresses.

One of the primary test variables was the displacement history imposed on the column. Figure 3 shows two a-typical displacement histories. The first, subjected the column to a large strain demand (to 8% drift) followed by a ratcheted history to determine the drift range needed to cause buckling. The second imposed a ratcheted history with a constant drift range (4%). Together they can be used to determine the combination of drift range and maximum drift needed to cause buckling.

Figure 3 - Displacement Histories

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, including reliable experimental data, of 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.

Expected milestones & Deliverable

The expected outcomes of the project include:
- 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
- Generation of experimental data for validation and calibration of performance and analytical models.
- Improvement of a practical performance model to predict bar buckling

Project Title—**ID Number**	*Transportation Network Design Following a Large Metropolitan Earthquake* - **2502005a**		
Start/End Dates	10/1/05—9/30/06	Funding Source	PEER-CA State Transp. Fund
Project Leader (boldface) and Other Team Members	**Yueyue Fan** (UCD/F), Changzheng Liu (UCD/GS), P.N. Raghavender (UCD/GS)		

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

Project goals and objectives

The highway system is one of the most important lifeline systems subject to natural and manmade hazards. The main objective of this research is to ensure a high level of reliability for continued operation of the system following an earthquake through more efficient transportation operation and resource allocation.

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

These results build closely on what has already been done, and will be relevant to both MAE and MCEER researchers pursuing related research. The proposed models would fit usefully into the FHWA/MCEER REDARS Project. REDARS does not currently include decision support components, and there are no plans to extend research at MCEER to address this problem. Therefore, it would greatly add to the tri-center initiative to provide the basis for implementing a network reliability analysis model and post-earthquake emergency vehicle routing and network reconstruction decision support models into REDARS. Once implemented, such a model would make REDARS a more attractive tool for investigating other issues of interest to PEER, for e.g.., evaluating the economic impact of improved bridge performance and/or the ability to more accurately predict performance through improved fragility models, and more importantly how limited resource might be more efficiently spent in disaster mitigation.

Methodology employed

Routing through damaged networks

Consider the stochastic network shown in the figure below with nodes numbered as *1, 2, …, N*. Given estimated link travel times (given as mean and deviation, or probability density function) on any link *ij*, a network routing problem finds the optimal routing strategy to go from a given node to the desired destination.
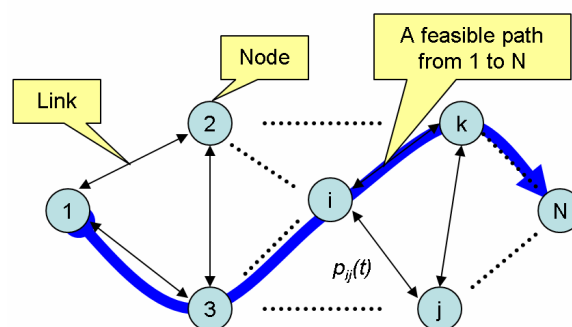
In this project, we focus on the movement of emergency vehicle immediately following earthquakes, and therefore do not consider the effect of traffic congestion. This is a reasonable modeling assumption since emergency vehicles usually do not need to compete with normal traffic. It reduces the computational complexity of the problem and avoids having to approximate the travel demand following disasters, which itself is a challenging socio-economic question due to too many uncertain aspects involved. The uncertainty of travel time mainly comes from the physical damage to the transportation facilities caused by the earthquake, rather than congestion and demand fluctuation. For example, a highway bridge of minor damage may still function at full capacity and speed level, whereas a highway bridge above some major damage level may be closed entirely. The probabilistic estimation on physical damage in a given earthquake scenario will be acquired from other PEER researchers or by using the risk assessment package REDARS. The decision criteria for routing are set to be (1) to choose a route that minimizes expected total time delay, and (2) to choose a route that maximizes the reliability of travel time between the given origin-destination pair.

Task 2: Network repairing strategy

Task (2) is newly added to our Years 9 and 10 research to address an equally important problem in disaster management, post-disaster recovery problem. Our previous work on the economic loss assessment (Years 6&7) 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 and repair projects should be undertaken. By retrofitting or repairing some subset of existing facilities, or by adding new components to a transportation network, system planners can change the post-earthquake network configuration. This changes network performance, and travelers' behavior. Broadly stated, our research goal is to find, subject to certain resource constraints, which components should be retrofitted (in pre-disaster scenario) or repaired (in post-disaster scenario) so that the overall performance of any metropolitan transportation system is most greatly improved. This well-defined network design problem is important in the transportation network literature [2].

We start investigating a post-earthquake network design problem, which is deterministic since we are given a deterministic initial network condition to start with. The standard objective function is aggregate network delay. Most studies set the performance measure as the total expected travel delay of all users in the network. In the conventional equilibrium model, the definition of the best route is a path between the specified origin-destination pair that is of the minimum travel time. Since the travel time over a certain link depends on how congested the link is, each individual's routing decision will affect others' choices. Therefore, routing decisions of all travelers in the transportation network must be studied simultaneously. Since individual users and network planners usually do not have the same objective, this kind of network design problem often involves multiple levels of optimization. At the upper level, the system planner makes decision on resource allocation in order to achieve the best system performance. At the lower level, the network users make their travel decision based on their individual travel preferences. For a large network such as the San Francisco Bay Area network, this kind of network design problem is computationally challenging. At present, we are developing effective approximation mechanism based on artificial intelligence techniques for solving large scale problems.

In contrast, in a pre-event network design problem, the occurrence and the scale of the damage and capacity loss resulting from seismic events in the planning period are uncertain. Therefore, the initial network configuration faced in the pre-event case is stochastic, and the optimal design problem becomes stochastic. This extra uncertainty makes the pre-event network design problem even more challenging. In this project, we will focus on the post-disaster recovery problem. Starting with a problem that is more tractable reflects the PEER spirit: first to make it work, then to make it work better. The major part of this research is to develop an optimization model with evolving modeling objectives. At the early stage of system recovery process, the primary recovery objective is to ensure timely and smooth movement of emergency activities. As the recovery process continues, we will gradually give more weights to public traffic, where the primary goal becomes to satisfy more travel demand from the public at an acceptable congestion level.

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

Task 1 is a continued effort from our Year 8 research. Currently, we are in the process of completing mathematical modeling and numerical implementation of the proposed path-finding models. In addition to development of various network routing methods addressing different risk attitudes and different level of environment uncertainty, we are coordinating with Prof. Ann Kiremidjian and her students regarding the study area and earthquake scenarios. The Stanford team is providing estimation of seismic damages of individual bridges and the correlations of damages among neighboring bridges. This information is being input to our shortest path model to compute the best routing strategy, where correlation and real-time feedback control are taken into account. Our current agreement is to start with a relatively small network (including about 50 bridges) in the northeastern San Francisco Bay area, then expand the study area to a county once the methods from the two teams are integrated and validated.

Results from Year 8 are:
- Computer module for computing the expected and reliability of travel time from point A to point B. The maximum probability of not exceeding a desired time threshold indicates whether emergency tasks between the two locations A and B can be carried out effectively. This information, together with other network performance measures, such as throughput and connectivity, can also be used as performance measures to guide decision making on network recovery planning.
- Routing strategy to be followed to achieve above-mentioned maximum probability. The routing strategy can guide the emergency vehicles through the damaged network via the in-vehicle guidance system.

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

As noted in the Objectives, this work will produce results that can be incorporated into the MCEER/FHWA REDARS model. This work plan has been constructed in consultation with ImageCat, Inc. and Seismic Systems personnel with the intent of complimenting and supporting development of the MCEER/FHWA REDARS (Risks from Earthquake Damage to Roadway Systems) tool and its deployment in the Caltrans demonstration project. The work done by Prof.

Moore and Prof. Fan in previous PEER fiscal years on variable demand and the economic cost of trips forgone following an earthquake has been partially incorporated into REDARS, and ultimately will be in its entirety.

Expected milestones & Deliverable

In Year 9, we expect to complete the development of mathematical model for the network recovery problem. In Year 10, we plan to test the optimization model(s) in several representative earthquake scenarios, and to integrate these models into geographic information systems, so that the projects results can be better understood and utilized by a broad audience. We will also coordinate with Stu Werner 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.

Thrust Area 2—Bridge and Transportation Systems

Project Title—ID Number	Tri-Center Collaboration on Geographically Distributed Systems - 2532005		
Start/End Dates	10/1/05—9/30/06	Funding Source	PEER-CA State Transp. Fund
Project Leader (boldface) and Other Team Members	**Jack Moehle** (UCB/F)		

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

Project goals and objectives

The goal 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 previous year's achievements, with emphasis on accomplishments during last year (Year 8)

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^{3}NS) to manage on-going research collaborations between the centers. Members are the Directors from each center (M. Bruneau, J. Moehle, A. Elnashai), 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. This year a joint research workshop was convened among key researchers to discuss available bridge fragilities and methodologies for their computation.

Work in this project contributes to the CALTRANS REDARS Demonstration Project, which is assessing the seismic performance of a portion of the highway network in Northern California.

Caltrans Demonstration Project

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.

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 & Deliverable

Various research reports by PEER-funded researchers.

Member company Benefits

Caltrans is involved in various project meetings and receives products for implementation in bridge design and assessment work.

Project Title—ID Number	*Simulation and Performance of Bridge Abutments* **- 2552005**		
Start/End Dates	10/1/05—9/30/06	Funding Source	PEER-CA State Transp. Fund
Project Leader (boldface) and Other Team Members	**Scott Ashford** (UCSD/F, Yohsuke Kawamata (UCSD/GS), Azadeh Bozorgzadeh (UCSD/GS), Teerawut Juirnarongrit (UCSD/PD), Gilberto Carrasco (UCSD/US), Alexandro Pena (UCSD/US)		

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 develop and validate numerical models in OPENSEES of bridge abutments over the next 2 years. We plan to utilize the results of ongoing Caltrans experiments on bridge abutments in the validation efforts. Specifically, the objectives in Year 9 are to:
1. Provide abutment structural details to Thrust Area Team for overall modeling effort.
2. Provide preliminary estimates of soil springs to Thrust Area Team for overall modeling effort, based on pseudo-static response. It is anticipated that improved dynamic springs would be periodically provided up through Year 10.
3. Participate in payload experiments with already planned Caltrans experiments on bridge abutments to be completed June 2006.
4. Collaborate on deep foundation and lateral spreading issues with PEER researchers.

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

This project supports PEER's vision by improving design methodologies for PBEE.

Methodology employed

The scope of this project is to provide the Thrust Area Team with input on bridge abutment modeling. This builds on current large-scale abutment experiments being carried out by the PI for Caltrans. This input will consist of structural details of abutments to improve the Team's modeling efforts, as well as input on geotechnical modeling and SFSI of the abutment system. In addition, the PI will continue to participate in the Thrust Area's efforts on liquefaction issues in regard to bridges.

A key component missing from PEER's OPENSEES bridge modeling efforts is proper modeling of the abutments. The ongoing abutment research being carried out by the PI presents a timely opportunity to efficiently provide this much needed input to PEER. The Phase 1 experiments focus on the translational pseudo-static soil springs behind the abutment as a function of soil type. These tests on 5.5-ft and 7.5-ft tall, 15-ft wide abutment backwalls in clayey sand and gravelly sand are to be completed in December 2005 and January 2006. These tests will be followed by an abutment system test, including pile and pile cap along with the back and wing walls in June 2006. Predictions of the pseudo-static response have already been made, and the details of the predictions including input parameters, will be provided to the Thrust Area Team. We will also collaborate with the team in order to provide necessary input for PEER's abutment modeling efforts. It is anticipated that an improved dynamic SFSI abutment model will be provided to PEER in Year 10.

Figure 1: Preparation for bridge abutment test.

Figure 2: Failure plane from abutment test.

Thrust Area 2—Bridge and Transportation Systems

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

Last years achievements include completion of the analyses of the Tokachi full-scale lateral spreading experiments.

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

This PEER project complements ongoing outside Caltrans research by implementing the results into OPENSEES bridge models, which would not be done otherwise. The PI is aware of some abutment testing to be carried out at UNR, and though quite similar to these experiments, will be carried out too late to use the results effectively within PEER.

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

Results from the Tokachi blast experiments analyzed in Year 8 have been used in the design of port facilities on the west coast.

Expected milestones & Deliverable

Milestones:
- December 2005: Provide initial abutment information to Thrust Area Team.
- February 2006: Complete Phase 1 Abutment Testing, provide refined static soil springs.
- June 2006: Complete Phase 2 Abutment Testing.
- September 2006: Provide updated soil springs.

Deliverables:
- PEER Quarterly Reports

Member company Benefits

Improved soil design procedures for bridge abutments.

Project Title—ID Number	Development and Implementation of Decision Variables for Bridges within Transportation Network Systems - 2562005		
Start/End Dates	10/1/05—9/30/06	Funding Source	PEER-NSF
Project Leader (boldface) and Other Team Members	**Anne Kiremidjian** (Stanford/F), Renee Lee (Stanford/GS), Evangelos Stergiou (Stanford/GS)		

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

Project goals and objectives

The objectives of the project are to:
- Include the uncertainty in replacement cost and damage factor arising from the transformation from damage state to damage factor.
- Explore methods for computing the probability distribution of loss from an ensemble of bridges without numerical integration or simulation.
- Estimate the total loss due to components damage and network disruption using the above formulations.
- Assess the behavior transportation networks for several earthquake scenarios
- Account for uncertainty in component loss (sL) for a spatially distributed transportation network arising from
  - Ground Motion Correlation
  - Damage Correlation

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

This project is part of the transportation demonstration project within PEER. It integrates the various components of performance based earthquake engineering as it applies to transportation network components and systems while advancing the science in risk analysis.

Methodology employed

Under this project the correlation model for spatially dependent ground motion and bridge damage was formulated. Data from the San Francisco Bay Area was used to estimate the correlation coefficients whenever possible. In addition, a complete convolution formulation was developed for the PEER loss estimation equation. The developments are summarized as follows:

1. Probability of Loss Evaluation for an Ensemble of Bridges
General Formulation of the PEER methodology

$$E[L|E_i] = \sum_{all\_components} \int \sum_d E[L|D,E_i] P[D|IM,E_i] f_{IM}(im) \partial d \partial im$$

$$\sigma_L^2 = \sum_{allcomponents} \left[\int_{u_i} \sum_{di} E[L_i^2|D_i = di] \times P[D = di|ui] \times f_{u_i} du_i - \left[\int_{u_i} \sum_{di} E[L_i|Di = di] \times P[D_i = di|u_i] \times f_{u_i} du_i \right]^2 \right]$$

The formulation of the PEER methodology is enhanced to include the uncertainty in replacement cost, RC, and the transformation from damage state, DS, to damage factor, DF, where DF is treated as a single valued constant. The new equation is listed below:

$$P[l > L_I] = \int \int \int \int f_{L/RC,DS} f_{RC} f_{DF/DS} f_{DS/PGA} f_{PGA} dL \, dRC \, dDF \, dDS \, dPGA$$

Loss   Replacement Cost   Damage Factor   Damage State   PGA
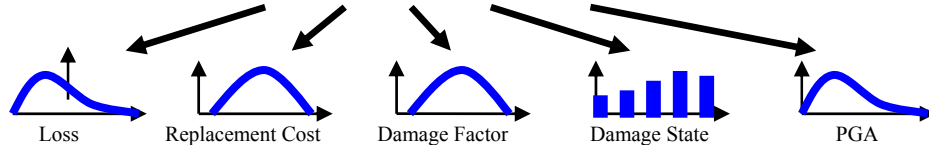
Closed form solutions of this integral cannot be obtained. Most current approaches use numerical integration or simulation to estimate the probability of loss exceedence. In addition when computing the loss from all bridges, the total loss is

$$L_{total} = \sum_{all\ sites} L_i$$

where L_i is the loss from the bridge at site i.

