Pacific Earthquake Engineering Research Center

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

Core Institutions

University of California, Berkeley ***(Lead Institution)***

California Institute of Technology

Stanford University

University of California, Davis

University of California, Irvine

University of California, Los Angeles

University of California, San Diego

University of Southern California

University of Washington

First Chapter of the Final Report 2007

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THE PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER – A TEN-YEAR PERSPECTIVE

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1.1 The Pacific Earthquake Engineering Research Center

The Pacific Earthquake Engineering Research Center (PEER) was established as a consortium of nine West Coast Universities in 1996 and gained status as a National Science Foundation Engineering Research Center in 1997. In addition to its nine Core Universities, PEER currently involves six Education Affiliates and 20 Business and Industry Partners (See Table 1.1). PEER operates a range of programs with principal funding from the US National Science Foundation, the State of California, and other government and industry partners.

Table 1.1 PEER Core Institutions, Educational Affiliates, and Business/Industry Partners

Core Institutions	Educational Affiliates
University of California, Berkeley - *Lead Institution*	California Polytechnic State University, San Luis Obispo
California Institute of Technology	California State University, Los Angeles
Stanford University	California State University, Northridge
University of California, Davis	Oregon State University
University of California, Irvine	San Jose State University
University of California, Los Angeles	University of Hawaii
University of California, San Diego	
University of Southern California	
University of Washington	
Business & Industry Partners	
AIR Worldwide	Fugro
Bechtel Corporation	Geomatrix Consultants, Inc.
BL Schmidt Consulting Structural Engineering	John A. Martin & Associates, Inc.
CDComartin	Kleinfelder, Inc.
Certus Consulting, Inc.	Miyamoto International
Degenkolb Engineers	Risk Management Solutions, Inc.
Earth Mechanics	Rutherford & Chekene
EQECat, Inc.	Simpson Gumpertz & Heger, Inc.
FM Global	URS Corporation
Forell/Elsesser Engineering	Wiss, Janney, Elstner Associates, Inc.

PEER has a mission to develop and disseminate performance-based earthquake engineering technology for design and evaluation of buildings, lifelines, and infrastructure to meet the diverse seismic performance objectives of individual stakeholders and society. PEER achieves its mission through research, education, and technology transfer programs aimed at cost-effective reduction of earthquake losses, with emphasis in the following areas:

- Definition of seismic hazard for engineering design applications;
- Engineering tools for the seismic assessment and design of constructed facilities, with emphasis on geotechnical structures, buildings, bridges, and lifelines;
- Design criteria to ensure safe and efficient performance of constructed facilities;

- Methodologies including engineering and public policy instruments for mitigating seismic hazards in existing buildings;
- Performance-based approaches for design and evaluation of constructed facilities to provide appropriate levels of safety for occupants, and protection of economic and functional objectives for essential facilities and operations.

PEER has entered its tenth year as a NSF Engineering Research Center and, as planned at the outset, is graduating from NSF funding at the end of September 2007. PEER will continue as an active earthquake engineering research center with wide spectrum of technical activities, supported by federal, state and regional agencies together with industry partners. This report documents the primary accomplishments of PEER in the past ten years, its current activities, and its plans for the future.

1.2 PEER's Vision for Performance-Based Earthquake Engineering

The PEER mission is to develop and disseminate procedures and supporting tools and data for 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. The approach has gained worldwide attention in the past decade with the realization that earthquakes in developed countries impose substantial economic and societal risks above and beyond potential loss of life and injuries. By providing quantitative tools for characterizing and managing these risks, performance-based earthquake engineering serves to address diverse economic and safety needs.

There are three levels of decision-making that are served by enhanced technologies for performance-based earthquake engineering and that have been focal points for PEER research. *One level* is that of owners or investors in individual facilities (e.g., a building, a bridge) who face decisions about risk management as influenced by the seismic integrity of a facility. PEER has developed a rigorous PBEE methodology to support informed decision-making about seismic design, retrofit, and financial management for individual facilities. *A second level* is that of owners, investors, or managers of a portfolio of buildings or facilities – a university or corporate campus, a highway transportation department, or a lifeline organization – for which decisions concern not only individual structures but also priorities among elements of that portfolio. PEER's work shows how to use the rigorous PBEE methodology to support informed decision-making about setting priorities for seismic improvements within such systems by making clear the tradeoffs among improved performance of elements of the system. *A third level* of decision-making is concerned with the societal impacts and regulatory choices relating to minimum performance standards for public and private facilities. PEER's products are being used to support the performance-based development of codes and standards, as well as the performance-based acceptance of specific facilities designed outside the prescriptive provisions of current codes. The direct beneficiaries of more rigorous approaches to performance-based earthquake engineering are the owners, investors, and risk managers who face these decisions. All of us, of course, ultimately benefit from decisions about seismic risk that better address tradeoffs between the costs of reducing risks and the benefits resulting from seismic improvements.

The clients for PBEE technologies are members of the engineering profession as broadly defined, entities with responsibility or interests in facility performance, and society at large.

Performance-based earthquake engineering is bringing about a change in the profession that alters both the role of earthquake engineers (broadening their involvement as consultants for management of earthquake risks) and the demands placed on the profession (changing the methods of risk evaluation, design, and engineering). PEER has worked hand-in-hand with business and industry partners to understand how advances in PBEE affect engineering practice and the construction regulatory environment, and to identify ways to lessen barriers to adoption and implementation of PBEE. In addition, PEER is very active in educating future generations of earthquake engineers and risk management professionals. As such, PEER has made a major contribution to the development of the earthquake engineering profession.

Despite advances in the use of performance-based earthquake engineering in practice in the past decade, prevalent technologies and methods for PBEE have fallen short in several ways. Although soil and structure responses to strong ground motions in most cases are expected to be nonlinear, earthquake hazard commonly has been represented by relatively simplistic single-parameter quantities such as linear spectral response. Likewise, structural evaluation and design commonly use linear analysis adjusted by factors whose values are based on tradition and limited earthquake experience rather than systematic performance considerations. Furthermore, engineering design and assessment in widespread use generally focus on engineering parameters and stop short of identifying performance measures or quantifying socio-economic parameters such as direct financial losses, downtime, and casualties. The result of this indirect and empirical approach is that seismic performance outcomes, as demonstrated in past earthquakes, are highly variable and often at odds with stakeholder expectations.

