PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

PEER Activities

2018–2020

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Pacific Earthquake Engineering Research Center
Univeristy of California, Berkeley

PEER Report 2020/08
Pacific Earthquake Engineering Research Center
Headquarters, University of California at Berkeley

PEER 2020/08
November 2020

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Headquarters at the University of California, Berkeley

November 2020

EXECUTIVE SUMMARY

The Pacific Earthquake Engineering Research Center (PEER) is a multi-institutional research and education center with headquarters at the University of California, Berkeley. PEER's mission is to (1) develop, validate, and disseminate performance-based engineering (PBE) technologies for buildings and infrastructure networks subjected to earthquakes and other natural hazards, with the goal of achieving community resilience; and (2) equip the earthquake engineering and other extreme-event communities with new tools. This report presents the activities of the Center over the period of July 1, 2018 to June 30, 2020. PEER staff, in particular Grace Kang, Erika Donald, Claire Johnson, Christina Bodnar-Anderson, Arpit Nema and Zulema Lara, helped in preparation of this report.

Key activities of the past two academic years include the following:

1. Requests for Proposals: PEER issued a Request for Proposal (RFP) in the Fall of 2018 and 2019 for the Transportation Systems Research Program (TSRP). The 2018 RFP funded 11 projects and the 2019 RFP funded 14 projects. Since 2017, TSRP funds have supported 47 projects by researchers from all 11 core institutions of PEER, spanning a wide range of thrust areas such as geo-hazards, computation, modeling, experimental work, and network vulnerability.
2. PEER Annual Meetings: PEER organized the 2019 PEER Annual Meeting at the UCLA campus, and the 2020 PEER Annual Meeting at UC Berkeley. The 2019 meeting was held on January 17 & 18, 2019, commemorating the 25th anniversary of the Northridge earthquake with active participation from over 200 people. The 2020 meeting, featuring the theme of 'The Future of Performance-Based Natural Hazards Engineering' had over 250 participants.
3. Major Projects: A new major project began in December 2019, when PEER was awarded \$4.9 million from the California Energy Commission (CEC) to develop seismic risk assessment tool for natural gas storage and transmission systems. Other major projects such as the Next Generation Liquefaction (NGL) by PEER researchers at UCLA and UW are continuing. Two major projects, the PEER-CEA Project to quantify the seismic performance of retrofitted homes with crawl spaces, and the Development of Bridge Design Guidelines for Tsunami Loads, are nearing their completion. The NGA-East project was completed with a final PEER report 2018/08 released and a seminar hosted by EERI in October 2019.
4. Researchers' Workshops: These forums for in-progress reporting of PEER-funded projects, were conducted in Summer of 2018 & 2019. With 20 presentations in 2 days and ample time for discussion, these workshops foster interaction between different projects and provide constructive feedback.
5. Blind Prediction Contests: A blind prediction contest on foundation settlement, the first of its kind in liquefaction studies, was held in Fall 2018, with robust participation from industry and research groups. In Fall 2019, a blind prediction contest was held on seismic response of rocking columns.
6. PEER Hub Imagenet (PHI-Net): The first image-based structural damage recognition competition (PHI Challenge) was conducted in Fall 2018, with excellent participation from

structural engineering groups and computer science groups. This work highlighted some of the pioneering work by PEER researchers in the emerging Data-to-Decision field.

7. Strategic Plan: PEER Headquarters developed a strategic plan and action plan for the organization, which was reviewed and approved by the Institutional Board. These plans provide a blueprint for the organization's direction and goals in the coming years.
8. PEER Committees: Three committees were formed: Research Committee, with the charge of shaping the general research direction of the organization; Industry Advisory Board, to serve as a bridge between research and practice; and, Resource Identification Committee, with the goal of identifying future funding sources for the Center. These committees took on their charges in early 2020.

Going forward, PEER aims to hold more focused workshops, leverage the new committees' activities, and draw on existing experience on PBE to systematically move towards Resilient Design for Extreme Events (RDEE).

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1 Mission, Vision, and Organization

1.1 BACKGROUND

The Pacific Earthquake Engineering Research Center (PEER) is a multi-institutional research and education center with headquarters at the University of California, Berkeley. Investigators from over 20 universities and several consulting companies, in addition to researchers at various State and Federal government agencies, contribute to research programs focused on performance-based earthquake engineering (PBEE) in various disciplines, including structural and geotechnical engineering, geology/seismology, lifelines, transportation, risk management, and public policy.

In addition, PEER is an Organized Research Unit (ORU) under the College of Engineering at the University of California, Berkeley, which provides space for PEER offices and largely covers the salaries of PEER staff. In addition, the National Information Service for Earthquake Engineering (NISEE) library and the earthquake simulator and structural research laboratories located at the U.C. Berkeley's Richmond Field Station are supported by PEER.

PEER's mission is to (1) develop, validate, and disseminate performance-based engineering technologies for buildings and infrastructure networks subjected to earthquakes and other natural hazards, with the goal of achieving community resilience; and (2) equip the earthquake engineering and other extreme event communities with new tools for seismic hazard mitigation, through collaboration between PEER institutions and industry partners. A key goal of PEER's research efforts is to define appropriate performance targets and develop engineering tools and criteria that can be used by practicing professionals to achieve those targets, such as safety, cost, and post-earthquake functionality. In addition, PEER actively disseminates its findings to professionals who are involved in the practice of earthquake engineering, through various mechanisms including workshops, conferences, and the PEER Report Series. PEER also conducts Education and Outreach programs to reach students, policy makers, practitioners, and others interested in public policy and research related to earthquakes and the built environment.

The core institutions, their researchers and facilities, and educational affiliates are crucial components for realizing the Center's mission and vision. The wide range of expertise among many researchers, unmatched capabilities of experimental facilities, and geographic spread of institutions make PEER a unique and impactful organization. Some of the most successful PEER projects have been multi-institution efforts with industry collaborations. In return, participating researchers benefit from the PEER infrastructure: access to well-maintained software and databases, dissemination of research through PEER reports, and regular communication efforts, and transparent opportunities and processes for research funding on regular basis with high rate of success.

1.2 VISION

Over the past few years, Director Mosalam has worked to broaden the focus of the Center and expand its reach. PEER's vision is to become the leader in Resilient Design for Extreme Events affecting the built environment. This vision is a natural extension of the current Performance-Based Earthquake Engineering (PBEE) on two fronts: expansion from *earthquake engineering* to *extreme events* affecting the built environment, and extension of the *performance-based design* to *resilient design* that focuses on people, communities, and regions. PEER will lead the research and development of tools and technologies for new modeling, analysis, assessment, and design frameworks, to enhance the resilience of communities exposed to natural hazards.

Director Khalid Mosalam

1.3 STRATEGIC OBJECTIVES

To move towards the goal of Resilient Design for Extreme Events, the Center has identified the following strategic objectives for the next few years:

1. Strengthen the collaborative relationships between PEER institutions, with a focus on multi-institution research work and interaction;
2. Continue innovative research in earthquake engineering and expand to extreme events;
3. Develop new AI tools for extreme events, in combination with physics-based analysis tools;
4. Expand outreach activities and increase the advocacy role in shaping public policy; and
5. Identify and pursue new, large, and sustained funding sources to achieve these goals.