Previous applications were limited to computing the mean and variance of the total loss **L**. Estimation of the probability distribution of total loss requires the convolution of the losses from individual bridges. If f_i is the probability density function of loss for bridge i, then the convolution is given by

$$f_{L_{total}} = f_{L_1} * f_{L_2} \ldots * f_{Ln}$$

Algorithms for computing the convolution integral with limited number of bridges were developed under this project. The algorithm transforms the probability densities into the frequency domain using the Fourier transformation. In the frequency domain the transformed distributions can then be multiplied and inverse transformed to obtain the distribution of total loss.

2. Loss Evaluation With Correlation Effects

Two sources of correlation were considered. These include the correlation of ground motion at bridge sites that have similar soil type classification and the damage correlation among bridges of similar structural type, year of construction and thus design specifications.

- Ground Motion Correlation:

    Two cases are investigated for ground motion correlation. We first present the case of anisotropic - distance dependent ground motion correlation. The correlation structure for this case is:

$$\rho_{A,B} = \frac{Cov(A,B)}{\sqrt{Var(A)}\sqrt{Var(B)}} = \frac{\sigma_e^2 + \exp\left\{-\left(r_{ij}/r_o\right)^2\right\}\sigma_s^2}{\sigma_e^2 + \sigma_r^2 + \sigma_s^2}$$

Where $r_{A,B}$ is the correlation between sites A and B, $Cov(A,B)$ is the covariance between the two sites, $Var(A)$ and $Var(B)$ are the respective variances. r_{ij} is the distance between sites A and B and r_0 is a base distance.

For the isotropic - distance independent correlation the formulation is given as follows:

$$Corr(Y_i, Y_j) = \rho_{A,B}\ for\ ^{i \neq j} \qquad \rho_{A,B} \in [0, 0.5, 1]$$

- The structure to structure damage correlation is expressed as

$$Corr(Y_i, Y_j) = \rho \quad For^{i \neq j} \qquad\qquad i \neq j$$

These formulations were used in sensitivity analysis for a set of bridge sites and bridge sites within the San Francisco Bay Area.

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

A sample application was tested on 9 bridges for the San Andreas 8.0 scenario. The loss curves for each of the bridges were defined according to the enhanced equation which takes into consideration the uncertainty in replacement cost and damage factor discritization. The curves were aggregated under the independence assumption. Loss estimates for this scenario are summarized below:
- The total value of the bridges is $6.75 M
- Direct summation of expected values gives $5.41 M
- Using convolution of loss curves assuming that RC, DF are constant provides an expected value of loss $3.48 M
- Using convolution of loss curves for variable RC, DF has expected value $3.92 M
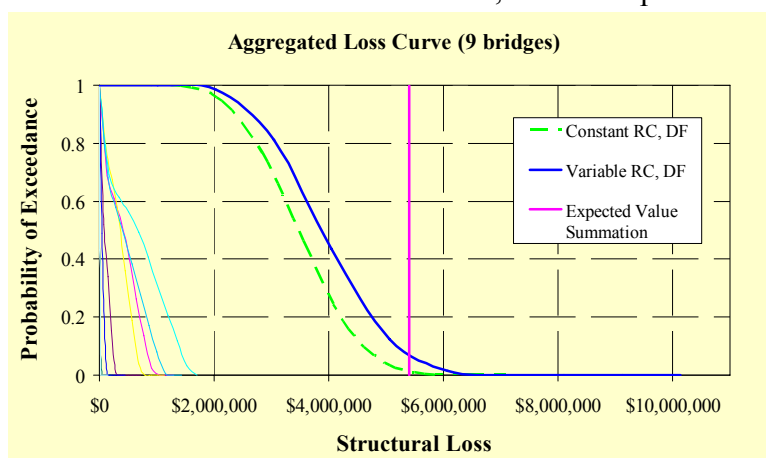
Figure 1 - Direct loss computation for nine bridges

The figure above shows the probability distributions of exceeding the direct loss with constant values of RC and DF, variable RC and DF, Expected value simple summation and convolution of these distributions.

The correlation of ground motion and bridge damage was investigated through sensitivity studies. First the joint exceedence probabilities were computed for two sites with correlated ground motions. Figure 2 shows the effect of correlation on ground motion as a function of the correlation coefficients and the number of sites. It can be observed that the uncertainty in total loss computation increases significantly with the increase in number of sites and the ground motion correlation coefficient.
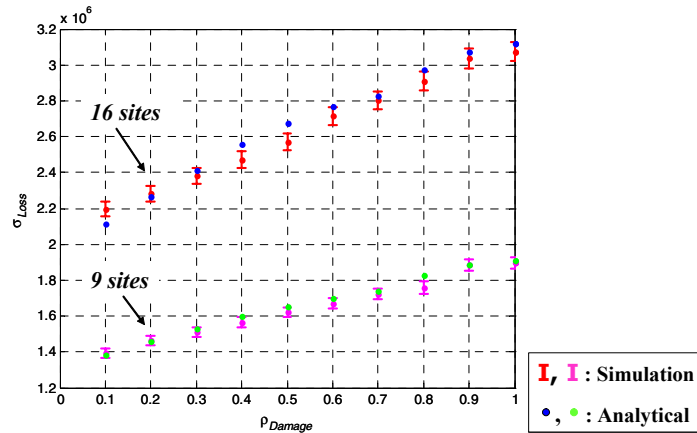
Figure 2 - Influence of ground motion correlation on the total loss standard deviation with separation distance dependence

Figure 3 shows the results of the sensitivity analysis of loss standard deviation as a function of the damage correlation and the number of bridges in the system.
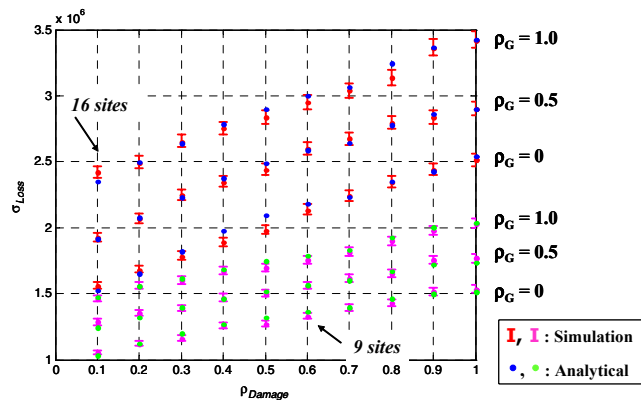
Figure 3 - Effect of damage correlation on loss uncertainty.

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

Part of the results reported here was supported through a grant from the UPS Foundation provided by Stanford University. These results could not have been obtained solely with the support of the PEER project.

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

Currently, the convolution integration of total aggregate loss is being investigated for possible adoption by Guy Carpenter Insurance Company for their portfolio risk management.

Expected milestones & Deliverable

- The following milestones and deliverables remain for the rest of this project:
- Application of the correlation to a network
- Estimation of probability distribution of losses for a network

- Development of the formulation for network performance with correlated ground motion and damage functions and its effect on travel time.
- Sample applications of these methods on a scaled down network within the San Francisco Bay Area.

Project Title—**ID Number**	*Improved Fragility Functions for Bridges Susceptible to Large Ground Deformations and Liquefaction* - **2572005**
Start/End Dates	10/1/05—9/30/06 Funding Source PEER-CA State Transp. Fund
Project Leader (boldface) and Other Team Members	**Scott Brandenberg** (UCLA/F), Pirooz Kashighandi (UCLA/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 improve fragility functions for bridges in liquefiable soil for assessing seismic risk of the San Francisco Bay Area transportation network. The need for improved fragility functions was identified through transportation network fragility analyses performed by Kiremidjian, which predicted that liquefaction would cause unrealistically widespread bridge damage and collapse. Liquefaction hazard was modeled using general guidelines inherent to the program HAZUS created by the Federal Emergency Management Agency, and the liquefaction hazard analysis was not specific to conditions in the Bay Area. A more careful region-specific consideration of liquefaction fragility is warranted since liquefaction was such a dominating factor in the transportation network analyses.

Topics that can be made more specific to the Bay area are:

1. Mapping of liquefaction triggering probability for a given level of ground shaking
2. Mapping of free-field ground displacement given liquefaction triggering
3. Estimating bridge damage state given a free-field ground displacement.

Each of these topics must specifically reflect conditions in the Bay area while remaining general enough to be implemented into the broad scope of the transportation network analysis program.

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

The improved fragility functions developed by this research will be utilized in a transportation network analysis that integrates all four aspects of the PEER PBEE framework (i.e. IM, EDP, DM and DV). It will demonstrate how improvements to a single component of the methodology can influence the global analysis results.

Methodology employed

This research consists of two primary tasks:

1. Utilize recent and ongoing efforts to map liquefaction in the Bay Area to develop probabilistic predictions of liquefaction triggering and ground displacement.
2. Perform suites of analyses in which ground displacements are imposed on bridge foundations to derive fragility functions relating bridge damage state to ground displacement. Uncertainty in the input parameters will be quantified and discrete event probabilities will be tracked for subsequent derivation of fragility functions.

Expected milestones & Deliverable

Fragility functions for modeling the influence of liquefaction on bridges in the Bay Area designed to be used in conjunction with the analyses of the transportation network that have been performed using HAZUS (Kiremidjian PEER Project No. 3392003). Improved fragility functions will be provided 12 months following the start date for the project. A report detailing the work performed in this project will be provided to PEER at the end of the project period.

Project Title—**ID Number**	*Directivity in Preliminary NGA Residuals* - **1M01**		
Start/End Dates	1/9/06—11/30/06	Funding Source	PEER-Caltrans
Project Leader (boldface) and Other Team Members	**Paul Spudich** (USGS/O), Brian S.J. Chiou (CalTrans/O)		

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

Project goals and objectives

Development and calibration of improved functional forms for directivity, based on isochrone theory, that can be used by NGA attenuation relation developers in their new attenuation models.

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

The PEER mission is to develop and disseminate technologies to support performance-based earthquake engineering (PBEE). The approach is aimed at improving decision-making about seismic risk by making the choice of performance goals and the tradeoffs that they entail apparent to facility owners and society at large. A crucial part of PBEE is the accurate assessment of the ground motion hazard for a site or a region. This project is aimed at improving the accuracy of predictions of ground motions for future earthquakes.

Methodology employed

Spudich et al, 2004, USGS Open File Report 2004-1268, http://pubs.usgs.gov/of/2004/1268 has proposed functional forms for directivity and ground motion polarization, based on isochrone theory, suitable for use in NGA ground motion prediction relations. These functional forms have some parameters that can only be derived by comparison with empirical data. I am examining residuals (observed FN, FP, and geometric mean 1-s and 3-s spectral accelerations minus corresponding predictions of non-directive relations) submitted to me by developers. I select for analysis a subset of earthquakes that are well-recorded aziumuthally. I (1) determine which of the proposed isochrone directivity parameters (IDPs, functional forms, p. 15 of Spudich et al., 2004), or other IDPs we have subsequently proposed is best, (2) use data to determine the undetermined empirical constants Dfloor, (Spudich and Chiou, memo to developers "Isochrone Directivity User's Guide v2", Aug. 1, 2005) and e, the radiation pattern water level (Spudich et al., 2004, eqn 15), and (3) report the results to developers. It is envisioned that the developers will take the results of this work and use/modify them as necessary to extend them to the entire period band, magnitude range and distance range of their prediction relations.

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

First year project. For related previous activities on a different project, please see above "Methodology" section.

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

Other work on near-fault ground motions and directivity is being done outside PEER, (e.g., Mavroeidis and Papageorgiou, BSSA, 2003; Hisada and Bielak, BSSA, 2003, B. Rowshandel, unpublished), but none of these works is using isochrone theory.

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

First year project, no results yet

Expected milestones & Deliverable

Oral report on initial analysis of ground motion residuals compared to isochrone directivity, March 7, 2006 (achieved). Consultation with developers on proper implementation of theory (as needed). Written report on analysis of residuals compared to isochrone directivity, Sept. 30, 2006.

Project Title—**ID Number**	*Next Generation Attenuation (NGA) Models, WUS Shallow Crustal Earthquakes* - **lL11**		
Start/End Dates	10/1/05—9/30/06	Funding Source	PEER-Caltrans
Project Leader (boldface) and Other Team Members	**Maurice Power** (Geomatrix/I), Norman Abrahamson (PG & E/I), Gail Atkinson (Carleton/O), David Boore (USGS/O), Yousef Bozorgnia (PEER/F), Kenneth Campbell (ABS Consulting/I), Brian Chiou (Caltrans/I), I.M. Idriss (UCD/I), Walter Silva (Pacific Engineering/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.

Thrust Area 3—Lifelines Systems

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

The project accomplishments through Year 8 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 data base is shown in Figure 1. (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; (e) and synthesis of empirical studies on site response. (3) Preliminary NGA relationships were developed; and (4) An external review of NGA relationships by the USGS was initiated.

During Year 8, preliminary sets of NGA relationships were developed and discussed at Workshop 7 in December 2004 and Workshop 8 in April 2005. The Five NGA Developer teams held a series of interaction meetings to exchange information on NGA model developments by the teams as well as continue to review and update the data base. The external review process with USGS was initiated by providing preliminary reports of NGA relationships to the USGS and receiving and reviewing initial comments from the USGS during August and September 2005.

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.

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 Spring 2006 and the final relationships will be in widespread use in Fall 2006.

Expected milestones & Deliverable

Expected milestones and deliverables in Year 9 include: review meetings with USGS in October 2005 (two meetings), December 2005, and March 2006; completion of final reports for NGA relationships for the average horizontal components of ground motion in May and June 2006; and completion of the USGS review process including attendance at a USGS workshop in September 2006. Work on additional components of NGA models for effects of near-source rupture directivity on ground motions and extensions of the models for the average horizontal

components of ground motion to include fault-strike-normal and fault-strike-parallel components and reporting of these additional model components is expected to occur by September 2006.

Project Title—**ID Number**	*Variance Analysis of Strong Motion Attenuation Relationships -* **1N01**		
Start/End Dates	10/1/05—9/30/06	Funding Source	PEER- Caltrans
Project Leader (boldface) and Other Team Members	**Robb Moss** (CalPoly/F)		

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

Project goals and objectives

Quantify measurement uncertainty of input parameters and perform variance analysis using Bayesian regression.

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

This work is to provide an improved assessment of the uncertainty in ground motion estimations for use in seismic hazard analysis and performance based earthquake engineering.

Methodology employed

(1) Evaluate and quantify measurement uncertainty of Mw and Vs.
- Identify original independent sources of magnitude estimates. Review methodology for uncertainty assignments.
- Develop measurement error models for Mw and Vs using NGA data and source material. Assess the theoretical probability distributions that best fit the uncertainty.
- Estimate the respective measurement errors associated with the different Vs tools.
(2) Complete and validate Bayesian regression code.
(3) Perform variance analysis by incorporating measurement uncertainty and using Bayesian regression. Improve characterization of attenuation model uncertainty. Evaluate sensitivity of attenuation model coefficients to Mw and Vs measurement uncertainty.

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

Work will be done in Year 9. Funding is due to arrive soon for summer research season.

Expected milestones & Deliverable

(A) Quantify measurement uncertainty of input parameters Mw and Vs.
(B) Assess the impact of measurement uncertainty on attenuation model coefficients and model error for one or more NGA models using the NGA database and Bayesian regression.