Seismic design in a complex and technologically advanced society should be more rational and scientifically based. It should provide information on expected seismic performance, measurable in terms that are meaningful to those who must make decisions about performance of facilities,

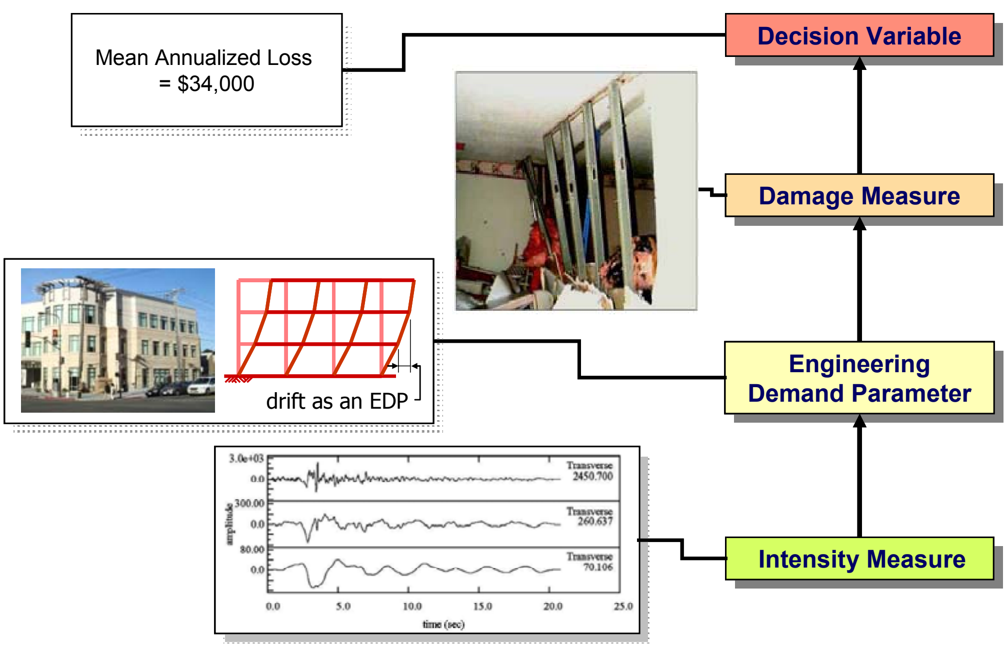

Figure 1.1 – Performance-based earthquake engineering framework. PEER is conducting research on the overall framework (right) and individual elements (left). In this example, building repair costs including structural, nonstructural, and contents losses are presented as a mean annual loss.

networks or campuses, or the built environment in a broad context. And it should provide options for selecting optimal seismic performance to meet the diverse needs of owners and society.

To meet this objective, PEER has developed a framework for performance-based earthquake engineering that integrates a series of distinct and logically related parts of the problem (Figure 1.1). The first part is definition of the seismic hazard, which we have represented by the term *intensity measure*. The second part is determination of *engineering demand parameters* (e.g., deformations, velocities, accelerations) given the seismic input. This leads naturally to definition of *damage measures* such as permanent deformation, toppling of equipment, or cracking or spalling of material in structural components and architectural finishes. Finally, these damage measures lead to quantification of decision variables that relate to casualties, cost, and downtime.

An essential component of PEER's success in developing performance-based earthquake engineering has been the integration of issues across disciplinary boundaries, as illustrated qualitatively in Figure 1.2. The central column of the figure suggests various steps that might be involved in a performance assessment of a system for a scenario earthquake. The left side of the figure shows discrete variables that PEER has defined as part of its framework for performance-based earthquake engineering (Figure 1.1). The right side of the figure identifies the traditional disciplinary contributions to the problem. Clearly, the solution of the earthquake problem is a multi-disciplinary endeavor.

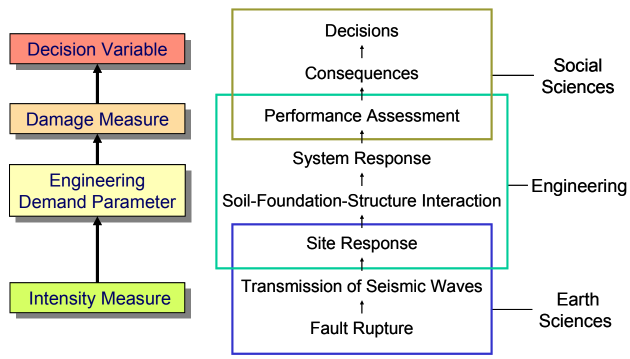

Figure 1.2 – Multi-disciplinary integration in performance-based earthquake engineering. Steps in performance-based earthquake engineering shown center, PEER's framework variables shown left, and traditional disciplines shown right.

PEER's programs in research, education, industry partnerships, and outreach have been geared to producing the technology and human resources necessary to transition from current design and assessment methods to performance-based methods. A primary goal has been to produce and test through research the fundamental information and enabling technologies required for performance-based earthquake engineering. The Education Program has promoted earthquake engineering awareness in the general public, and attracted and trained undergraduate and graduate students to conduct research and to implement research findings developed in the PEER program. The Business and Industry Partner Program has involved earthquake professionals, relevant industry, and earthquake information users in PEER activities to ensure the utility of the research and to speed its implementation. The Outreach Program has presented PEER's activities and products to a broad audience including students, researchers, industry, and the general public.

A key objective of the PEER program has been to facilitate the development of practical guidelines and code provisions that formalize performance-based earthquake engineering in practice, replacing some of the first-generation documents on this approach [e.g., FEMA 273, ATC 32, FEMA 354]. PEER continues to work closely with other organizations, including the Applied Technology Council and the Federal Emergency Management Agency on the ATC 58 project, *Development of Next-Generation Performance-Based Seismic Design Procedures for New and Existing Buildings*, where PEER's methodology and basic tools are forming the basis for this FEMA-funded project. Additionally, PEER continues to produce models and data that are useful, useable, and used in industry. The process is aided by the involvement of practicing earthquake professionals in our program, who help guide and incorporate our research advances as they occur. As a result, the PEER program is an important contributor to national, state, and local efforts to reduce earthquake risks that threaten the interests of government, industry, and the general public.

1.3 Program Implementation

PEER implemented its vision for performance-based earthquake engineering through three primary programs: ***Research***, ***Education***, and ***Technology Transfer***. Each of these programs evolved over time, in part because of experiences gained and lessons learned, in part because increasing maturity of the program required transitions to different focus and organization. Key elements of these programs, including their transitions, are described below.

1.3.1 Research Program

PEER's research was guided by its overall mission, developed in Year 2, and retained throughout, as stated below:

> *The PEER mission is to develop, validate, and disseminate performance-based seismic design technologies for facilities and infrastructure to meet the diverse economic and safety needs of owners and society.*

To achieve this mission, PEER worked with its Implementation Advisory Board, a group of key industry and government partners, to identify industry needs as well as the products that would be required to meet these needs. The PEER Research Committee then identified specific tasks that needed to be accomplished and assigned work to qualified researchers. This process was an evolution from the inaugural year, in which PEER issued a general request for proposals to the faculty of its core and affiliated universities (Figure 1.3).