To achieve these goals, PEER plans to draw on existing resources and form a new committee structure. In addition, PEER will continue to hold focused workshops to determine the research needs, shape the research direction, and identify sources of funding. The following committees help PEER achieve these strategic objectives:

1. <u>The Institutional Board (IB)</u>: The board provides policy-level guidance and oversight to the PEER Director and Associate Director in support of the Center realizing its goals and mission. Most importantly, the IB will assist in collaborative research efforts (Goal 1), with advocacy activities (Goal 4), and identification of funding opportunities (Goal 5).
2. <u>The Research Committee (RC):</u> This committee will set the research agenda based on PEER's vision. It will work with stakeholders and industry partners to identify the needs of the community and integrate them into the research plan. This committee will be deeply engaged in achieving Goals 2 and 3.

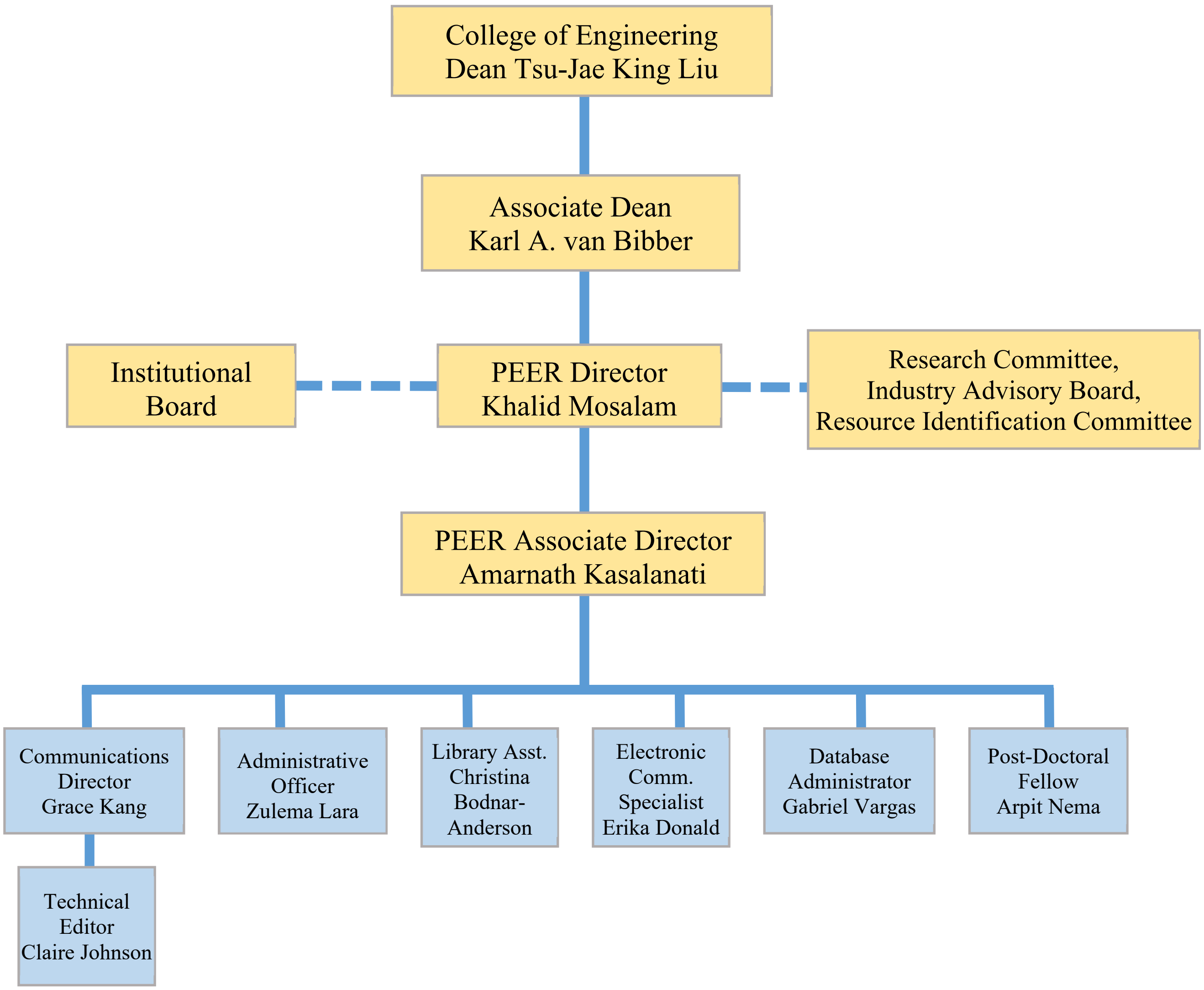
3. Industry Advisory Board (IAB): This committee will identify the present and future needs of the profession and the engineering community. Input from the IAB will be used by the RC to develop the research plan for PEER. IAB will advise PEER on Goals 2, 3, and 5.
4. The Resource Identification Committee (RIC): This committee will pursue existing opportunities and actively seek out new sources of funding to help realize PEER's vision. The committee will consist of senior faculty members with strong ties to various funding sources, industry members, and representatives of some of the funding agencies. Currently, PEER has no such committee. Establishing such a committee of 4 to 6 members will greatly improve the reach and success rate of PEER's funding efforts. The RIC will mainly assist PEER in achieving Goal 5 and with the advocacy efforts of Goal 4.

In August 2018, PEER reinstated the annual PEER Researchers' Workshop—a gathering of all PEER-funded researchers to present their in-progress work, receive input from other researchers, and identify ways to collaborate. Since 2017, 47 projects have been funded through the TSRP's Request for Proposal (RFP) process. In addition, the PEER Annual Meeting has been an effective way to bring together stakeholders, researchers, and industry partners for developing actionable research plans. These activities—together with regular RFPs, collaborative workshops, and comprehensive annual meetings—have been instrumental in maintaining PEER's position as a leading research center.

1.4 ORGANIZATIONAL STRUCTURE

In addition to being a Multi-Institutional Research and Education Center, PEER is an Organized Research Unit (ORU) under the College of Engineering at University of California, Berkeley. PEER headquarters has 8 full-time staff members and several other Research Engineers, Project Scientists, and Graduate Student Researchers.

The organizational structure of PEER is shown here for the period of July 1, 2018 through June 30, 2020. More details of PEER's key personnel, IB members, and PEER resources are presented in Section 6 of this report.


College of Engineering
Dean Tsu-Jae King Liu
Associate Dean
Karl A. van Bibber
Institutional
Board
PEER Director
Khalid Mosalam
Research Committee,
Industry Advisory Board,
Resource Identification Committee
PEER Associate Director
Amarnath Kasalanati
Communications
Director
Grace Kang
Administrative
Officer
Zulema Lara
Library Asst.
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Bodnar-
Anderson
Electronic
Comm.
Specialist
Erika Donald
Database
Administrator
Gabriel Vargas
Post-Doctoral
Fellow
Arpit Nema
Technical
Editor
Claire Johnson

2 Major Research Projects

PEER manages several multi-year, multi-institutional projects. These projects explore key thrust areas and are broad in their scope and impact areas. Details of current major projects are provided in this chapter.