Project Title—ID Number	Benchmarking of Nonlinear Geotechnical Ground Response Analysis Procedures - 2G03		
Start/End Dates	10/1/05—12/31/06	Funding Source	PEER-Caltrans
Project Leader (boldface) and Other Team Members	**Jonathan Stewart** (UCLA/F), Onlei Annie Kwok (UCLA/GS), Walter Silva (Pacific Engineering/I), Robert Kayen (USGS/O)		

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

Project goals and objectives

(a) Obtain Vs profiles for vertical array sites in Japan using SASW testing.
(b) Process Italian strong motion data (about 500 records).
(c) Completion of validation exercise from PEER Lifelines Project 2G02 and preparation of final report.

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

This project is developing site and ground motion data needed for ongoing ground motion research projects.

The final stage of 2G02 project work involves the validation of nonlinear ground response analysis codes, which contributes to the estimation of IM.

Methodology employed

Shear wave velocities are being measured using SASW techniques. The field work is now complete and data analysis is in progress.

The data processing follows normal protocols for the PEER-NGA project. This work is complete.

The validation work at the end of 2G02 comprises analysis of vertical array data.

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

Previous years accomplishments were in the 2G02 project.

We have completed a significant theoretical verification exercise in which consensus guidelines were developed regarding specification of input motions for nonlinear codes and specification of viscous damping. These results are being synthesized into a journal paper that will be submitted for review shortly.

We have completed a set of blind predictions for the Turkey Flat site (2004 Parkfield earthquake) and have compared our results to those of our developer teams. This work is being published in conference proceedings.

Thrust Area 3—Lifelines Systems

We have completed exercises that have demonstrated significant differences in the codes when they are used with large input motions. This is being further investigated in ongoing work.

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

Our guidelines on code usage are being implemented in industry by users of the codes exercised in this project (DEEPSOIL, DMOD, TESS, OPENSEES, SUMDES).

Expected milestones & Deliverable

- Completion of Vs logs for Japanese downhole array sites.
- Completion of Italian data processing
- Completion of downhole array studies
- Development of recommendations for parameter selection related to backbone curves and parameters that control the shape of hysteresis curves.
- Completion of final project report.

Project Title—ID Number	Liquefaction Hazard Screening of Caltrans Bridge Sites - **3I01**		
Start/End Dates	5/26/05—12/31/06	Funding Source	PEER-Caltrans
Project Leader (boldface) and Other Team Members	**Keith L. Knudsen** (CGS/O), Jacqueline Bott (CGS/O)		

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

Project goals and objectives

There are two principal goals of this project:
1. Develop a methodology for screening and prioritizing highway bridge sites for retrofit and/or site–specific field investigations based on exposure to liquefaction-induced ground failure hazard, and
2. Apply the methodology(ies) to identify those Caltrans bridge sites at highest risk from liquefaction-related damage.

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

Development and demonstration of a successful cost-effective strategy to prioritize exposure of transportation structures to ground failure hazards can have nationwide applicability. Combining estimates of hazard exposure (this project) with information on structural vulnerability and importance (potential parallel project) can provide an estimate of risk that is a logical basis for prioritizing the expenditure of mitigation funds for earthquake and liquefaction retrofitting. Such an approach may be applicable to a variety of lifeline systems/organizations, not exclusively transportation systems. The results of this study will allow Caltrans to focus its resources on facilities that have been prioritized for future site-specific work using a sound approach that ranks bridge sites from throughout the entire state.

Methodology employed

Development of a screening/prioritizing procedure for liquefaction hazard and application of this screening procedure to Caltrans bridge sites are the goals of this project. Phase 1 screening of the approximately 12,000 Caltrans bridge sites is being performed using available geologic, hazard and seismologic data, much of which is existing data held by various programs within CGS. An integral aspect of Phase 1 is development of a screening methodology in coordination with Caltrans engineers and geologists. Maps of liquefaction hazard, liquefaction zones of required investigation, geology, and strong-ground motion are being evaluated and placed in an evaluation scheme during Phase I. Phase 2 screening will consist of refinement of the Phase 1 results by making use of geotechnical boring data that are available in our GIS database. The screening methodology in Phase 2 will be developed in collaboration with Caltrans and PEER colleagues. Our preliminary analyses tell us that our CGS database contains at least one boring for about 800 bridge sites in Southern California and at least one boring for about 200 bridge sites in Northern California. Part of Phase 2 will include an analysis of the "value-added" by incorporation of one or two borings for a bridge site into the screening analysis. This analysis will include consideration of peak ground motions (10% in 50 years exceedence), and estimation of permanent, liquefaction-induced vertical and horizontal displacements using newly developed approaches (making use of the results of PEER projects 3G01 and 3G02).

Thrust Area 3—Lifelines Systems

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

We have: (1) converted the database of bridge locations provided by Caltrans to a GIS database, (2) begun to query against regional datasets, including a) liquefaction zones of required investigation, b) water bodies and streams, c) liquefaction susceptibility maps, d) probabilistic shaking maps of the state, e) maps of active faults, (3) begun compiling case histories of bridges that have been exposed to liquefaction, and (4) begun laying out draft screening procedures based, in part, on an unpublished "Susceptibility Rating Factor" developed by Professor Steve Kramer at University of Washington.

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

We are aware of work being conducted by Professor Kramer at University of Washington who is working with the Washington Dept. of Transportation, and Professor Dickenson at Oregon State University who recently completed a project for the Oregon Dept. of Transportation. Finally, we are aware of a proposed project by Professor Scott Brandenberg of UCLA who may be working on a project for Caltrans that focuses on ranking bridge foundations as to their susceptibility to liquefaction hazards. Our project differs from the ones in Washington and Oregon in that Caltrans has an inventory of ~13,000 bridges, many more than in the other states, and we are developing a procedure and implementing the screening procedure for all of Caltrans bridges in a GIS. One of the aspects of this study that is different is that we will have widely varying amounts (and scales) of information available for the set of bridges. For some bridge sites we will make use of geotechnical borings in our database, while for other sites the bet available information may be small-scale geologic mapping.

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

We are in the beginning of the project and thus no results have been applied in industry.

Expected milestones & Deliverable

We expect to complete our project and hand over a liquefaction hazard screening tool to Caltrans by December of 2006.

Member company Benefits

Development and demonstration of a successful cost-effective strategy to prioritize exposure of transportation structures to ground failure hazards can have nationwide applicability.

Project Title—ID Number	Guidelines for Nonlinear Analysis of Bridge Structures - 9A01		
Start/End Dates	1/15/06—1/15/07	Funding Source	PEER-Caltrans
Project Leader (boldface) and Other Team Members	**Bozidar Stojadinovic** (UCB/F), Kevin Mackie (UCB/PD), Vesna Majstorovic (UCB/GS), Ady Aviramtraubita (UCB/GS)		

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

Project goals and objectives

1. Ensure that accurate nonlinear modeling techniques are employed by Caltrans.
2. Ensure that PEER researchers realistically model typical Caltrans bridge details.
3. Identify incompatibilities or inconsistencies between SAP2000 and OPENSEES.
4. Identify bridge components that require special modeling consideration.
5. Establish criteria for when specific bridge components require nonlinear characterization as well as the level of sophistication of that nonlinear characterization.
6. Develop summary guidelines for nonlinear modeling of bridges.

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

The work in this project may be viewed as the transition-to-practice of the projects on probabilistic performance-based evaluations of bridges conducted within the PEER Bridge Thrust. The project in the Bridge Thrust are grouped into three groups: (1) the predominantly geotechnical ones, focusing on assessing liquefaction and soil spreading hazard; (2) the predominantly structural ones, focusing on fragility assessment of bridge components and development of new design concepts, such as application of new materials and devices to reduce residual displacement, to improve bridge seismic resistance; and (3) the system-related ones, where complex models of a set of test-bed bridges are developed to asses the probability distribution of decision variables, such as the repair cost or the ability to carry traffic load after an earthquake, and to evaluate the quality of combined soil-structure models to model soil-structure interaction.

Methodology employed

The project will be performed in three stages.

In Stage 1, a comparison of SAP2000 and OPENSEES will be made using 4 bridge models previously developed by Tsai (2003). Each bridge will be run longitudinal only, transverse only, and longitudinal and transverse combined. For transverse loading SDC recommendations for abutment modeling will be used. For longitudinal loading abutment models developed by Tsai will be used. Caltrans will provide the data required to develop the OPENSEES and SAP2000 models, as well as the existing SAP2000 (if any) at the start of the project.

For each bridge, comparisons will be made using approximately 3 time-series, each scaled to a low, moderate, and high level of excitation. (i.e. linear, ductilities of 2-3, and ductilities of 4-6). The ground motions will be chosen using the PEER ground motion database in consultation between the PIs and Caltrans engineers within the first half of Stage 1 of the project.

The primary objective of Stage 1 is to identify and resolve inconsistencies between SAP2000 and OPENSEES. Issues requiring parametric study will be identified.

In Stage 2, parametric analysis will be performed to quantify the consequences of various modeling choices through determination of median and sigma structural response resulting from excitation by a suite of input motion (approximately 30 records). The ground motions will be chosen using the PEER ground motion database in consultation between the PIs and Caltrans engineers at the beginning of Stage 2 of the project. Modeling choices will be evaluated in consultation between the PI and Caltrans engineers during Stage 1 of the project so as to arrive at a defined set of alternatives early on in Stage 2 of the project.

Stage 3 consists of developing guidelines as described in Section 2 (above) utilizing the results of the parametric study in Stage 2 (as well as other sources selected by the PI). These guidelines will be developed in consultation with Caltrans engineers.

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

This is the first year for this project.

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

It is anticipated that the models developed for this study (both SAP2000 based and OPENSEES based) will be of potential value to investigators studying issues of time-series selection and scaling. These models will be made available if requested.

Two NEES Small Group awards have been made in the bridge area. One project focuses on the seismic simulation and design of bridge columns under combined actions and implications on the system response. This experimentally-based project aims to produce fragility relations for columns under combined loading, analysis guidelines and design methods for combined bridge column loading. However, it is not clear if the columns tested will be similar to the typical Caltrans columns. The other project focuses on the seismic performance of bridge systems with conventional and innovative materials. This project comprises tests of a full-scale abutment model and tests of a four-span bridge models on a shaking table. The expected outcomes of the project are better understanding of the response of bridge systems, with and without soil-structure interaction, development of wireless sensors and numerical modeling using OpenSees. Again, it is not clear if the examined bridge structures will conform to Caltrans SDC. Thus, while these projects are certainly interesting, it is not clear if they will apply to typical Caltrans bridges directly.

Work on analysis and seismic evaluation of bridges is ongoing within the MAE and MCEER centers. The MAE Center is focused on typical East Coast bridges. While the approach taken by the MAE Center is quite similar to the PEER Center approach, the bridge details are so different from typical California bridges that only a small fraction of their findings may apply. The MCEER Center is focused on developing REDARS. Caltrans is already participating in this effort.

Work conducted within the NCHRP 12-49 project on developing a comprehensive specification for the seismic design of bridges resulted in an NCHRP Report 472 which contains the finding of the project and the background for the AASHTO Guide Specification. The findings of this report that pertain to bridge modeling and, further, to design philosophy will be taken into account in this project.

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

None just yet.

Expected milestones & Deliverable

Stage 1 SAP2000 – OPENSEES comparison report: Following comparisons of SAP2000 and OPENSEES bridge models, the PI will prepare a short report that provides guidelines for nonlinear bridge modeling using SAP. This report will also identify unresolved issues that will be the focus of parametric study in Stage 2.

Stage 2 data report: Following parametric evaluation of various bridge models and modeling options, a data report will be prepared documenting median and dispersion (sigma) values of displacement demand for the various models considered in the parametric study. A simple description of the models considered will also be provided.

Final Report: A final report will be prepared that includes guidelines for (1) determining when linear methods are sufficiently accurate to estimate structural demands, (2) determining what components require nonlinear characterization (when nonlinear analysis is required), and (3) how to model nonlinear bridge components.

Member company Benefits

The objective of this project is the development of practical guidelines for non-linear analysis of bridge structures. The goal is to help practicing engineers implement nonlinear methods for bridge design and analysis in their every-day practice. The project is viewed as a collaborative effort between university researchers and practicing bridge designers. As such, it is hoped that these guidelines will be readily implemented in practice.

Project Title—ID Number	Analysis of Lateral Pile-Ground Interaction - 9B01		
Start/End Dates	10/1/05—9/30/06	Funding Source	PEER-Caltrans
Project Leader (boldface) and Other Team Members	**Ahmed Elgamal** (UCSD/F), Jinchi Lu (UCSD/PD)		

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

Project goals and objectives

The main goal is to develop a 3-dimensional finite element analysis tool for use by practice to estimate seismic lateral loading effects on piles and large diameter piers
Figure 1). This tool, OpenSeesPL, will allow for the execution of single pile and pile group simulations under seismic excitation scenarios as well as push-over situations.

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

Provide an interface for efficient utilization of an OpenSees high end computational tool for a wide class of applications in seismic Bridge-ground analyses, and similar ground-structure situations.

Methodology employed

Scenario-specific Windows-based user interface for pre- and post- processing, driven by the OpenSees Computational Platform.

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

New Project

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

OpenSees development efforts include development of user-interfaces by other PEER researchers, and through national collaborative efforts led by Professor Greg Fenves.

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

New project aimed at facilitating the use of OpenSees by the research and practicing communities.

Expected milestones & Deliverable

The anticipated long-term project will eventually cover:

The overall effort will eventually allow the interface to cover:

1. Circular piles and large diameter piers embedded in uniform or layered ground profiles.
2. Square piles or large piers embedded in uniform or layered ground profiles.
3. Pile groups in level ground.
4. Pile or Pier in sloping ground.
5. Pile group in sloping ground.
6. Push over analysis in 1 lateral direction.
7. Push over analysis in 2 lateral directions.
8. Response due to seismic excitation in one or two lateral directions.
9. Availability of graphical output in a word file for use in writing report.
10. Linear and nonlinear soil properties.
11. Linear pile properties (reinforced concrete, cased piles, or steel).
12. Nonlinear pile/Pier properties using fiber discretization (reinforced concrete, cased piles, or steel)
13. Nonlinear pile properties with nonlinear moment curvature relation (reinforced concrete, cased piles, or steel).
14. Pile/Pier will bridge deck included.
15. Analysis of Liquefaction Scenarios and countermeasures.
16. Inclusion of pile-soil interface boundary elements.

Tasks 1, 2, 6, 7, 10, 11, 13, and 14 will be complete by May 2006.