A key element to planning the program was development and continual reassessment of the strategic plan. In addition to striving to meet the needs of PEER's stakeholders according to a schedule, the plan achieved a balance among research producing fundamental knowledge, research developing enabling technologies and tools, and research in which the performance-based methodology was tested in proof-of-concept test beds. These test beds eventually evolved to benchmarking studies in which the implications of PEER's performance-based methodology were investigated for specific types of constructed facilities.

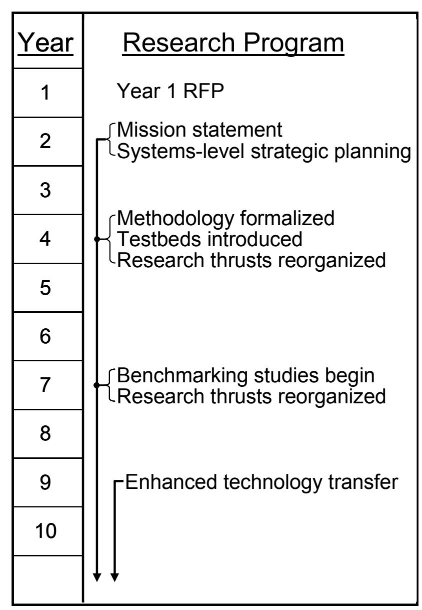

Figure 1.3 –Evolution of the Research Program

Another key element in the research program implementation was evolution of the research thrust areas. In PEER's early years, the research thrusts were organized along disciplinary lines. This organization was a convenient starting point for individuals with similar knowledge base and research culture to work together. Toward PEER's middle years, as the performance-based earthquake engineering methodology was taking form, the research thrust areas were realigned around elements of the methodology, which forced co-mingling of different disciplines. This process was carried further in the past few years by realigning the thrust areas yet again, this time organized around specific constructed facility types so that products could be better directed to the different industries associated with those facility types. In the process, a multidisciplinary research effort became truly interdisciplinary, with different disciplines working together in support of a common goal.

1.3.2 Education Program

PEER's Education Program was designed to introduce and educate undergraduate and graduate students in the broad subject of performance-based earthquake engineering, with programs designed to stimulate interest and cultivate participatory and leadership skills that will foster their future engagement in earthquake engineering practice, education, and research. The program generally aimed to attract students to earthquake engineering early in their academic careers and aimed to retain them through graduate study and beyond. While the principal audience of the Education Program was undergraduate and graduate students, K–12 students also benefited directly. As with the Research Program, the Education Program evolved over time (Figure 1.4).

The PEER Center involves nine Core Universities and six Education Affiliate Universities, distributed over a broad geographic region. Creating and maintaining an esprit d' corps among the scattered student groups was a challenge. Three mechanisms contributed to PEER's success in this regard. First, PEER established an Education Committee comprising representatives from all Core and Educational Affiliate Universities, supported by an enthusiastic and strong Education Director (from the Professorial ranks) with excellent support staff. Second, PEER established a Student Leadership Council (SLC), with active membership at all the schools, which became an increasingly important partner in program implementation. Finally, the Education Program components generally aimed to bring students together at frequent intervals.

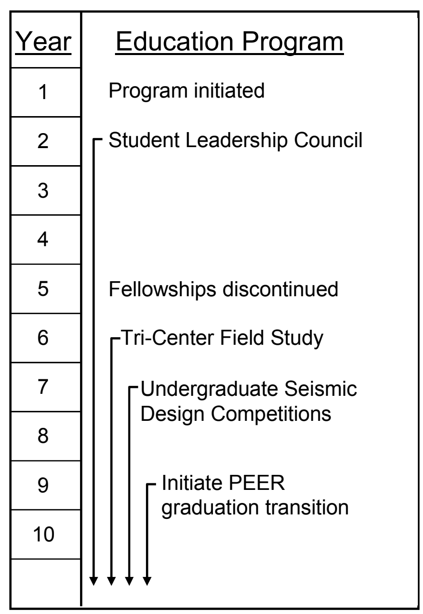

Figure 1.4 –Evolution of the Education Program

PEER has been proactive in increasing the diversity of students in earthquake engineering, generally by ensuring that our programs are highly visible within institutions that traditionally have high populations of underrepresented students and by targeting some programs. In PEER's first years, a fellowship program provided financial support to several students from underrepresented groups; this program was discontinued over concerns about its legality relative to

California law. In later years, PEER added "overcoming adversity" in addition to "academic preparation" as a criterion for PEER Summer and REU Internships. Finally, PEER reorganized its Education Affiliates Universities to target six schools with traditionally large populations of underrepresented students. These and other efforts have increased the diversity of our applicant pool for the PEER Education Program.

PEER is seeking various mechanisms to graduate its Education Program after Year 10. One mechanism is through alternative sources of external funding. Another is by transitioning some programs to become part of other organizations, where they can be maintained into the future. Additional details on this transition are provided elsewhere.

1.3.3 Technology Transfer Program

Technology transfer is achieved through a variety of mechanisms, some planned and some that were unforeseen opportunities that PEER adapted to along the way. Active participation of a supportive Implementation Advisory Board involving key business, industry, and government partners ensured that PEER was aware of stakeholder needs, and provided many excellent ideas for research topics, several of which turned out to be defining elements of the PEER program.

PEER initiated a user-driven research program early in its life. Initially, this program operated separately from the core research program funded by NSF and the state matching funds. Known as the Lifelines Program because its primary interest in lifelines systems, this program brought significant funds from the State government and industry sources for research on short-to-intermediate-term needs of the industry participants. A joint management committee comprising PEER and representatives of the funding agencies managed the program. This led to immediate technology transfer back to the industry and government sponsors, as well as others who participated in frequent workshops.

PEER also established a Business and Industry Program (BIP) that engaged industry partners in research and education programs. As with the Lifelines Program, BIP involvement helped focus PEER research and provided an easy mechanism for technology transfer. Student programs also benefited from BIP involvement.

Part of PEER's technology transfer plan has been to work with related professional activities ongoing outside PEER. These have included FEMA-funded projects at the Applied Technology Council and of the Structural Engineers Association of California. PEER has also actively engaged in focused discussions with groups, such as the Inter-jurisdictional Regulatory Collaboration Committee, to explore how performance-based earthquake engineering approach is synergistic with risk-based public policy and regulations. Through these activities, the PEER performance-based earthquake engineering approach has established the technical basis for nationally and internationally recognized standards in performance-based engineering.