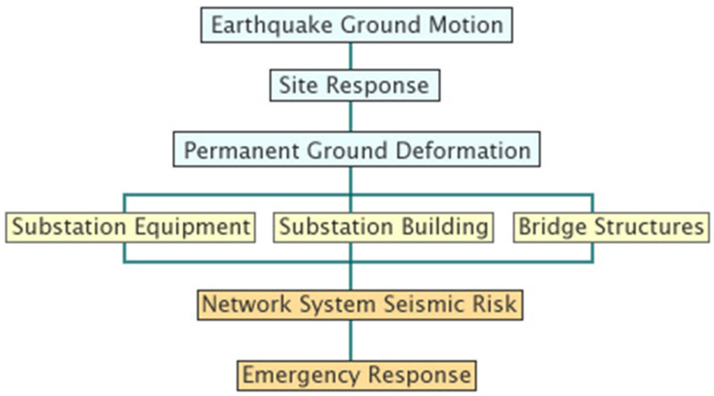
2.1 TRANSPORTATION SYSTEMS RESEARCH PROGRAM (TSRP)

PEER receives funding from the State of California to conduct research related to the seismic performance of transportation systems. The purpose of the TSRP is to reduce the negative impact of earthquakes on California's transportation systems, including highways and bridges, port facilities, high-speed rail, and airports. The research utilizes and extends PEER's PBEE methodologies by integrating fundamental knowledge, emerging technologies, and systems. The research program also integrates seismological, geotechnical, structural, and socio-economical aspects of earthquake and tsunami engineering through computational, experimental, and theoretical investigations.

PEER has funded 42 projects from the TSRP since 2017. Funded research includes researchers from all of PEER's 11 core institutions. Thrust areas of these projects include the following: geo-hazards, modeling, computation, assessment of vulnerability of ports, transportation networks, experimental research, fire research, and tsunami research. Appendix A lists the names of funded projects. Details of these projects are available at the TSRP website. Research highlights from projects of the last two years are presented in Chapter 3.

2.2 LIFELINES PROGRAM

The goal of the PEER Lifelines program is to improve seismic safety and reliability of lifeline systems. The projects in this program are primarily user-driven research projects, with strong collaboration among sponsoring lifelines organizations and PEER researchers. These projects range from engineering characterization of ground motions, to local soil response, response of bridge structures, and performance of electric substation equipment. The lifelines research projects are organized into eight topics, as shown in the diagram below.



Lifelines Research Topics

The Lifelines program brings together multidisciplinary teams of practicing engineers (geotechnical, structural); scientists (geologists, seismologists, and social scientists); funding agencies (Federal, State of California, and private industry); academicians; and end-users. An example of such successful multidisciplinary collaboration that was funded by the Lifelines Program is the NGA-West initiative, which resulted in major advances in characterization of seismic hazard, especially in the western U.S. Sources of funding for the Lifelines program and research projects are diverse and include the California Department of Transportation (Caltrans) and the Pacific Gas and Electric Company.

Since August 2019, Norman Abrahamson, Adjunct Professor in the Civil and Environmental Engineering Departments at UC Berkeley and UC Davis, has been leading the PEER Lifelines Research Program.

2.3 TSUNAMI RESEARCH PROGRAM

2004 Indian Ocean Tsunami Damage

There has been increasing public attention given to tsunamis since 2004 when the Indian Ocean Tsunami killed more than 230,000 people. Attention increased even further following the 2011 East Japan Tsunami, which killed more than 18,000 people and caused enormous economic damage, including a devastating nuclear disaster at the Fukushima Daiichi Nuclear Power Plant.

The U.S. Pacific Northwest (Washington, Oregon, and Northern California) is vulnerable to similar local tsunami generated by an earthquake in the Cascadia subduction-zone region. In Southern California, a submarine landslide off the Santa Barbara or Los Angeles Basins could trigger a tsunami. Based on the directivity characteristics of tsunami-energy propagation, the entire U.S. west coast is vulnerable to distant tsunamis originating in the eastern end of the Aleutian (Alaska) and Philippine Main Islands. The extreme scenario would be strong, long-duration ground shaking associated with the subduction fault rupture, followed by large tsunami inundation. Such a scenario is not an exception; it is a common occurrence in the continental margin where major geologic subduction processes occur. Substantial structural damage caused by tsunamis in Japan underscores the urgency of re-examining the present engineering design practice for the multiple-hazard scenarios.

PEER's tsunami research program includes the development of an effective methodology for hazard, structural, damage, and loss analyses for critical structures and lifelines: e.g., nuclear and fossil power plants, liquefied natural gas and oil storage facilities, civilian and military ports, emergency tsunami shelters, transportation corridors (including coastal bridges), and important public facilities (e.g., fire and police stations, hospitals, and schools). Failure of critical coastal structures and lifelines will likely lead to loss of life, delays in emergency response, and long-term economic impact. This research is focused on filling a crucial gap that currently exists in tsunami research efforts. PEER's methodology development—called Performance-Based Tsunami Engineering (PBTE)—expands and extends the existing PBEE methodology.

The project to develop Guidelines for Tsunami Loads, which was sponsored by U.S. Federal Highway Administration and the Departments of Transportation of California, Oregon, Washington, and Alaska, is scheduled to be completed in 2020.

2.4 SEISMIC PERFORMANCE OF RETROFITTED HOMES

CEA CALIFORNIA EARTHQUAKE AUTHORITY™ THE STRENGTH TO REBUILD®

The California Earthquake Authority (CEA), one of the world's largest providers of residential earthquake insurance, awarded a $3.4 million, 3.5-year research contract to PEER. The research project, entitled "Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings," evaluated the seismic performance of residential homes with crawl spaces, directly contributing to the improvement of seismic resiliency of California's housing stock. This multi-year project is led by Principal investigator Professor Yousef Bozorgnia, UCLA, and conducted by a team of academic and practicing experts with nationally recognized expertise in seismic design, analysis, testing, and earthquake-risk modeling. The team includes researchers from UC Berkeley, UC Irvine, UCLA, UC San Diego, and Stanford University, as well as experienced practicing engineers in California.

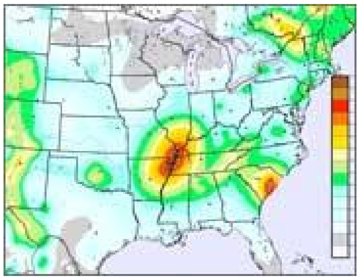
This project was featured in several dedicated sessions in previous PEER Annual Meetings with detailed presentations of the experimental and analytical studies. The project is due to be completed in November 2020, culminating with a collection of PEER reports.

2.5 NEXT GENERATION LIQUEFACTION PROJECT

NGL NEXT GENERATION LIQUEFACTION

The Next Generation Liquefaction (NGL) Project is a collaborative research project organized by PEER, with logistical and technical support from the Southwest Research Institute (SWRI). The NGL Project includes major international collaboration with researchers from Japan, New Zealand, Turkey, Taiwan, Italy, Abu Dhabi, and Chile. The project is currently led by Professor Jonathan P. Stewart, UCLA, and Professor Steven Kramer, University of Washington. The project's goals are as follows: (1) substantially improve the quality, transparency, and accessibility of case-history data related to ground failure; (2) provide a coordinated framework for supporting studies to augment case-history data for conditions important for applications but poorly represented in empirical databases; and (3) provide an open, collaborative process for model development in which developer teams have access to common resources and share ideas and results during model development so as to reduce the potential for mistakes and to mutually benefit from best practices.