ACCOMPLISHMENTS

Tasks 1, 2, 6, 7, 10, and 11 were complete by March 2006. Sample dialog windows of OpenSeesPL are shown in Figures 1-7. In OpenSeesPL, definition of pile dimension and material properties is an important element. In this interface, pile cross section can be circular (Figure 2, Task 1) or square (Figure 3, Task 2). The interface can generate meshes for piles in slopes, knowing that this problem is one of much significance. In addition, OpenSeesPL allows for simulations for any size of pile diameter.
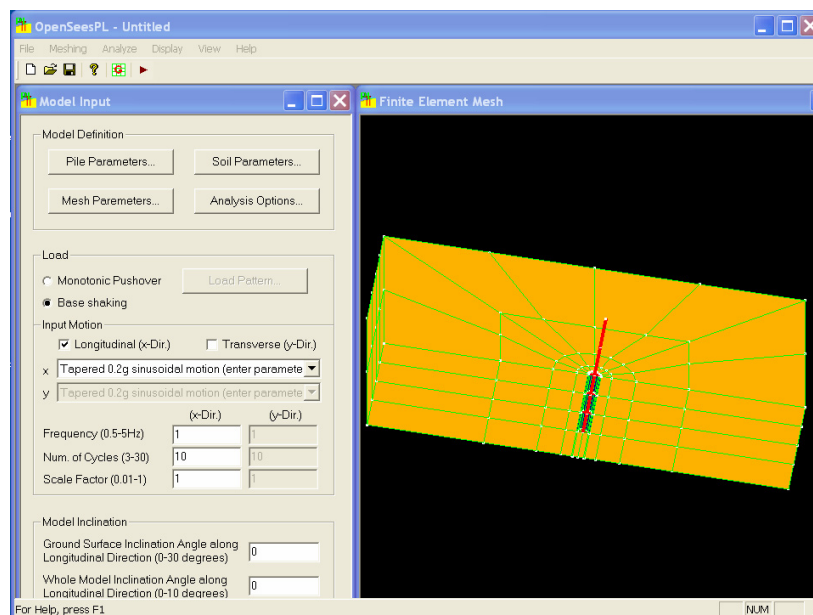
Figure 1 - Default Configuration for the Window User Interface OpenSeesPL.

OpenSeesPL allows for selection of soil materials from an available menu of cohesionless and cohesive soil materials (Figure 6). The menu of soil materials (Table) includes a complementary set of soil modeling parameters representing loose, medium and dense cohesionless materials (with silt, sand or gravel permeability), and soft, medium and stiff clay (J2 plasticity cyclic model). Representative soil properties are pre-defined for each of these soils (Table). The theoretical background is discussed in Parra (1996), Elgamal et al. (2002a; 2002b; 2003), and Yang (2000; 2002; 2003).

Table 2 - Representative set of basic material parameters (data based on Seed and Idriss (1970), Holtz and Kovacs (1981), Das (1983), and Das (1995)).

Cohesionless Soils	Shear wave velocity* at 10m depth (m/s)	Friction angle (degrees)	Possion's ratio	Mass density (kg/m^3)
Loose	185	29	0.4	1.7x10^3
Medium	205	31.5	0.4	1.9x10^3
Medium-dense	225	35	0.4	2.0x10^3
Dense	255	40	0.4	2.1x10^3
Cohesive Soils	Shear wave velocity (m/s)	Undrained shear strength (kPa)	Poisson's ratio	Mass density (kg/m^3)
Soft clay	100	18.0	0.4	1.3x10^3
Medium clay	200	37.0	0.4	1.5x10^3
Stiff clay	300	75.0	0.4	1.8x10^3

* Shear wave velocity of cohesionless soils in proportion to (pm)1/4 where pm is effective mean confinement.

OpenSeesPL also allows users to control soil parameters such as yield strength (Su) for instance, making the definition of properties as simple as the user wishes and the situation demands. In addition, appropriate windows can be created for users to include their own material models (Figure 7) in OpenSees, and access these materials through the finite element program OpenSees (McKenna 1997; McKenna and Fenves 2001).
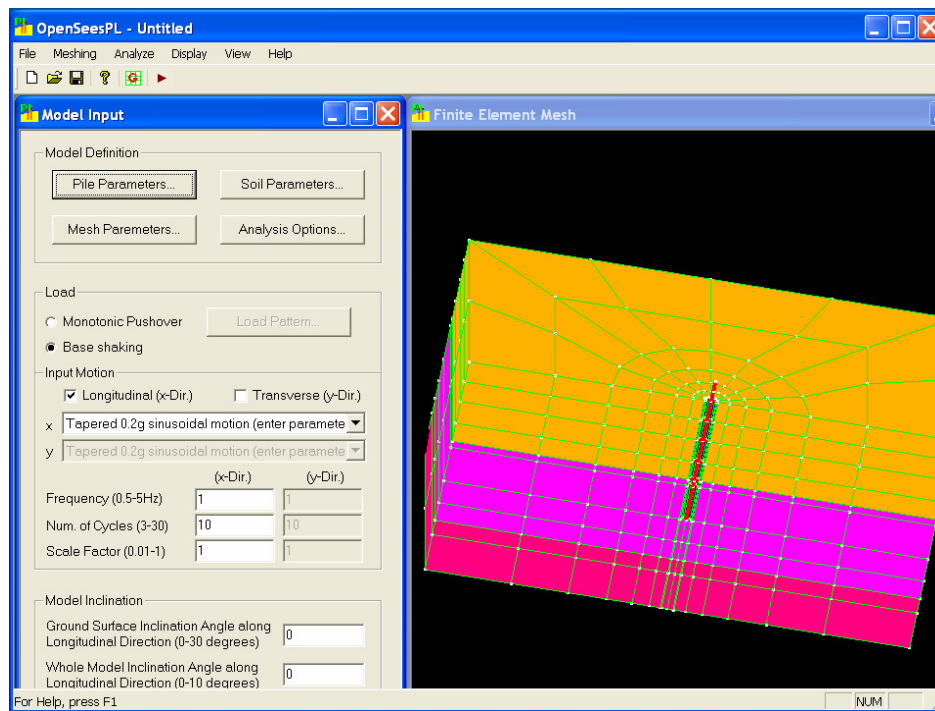
Figure 2: Circular Pile in Layered Ground (Task 1).
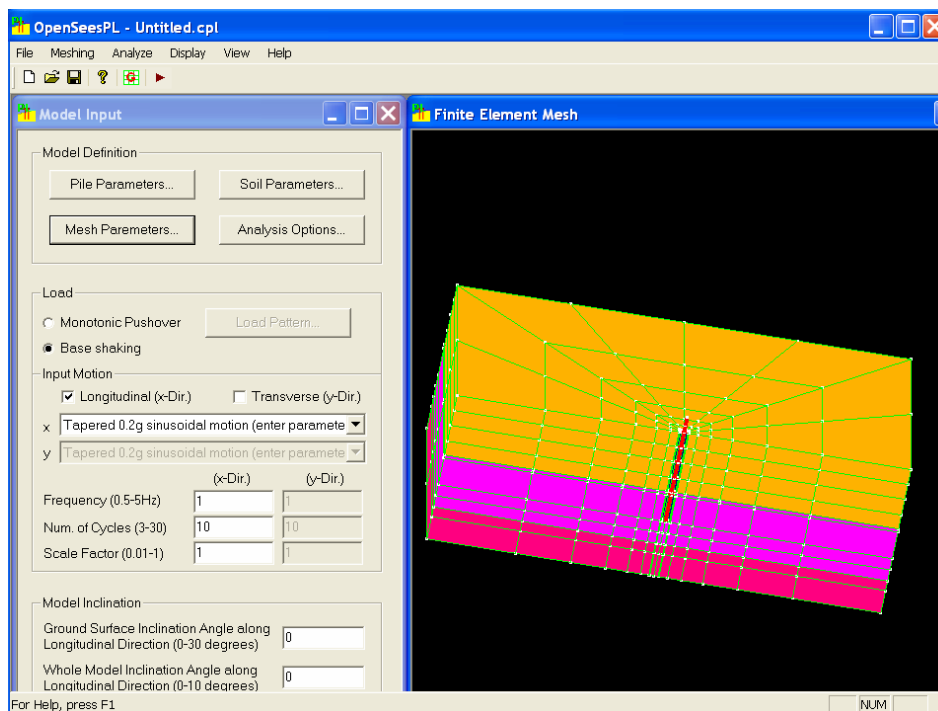
Figure 3- Square Pile in Layered Ground (Task 2).
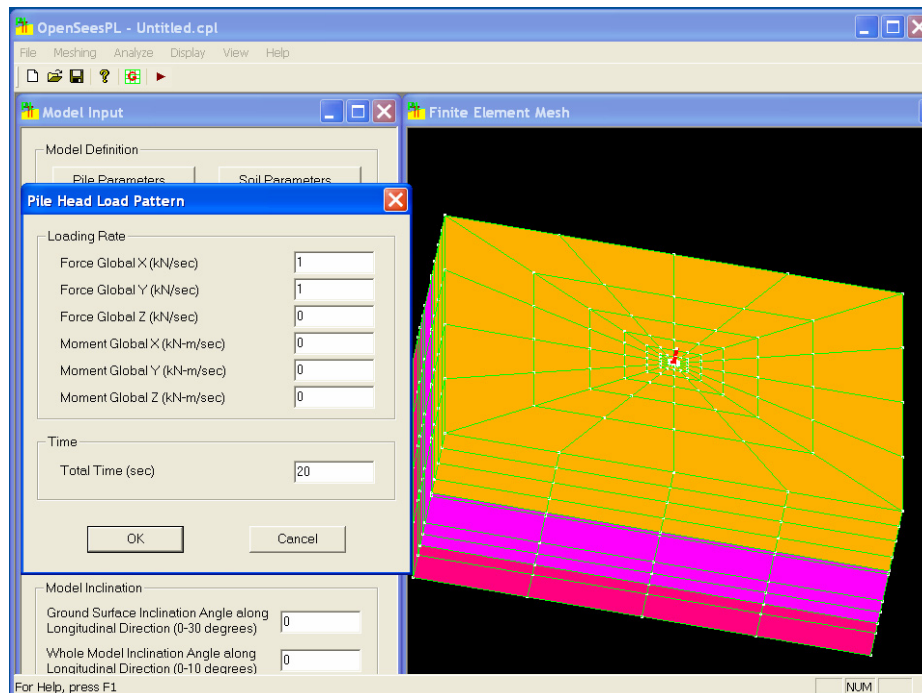
Figure 4 - Pushover Analysis in 2 Directions (Task 7).
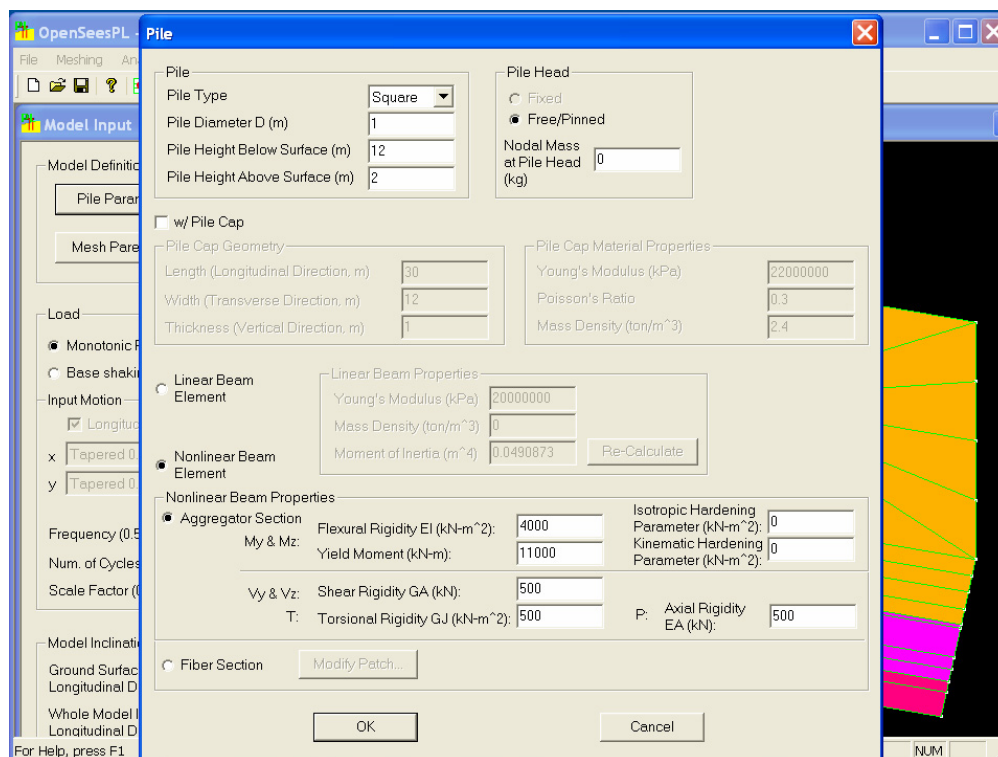
Figure 5 - Definition of Linear & Nonlinear Pile Properties (Tasks 11& 13).

Figure 6 - Definition of Foundation/Soil Properties (Task 10).

Figure 7 - Definition of User-Defined Sand (U-Sand).

ONGOING WORK

Currently, a user manual is being prepared including documentation for 2 response scenarios to be defined in collaboration with Caltrans engineers.

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Thrust Area 3—Lifelines Systems

Project Title—ID Number	Development of Improved Procedures for Seismic Design of Buried and Partially-Buried Structures - **BART**		
Start/End Dates	1/406 – 1/3007	Funding Source	PEER-BART
Project Leader (boldface) and Other Team Members	**Jack Moehle** (UCB/F), Nicholas Sitar (UCB/F), Jon Bray (UCB/F), Yousef Bozorgnia (UCB/F)		

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

Project goals and objectives

Investigate seismic response of partially embedded structures

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

To provide practical guidelines for seismic response of partially embedded structures

Methodology employed

Combination of centrifuge testing and analysis

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

It is a new project in TA III

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

No other similar project

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

This is a new project

Expected milestones & Deliverable

June 8 will be a workshop; January 30, 2007 will be the final date of project

Project Title—ID Number	*Processing of Recent Earthquake Records* - **1E08**		
Start/End Dates	11/105 – 12/3105	Funding Source	PEER-Caltrans
Project Leader (boldface) and Other Team Members	**Robert Darragh** (Pacific Engineering & Analysis/I)		

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

Project goals and objectives

Provide processed strong-motion records of six recent earthquakes

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

The data will be used for PEER NGA database; for IM issues

Methodology employed

Filtering, integration, spectral computation of strong-motion data

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

New project

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

The records are for the recent earthquakes – not previously processed

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

This is a new project adding more records to NGA database. The NGA database has been used on many research and practical projects, including NGA models.

Expected milestones & Deliverable

The project was finished December 2005

Project Title—ID Number	PEER Analysis Platform for Demand Simulation - 4102005		
Start/End Dates	10/1/05—9/30/06	Funding Source	PEER-CA-General Fund
Project Leader (boldface) and Other Team Members	**Gregory L. Fenves** (UCB/F), Frank McKenna (UCB/PD), George Petropoulis (UCB/GS)		

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

Project goals and objectives

The objectives of this project are to 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, and the lessons-learned in the testbed projects have been 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 9, we are continuing work on parameterization of models and extending the framework for multi-physics. On the latter, a graduate student has been developing OpenSees applications for large-scale computation of ground motion simulation. The goal will be to analyze "soil islands"

with building and foundation systems to represent site response effects, soil-foundation-structure interaction, and building response. This is important because the local site response and interaction effects are known to have a large effect on engineering demand parameters and ultimately performance of buildings and also bridges.

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 utilized and extend OpenSees. Also included in this component is continual updating of the documentation and holding workshops.

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

In Year 8, continuous improvement in the modeling and computational capability of OpenSees has been pursued. A number of new models developed by PEER researchers have been incorporated into the base software, including concrete models, a reinforcing steel model, and new solid elements. There is ongoing effort to document, validate, and distribute the many contributions.