PEER also has maintained an active outreach program, increasing in later years as products increased and matured. These have included topical workshops and seminars related to PEER's research; Internet resources including databases of key contacts and prospects; a newly designed website that clarifies PEER's mission and enhances the usability of its products and research tools; various printed resources that reinforce PEER's mission; and news coverage in relevant trade publications of professional organizations.

1.4 Program Impacts

PEER's impacts on engineering science, technology, and practice can broadly be distinguished among (1) establishing a comprehensive methodology framework for PBEE (performance-based earthquake engineering), (2) development and validation of tools, such as building performance simulation models, to enable the implementation of performance-based methods, (3) fundamental advancements in knowledge to characterize the seismic performance of buildings, bridges, and lifeline systems and ways to inform risk management decision making, (4) implementation of performance-based approaches and tools in engineering practice, and (5) creating an academic culture of multi-disciplinary collaboration that has impacted education and research. These five subcategories are outlined separately in the text that follows.

1.4.1 Methodology Framework for PBEE

The first generation of PBEE approaches, such as the FEMA 273 "NEHRP Guidelines for the Seismic Rehabilitation of Buildings" (1997), were major advancements that specified procedures to apply nonlinear analysis concepts to evaluate the response of buildings subjected to earthquakes. Notwithstanding the advancements that they provided, the first-generation procedures were limited in several respects. In particular, the methods were limited to deterministic measures of localized structural component response, from which performance limit states of the overall building were estimated. As illustrated in Figure 1.5, PEER's PBEE methodology builds upon the first-generation concepts to quantify more explicit measures of performance, which relate to the risk of financial losses, human casualties, and downtime of the facility. The methodology framework is generally applicable, and has been demonstrated for buildings and bridges.

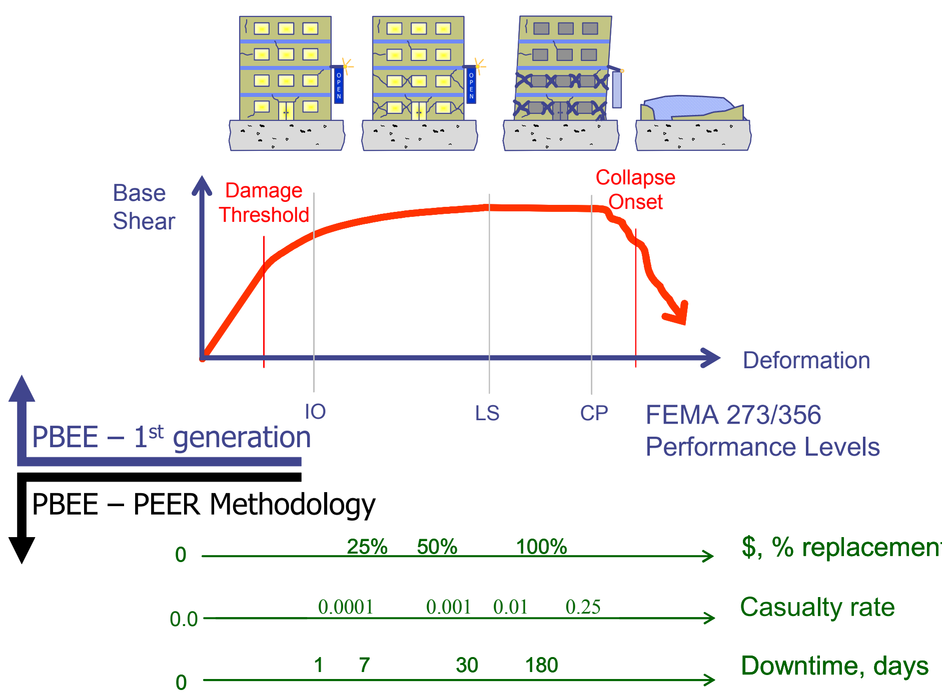

Figure 1.5 - First and second generation of PBEE methodology

A few of key improvements offered by the PEER methodology are summarized in the following text.

Nonlinear Response Simulation: Whereas first-generation PBEE methods relied on either dynamic linear analysis or nonlinear static analysis, the PEER methodology establishes a rigorous basis to use nonlinear dynamic analyses to simulate structural response from low-response levels up to the point of incipient collapse. Two key new contributions of this approach are to establish criteria for (a) characterizing ground motions, including the site-specific intensity of the earthquake hazard and the selection/scaling of input ground motions, (b) modeling strength and stiffness degradation, including loss of vertical load carrying capacity.

- *Modeling and Propagation of Uncertainties:* Underlying the PEER methodology is a rigorous probabilistic basis that accounts for inherent uncertainties in all aspects of the performance assessment, including uncertainties in (a) the earthquake shaking hazard and site effects, (b) input ground motions, (c) structural modeling parameters, (d) component damage functions, and (e) loss functions.
- *Explicit Damage Measures:* Whereas first-generation PBEE methods primary focus stopped with evaluating engineering demand (response) parameters, the PEER PBEE methodology provides functions that relate structural demand parameters to the resulting damage to structural and nonstructural components. Associated with descriptions of physical damage to the component(s) are the consequences of the damage, such as the repair measures necessary to restore a component to its pre-earthquake condition or other implications on the damage on facility operation or safety.
- *System-Level Performance Metrics:* Whereas the performance limit states of first-generation PBEE methods (i.e.,"immediate occupancy," "life-safety," and "collapse prevention," Figure 1.5) were somewhat ill-defined and loosely quantified, PEER's PBEE methodology establishes clear metrics that are probabilistically quantified in exact terms that relate to stakeholder decision making. For example, financial losses associated with earthquake repair costs are evaluated in terms of mean annual frequencies, which can be manipulated to inform risk decisions regarding (a) management of risks through mitigation or insurance, or (b) scenario-based evaluations to evaluate risk of ruin. Another metric, risk of casualties is a key decision quantity for establishing appropriate minimum safety levels for code requirements.

1.4.2 Models and Tools for Implementation of PBEE

PEER's research to develop robust tools for accurate simulation of response and performance assessment was greatly facilitated by the Engineering Research Center systems-based approach. PEER prioritized the development of simulation models and tools to facilitate validation and implementation of the PEER PBEE methodology. In addition to their role for enabling the PBEE approach, many of the models and tools developed by PEER are being applied to generally improve the state-of-the-art in engineering practice and research. Some of the most notable of model and tool developments are described below.