2.6 NGA-EAST PROJECT



The NGA-East is a multi-disciplinary research project coordinated by PEER with a large number of participating researchers from various organizations in academia, industry, and government. The project was jointly sponsored by the U.S. Nuclear Regulatory Commission (NRC), the U.S. Department of Energy (DOE), the Electric Power Research Institute (EPRI) and the U.S. Geological Survey (USGS). The objective of NGA-East was to develop a new ground-motion characterization (GMC) model for the Central and Eastern North America (CENA) region. The GMC model consisted of a set of new ground-motion prediction equations (GMPEs) for median and standard deviation of ground motions and their associated weights in logic trees for use in probabilistic seismic hazard analyses (PSHA).

The NGA-East Project was led by principal investigator Professor Yousef Bozorgnia and coordinated by Dr. Christine Goulet. A final PEER Report (2018/08) was released in 2008 that summarized the findings and an accompanying seminar hosted by EERI in October 2019.

2.7 SEISMIC RISK ASSESSMENT OF NATURAL GAS INFRASTRUCTURE

FUNDING PROVIDED BY THE CALIFORNIA ENERGY COMMISSION

The California Energy Commission (CEC) awarded a $4.9 million grant to PEER on May 15, 2019, to improve the seismic risk assessment of natural gas storage and pipeline infrastructure. During the 2.5-year project, PEER will develop open-source software to better assess risks to natural gas storage and pipeline systems from seismic activity. The tool will improve the safety and integrity of natural gas storage, piping, and infrastructure systems by helping regulators and owners direct seismic mitigation efforts to the most vulnerable components.

“In the event of an earthquake, natural gas pipeline and storage facilities could experience significant damage,” said Professor Jonathan Bray, Principal Investigator of the project. “It is not hard to imagine the impact that damage of our natural gas system could have on everything from response to recovery efforts.” The tool will be developed by researchers and experts from UC Berkeley, Lawrence Berkeley National Laboratory, Slate Geotechnical Consultants, UC San Diego,, and the University of Nevada, Reno, with support from the NHERI Computational Modeling and Simulation Center (the SimCenter). Utilities cooperating in this effort include Southern California Gas Company and Pacific Gas & Electric Company.

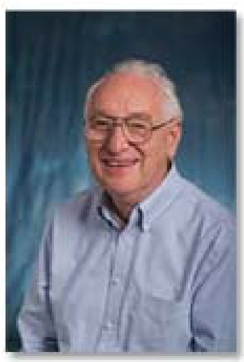
3 Research Highlights and PEER Reports

PEER-funded projects covered key thrust areas of geo-hazards, computational modeling and simulation, tsunami research, transportation, and infrastructure systems. Highlights of these funded projects and published PEER reports are presented below.

Projects Funded in 2019–2020

3.1 NEW SEISMICALLY RESILIENT SYSTEM FOR HSR, PORTS, AND VEHICULAR TRANSPORTATION SYSTEMS REDUCING DOWNTIME, CONSTRUCTION COSTS, AND POST-EARTHQUAKE REPAIR

Dawn Lehman



Charles Roeder

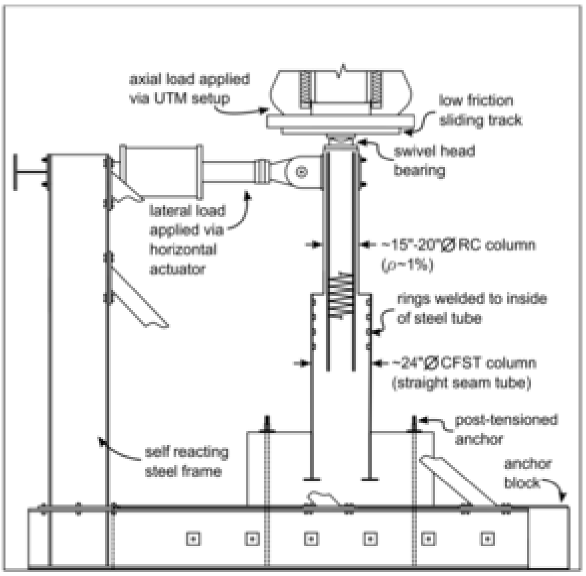
The Project Principal Investigators are Dawn Lehman, Civil & Environmental Engineering, University of Washington, and Charles Roeder, Civil & Environmental Engineering, University of Washington. The research team includes Zhao Muzi, Ph.D. Candidate.

ABSTRACT

Transportation systems including elevated bridges for vehicles, high-speed rail, and ports are moving towards modular systems that promote and facilitate accelerated construction. Accelerated construction (AC) of transportation systems is important and advantageous: (1) it reduces traffic interruption and downtime of the system; (2) it reduces labor; and (3) it reduces on-site construction time, which in turn, reduces cost. However, most AC techniques use precast components as the piers, which is advantageous from the perspective of schedule but requires using heavy equipment that can increase the cost and thereby reduce the cost-effectiveness of AC. In addition, AC typically ignores the foundation construction cost and schedule, which misses a critical point because foundations typically make up more than 50% of the cost of the structural system. A solution to reduce equipment cost and promote AC of transportation systems is to use concrete-filled steel tubes (CFSTs) An alternative system has been investigated for AC that uses CFSTs as piles and/or piers; see figure below. By design, these connections promote AC and reduce damage through elongation of the steel without damage to the concrete and promote ductile response without permanent

damage, thereby meeting higher performance objectives. A missing piece of this new structural system is the foundation system, including the direct pier-to-pile connection and the contribution of soil–structure interaction. This is an economical solution that reduces the cost of the structural foundation system. Using this work as a basis and understanding the performance objectives for post-event functionality required for HSR and ports, this project investigates: (1) a new seismically resilient pile-to-pier connection; (2) system structural performance using the PEER Bridge PBEE tool as well and OpenSees; and (3) developing new PBEE tools for HSR structural geometries to inform design and evaluation of post-earthquake functionality.

RESEARCH IMPACT



Although it is not possible to estimate the cost savings to future project, it is possible to illustrate the potential cost savings, both in terms of material and labor. Prior research shows that using CFST components in place of RC components can decrease the material required by 30–60%. Contractors indicate that the comparable cost savings is directly related to the material saved. An additional benefit is that it eliminates the need for an internal reinforcing bar cage for CFST shafts. These cages are currently used to transfer the load from the bridge pier to the shaft. Eliminating this internal cage would result substantial material and cost savings. As an illustration, consider a typical 60-ft-long, 8 ft-0-in. diameter shaft that would normally have roughly 50,000 lb. of rebar for the internal cage. The cost to fabricate, handle with large cranes, and set into the shaft would cost on the order of $75,000 to $100,000 dollars. Eliminating the shaft and using the shaft casing for flexural and shear strength would not only eliminate the rebar but also the need for a large crane to pick the constructed rebar cage and set it in the hole. There are several bridges, HSR, and port projects that could take advantage of this technology.

3.2 BRIDGE FUNCTIONALITY INSTEAD OF COMPONENT DAMAGE AS A PBEE METRIC

Michael H. Scott

Kevin R. Mackie

The Project Principal Investigators are Michael H. Scott, Professor of Structural Engineering, Oregon State University, and Kevin R. Mackie, Professor of Structural Engineering, University of Central Florida.

ABSTRACT

The project will develop functionality fragilities that relate bridge-level limit states to existing component-level limit states. The states-of the-art and practice for bridge functionality focus on component-level limit

relationship to component limit states and economic consequences of loss of functionality. There are no formal demand parameters or damage measures that describe bridge-level response, damage, or functionality. All current methods, HAZUS or otherwise, utilize a component-to-system map that is not based on bridge-level functionality and is not invertible.