In the high-performance computing arena, considerable progress has been made in optimizing the software on computing clusters. For example, we are working with SDSC on an implementation on the DataStar for parallel computation of ground motion in a soil island. A new explicit solver was developed in OpenSees, which is very scalable. As one example, shown below is an OpenSees mesh of a 1200m x 700m x 200m layered soil region with 5.25 million elements (16 million DOF). The ground motion simulation is run on 400 processors using the DRM method for defining the boundary conditions on all sides. The computation is accurate up to about 4 Hz. The top figure is the mesh, and the second figure uses coloring to show the distribution of the mesh to the 400 processors. Total throughput is over 60Gflops. We are currently working on extending the analysis to include building and foundation models.
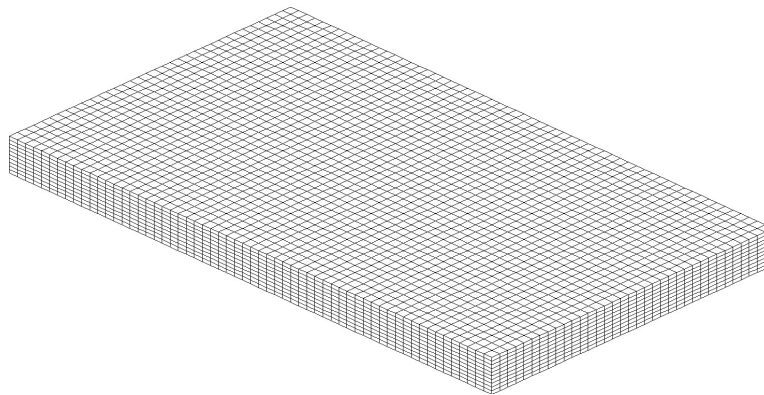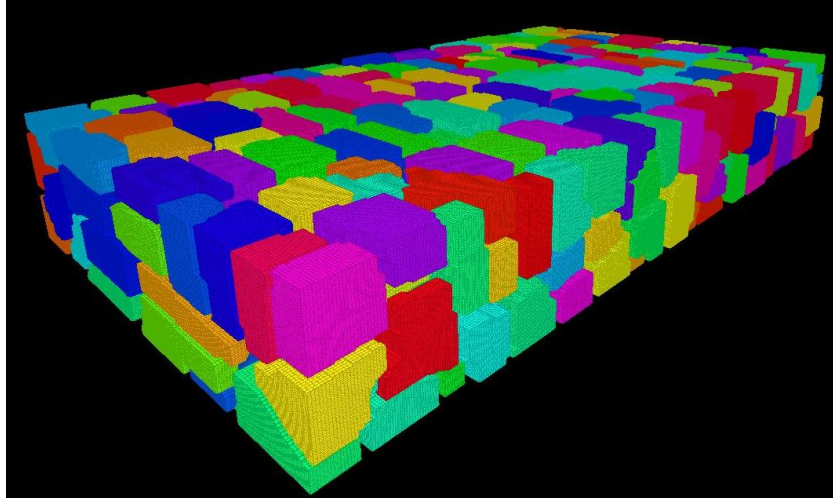
Other similar work being conducted within and outside PEER and how this project differs

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.

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

We have a number of users in industry and are starting to field inquires about licensing OpenSees. The software is widely used around the world by researchers as evidenced by Google hits and the number of OpenSees websites, particularly in Asia.

Expected milestones & Deliverable

Continued development and support of the base software.
Integrate developments in other PEER projects into OpenSees.
Continued validation of models.
Development of implicit-explicit solver for soil-structure-foundation-interaction on parallel computers.

Member company Benefits

Access to advanced modeling and simulation software and expertise on how to use it.

Project Title—ID Number	*Reliability of Soil-Structure-Foundation Systems* - **4132005**		
Start/End Dates	10/1/05—9/30/06	Funding Source	PEER-CA State Transp. Funds
Project Leader (boldface) and Other Team Members	**Joel Conte** (UCSD/F), 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 perform probabilistic response analysis and reliability analysis of Soil-Structure-Foundation (SSF) systems.
- Implementation in OpenSees of stochastic earthquake ground motion model.
- Extend current OpenSees capabilities for solving the large-scale nonlinear constrained optimization problems that the search for the design point(s) reduces to.
- Extend OpenSees framework for response sensitivity and reliability analysis of SSF systems to high-performance computing (to enable treatment of 3-D large-scale problems).
- Development of "demonstration" applications for building and bridge structures.

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 all system components. Such tools for uncertainty propagation analysis 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 previous year's achievements, with emphasis on accomplishments during last year (Year 8)
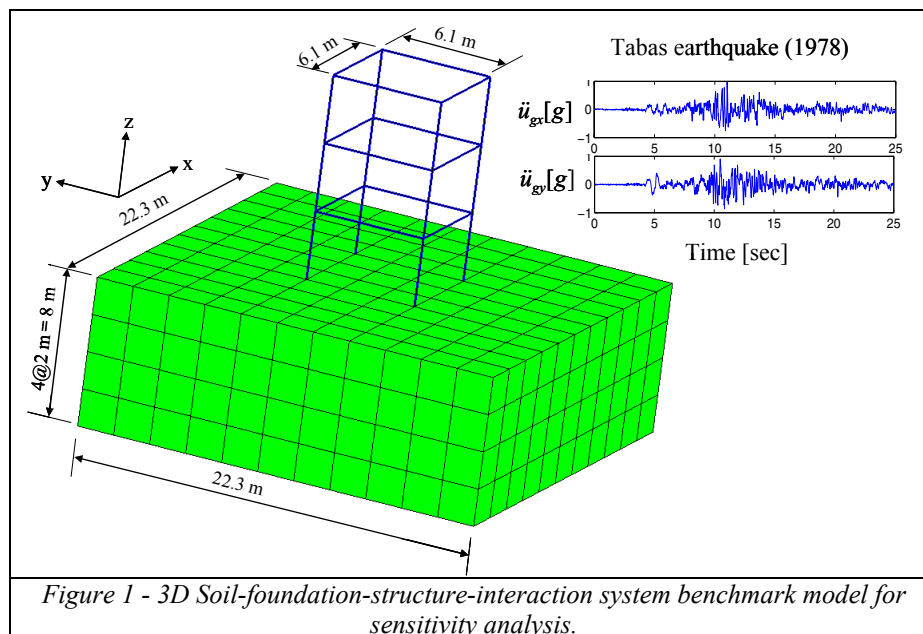
We performed the following extensions of the finite element response sensitivity analysis (based on the Direct Differentiation Method, DDM) framework in OpenSees to enable response sensitivity analysis (needed for reliability analysis) of 3-D soil-foundation-structure-interaction (SFSI) systems:

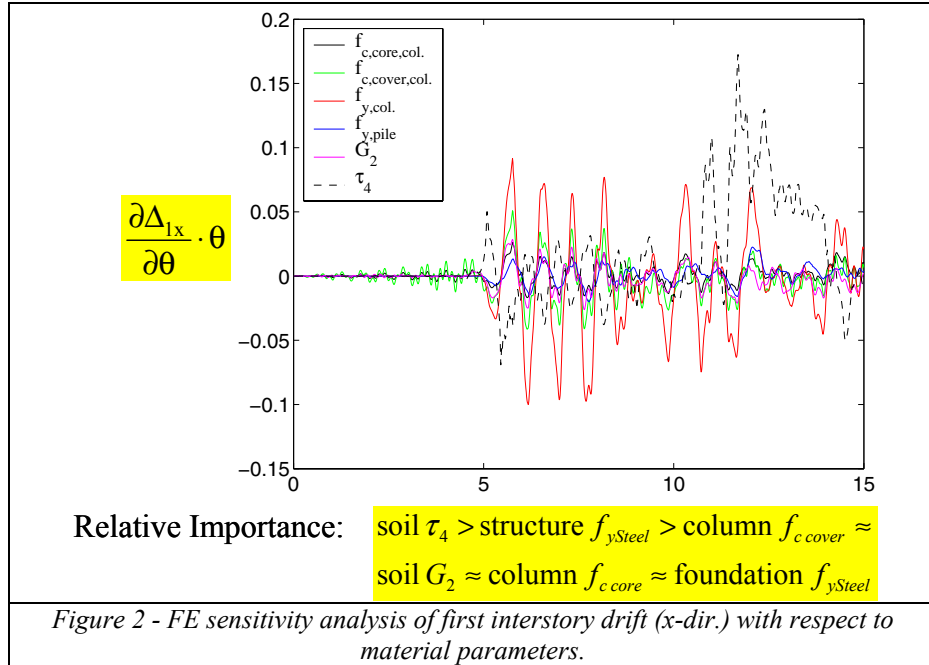- Extended transformation constraints (useful for connecting foundation elements to the soil domain and modeling rigid diaphragms of building structures) for sensitivity computation to the 3D case.
- Added nodal and local (i.e., Gauss point level) sensitivity recorders.
- Extended DispBeamColumn3d (used in modeling 3D bridge and building structures), FiberSection3d, LinearCrdTransf3d (coordinate transformation from element basic to

global DOFs), ElasticSection3d, and section Aggregator, for sensitivity computation capabilities.

- Extended for sensitivity computation the pressure-independent multi-yield surface material model from 2D to 3D.
- Extended variableTransient integration Analysis for sensitivity computation to enable response sensitivity analysis when using the adaptive time stepping scheme in OpenSees.
- Extended for sensitivity computation the 3D bbarbrick element (8 Gauss points for deviatoric part and reduced integration for volumetric part) available in OpenSees. We also modified the algorithm for the response computation part of the element to improve computational efficiency (by avoiding duplications in element state determination).

We also developed and implemented in OpenSees algorithms for finite element response sensitivity analysis for two smooth material models, namely the steel Menegotto-Pinto and concrete Popovic-Saenz models. We developed demonstration applications of response sensitivity analysis of 3D SFSI systems (see Figs. 1 and 2). For example, Fig. 2 shows the normalized DDM sensitivities to various materials (concrete, reinforcing steel, soil layers) of the first interstory drift response (in the x-direction) to the 1978 Tabas earthquake of the 3D building structure with deep pile foundations shown in Fig. 1. In addition of their use for time-variant reliability analysis, these normalized sensitivities indicate the relative importance of the corresponding material parameters, e.g., the yield strength $f_{y,col}$ of the longitudinal steel in the columns (red curve in Fig. 2) and the shear strength $_4$ of the fourth (bottom) soil layer (dashed black curve in Fig. 2) are the most important parameters for this problem.

Figure 1 - 3D Soil-foundation-structure-interaction system benchmark model for sensitivity analysis.

$$\frac{\partial \Delta_{1x}}{\partial \theta} \cdot \theta$$

Relative Importance: $\text{soil } \tau_4 > \text{structure } f_{ySteel} > \text{column } f_{c\,cover} \approx$

$\text{soil } G_2 \approx \text{column } f_{c\,core} \approx \text{foundation } f_{ySteel}$

Figure 2 - FE sensitivity analysis of first interstory drift (x-dir.) with respect to material parameters.

We investigated the effects of using (1) smooth versus non-smooth material models, (2) static versus dynamic analysis, and (3) insufficiently small time steps to integrate the equations of motion, on discontinuities in FE response sensitivities and convergence to the design point(s) when performing reliability analyses. As an illustration, Fig. 3 shows the FE response sensitivity surface for the roof relative displacement of a 3-story shear frame modeled using the Menegotto-Pinto constitutive law (smooth model) and subjected to the El Centro 1940 earthquake scaled by a factor 3. The discontinuities along the parameter axis (interstory initial yield strength F_{y0}) are due to the fact that the integration time step ($t = 0.02$ sec) is too large.

Figure 2 - FE response sensitivity surface for a 3-story shear frame modeled using the Menegotto-Pinto constitutive law (integration time step $t = 0.02$ sec)
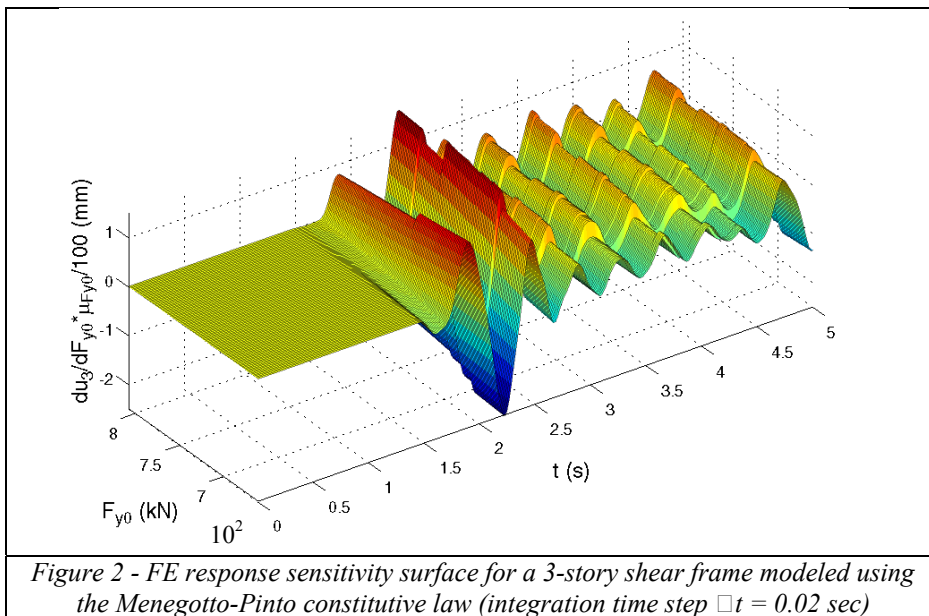
We developed and implemented in OpenSees analytical tools for performing probabilistic quasi-static response analysis (e.g., push-over analysis) of structural and/or geotechnical systems. These tools are based on the First-Order Second-Moment (FOSM) method of probabilistic analysis and allow to compute first-order approximations of the first moment (mean) and second moment (standard deviation and correlation coefficient) of any FE response quantities based on the first and second moments of basic random/uncertain loading/material/geometric parameters. The approximate analytical FOSM results were validated with Monte Carlo Simulation and were found to be accurate up to the range of moderate nonlinear behavior. We also investigated the use of FOSM in the case of dynamic earthquake response analysis and found that it does not provide satisfactory results in terms of accuracy.

Problems of time-invariant and time-variant reliability analysis of structural or SFSI systems reduce to solving a large-scale nonlinear constrained optimization problem in the search for the design point(s), which represents the heart of the finite element reliability analysis methodology. This is in general a very challenging computational task, which often suffers of non-convergence problems. We have already augmented the computational optimization capabilities previously implemented in OpenSees by Haukaas and Der Kiureghian by linking SNOPT with OpenSees. SNOPT is a state-of-the-art software package for nonlinear constrained optimization based on sequential quadratic programming (developed by Prof. Philip Gill at UCSD). The resulting combined software OpenSees-SNOPT can also be used for general purpose optimization (e.g., structural optimization, finite element model updating). The topology of the limit-state surface (in both the physical and standard normal spaces) for time-invariant and time-variant reliability problems will be investigated. Based on the insight gained from these studies, more efficient and more robust approaches/schemes for the design point(s) search and for evaluating the probability content of the failure domain will be developed and implemented in OpenSees. Some of these approaches will consist of customizing state-of-the-art optimization algorithms so as to exploit the physics and geometry of the specific problems at hand. Alternative approaches will consist of reformulating the problem in a form that can be solved efficiently by using the state-of-the-art algorithm in computational optimization. For accurate evaluation of the probability content of the failure domain, we are also investigating the use of hybrid methods combining the use of the design point(s) with variance-reduction simulation techniques such as importance sampling, directional simulation and subset simulation.

Using the finite element response sensitivity and reliability analysis framework in OpenSees, we are in the process of performing time-variant reliability analysis (i.e., computation of the mean rate of a critical FE response quantity exceeding a specified threshold) of deterministic SDOF and simple MDOF benchmark problems subjected to stochastic broad-band earthquake excitation. Initial results on the search for the design point(s) are promising. However, it appears that in the case of large nonlinearities, approximation of the probability content of the failure domain (for mean up-crossing rate calculation) using the First-Order Reliability Method (FORM) is not satisfactory (i.e., not accurate enough). We are investigating alternative procedures/methods to obtain more accurate results, keeping the computational cost within acceptable limits.