Advanced Simulation Technologies are an essential aspect of PBEE to accurately simulate nonlinear response of buildings, bridges and other structures, including (where appropriate) soil-structure interaction and large ground deformation effects (see Figure 1.6). Recognizing the need to integrate state-of-the-art technologies in geotechnical and structural modeling, computational

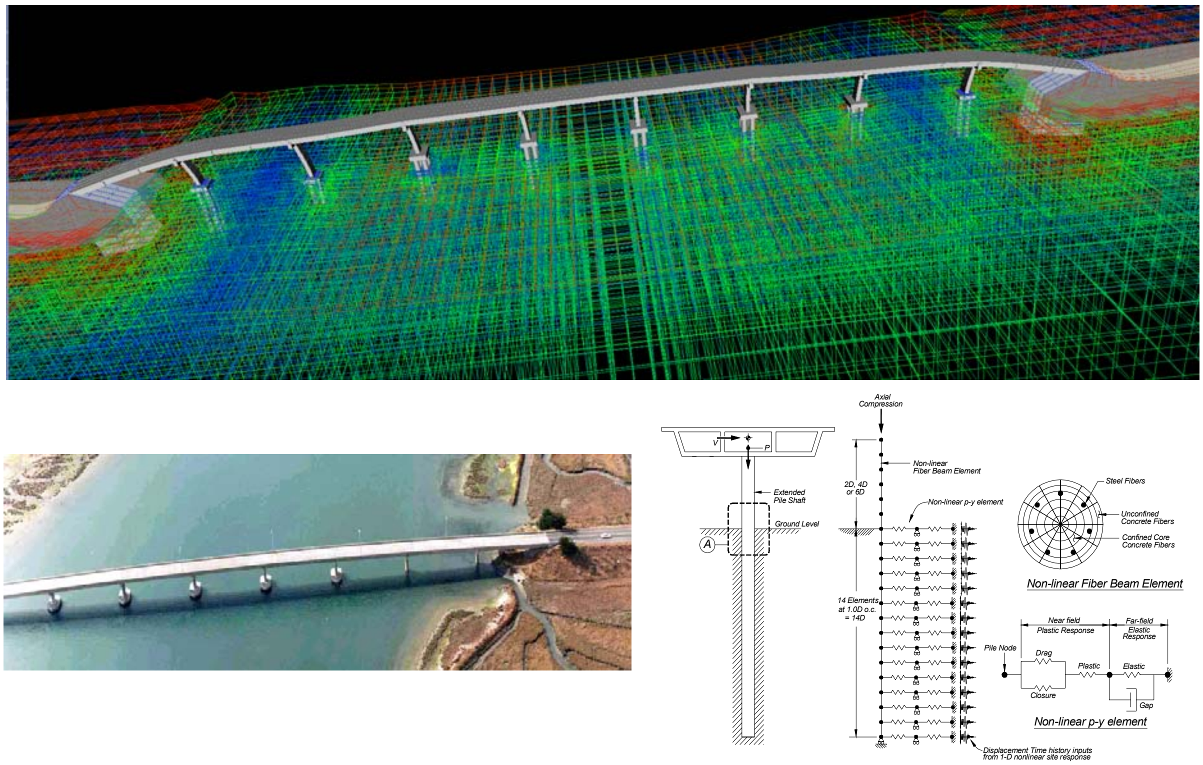

Figure 1.6 - OpenSees model for nonlinear simulation of bridge structure including ground deformations

methods, and database technologies PEER created the computational platform called *OpenSees* (Open System for Earthquake Engineering Simulation, http://opensees.berkeley.edu/). Organized and programmed using an open-source object-oriented approach, *OpenSees* has been an effective platform to implement and test alternative models and solution strategies. As judged by its large user base and adoption as a key computational component of *NEESit (http://it.nees.org/), OpenSees* has and is expected to have a major impact on earthquake engineering research. As part of its continued development, PEER has developed a companion platform called *OpenFresco*, which enables hybrid testing and simulation between *OpenSees* and physical experiments.

Ground Motion Hazard Characterization: A key element of seismic design and analysis in general, and PBEE in particular, is the characterization of earthquake ground motion. PEER has carried out extensive work in this important area. An example of such research projects at PEER is the Next Generation Attenuation (NGA) project. NGA is a comprehensive multi-disciplinary research project to characterize ground motions for shallow crustal earthquakes; such as those events in California. The first component of NGA was to compile a database of strong ground motions recorded worldwide. The PEER NGA database is now one of the largest uniformly-processed strong-motion databases in the world. The database includes the recorded ground motions, response spectra, and a comprehensive meta data such as earthquake fault mechanisms, various site-to-source distance measures, various shallow site characterization including shear-wave velocity in top 30-m of soil, among other parameters. The database is available on-line and can be downloaded from PEER web site at http://peer.berkeley.edu/products/nga_project.html.

Teams of seismologists, geotechnical engineers, and structural engineers used the NGA database to develop the most comprehensive models for prediction of ground motions available today. The NGA models are applicable to spectral ordinates over a period range of 0.01 to 10 sec. This is a major improvement over the previous models that were only applicable to a period of at most 4 sec. The models are also applicable to distance range of 0 to 200 km from the source, and they include the style of faulting, as well as local soil conditions. The NGA models successfully went through a comprehensive review process carried out by the USGS. The USGS is now adopting the NGA models for generation of the 2007 US National Seismic Hazard Maps. This will affect seismic design of many structures and facilities in the western US. As an example, Figure 1.7 shows a sample of the results from the NGA project. The NGA project was funded primarily by the State of California and private industry.

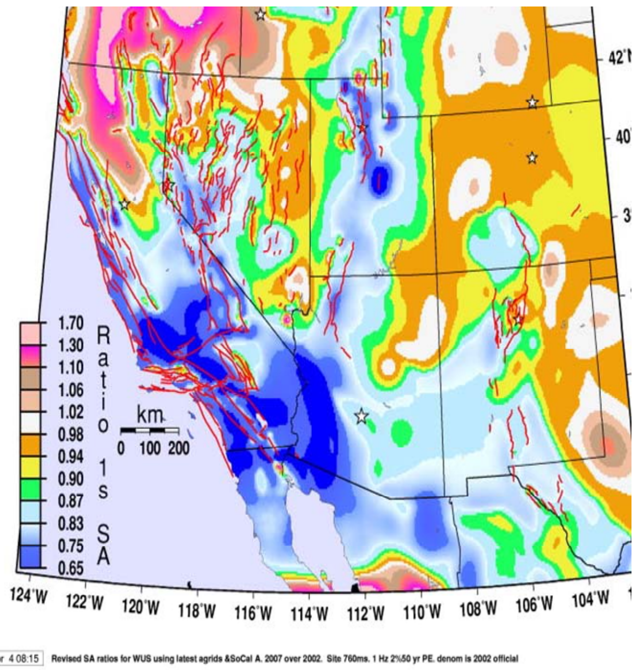

Figure 1.7 – Preliminary impact of NGA models on the US National Seismic Hazard Map for the western US. Colors indicate ratio of 2007 based on NGA divided by 2002 spectral ordinates, one-second period, 2%/50yr hazard level. Orange, yellow, green, and blue colors indicate reduction.