This project will engage stakeholders to establish risk-based thresholds for operation decisions based on functionality. It is anticipated that risk-based thresholds could change the way PEER conducts future PBEE studies. Currently, for every new protective system or innovative material/component tested, it is necessary to independently identify and quantify limit states to generate component damage fragilities, and then perform cost estimation and scheduling to understand the system impacts. From this project, researchers calibrating analytical and numerical models based on their tests will be able to extend their results to system- and network-level quantities of resilience and life cycle costs using functionality as the conduit rather than component damage.

Collapse simulation and collapse probabilities are common terms in the seismic risk assessment of buildings. The methods of collapse prediction are often extended to bridges using moment-rotation degradation models calibrated for building response but ignore collapse potential in other components of a bridge system. This project will extend OpenSees models generated for previous and ongoing Caltrans projects to capture column degradation mechanisms, as well as support settlement and abutment or internal hinge unseating. Column model calibration will be based on recent experimental testing that considered variable axial load.

RESEARCH IMPACT

A considerable body of knowledge has been generated in the last 15 years on bridge component-level limit states and their corresponding fragilities. A focus on component-damage limit states, particularly those for columns, has enabled a better relationship between experimental testing on traditional cast-in-place and new column systems, numerical modeling and tools for predicting observed behaviors, and bridge- and network-level modeling to produce bridge-specific fragilities and network risk assessment. However, a major disconnect remains in that bridge and network decisions are ideally based on functionality, and there is little and often unknown correlation between column-damage limit states and bridge functionality.

In addition, work performed on extending decision variables (DVs) to economic losses has not always been applied to new materials and structural systems due to the difficulties in obtaining repair schematics and cost estimations. At the transportation-network level, the resulting direct costs associated with bridge repair do not drive a substantial portion of the total economic losses due to loss of function. Transitioning industry and research beyond the 3 Ds (death, dollars, and downtime) towards resilience requires a quantifiable measure of functionality. In addition, it should be recognized that existing network risk assessment software already utilize functionality versus time curves to simulate costs for a region. Therefore, the proposed work will give a more direct representation of this functionality loss, potentially eliminating the DM variable introduced in the early years of PEER.

3.3 ESTABLISHING BRIDGE COLUMN CAPACITY LIMIT STATES THROUGH MODELING AND SIMULATION

Sashi K. Kunnath

The Project Principal Investigator is Sashi K. Kunnath, Professor of Civil Engineering, UC Davis. The research team includes Jin Zhou, Graduate Student Researcher, UC Davis.

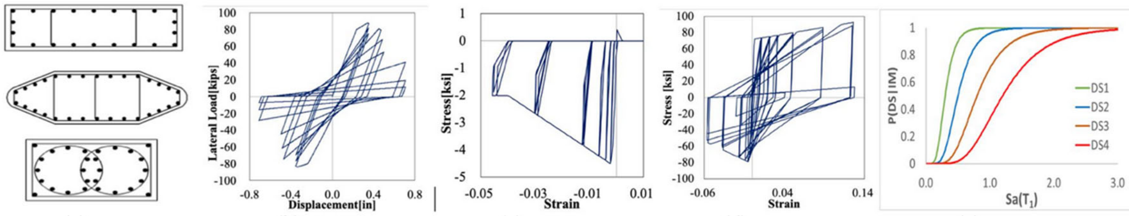
ABSTRACT

Shakecast, a software tool used by Caltrans since 2008, uses near real-time ground shaking maps generated by USGS in conjunction with predictive seismic demand models and component/system capacity models to predict the likely damage to all bridges in the vicinity of the event. While the development of demand models has seen considerable progress, there is a significant gap in the ability of the Shakecast platform to correlate demands with component- and system-capacity limit states, particularly for older non-ductile California bridges. This project aims to address this gap by developing a range of capacity limit states for classes of pre-1990 Caltrans bridge columns through rigorous modeling and comprehensive simulations.

The current inventory of pre-1990 Caltrans bridge columns has been classified into suitable subsets based on bridge type (single or multi-column bent), cross-section shape, and transverse and longitudinal reinforcement detailing. Capacity limit states for each column type are being established by examining critical response parameters under different loading protocols. Material strains in the core, cover concrete and reinforcing steel are monitored, and damage states are defined based on strain limits and then correlated with global response measures such as drift and ductility. For example, the initiation of cracking, spalling of concrete, bar buckling, etc., are associated with well-defined strain states in the material. The calibration of limit states will be validated using an existing database of over 80 columns with axial load ratios comparable to Caltrans bridge columns and reinforcing details that classify them as components with limited ductility. Results from the numerical simulations will be compiled, and the full range of damage states (from minor damage up to collapse) for each column type will be developed.

RESEARCH IMPACT

Project outcomes will enhance the capability of Caltrans to rapidly estimate damage to their bridge inventory following an earthquake to facilitate the planning, management, and mobilization of emergency response. Highway bridges comprise a critical component of California's infrastructure and transportation network. The deployment of emergency response following a major seismic event is essential to post-earthquake recovery. In addition to enhancing emergency response capabilities following an earthquake, the establishment of capacity limit states will complement ongoing Caltrans efforts to develop probabilistic seismic demand models for a range of bridge types and consequently support and enhance planning decisions at Caltrans for effective allocation of resources (such as prioritizing retrofit needs for deficient bridges) for improved seismic safety. While acknowledging that the damage state of a bridge system can be controlled by other factors, Caltrans practice requires that inelastic action be limited to column elements and that the superstructure and foundation remain undamaged. Hence the development of column capacity limit states is an important first step in the enhancement of the Shakecast platform. The overall methodology is schematically displayed in Figure 1.



(a) (b) (c) (d) (e)

Figure 1: (a) Sample pre-1990 cross-sections; (b) Force-deformation response; (c) Material response: concrete; (d) Material response: reinforcing steel; (e) Sample fragility functions

3.4 IDENTIFICATION OF TRANSPORTATION NETWORK CORRIDORS FOR ENHANCING NETWORK RESILIENCE

Jack W. Baker

The Project Principal Investigator is Jack W. Baker, Professor of Civil & Environmental Engineering, Stanford University. The research team includes Rodrigo Silva Lopez, PhD Student, Stanford University.

ABSTRACT

The goal of this project is to use network analysis and network clustering techniques to identify and evaluate transportation corridors as a potentially useful analysis unit for managing transportation system risk. A corridor is defined here as a set of network links with dependence on each other for delivering network services. If corridors function as a unit, then vulnerabilities to components of corridors should be mitigated simultaneously to reliably deliver network services. An idealized corridor would be a set of links connected in series, so that each link must be functioning for the path to exist, though the situation is more complex in real-world networks. This project will evaluate algorithms for identifying corridors, and then performing seismic risk analysis using the PEER Framework to evaluate the effectiveness of strategies for retrofitting networks.

RESEARCH IMPACT

The project evaluates the suitability of various network analysis algorithms for detecting corridors within the transportation network, and then evaluate whether retrofit strategies that consider these corridors are more effective in limiting seismic risk than alternatives. Figure 1 shows some preliminary results, performed using the Markov Clustering algorithm with road links weighed by their travel time and capacity. The approach is producing reasonably intuitive corridor results, but will be more valuable once we have: (1) evaluated the impact of considering larger versus smaller clusters of bridges; and (2) determined whether corridor-based retrofit strategies are effective in reducing the probability of severe transportation disruptions after a large earthquake. The broader aim of this work is to develop new tools for identifying strategies to improve the performance of complex networks. While road networks are the specific focus of this project, the approach may be applicable to other critical infrastructure networks.