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), the Technical University of Denmark (PROBAN software), and the University of Innsbruck (COSSAN software). To our knowledge, none of this software is under an objected-oriented platform, or aimed specifically at soil-structure-foundation systems and seismic reliability problems. In this sense, the framework in OpenSees for sensitivity and reliability analysis of SSF systems will be unique.

Expected milestones & Deliverable

- Developments in OpenSees for sensitivity, probabilistic response, and reliability analyses of SSF systems.
- Documentation of demonstration applications.
- PEER technical report, papers, and User's Guide

Project Title—**ID Number**	*Reliability of Degrading Systems* - **4142005**		
Start/End Dates	10/1/05—9/30/06	Funding Source	PEER- CA Transp. Fund
Project Leader (boldface) and Other Team Members	**Armen Der Kiureghian** (UCB/F), Kazuya Fujimura (GS), Sanaz Rezaeian (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 develop a nonlinear random vibration approach that is appropriate for reliability analysis in the context performance-based earthquake engineering. The Tail-Equivalent Linearization Method (TELM) has already been developed in the previous phases of this project. For the present phase, the objectives are: (a) extend the method for non-stationary response, (b) apply to degrading systems, which necessarily require non-stationary analysis, (c) demonstrate the use of the TELM in the PEER PBEE framework, (d) complete and refine the implementation of TELM in OpenSees.

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

This project provides an alternative for computing the distribution of engineering demands parameters in the PEER PBE framework. Specifically, by using a stochastic model of the ground motion, the approach avoids the problem of selecting and scaling recorded ground motion time histories.

Methodology employed

TELM is an equivalent linearization method. However, in contrast to the conventional ELM which is a second-moment based method, it defines the equivalent linear system by matching the tail probability of the linear response with the first-order approximation of the tail probability of the nonlinear response. Methods used include stochastic modeling of the ground motion, the first-order reliability method, optimization algorithms, nonlinear time history analysis, and response sensitivity analysis.

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

The development of TELM for stationary random vibration analysis was completed in Year 8. Extensive parametric studies were carried out to determine the characteristics of the tail-equivalent linear system and to determine the range of accuracy of the method. Example applications with building and bridge structures were carried out. The method has been implemented in OpenSees, though refinements in this implementation are still on-going. A paper on this development has been completed and submitted for publication. The work has also been presented in a keynote lecture at one conference.

Figure 1 and Table 1 present the results of an analysis with TELM for a six-story example hysteretic system subjected to stochastic ground motions. Table 1 compares the mean and coefficients of the interstory drifts as obtained by TELM and by the conventional PEER PBEE

approach employing 10 scaled recorded ground motions. The comparison shows that the c.o.v. estimated by the conventional method is too high. We believe this is due to the site-to-site variability of recorded ground motions. It is also apparent that the TELM approach is able to properly account for the site conditions.
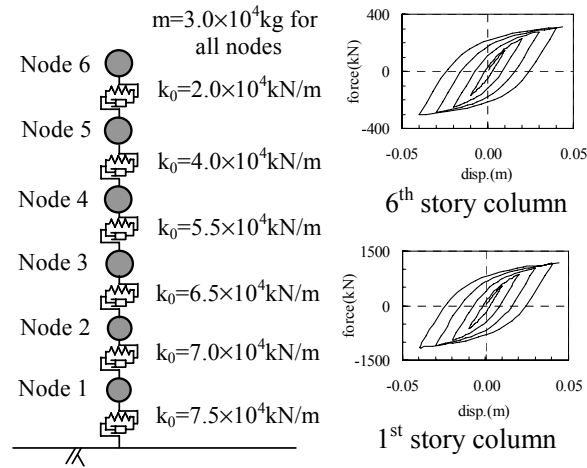

Figure 1. 6-story shear building model

Table 1 - EDP statistics based on recorded and stochastic ground motions

EDP	input motion		mean	c.o.v.
1st inter-story drift	recorded motion		0.0263	0.390
	stochastic	rock site	0.0252	0.206
		firm site	0.0215	0.203
		soft site	0.0210	0.226
		mixture	0.0212	0.215
6th inter-story drift	recorded motion		0.0238	0.334
	stochastic	rock site	0.0385	0.164
		firm site	0.0307	0.179
		soft site	0.0199	0.176
		mixture	0.0253	0.282

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

Within PEER, many researchers are using the PEER PBEE approach based on selection and scaling of time history analysis. We are the only group developing an alternative. Outside PEER, we are not aware of any other work in nonlinear random vibration analysis that has similar objective and approach as ours.

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

The approach is in developmental stage. It has not yet been used by the industry.

Expected milestones & Deliverable

(a) Develop a new stochastic model for non-stationary ground motion appropriate for TELM analysis.
(b) Develop algorithms for TELM analysis of non-stationary response - June 2006.
(c) Investigate applications to degrading systems - August 2006
(d) Demonstration of application to PEER PBEE analysis - Oct 2006.
(e) Implementation in OpenSees - October 2006.

Member company Benefits

Having an alternative for PBEE analysis, which avoid selecting and scaling recorded time histories.

Project Title—**ID Number**	*Modeling and Simulation of Degrading Shear Behavior in RC -* **4212005**		
Start/End Dates	10/1/05—9/30/06	Funding Source	PEER-CA State Transp. Fund
Project Leader (boldface) and Other Team Members	**Filip Filippou** (UCB/F), Afsin Saritas (UCB/GS), Chin-Long Lee (UCB/GS)		

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

Project goals and objectives

Development of a rational, yet computationally affordable, beam-column model for the analysis of new and existing reinforced concrete members under the combined action of axial force, bending moment and shear.

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

The project supports the simulation capabilities of PEER for structural elements that are sensitive to the interaction of shear with flexure and axial force.

Methodology employed

Force formulation of beam-column element with 3d dimensional constitutive modeling of fibers; transverse equilibrium accounts for confinement effects.

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

3d concrete constitutive model.
Simulation of shear wall specimens with different aspect ratios under monotonic and cyclic loads.

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

This project focuses on a rational and computationally efficient model that is capable of simulating 3d effects of concrete under monotonic and cyclic loads; attempts to date at other institutions do not have such broad objectives and are limited to specific cases or loading conditions.

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

Beam-column element is available for use with OpenSees; shear capability is not deployed yet.

Expected milestones & Deliverable

Beam-column element with shear interaction in OpenSees for the simulation of metallic devices, slender and squat concrete beam-columns and shear walls and 3d confinement effects.

Project Title—ID Number	Simulation and Performance Models for Cyclic Degradation Effects in RC Bridge Columns - **4232005**		
Start/End Dates	10/1/05—9/30/06	Funding Source	PEER-CA State Transp. Fund
Project Leader (boldface) and Other Team Members	**Sashi Kunnath** (UCD/F), Jon Mohle (UCD/GS), Zhiyu Zong (UCD/GS)		

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

Project goals and objectives

This project will pursue the development, validation and calibration of phenomenological material models in the context of fiber-based nonlinear beam-column elements currently implemented in OpenSees. In particular, the project will focus on the development of a reinforcing steel material model that collectively incorporate the effects of observed phenomena such as bar buckling, cyclic degradation and low-cycle fatigue. A parallel objective is the implementation of damage modeling schemes for use in performance assessment of RC structures. While this effort will focus on material-based damage models, the overall development will facilitate the incorporation of a general class of damage measures for use in performance-based seismic assessment.

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 development of advanced material models will increase the reliability of fiber-based section models to better predict the inelastic response of reinforced concrete members. 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 in nature and will comprise the extension and refinement of existing constitutive models. The model development will include extensive 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 previous year's achievements, with emphasis on accomplishments during last year (Year 8)

A new material model that incorporates the effects of bar buckling and low-cycle fatigue is developed. To facilitate the development of the model, it was first necessary to develop a base material model to describe the primary cyclic stress-strain relationships of reinforcing steel. Features of the model include the following:

Monotonic Behavior: The monotonic tensile and compressive stress-strain curves are based on a model proposed by Chang and Mander (1994) with several modifications. Only the tension backbone curve is required to be input by the user. The curve is then transformed from engineering stress-strain space to natural stress-strain space (accounting for the instantaneous change in cross-section area as the bar is stressed). This transformed curve is used to generate both the tensile and compressive backbone curves. The stress-strain conversion follows the assumption that the steel volume remains constant as detailed by Dodd and Restrepo-Posada (1995).

Diminishing Yield Plateau: It has been observed that when a reinforcing bar is subjected to plastic strain reversals within the yield plateau, strain hardening will initiate at a lower strain than that of the same bar loaded monotonically. Additionally, isotropic hardening can result from repeated strain reversals and is commonly related to cumulative plastic strain. These two aspects of the stress-strain behavior of steel bars are somewhat related and that by shortening the yield plateau as a function of accumulated plastic strain, the model will have some capability to simulate both the diminishing yield plateau and isotropic hardening. The Chang and Mander model, on which this formulation is based, models only anisotropic hardening. By adding a component of isotropic hardening, the model has additional capabilities and is able to more accurately simulate test data.

Buckling Response: Two models have been implemented:
Modified Gomes-Appleton Buckling Model: Figure 1 describes the use of the buckling parameters modified from Gomes and Appleton (1997).
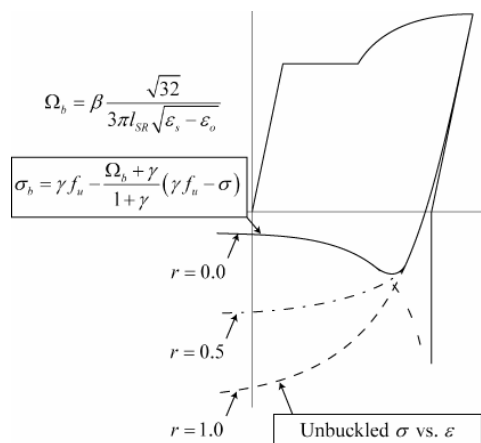

$$\Omega_b = \beta \frac{\sqrt{32}}{3\pi l_{SR} \sqrt{\varepsilon_s - \varepsilon_o}}$$

$$\sigma_b = \gamma f_u - \frac{\Omega_b + \gamma}{1 + \gamma}(\gamma f_u - \sigma)$$

$r = 0.0$

$r = 0.5$

$r = 1.0$

Unbuckled σ vs. ε

Figure 1- Modified Gomes-Appleton Buckling Model

β is an amplification factor that allows the user to scale the buckling curve. The *r* factor adjusts the curve between the buckled curve and the unbuckled curve. The γ factor is the positive stress location about which the buckling factor is initiated. This factor was introduced to avoid kinks in the reloading branch. γ should be between 0.0 and 1.0. The variable *r* can only be a real number between 0.0 and 1.0. Good results have been obtained using the following values for the buckling constants: β = 1.0; *r* = 0.4 and γ = 0.5; or β = 2.0; *r* = 0.0 and γ = 0.5.

Figure 2 displays the buckling behavior due to the variation of the different constants. The response shown on the upper left is the unbuckled case. In each of the other cases, buckling behavior is defined by the constants shown.
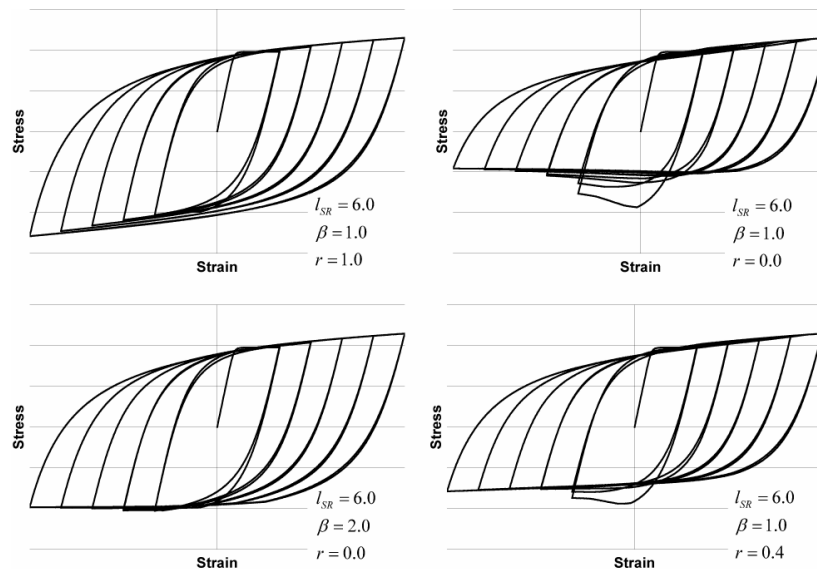

Figure 2- Effect of Sample Parameters in Gomes-Appleton Model

Dhakal-Maekawa Buckling Model: This response is based on model proposed by Dhakal and Maekawa (2002). This model takes two terms, lsr and α. lsr is the slenderness ratio and α is an amplification factor. Dhakal and Maekawa suggest a value of α =1.0 for linear strain hardening and α =0.75 for elastic perfectly plastic material behavior. The material model in this implementation is neither linear strain hardening nor elastic perfectly plastic. However, since the material model does include strain hardening α=1.0 has been assumed as the default value. Figure 3 describes the basic characteristics of the model.
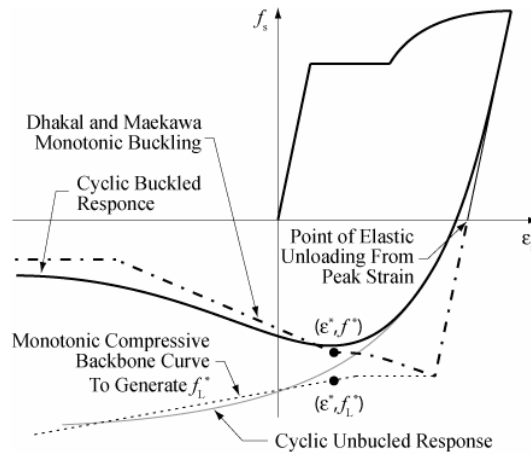
Figure 3- Dhakal-Maekawa Buckling Model

Cyclic Degradation: C_f and α are factors used to relate the number of half cycles to fracture to the half cycle plastic strain amplitude (Figure 4a). Plastic strain half cycle amplitude is defined by Equation 1. The total half cycle strain amplitude, ε_t, is shown in Figure 4b as the change in strain from reversal A to reversal B.
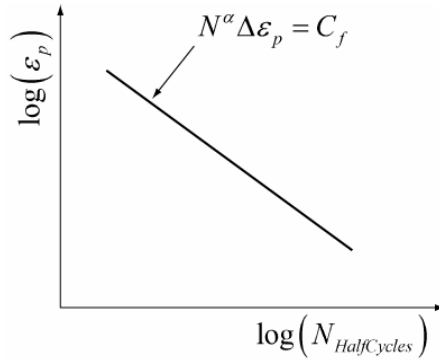

Figure 4a - Coffin-Manson Constants   *Figure 4b - Half Cycle Terms Defined*
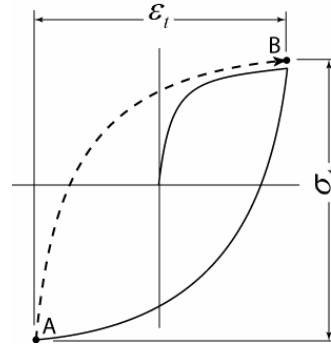
C_f and α are used to define a cumulative damage factor, D, as described in Equation 2.

$$\varepsilon_p = \varepsilon_t - \frac{\sigma_t}{E_s} \tag{1}$$

$$D = \sum \left(\frac{\Delta\varepsilon_p}{C_f} \right)^{\frac{1}{\alpha}} \tag{2}$$