Structural Simulation Models: To simulate structural response from the onset of damage up to the point of incipient collapse, PEER has developed new analysis models to represent strength and stiffness degradation, with an emphasis on models to simulate reinforced concrete structures. In addition to capabilities to simulate large deformation response and strength/stiffness degradation, these models are unique in their ability to simulate the nonlinear interaction of axial, shear and flexural effects. In conjunction with the model development and implementation in *OpenSees*, PEER has conducted reinforced-concrete component and frame system tests to calibrated and validate the nonlinear analysis models. Data from over 400 reinforced concrete column tests have been archived and are available on-line in the PEER Column Performance Database, http://nisee.berkeley.edu/spd/. Shown in Figure 1.8 is an example of a frame test to assess and validate models to simulate collapse in existing reinforced concrete buildings that are sensitive to shear and axial column failure.

Figure 1.8 Shaking table test to validate models for simulating collapse of nonductile concrete frame. Right-hand portion collapsed onto restraining frame.

Geotechnical Simulation Models: Models to simulate geotechnical materials and nonlinear soil-foundation response have been developed and implemented in OpenSees. The geotechnical material models include plasticity-based continuum models in addition to fully coupled (porous solid-fluid) models to simulate earthquake-induced pore water pressure and liquefaction. The soil models have been validated against data from centrifuge studies, lamellar box shaking table tests, and full-scale lateral spreading tests conducted in Japan. Models to simulate soil-foundation-structure effects include a variety of approaches, ranging from phenomenological nonlinear springs to 3D continuum models. These have been applied and validated against shaking table and centrifuge data for shallow (spread footing) and deep (drilled shaft and pile) foundations. The models have been exercised in studies of bridge structures to assess the influence of large ground deformations and introduction of spatially distributed strong ground shaking (e.g., Figure 1.6).

Loss Assessment Models and Tools: To facilitate implementation of the PBEE methodology, PEER researchers have developed toolboxes of structural and nonstructural component damage fragility functions and loss assessment toolboxes. Structural fragility functions have been developed to evaluate damage to reinforced concrete structures, including columns, beams, joints, and slab-column connections. Fragility functions for nonstructural components include ones for partition walls, glazing/façade, laboratory equipment, and electric power equipment. These damage functions have been implemented in loss assessment toolboxes and been applied to the assessment of existing and new buildings. Figure 1.9 illustrates the type of information these tools can produce. A version of one of these toolboxes is being implemented into a

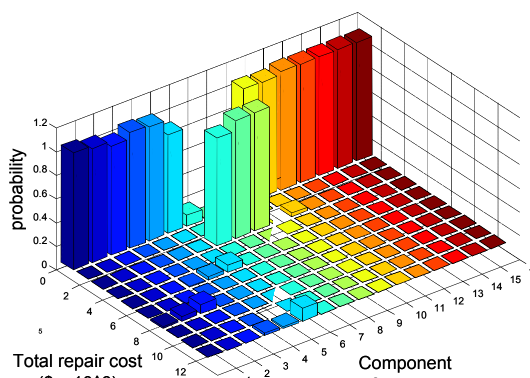

Figure 1.9 – Loss models in the PEER methodology enable an engineer to assess what building components contribute most to future losses.

performance assessment toolbox as part of the FEMA supported ATC 58 project to develop performance-based seismic design guidelines and tools for practice.

1.4.2 Fundamental Knowledge Based for PBEE

PEER has developed fundamental new knowledge in several areas that serves to support development of performance-based tools and the overall PBEE methodology. Furthermore, application of the PBEE tools and methodology has enabled PEER to improve and explore seismic design concepts and systems, thereby creating new fundamental knowledge. Focal areas in PEER's research that has supported and/or utilized development of the PBEE methodology and tools include the following:

Performance of New and Existing RC Buildings: The PBEE methodology and calibrated response simulation techniques have been applied to examine the expected response of reinforced concrete buildings in the western United States and other regions of high seismicity. Benchmarking studies of archetypical buildings have been used to quantify and compare the collapse safety of new versus existing (non-conforming) reinforced concrete buildings. Shown in Figure 1.10 is an example of one such study of a low-rise office building. Studies of this sort have been conducted in support of building code development through the ATC 58 and ATC 62 projects and the EERI initiative to examine policy issues for existing (non-ductile) reinforced concrete buildings.

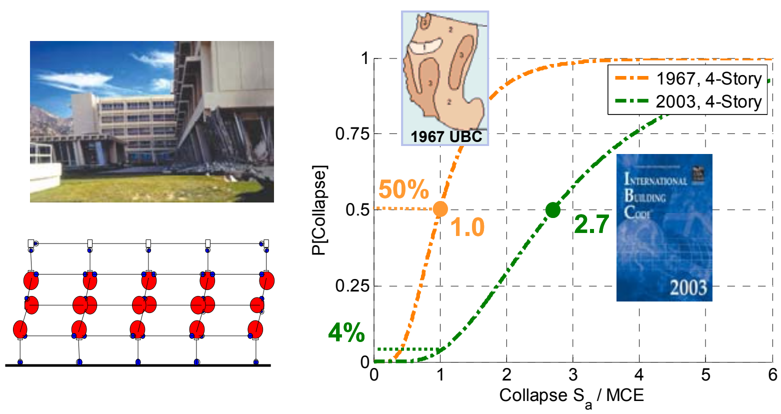

Figure 1.10 Comparison of collapse fragility curves for RC building frames designed according to 1967 and 2003 building code requirements. Advances in earthquake engineering have resulted in ten-fold (and more) increases in seismic safety.

Bridges and Geographically Distributed Highway Networks: PEER's research on the performance of bridges and distributed highway networks (Figure 1.11) has led to new understanding of significant factors that can lead to damage and reduced capacity of bridges and thereby to the overall transportation systems. One of the important problems addressed in this research has been the influence of ground deformations on bridge foundation and abutment response. Studies of highway systems have shown that damage estimates due to ground deformations are an overwhelming contributor to regional loss assessments; and detailed studies of individual bridges have demonstrated the viability of new simulation tools to improve bridge fragility models. Related studies on bridge piers using simulation models indicate that bridges designed per current standards will experience only moderate inelastic deformations and damage under strong ground shaking. More recent studies have applied performance-based approaches to investigate innovative technologies and solutions to develop more economical bridge systems. For example, complementary analysis and testing of new pier design concepts using post-tensioning have demonstrated the viability of cost-effective bridge pier designs. Studies of foundations have investigated cost-effective countermeasures to limit damage due to large ground motions. And, studies of highway network performance have been applied to examine strategies to improve emergency routing, including both pre-earthquake planning and post-earthquake response strategies.