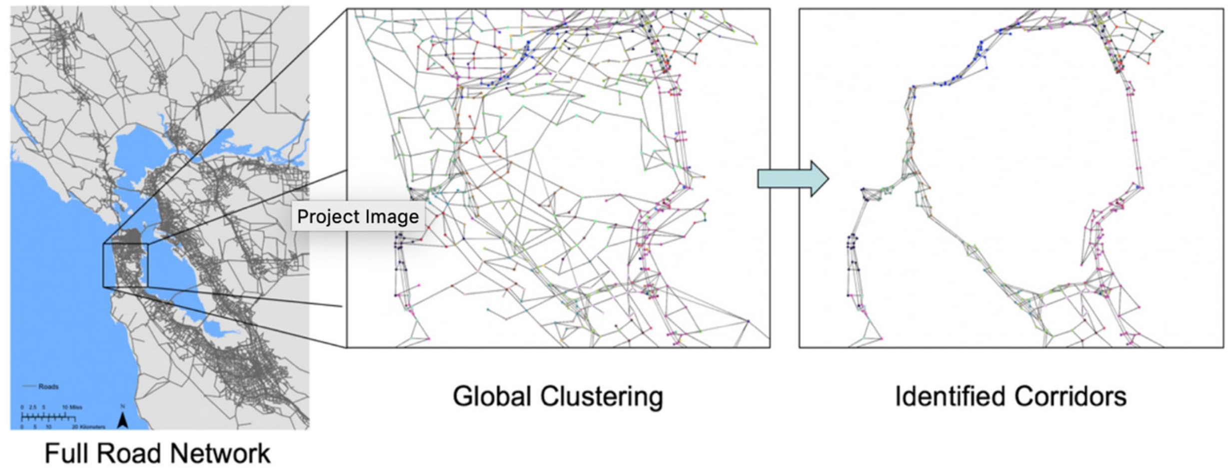


Figure 1: Preliminary results from Markov Clustering of the network, and identified corridors.

3.5 DEM MODELING OF THE INFLUENCE OF DEPOSITIONAL FABRIC ON THE MECHANICAL PROPERTIES OF GRANULAR SEDIMENTS USING XRT DATA

Nicholas Sitar

The Project Principal Investigator is Nicholas Sitar, Edward G. Cahill, and John R. Cahill Professor, UC Berkeley. The research team includes Fernando Estefan T. Garcia, Post-doctoral student, UC Berkeley.

ABSTRACT

The goal of this project is to use computed X-ray tomography (XRT) to characterize the three-dimensional fabric of naturally deposited sands and to observe deformation characteristics in triaxial compression. This data will then be used to drive discrete element method (DEM) modeling of micromechanical properties of naturally deposited sands to determine the role of fabric in the development of shear zones and its effect on the deformation properties of the material. The specific objectives are as follows: (1) use computed X-ray tomography to observe shear zone formation in undisturbed samples of sand from at least two different environments to contrast their behavior with previous work on samples pluviated in the laboratory; and (2) develop a realistic mathematical description of the fabric and then use DEM to model the micro-mechanical behavior of these materials to advance the state-of-the-art toward more realistic multi-scale constitutive models for the response of sedimentary deposits under different types of loading.

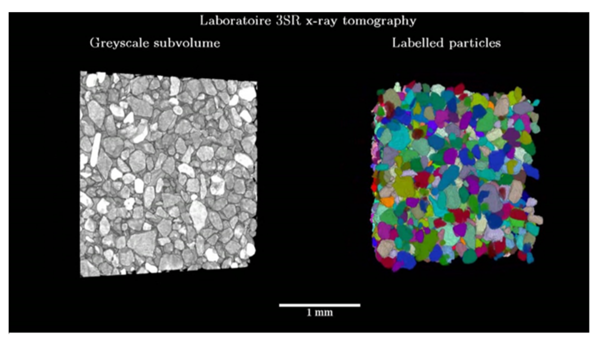


Figure 1. X-Ray Tomography Scans of Fine Sand Fabric

RESEARCH IMPACT

This research effort represents initial investment in a major research thrust to accurately characterize the fabric of natural deposits and to use these results to develop mechanics-based models of granular deposits using massively parallel DEM codes. Specifically, the role of depositional environment is currently not being taken into account in typical field characterization of potentially liquefiable deposits, even though the differences in observed site response due to the different origin of the materials have been addressed extensively in recent research. Similarly, due to the lack of data, to date, the natural fabric of the granular deposits—in this case sands—has not been modeled either by DEM or by using an appropriately configured constitutive model using continuum representations, e.g., finite element method (FEM) or material point method (MPM).

Our preliminary results from trial scans show that due to the intimate contact and packing of particles, naturally deposited sands exhibit much high mobilized friction angle at low confining pressures than either hydraulic fill or pluviated samples used in most of the studies to date. We expect that our work will show that there is a significant difference between reconstituted and naturally occurring deposits that has a significant impact on their behavior under both static and cyclic loading. Most importantly, the results of the experimental work will allow for the development of higher fidelity representations in DEM simulations and development of more accurate and representative parameters for constitutive models used in continuum simulations.

3.6 FRACTURE OF DEFICIENT STEEL DETAILS IN PRE-NORTHRIDGE TRANSPORTATION INFRASTRUCTURE

Amit Kanvinde

The Project Principal Investigator is Amit Kanvinde, Professor of Civil and Environmental Engineering, UC Davis. The research team includes James Malley, Group Director and Senior Principal, Degenkolb Engineers, San Francisco, and Robert Pekelnicky, Senior Principal, Degenkolb Engineers, San Francisco.

ABSTRACT

The transportation infrastructure consists of numerous pre-Northridge welded steel moment frames in airports (a large majority of airports in California utilize steel moment frames to achieve unobstructed bays), as well as other facilities, including transportation control centers. Numerous recent studies in professional practice, the insurance industry, and academia suggest an alarming potential for catastrophic fracture in these buildings that are constructed with brittle materials and poor detailing. This has serious safety and downtime consequences for transportation and other infrastructure. Although a post-Northridge building, the recent fracture in the TransBay Terminal in San Francisco is a timely reminder of such consequences. While some pre-Northridge transportation structures have undergone expensive retrofit to address these deficiencies, a vast majority of connections in these buildings remain unretrofitted. Specifically, pre-Northridge column splices are extraordinarily susceptible to fracture, due to the presence of large flaws (containing Partial Joint Penetration – PJP welds with ~50% penetration) and low-toughness materials, such that the return period of splice fracture in many structures is on the order of 80–100 years, which is unacceptable given that column failure (especially loss of shear capacity) has the potential to trigger structural collapse.

Motivated by these issues, the Project will conduct simulations to support large-scale tests on prototypical pre-Northridge column splices to develop: (1) performance-based decision support frameworks for whether splice retrofit is required, and (2) validated design guidelines and details for effective retrofit in cases where it is necessary.

RESEARCH IMPACT

Cumulatively, the work (including the PEER and other related projects involving academics and industry experts) will result in decision support frameworks and guidelines for retrofit of vulnerable pre-Northridge column splices, with the following broad impacts: (1) averting a significant catastrophe (similar to or worse than the TransBay Terminal fracture) due to failure of pre-Northridge splices in the transportation infrastructure; (2) achieving the above while minimizing unnecessary conservatisms through probabilistic performance assessment of retrofit strategies; and (3) increased awareness regarding this issue, leading to cities/transportation districts examining and repairing their infrastructure.