The cumulative damage factor is zero at no damage and 1.0 at fracture. Once a bar has been determined to have fractured, the strength is rapidly degraded to zero.
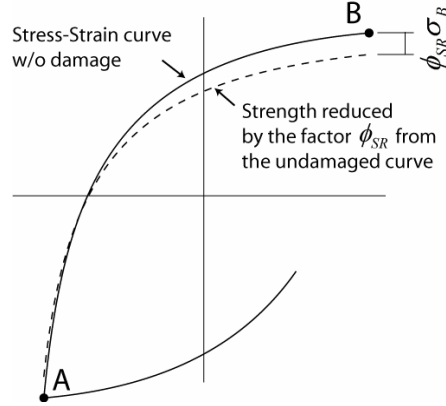
Figure 5 - Strength Reduction

A degrade constant, K_1, is used to describe loss in strength due to damage or other phenomenon resulting in softening due to plastic reversals. The degradation is currently assumed to have a simple linear relationship with D. This is used to correlate strength degradation to the cumulative damage factor. This linear relationship is shown in Equation 3.

$$\phi_{SR} = K_1 D \tag{3}$$

Alternately this simple linear equation can be rewritten in a way that makes the strength degradation independent of the number of half cycles to failure. Keeping the failure and degradation terms independent is convenient for calibration. Equation 3 is rewritten below utilizing the strength degradation constant C_d.

$$\phi_{SR} = \sum \left(\frac{\Delta\varepsilon_p}{C_d} \right)^{\frac{1}{\alpha}} \tag{4}$$

The constants K_1 and C_d can be related as shown in Equation 5.

$$C_d = \frac{C_f}{K_1^{\alpha}} \tag{5}$$

Suggested starting values have been obtained from data reported by Brown and Kunnath (2000) for bars with a slenderness of 6.0. Note that this experimental data is limited and additional calibration will be necessary to capture realistic behavior in a reinforcing bar embedded in concrete and influenced by other factors such as confinement. The initial suggested values are: α: 0.506; C_f: 0.26; C_d: 0.389

Sample Simulations of Degradation Behavior
The parameter α is best obtained from calibration of test results and is used to relate damage from one strain range to an equivalent damage at another strain range. This is usually constant for a material type. The parameter C_f is the ductility constant used to adjust the number of cycles to failure. A higher value for C_f translates to a larger number of cycles to failure. Finally, C_d is the strength reduction constant. A larger value for C_d will result in a lower reduction of strength for each cycle. The four charts shown in Figure 6 demonstrate the effect that some of the variables have on the cyclic response.
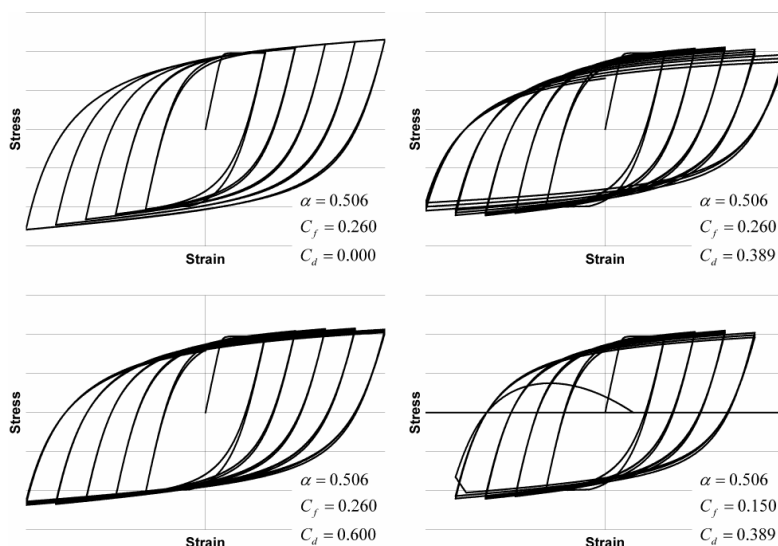
Figure 6: Fatigue and Degradation Parameter Examples

In Figure 6, the upper left response contains no strength degradation ($C_d = 0.0$). The upper right response shows strength degradation due to the suggested values of C_f, α, and C_d. The response shown on the lower left demonstrates the change in the response when the suggested values of C_f and α are used with $C_d=0.6$. An increase in the value of C_d results in less strength reduction. The response on the lower right uses the suggested values but C_f is changed to 0.15. This results in a more rapid damage accumulation causing the bar to fail sooner. Note however that the strength degradation is unaffected. The strength reduction and failure are not interdependent making the model easier to calibrate.

The above formulation has been implemented in OpenSees as a uniaxial material object. This object is intended to be used in a reinforced concrete fiber section as the steel reinforcing material. The following command is used to invoke the object and provides a significant level of control to enable the simulation of the cyclic behavior of reinforcing steel including buckling:

```
uniaxialMaterial ReinforcingSteel  $matTag $fy $fu $Es $Esh $esh $eult  < -GABuck $lsr $beta $r $gama >  < -
          DMBuck $lsr < $alpha >>   < -CMFatigue $Cf $alpha $Cd >  < -IsoHard <$a1 <$limit> >>
```

$matTag	unique material object integer tag
$fy	Yield stress in tension (see Figure 1)
$fu	Ultimate stress in tension
$Es	Initial elastic tangent
$Esh	Tangent at initial strain hardening
$esh	Strain corresponding to initial strain hardening
$eult	Strain at peak stress

-GABuck	**Buckling Model Based on Gomes and Appleton (1997)**	
	$lsr	Slenderness Ratio (see Figure 2)
	$beta	Amplification factor for the buckled stress strain curve. (see Figure 3)
	$r	Buckling reduction factor (0.0<r<1.0) r=1.0 full reduction (no buckling) r=0.0 no reduction 0.0<r<1.0 linear interpolation between buckled and unbuckled curves
	$gamma	Buckling constant (see Figures 3 and 4)
-DMBuck	**Buckling model based on Dhakal and Maekawa (2002)**	
	$lsr	Slenderness Ratio (see Figure 2)
	$alpha	Adjustment Constant usually between 0.75 and 1.0 (default = 1.0)
-CMFatigue	**Coffin-Manson Fatigue and Strength Reduction**	
	$Cf	Coffin-Manson constant C (see Figure 5)
	$alpha	Coffin-Manson constant α (see Figure 5)
	$Cd	Cyclic strength reduction constant (see Figure 6 and Equation 3)
-IsoHard	**Isotropic Hardening / Diminishing Yield Plateau**	
	$a1	Hardening constant (default = 4.3)
	$limit	Limit for the reduction of the yield plateau. % of original plateau length to remain (0.01 < limit < 1.0) (default =0.01)
-MPCurveParams	**Menegotto and Pinto Curve Parameters** $R = R_2 \left(1.0 - R_3 \varepsilon_t \right) \left(\varepsilon_y' \right)^{R_1}$ see Fig 6b	
	$R1	(default = 0.333)
	$R2	(default = 18)
	$R3	(default = 4)

References
1 Chang, G. and Mander, J. (1994). "Seismic Energy Based Fatigue Damage Analysis of Bridge Columns: Part I – Evaluation of Seismic Capacity." NCEER Technical Report 94-0006.
2 Dodd, L. and Restrepo-Posada, J. (1995). "Model for Predicting Cyclic Behavior of Reinforcing Steel" J. Struct. Eng., 121(3), 433-445.
3 Gomes, A., and Appleton, J. (1997). "Nonlinear Cyclic Stress-Strain Relationship of Reinforcing Bars Including Buckling." Eng. Struct., 19(10), 822–826.
4 Brown, J. and Kunnath, S.K. (2000). "Low Cycle Fatigue Behavior of Longitudinal Reinforcement in Reinforced Concrete Bridge Columns." NCEER Technical Report 00-0007.
5 Dhakal, R. and Maekawa, K. (2002). "Modeling for Postyield Buckled of Reinforcement" J. Struct. Eng., 128(9), 1139-1147.

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

Within PEER, work is ongoing at Univ. of Washington (PI: Eberhard) to develop empirical models from experimental data to characterize damage states in reinforced concrete columns; research is also underway at Washington (PIs: Stanton and Lehman) to characterize buckling in longitudinal bars. The work being carried out in this project is analytical and being conducted at the material scale using a phenomenological approach. Experimental data will provide a basis to validate the approach and the ensuing developments will enable verification of the empirical modeling.

Outside PEER, there have been experimental studies investigating buckling of reinforcing bars (U of Texas, Austin). Also, some studies investigating empirical damage models have appeared in the literature (numerous institutions). However, none of these efforts involve the combined effects of degradation, low-cycle fatigue and buckling and none of the reported work focus on improving fiber-based modeling of RC members.

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

n/a

Expected milestones & Deliverable

A beta version of the material model has already been implemented in OpenSees and is available for general use.

Other milestones for the remainder of the project duration include:
- Validation studies with experimental data (at component level as opposed to material level)
- Development of a new buckling model (overcoming limitations of empirical models) and implementation in OpenSees. (This task may need to be extended to Year 10).
- Technical paper documenting development
- PEER report documenting development, calibration and validation studies

Project Title—**ID Number**	*Abutment and Deep Foundation Modeling and Simulation -* **4242005**
Start/End Dates	10/1/05—9/30/06	**Funding Source**	PEER/CA Transp. Fund
Project Leader (boldface) and Other Team Members	**Ahmed Elgamal** (UCSD/F), Jinchi Lu (GS), Liangcai He (GS), Linjun Yan (GS)

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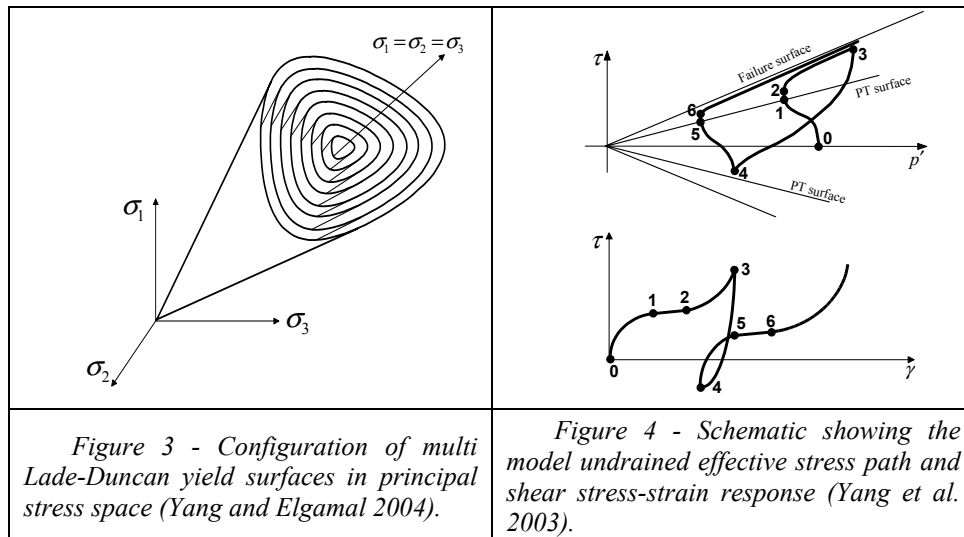
Project goals and objectives

With a focus on ground-foundation-structure simulation efforts, develop and provide computational modeling capabilities for Abutment and Deep Foundations. Developments within the PEER OpenSees Platform are a main goal.

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

(1) Development of Geotechnical and Soil-Structure Interaction Capabilities within the PEER OpenSees Simulation Platform, (2) Utilization of OpenSees for Large-Scale Simulation of Seismic Response of Ground-Structure Systems, and (3) Contributions towards the PEER Performance-Based Earthquake Engineering (PBEE) Simulation capabilities.

Methodology employed

(1) Continued development of geomechanics seismic response constitutive models (e.g., Figs. 1 and 2) and soil 2D and 3D elements within the OpenSees simulation Platform, (2) Numerical implementation of the related algorithms within the OpenSees main code, (3) Preparation of documentation for the implemented elements and constitutive models with demonstrative examples (currently available through the OpenSees website http://opensees.berkeley.edu under Developer pages, University of California, San Diego, and (4) Development of user-interfaces for utilization of OpenSees in analyses in large-scale soil-structure interaction simulations.

Figure 3 - Configuration of multi Lade-Duncan yield surfaces in principal stress space (Yang and Elgamal 2004).	*Figure 4 - Schematic showing the model undrained effective stress path and shear stress-strain response (Yang et al. 2003).*

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

(1) Effort towards 3D modeling of the PEER Humboldt Bay Bridge has been completed and Journal publications have been submitted.

(2) Large-scale modeling of pile supported structures under seismic excitation is underway, and (3) Calibration using data from the PEER/NSF supported US-Japan shake-table experiments (Table 1 and Fig. 2) has been undertaken, numerical simulations have been conducted (Figure 3), and design-oriented guidelines have been proposed.

			5.0	31.8	0.3	7360	8500

Table 1- Summary of soil profiles and pile foundations in shake table experiments

Test	Soil profile		Pile Properties				
	Height (m)	Water table	Embedded length (m)	Diameter (cm)	Wall thickness (cm)	Bending stiffness EI (kN·m^2)	Base fixity[*] (kN·m/rad)
UCSD1	1.89	Covers the entire soil layer	1.70	25.0	0.625	120	110
UCSD2	1.75		1.56	25.0	0.625	2600	200
UCSD3	1.71		1.52	25.0	0.625	2600	200
Japan1	5.5	At downslope ground surface	5.5	31.8	0.6	14320	18500
Japan2	5.5	1.0 m below ground surface	5.5	31.8	0.6	14320	18500
Japan3	5	1.0 m below ground surface	5.0	31.8	0.6	14320	18500
			5.0	31.8	0.3	7360	8500
Japan4	5	Covers the entire soil layer	5.0	31.8	0.6	14320	18500

Pile base fixity condition is characterized by a rotational spring with constant stiffness shown in this column
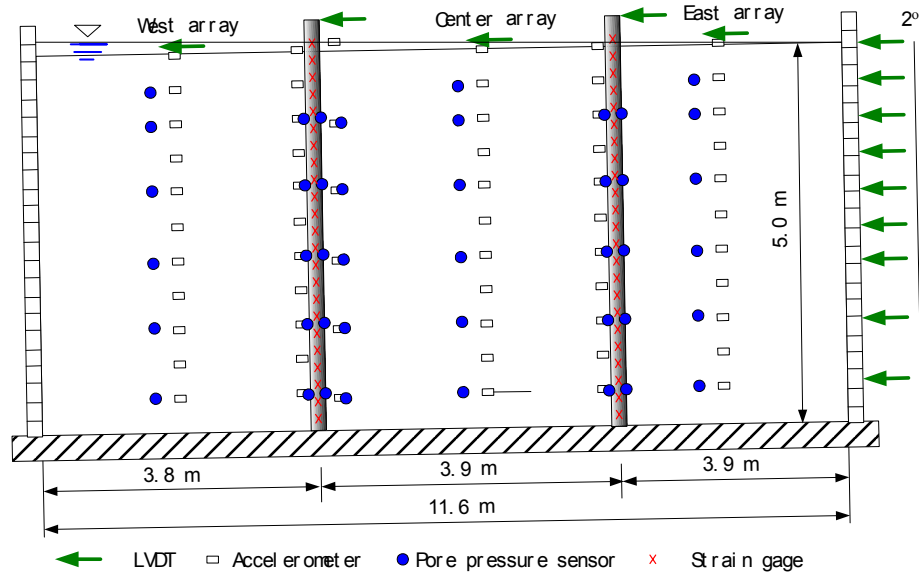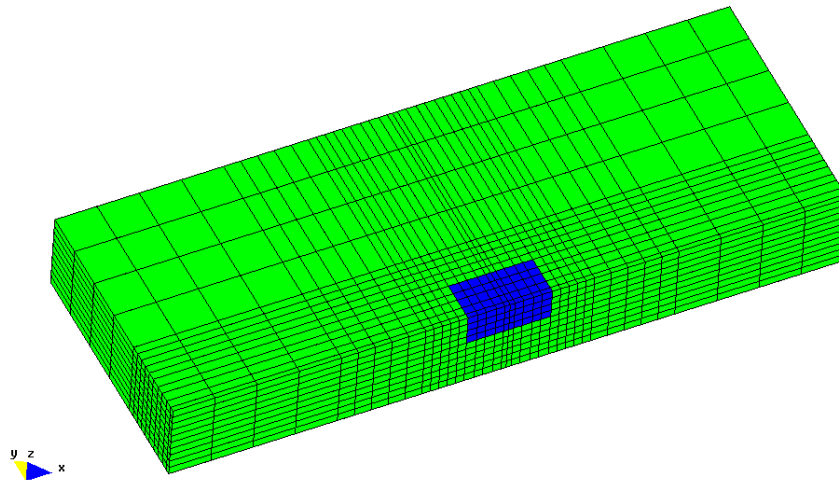
Figure 2 - Japan4 test setup.