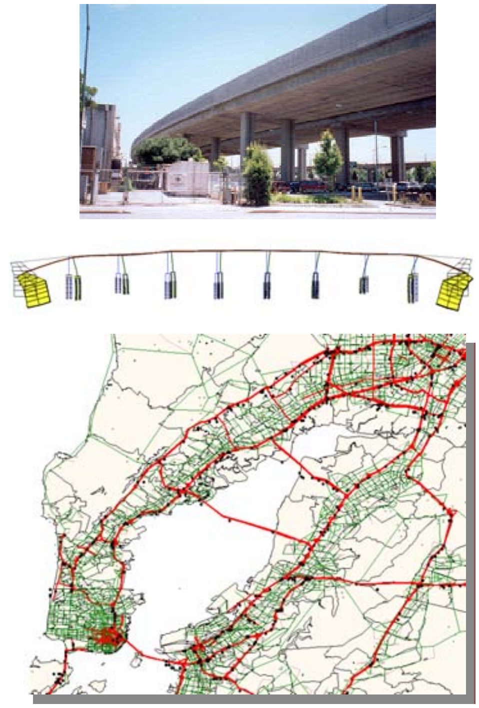

Figure 1.9 Inter-relationship of bridge and transportation system performance

Risk Management and Decision Making: PEER research has advanced understanding of ways in which performance-based approaches can be used to improve risk-informed decision making. Studies of decision making for other types of risks and decision making in the political arena have successfully argued to recast the common question of determining "acceptable risk" to instead focus on a "benefit-cost" approach. Studies have also explored how earthquake risk performance metrics should be expressed, so as to be most effective for different stakeholder groups. Finally, the research has identified strategies, which PEER is following, to accelerate the implementation and adoption of performance-based methods in engineering practice and regulatory agencies.

1.4.4 Implementation and Impact on Engineering Practice

While conventional engineering practice is not yet fully implementing the performance-based framework described above, PEER's research has had and will continue to have a considerable effect on engineering practice. Among the most significant impacts to date are those related to (a) earthquake hazard mapping and real-time assessment, (b) models and criteria to evaluate existing reinforced concrete buildings, (c) models and criteria for evaluation of liquefaction and large ground deformations, (d) analytical tools such as OpenSees for nonlinear analysis, (e) development of performance-based building code requirements, and (f) implementation of PEER's methodology for building loss estimation (ATC 58).

In areas related to earthquake hazards, PEER is collaborating with the USGS on developing new hazard maps that will form the basis of earthquake design requirements for national codes and standards, such as the ASCE 7 *Minimum Design Loads for Buildings and Other Structures.* Specifically, the latest mapping efforts in USGS are utilizing new ground motion attenuation functions developed through PEER research along with research on how to adjust the design ground motions to take into account the effect of spectral shape for extreme ground motions. The net result of this effort will be more accurate and risk-consistent design criteria in high seismic regions of the United States. Related to this, PEER's research on simulating ground motion effects is being incorporated in the latest release of ShakeMap to improve the resolution of real-time ground motion maps determined from sparsely located strong motion sensors (http://earthquake.usgs.gov/eqcenter/shakemap/).

PEER's research to characterize the nonlinear collapse performance of older-type (nonductile) reinforced concrete buildings has markedly improved the tools used in design practice. Through proactive efforts of PEER researchers working with practitioners, PEER research findings have been moved into the recently released standard *ASCE/SEI 41 Seismic Rehabilitation of Existing Buildings* (2007), resulting in numerous substantive changes to the concrete provisions. Aside from improving the accuracy of the models in this standard, PEER research has been instrumental in establishing more statistically consistent methods to determine modeling and acceptance criteria for strength and stiffness degradation. PEER, in collaboration with the Earthquake Engineering Research Institute, has further provided leadership to increase awareness and seek solutions to collapse risks posed by existing reinforced concrete buildings in high seismic regions. PEER provided critical technical input and has been instrumental in the formation of a coalition of practicing engineers and researchers to address this problem.

Large ground deformations are a leading risk to bridges, buildings, ports facilities, levees, and other structures built in locations susceptible to soil liquefaction. Improved models for predicting the triggering (onset) of liquefaction and the extent of large ground deformations have been implemented in practice. Another important example of "tools" developed by PEER is the Virtual Geotechnical Data Center (VGDC). The project is developing an IT methodology and tool to organize geotechnical data and make them available to the public. Computer servers can access geotechnical data collected and maintained by the USGS, California Geological Survey, California Department of Transportation (Caltrans), and Pacific Gas & Electric Company. The users can access the servers to examine and download the data for their seismic design and evaluation. The project has been funded by Caltrans.

Another example of practical impacts of PEER projects is development of a standard set of input motions for shaking table tests for seismic performance evaluation of electric equipment. PEER researchers developed such broadband input motions, and the IEEE Standard 693, a national standard, has adopted the motions for seismic qualification of electric equipment. The project was funded by the State of California and Pacific Gas & Electric Company.

The performance-based methodology and tools are impacting both the development of future performance-based design standards and refinements to existing codes and standards. With regard to future design standards, PEER has had a significant impact on the FEMA-funded ATC 58 project to develop guidelines for performance-based design. In many respects, the ATC 58 project has adopted directly into the draft guidelines the PEER methodology and some of its tools. Moreover, several PEER researchers and business and industry partners are members of the ATC 58 project team, providing leadership in the direction of this project. With regard to current codes and practice, PEER research has provided much of the technical basis for other ATC projects, including ATC 55 (2005) whose goal is to improve assessment approaches based on static nonlinear analysis and ATC 63 (2007) whose goal is to establish a consistent methodology for evaluating the collapse safety of newly proposed earthquake-resisting systems and design requirements for buildings. On the topic of bridges, PEER researchers are collaborating with engineers from Caltrans to improve their seismic design requirements, specifically with regard to challenges associated with design for sites with large ground deformations.