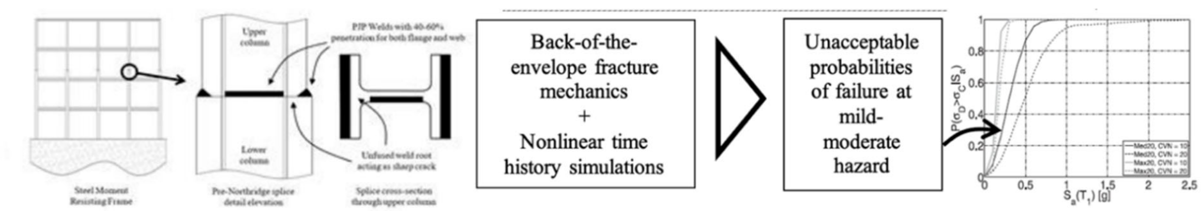


Figure 1: Risk of pre-Northridge connection fracture

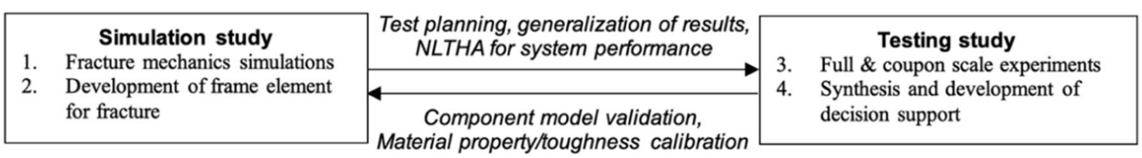
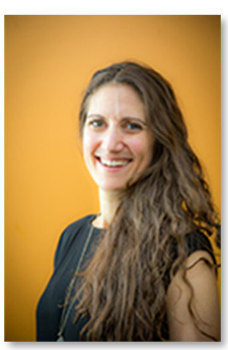


Figure 2: Overview of research plan

3.7 FIRE PERFORMANCE OF STEEL-FRAME BUILDINGS USING OPENSEES



Erica C. Fischer

The Project Principal Investigator is Erica C. Fischer, PE, Assistant Professor, Oregon State University.

ABSTRACT

During a fire, significant plastic deformations are imposed on structural members due to the degradation of material properties and thermal expansion of the members themselves. During an earthquake, large plastic deformations occur in the lateral framing systems; during a fire, plastic deformations occur in the gravity floor framing. Due to the ability of OpenSees to simulate this behavior of steel-frame structures in earthquakes, it is uniquely positioned to incorporate structural fire engineering simulation abilities for gravity

framing and multi-hazard simulations. This project is a multi-agency collaboration between Oregon State University, the National Institute of Standards and Technology, and the American Institute of Steel Construction that aims to develop benchmarked, open-sourced models for the fire behavior of steel-frame structures through the use of OpenSees. The research will: (1) develop a new connector definition in OpenSees that can simulate the force-deformation-moment-rotation behavior of simple connections; (2) use the already developed modeling methodologies and the new connector definition to benchmark three-dimensional system level behavior of steel-frame buildings in fires against large-scale experimental tests at NIST; (3) further develop Wikipages for other researchers or industry practitioners to use to utilize OpenSees for structural fire engineering; and (4) create a simplified connection model for prediction for axial force demand for design of connections during fire, working collaboratively with AISC *Specification* Technical Committee 8.

RESEARCH IMPACT

The development of benchmarked finite-element modeling capabilities for structural fire engineering to be performed by practitioners would allow the field of structural fire engineering to be adopted by more high-quality practicing engineers. Due to the overwhelming use of OpenSees among the seismic and steel research community, there are a significant number of practicing engineers currently in industry with extensive knowledge on the program. This knowledge base makes this program a unique player for implementing structural fire engineering within industry practice. The ability of finite-element modeling programs to consider the capacity of simple connections to resist imposed flexural and axial demands can demonstrate the inherent robustness of many existing steel buildings to fire loading conditions. This research also demonstrates a growing trend in structural engineering to move towards buildings that can be occupiable after an extreme loading scenario (fire, seismic, column removal). This trend supports business continuity and shelter-in-place goals for post-extreme event conditions in addition to economic security and stability throughout a community. The results of this research can lead to more economic connection design that considers multi-hazard resilience. This more economical design could potentially lead to more sustainable benefits for steel construction in a life cycle analysis.

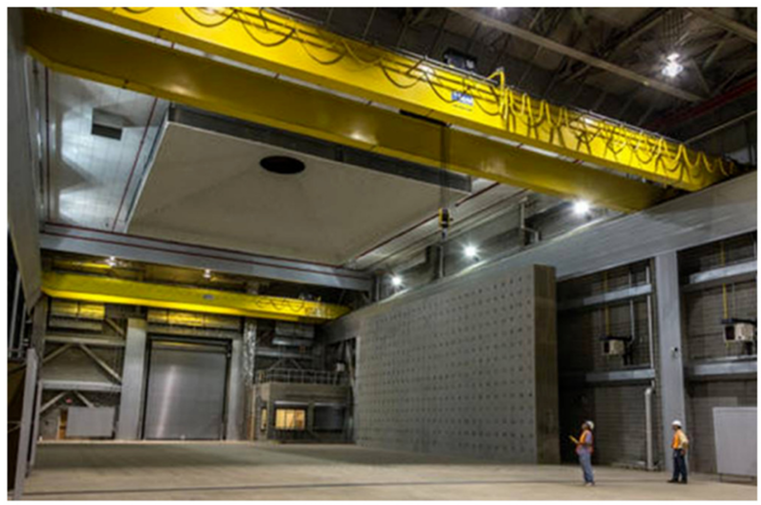


Figure 1: National Fire Research Laboratory at the National Institute of Standards and Technology (source: https://www.nist.gov/el/fire-research-division-73300/national-fire-research-laboratory-73306)

3.8 LEVERAGING LEADING INDICATORS FOR WILDFIRE RISK REDUCTION

Rune Storesund

The Project Principal Investigator is Rune Storesund, Executive Director, Center for Catastrophic Risk Management, UC Berkeley. The research team includes Karlene Roberts, Director, Center for Catastrophic Risk Management, UC Berkeley, and Khalid Mosalam, Director, PEER.

ABSTRACT

This integrated study by engineers and social scientists will advance the reach of Performance-Based Engineering (PBE) into public policy by identifying "leading indicators" that can be used to enable the characterization and measurement of the skew between "predicted" and "actual/experienced" across system life-cycles phases of critical infrastructures subject to extreme events in the face of climate change—in this case a focus on wildfires and impacts to California transportation systems. The "expected condition" during operations can be used as a component of a "leading indicator" program to enable early detection and correction by operators and managers to ensure the desired level of safety and reliability are achieved throughout the infrastructure life cycle.

The tools and method frameworks will be developed to: (1) capture and archive initial assumptions associated with the original configuration of the system {Assumption Register}; (2) establishing operational parameters that constitute the "expected condition" of the system and associated envisioned "decision points" {Performance Manual}; (3) generating a "feedback" mechanism across organizational perspectives to capture questions/issues/omissions associated with actual system performance relative to envisioned performance {Issue Tracker}; and (4) parameters for configuration of an organizational "tactical team" to review "unexpected" performance instances, analyze relative to original performance assumptions, and provide integrated response plans to system managers for implementation {Safety/Reliability Response Team}.