Figure 3 - Finite element mesh of a shallow foundation model (dark zone shows the remediated area as a liquefaction countermeasure).

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

The project complements the numerical simulation efforts related to seismic response of ground-foundation-structure systems, within and outside PEER. It differs in terms of the current focus on large-scale 3-dimensional (3D) modeling efforts utilizing the PEER simulation Platform OpenSees, and the efforts towards modeling of lateral spreading effects on foundation systems and the supported superstructure.

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

Discussions are underway with Earth Mechanics, Inc. to collaborate on numerical simulation using OpenSees for the important situation of seismic response of Port facilities (Pile supported Wharfs), and employment of OpenSees to provide further capabilities compared to other available tools in practice, such as the computer program FLAC.

Expected milestones & Deliverable

(1) Journal and conference publications focused on large-scale 3D seismic response of soil-structure systems, (2) Continued developments within the OpenSees framework in collaboration with other PEER researchers within the geomechanics and structural domains of research.

Project Title—**ID Number**	*Simulation of Structural Collapse* - **4252005**		
Start/End Dates	10/1/05—9/30/06	Funding Source	PEER-CA State General Fund
Project Leader (boldface) and Other Team Members	**Khalid M. Mosalam** (UCB/F), 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 RC 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 will 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 will lead to proper design of new RC framed structures against the undesired limit state of collapse

Methodology employed

- Identification of generic systems representative of old non-ductile construction, and retrofitted construction.
- Implementation, validation, and calibration of novel material models enhanced to capture the degrading behavior of components at extreme events (lap-splice failure, bar buckling, concrete crushing, loss of lateral confinement) and predict component collapse.
- 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, accounting for the asymmetry in the behavior of shear-damaged columns, and criteria to trigger the removal of failed columns.
- Implementation of a robust element elimination technique(s).

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

- This project is a continuation of a year 8 project. The following accomplished tasks derive from those previously identified:
- Development of an analytical model for the full cyclic response of uniaxial concrete fibers under the effect of passive lateral confining stresses and hysteretic strength degradation (Figure 5).
- Development of an analytical model for the distribution of confining stresses within the cross-section of a concrete member confined by transverse steel or external FRP wraps (Figure).
- Combining the confined uniaxial material and confinement distribution models into a fiber-discretized cross-section model capable of tracking the deformation and failure in

the confining medium through enforcing compatibility between its circumferential strains and the lateral strains in concrete.

- OpenSees implementation (Figure) of the developed models into a computational tool for analyzing the axial-bending response of fiber-discretized confined concrete sections.
- Experimental verification of the newly developed models by numerically simulating the experimentally-observed response of laterally-loaded RC columns. These included an experimental program (conducted with the participation of the PI) on monotonically-loaded columns using conventional and FRP confined columns (Figure , Figure), in addition to experiments on cyclically-loaded columns using FRP confinement obtained from the literature (Figure 10).
- Adaptation and verification of a confining stress-dependant analytical model for lap-splice failure; for implementation and use within the framework of the confined fiber section tool.

Enhancement of an analytical model for longitudinal reinforcement buckling, for implementation within the framework of the confined fiber section computational tool. The model relies on assessing the stiffness of the confining medium to accurately compute the critical buckling stress and length of individual reinforcing bars.

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 proposed research. We are closely collaborating with the researchers of this project and are making use of pervious study documented in the following PhD dissertation. The main difference is that the focus in our project is on implementation and numerical robustness, besides to 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.

Shear-Flexural-Axial Interaction Models —4082004 (PI: Filippou) and **Advanced Models for Cyclic Degradation of RC Members Including Low-Cycle Fatigue —4062004 (PI: Kunnath)**
We intend to interact with the researchers of these two projects to make full use of their development in relevant areas to our objectives.

Dynamic Gravity Load Collapse Experiments of Low-Confinement RC Columns – National Science Council, Taiwan NSC92-2811-E-002-023 (PI: Wu)
This project is an ongoing research program to establish experimental data on the system interaction due to shear-axial collapse of columns. A direct use of the specimen and findings from this program will be used for validation of the shear-axial interaction model and the element removal algorithm. Documentation and information on this project is available online at:

http://myweb.caece.net/yuansen/publications/aese2005/T087.PDF

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

Expected milestones & Deliverable

Implemented classes and algorithms into OpenSees that enable the simulation of progressive collapse in RC framed structures.
Manual to use newly-developed capabilities.
Illustrative verification examples.

(a) Section   (b) Strain Profile (c) Confining Stress

Figure 5 Section lateral stress distribution model

Specimen 1   Specimen 2   Specimen 3   Specimen 4

Figure 6   Failed specimens from experimental validation program

Figure 7 Hysteretic confined concrete material model

Figure 8 (a) Measured and (b) simulated moment-curvature response

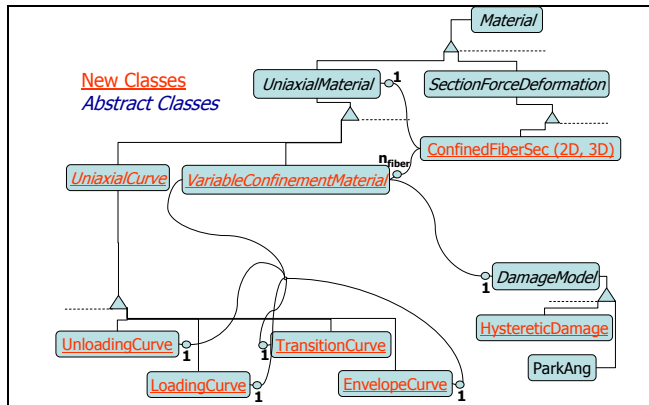*Figure 9 OpenSees partial class map for new components*

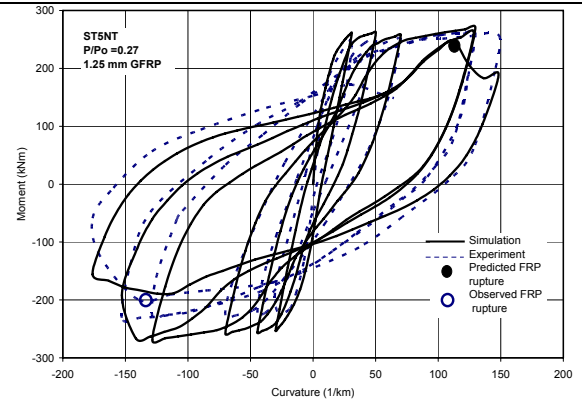*Figure 10 Measured and simulated cyclic moment-curvature response*

Project Title—ID Number	Geomechanics Simulations Tools for PBEE - 4262005		
Start/End Dates	10/1/05—9/30/06	Funding Source	PEER-CA State Transp. Fund
Project Leader (boldface) and Other Team Members	**Boris Jeremic** (UCD/F), Zhao Cheng (UCD/GS), Ian Tucker (UCD/US)		

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

Project goals and objectives

The main goal if this project is to provide a number of simulations tools for use in Performance Based Earthquake Engineering. Of particular interest are tools for modeling and simulations of soil-foundation-structure interaction (SFSI). Among the developed tools so far are the ones used for:

- Elastic plastic modeling of soils (through template elastic plastic methodology)
- Seismic motions input (through the domain reduction method)
- Parallel computational methodology for large scale geotechnical and structural models
- Fully coupled (porous solid – fluid) methodology for modeling of saturated soils, cyclic mobility and liquefaction.

Current project is focusing on issues related to SFSI in saturated soils.

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

This project supports PEER's mission by providing verified and validated simulation tools that can be used for detailed, high fidelity simulations of behavior of constructed facilities during earthquakes.

Methodology employed

Methodology employed for this particular focus area (behavior of fully coupled soils in SFSI problems) is based on u-p-U formulation that uses displacements of solid phase (u), pore fluid pressures (p) and displacements of fluid phase (U) as main unknowns. This approach allows for simulations of a very general set of coupled problems as found in SFSI modeling.

Brief Description of previous year's achievements, with emphasis on accomplishments during last year (Year 8)

During the previous year we have successfully verified our implementation on a number of developed closed form solutions. We have also started the implementation of the latest version of Dafalias Manzari material model that is currently used for validation study.
For example, figures below show stresses and pore water pressures for a vertical soil profile, make of liquefiable Toyura sand, with a seismic wave propagating vertically. The results are plotted at each meter, and it is obvious that the top three layers experience cyclic mobility, which becomes liquefaction for top two layers.
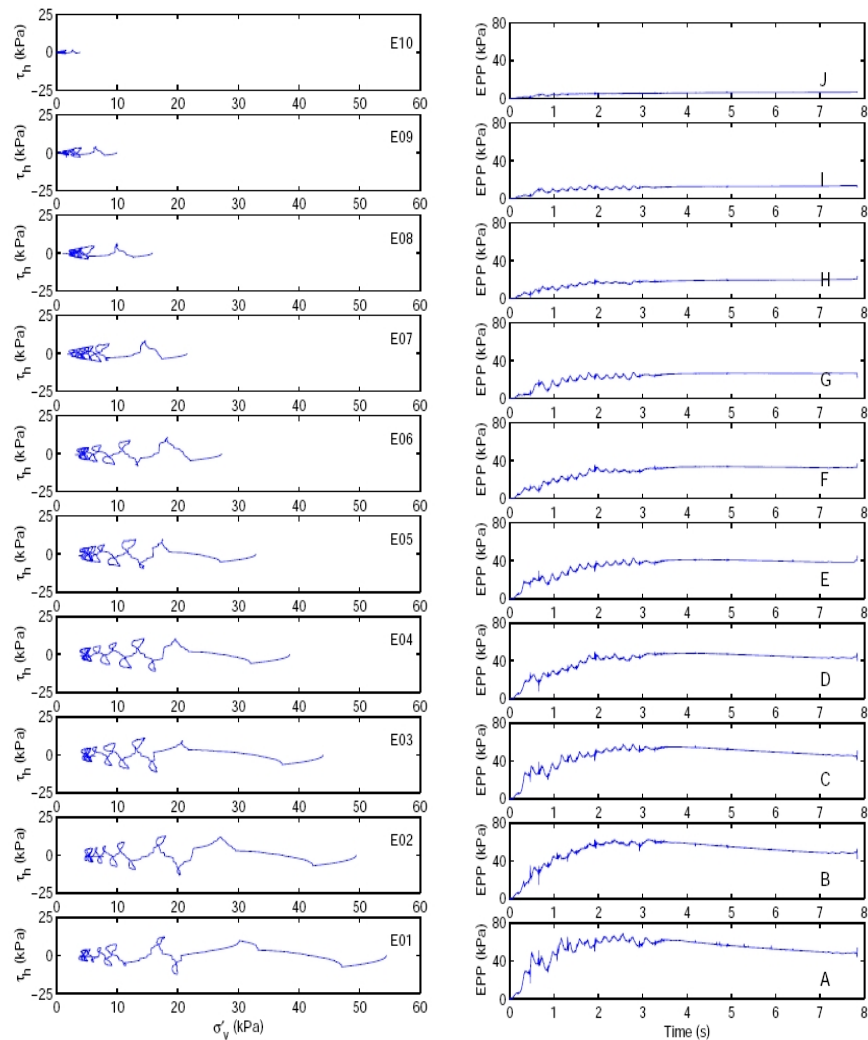
Figure 1 - Wave propagation through a soil profile made of Toyura send, left: shear versus normal stress and excess pore water pressures, all plotted at one meter increments, from surface (top) to 10m depth (bottom).

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

Similar work has been done by the UCSD group, which has developed the u-p formulation for saturated soils. Our formulation and implementation is different in that it is more general, and allows us to simulate problems where the acceleration of pore fluid plays a role in response. This is the case, for example, in analyzing SFSI where stiff piles interact with soft (liquefied) soils and pore fluid is experiencing significant accelerations.

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

We are aware of Caltrans engineers inquiring about (and possibly using) our developments. In addition to that, we are also aware that some companies (like Earth Mechanics) are showing interest and might be using (or are getting ready) to use our developments.

Expected milestones & Deliverable

We expect to have a fully validated set of models by late this summer. In parallel, we are developing models for SFSI in liquefied soils that we will be analyzing this coming fall and winter.

Project Title—ID Number	RC Frame Validation Tests - **4282005**		
Start/End Dates	10/1/05—9/30/06	Funding Source	PEER-CA State General Fund
Project Leader (boldface) and Other Team Members	**Jack Moehle** (UCB/F), Wassim Ghannoum (UCB/G), Yoon Bong Shin (UCB/G), Matt Lackows (UCB/U), Lauren Kuntz (UCB/U), Kyle Chatman (UCB/U), Indra Wijaya Wong (UCB/U), Zhongjie Chen (UCB/U), Gletwin Shanahan (UCB/U), Rose Li (UCB/U)		

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 previous year's achievements, with emphasis on accomplishments during last year (Year 8)

Column collapse in three-story frame test

This past year we completed shaking table tests to collapse on twelve one-story, one-bay frames and one three-story, three-bay frame. The one-story frame specimens comprised various combinations of ductile and nonductile concrete columns with varied axial loads and either long-duration ground motion or short-duration impulsive motion. Behavior generally was consistent with models for shear and axial failure developed in earlier phases of this research, an also was consistent with pre-test dynamic simulations. The three-story frame was subjected to the long-duration ground motion. The indeterminate framing apparently enabled redistribution of internal forces following initial failures, such that collapse of the frame system was delayed beyond initial expectations.

Continuing work on these projects will study the following:
- Load-deformation characteristics of shear-critical columns subjected to loadings resulting in shear and axial failures.
- Computational procedures for response simulation of strength-degrading systems.
- Parameter studies to identify sensitivity of results to variations in ground motions and component properties.

- Extrapolation of results using simulation tools to understand implications for seismic assessment of existing buildings.

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 Years 9 and 10. 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.

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. The results were presented in the EERI/PEER seminar in January and February 2006, as well as the 2006 Earthquake Conference, where they reached nearly 400 engineers. Results have been incorporated by reference into the ASCE-41 guidelines for seismic rehabilitation of existing buildings.

Expected milestones & Deliverable

Complete analyses of test results and write final report.

Member company Benefits

Useable data and models for assessment of existing buildings, as well as invitations to view tests.