1.4.4 Collaboration in Academic Research, Education, and Outreach

From its beginning, PEER aimed to develop a highly collaborative academic research and education culture among the nine core institutions, affiliated outreach institutions, and business and industry partners. In part, this has occurred through specific education and outreach initiatives, a few of which are described below. Beyond these formal programs, collaboration has been encouraged throughout the research program, ranging from the extensive interactions within research thrust areas to the planning of focused group research projects. Student researchers have been included as partners in presentations and less formal research discussions at annual meetings, site visits, and thrust area meetings. In some of the best examples, this atmosphere has led to students from collaborating institutions taking the lead in planning group meetings and research milestones. The result is that both undergraduate and graduate students have gained participatory and leadership skills, as well as a broader appreciation for where their own research fits within the larger research agenda and the practice of earthquake engineering.

A few of the very successful education initiatives to engage undergraduate students have been the PEER Scholars Course, the REU Summer Program, and the Undergraduate Seismic Competition. Many of these programs were jointly planned and conducted with participation from the other two NSF EERCs (the MAE Center and MCEER) through the Tri-Centers Initiative.

Education and research collaborations among graduate students were enhanced through a highly effective Student Leadership Council and activities to promote collaboration both within PEER and with the other two EERCs. This included, for example, the Tri-Center Doctoral Research Seminars, which provided opportunities and support for advanced graduate students to visit and present their research at other EERC institutions and, in some cases, at international gatherings organized through ANCER. The Tri-Center activities also included Field Missions, organized each summer to provide students the opportunity to learn first-hand about earthquake effects and studies in another country.

For the past several years, over 50 undergraduate students participated annually in PEER Education Programs. This number has grown in recent years to exceed 100 annually with the overwhelming success of the Undergraduate Seismic Competition. Based on feedback from students, the PEER Education Program has had a significant effect on the decisions to attend graduate school. One of PEER’s recent surveys showed that over 85% of undergraduate participates went on to graduate school, including over 50% working towards their PhD. Some of our past participants are now faculty members at PEER universities.

With the assistance of the Education Program, PEER has developed a culture of collaboration among our graduate students. Participation on multi-disciplinary teams is now the norm, not the exception. Many of our graduate student researchers seek undergraduate interns to participate in research over the summer months. These graduates have experienced the advantages of collaboration through an Engineering Research Center, and are continuing to strive for that in their careers.

PEER’s emphasis on collaborative, interdisciplinary research has enriched the thinking and capabilities of PEER’s most active participants, and will continue to influence these individuals as they continue their work past the tenth year of NSF funding. Whereas highly focused, discipline-based, single-investigator research certainly will be pursued, most of PEER’s active participants will also continue to pursue interdisciplinary, multi-investigator research with the confidence that they have gained through participation in PEER. Already, several PEER researchers have become collaborators on other large projects through the Network for Earthquake Engineering Simulation (NEES) and other funding avenues, including a NEES Grand Challenge project on mitigation of collapse risk in older hazardous concrete construction.

PEER also has paved the way for collaborative outreach activities, whereby participants from multiple PEER institutions join in technology transfer activities to practicing professionals. Recent examples include the PEER/EERI seminars on *New Information on the Seismic Performance of Existing Concrete Buildings* (2006), the EERI seminars *Performance-based Earthquake Engineering for Structural and Geotechnical Engineers: Impact of Soil-Structure Interaction on Response of Structures* (2007), the ASCE/SEI 41 Ad Hoc Committee on Updates to ASCE/SEI 41 (2006), the coordinated presentations at the Los Angeles Tall Buildings Structural Design Council Annual Meeting (2007), and others.

1.5 PEER Today

The Pacific Earthquake Engineering Center today is a vibrant center for research, education, and outreach in earthquake engineering, actively involving researchers, educators, and practitioners from several academic, government, and private organizations. PEER will continue its activities beyond Year 10, carrying on the tradition of collaborative, multi-institutional, inter-disciplinary activity that has been its hallmark for the past ten years. Undoubtedly there will be shifts in the focus of PEER's activity, as it adapts to requirements of its various funding sources, but many of PEER's programs will continue.

The California Seismic Safety Commission conducted a review of PEER during Year 10 (http://www.seismic.ca.gov/pub/PEER_Review_Years_7-9.pdf). Among its findings and recommendations were:

- PEER is the primary earthquake engineering research arm of the State of California.
- PEER's efforts have produced cost-effective products that benefit the State of California consistent with the goals and initiatives of the California Earthquake Loss Reduction Plan. PEER continues to meet its goals, and has been instrumental in affecting State laws and regulations.
- Both the State of California and the private sector (should) continue to fund PEER at twice the state's current financial support of PEER's core program to offset the pending loss of National Science Foundation funding.
- Because of the large amount of the public works bonds (Propositions 1B through 1E, as well as future bonds), fiscal responsibility dictates that the State dedicate a reasonable percentage of future bonds for research in all applicable disciplines to ensure that funds are invested wisely and in the most-cost-effective manner.

In view of these statements, and the stated support of the University of California, PEER is confident that State of California matching funds will continue. The total amount of these funds is yet to be determined in the State budget process, but we anticipate being able to support the basic administration, management, and outreach structure of PEER at the current levels, plus support a considerable research program.

PEER also has several other programs ongoing and in various stages of development, including:

- PEER Director Moehle led a team of researchers in the submission of proposal for a NEES-R Grand Challenge project on the subject of mitigation of collapse risk in older nonductile concrete buildings. That project was funded at the beginning of 2007 and will continue under the auspices of PEER for five years. PEER is seeking supplementary funds from other organizations to further expand this project.
- PEER is leading an effort known as the Tall Buildings Initiative, which aims in the next two years to conduct research in support of development of performance-based design guidelines for tall buildings in regions of high seismicity. The project currently is funded by PEER, the Southern California Earthquake Center, USGS, and FEMA; with promised funding from several other organizations. Total anticipated funding, considering only money already in place or promised is over $1.5M.
- PEER continues to work with organizations formerly involved in the PEER Lifelines Program to operate user-driven research programs. PEER currently has research funds from Caltrans and PG&E Company, with promised funding from the California Energy Commission pending.
- PEER also has several other active efforts under way to secure major funding to support future research activities.

One of the challenges will be to maintain PEER's education programs. A limited undergraduate summer research program will continue under the NEESR Grand Challenge project. The Undergraduate Scholars Course currently is without a plan for continuation, though we are actively seeking funds to support this important activity. For the past two years, PEER has worked to find a home for the Undergraduate Seismic Competition at EERI, and has conducted to highly successful Competitions in coordination with the EERI Annual Meeting. We have strong indications that this program will be able to continue under the auspices of EERI.

The investments of the National Science Foundation over the past ten years have created an environment, supporting infrastructure, and leadership that will continue to support the vision of PEER for many years ahead. The value of PEER is well recognized by the University of California, the State of California, and PEER's Business and Industry Partners. We will continue to work with these groups and others to ensure a strong PEER in the years ahead.