RESEARCH IMPACT

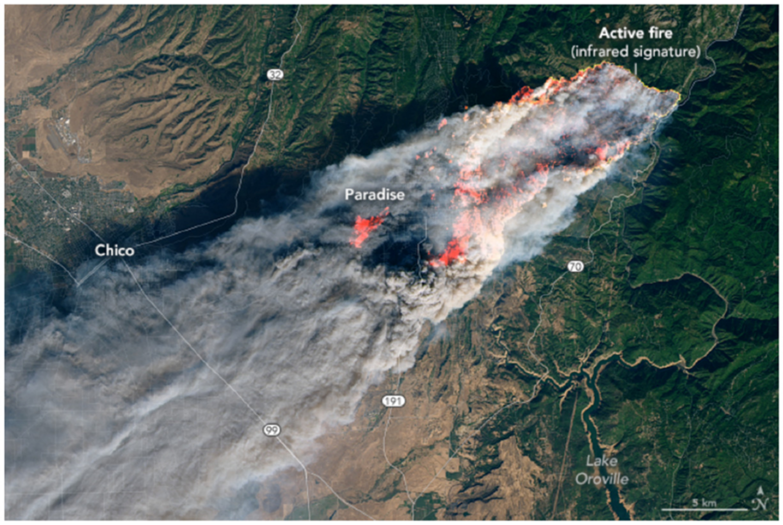


Image from NASA's Earth Observatory showing the extents of the 2018 Camp Fire.
(Source: https://visibleearth.nasa.gov/images/144225/camp-fire-rages-in-california/144225t)

There is increasing recognition of the need to assess consequences and identify and prioritize risk-based solutions to increase the resilience of California's interdependent energy and other critical infrastructures to climate change-driven extreme weather events. This requires gaining infrastructure operator and public support to make the necessary investments for often costly and long-term upgrades, building new or more resilient infrastructure, and economic, environmental, and other policy and regulatory changes. Securing this support and enabling informed decision-making requires a "whole sector and multi-stakeholder approach" that engages and takes into account the needs of key private and public sector customers, as well as the implications for public health and safety, regional economies, and overall societal well-being.

3.9 PROBABILISTIC SIMULATION-BASED EVALUATION OF THE EFFECT OF NEAR-FIELD SPATIALLY VARYING GROUND MOTIONS ON DISTRIBUTED MOTIONS ON DISTRIBUTED INFRASTRUCTURE SYSTEMS

Floriana Petrone

The Project Principal Investigator is Floriana Petrone, Assistant Professor of Civil Engineering, University of Nevada, Reno. The research team includes Norman Abrahamson, Adjunct Professor, UC Berkeley, and David McCallen, Professor, University of Nevada Reno.

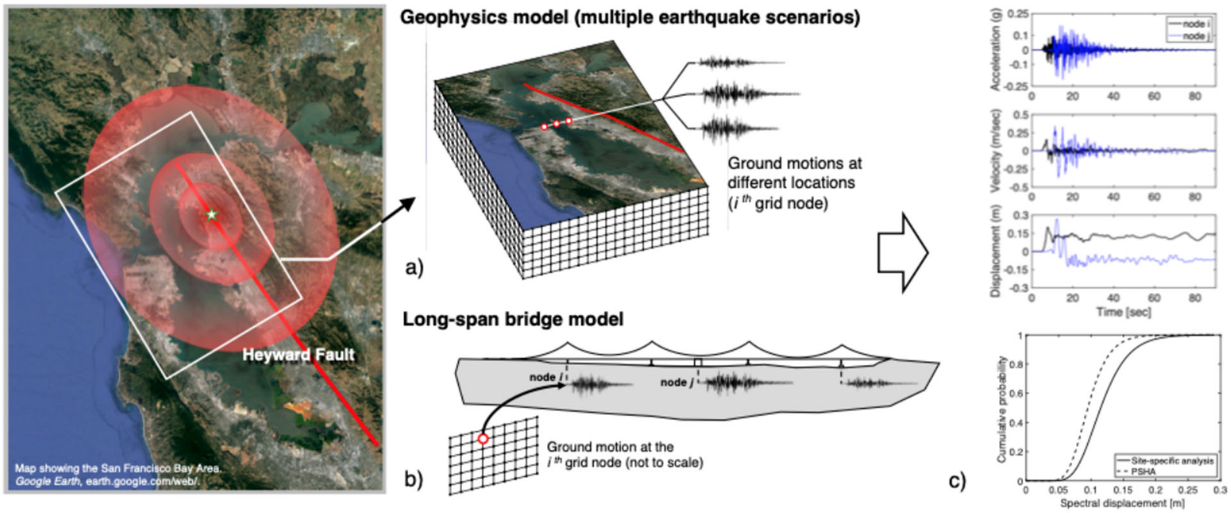
ABSTRACT

The proposed project will provide a simulation framework for performing probabilistic risk-informed analysis of distributed systems. The application portion of the study focuses on the potential damaging effects of long-period displacement pulses, permanent ground displacements, and spatially variable ground motions on the nonlinear seismic response of long-period transportation systems. Simulated ground motions from physics-based wave-propagation models will be utilized to perform site-specific evaluations of the earthquake risk to major distributed infrastructure. This approach will assist in overcoming the limitations imposed by the sparse existing observational database of near-field ground motion records and building a statistically significant basis for developing a full understanding of the variability of the demand posed to distributed systems. The subject of the study will include long-span bay crossing bridges residing in the San Francisco Bay Area.

The project will start with the investigation of a suite of simulated ground motions obtained from multiple M7 scenarios, providing a measure of the potential variability of the demand generated by the same fault-rupture; Project Image a). This investigation will be primarily aimed at building confidence in the use of simulated ground-motion records for engineering applications. Concurrently, a representative numerical model of a long-period bridge will be developed to perform multi-support ground-motion excitation analysis, with the inclusion of uncertainties associated with structural properties; see Project Image b). Analysis of the ground-motion features that mostly influence the nonlinear structural response of long-span structures residing in the vicinity of an active major fault will be conducted. Comparisons with the structural performance obtained with the classical probabilistic seismic hazard analysis (PSHA) approach will be also developed; see Project Image c). The proposed research is expected to shed new light on probabilistic evaluation of the variability of the seismic risk posed to distributed infrastructure and inform earthquake performance-based infrastructure design and evaluation.

RESEARCH IMPACT

Traditional approaches to earthquake structural risk evaluation rely on PSHA, whereby the potential damage of a particular structure is evaluated from fragility functions and hazard curves derived from an ergodic assumption of earthquake processes. Although widely employed, this methodology does not fully account for the potentially large site-specific variability of the demand for sites in the vicinity of a major fault, nor the sensitivity of structural response to specific ground-motion characteristics that are not represented by hazard curves. Leveraging the use of a statistically significant database of simulated broadband ground motions and advanced structural model simulation tools will provide new understanding of the influence of ground-motion spatial variability on long-period distributed systems. Covering a broad range of frequencies and ground-motion features represents a key aspect for the analysis of long-span bridge structures, which can exhibit very low frequencies (0.1 Hz–0.05 Hz) associated to the long wavelength modes of the deck system and relatively high frequencies associated to the vibration of the bridge towers (5–8 Hz). While work is being conducted on the use of simulated ground motions (1 Hz resolution) for structural response analysis, the proposed research will adopt a suite of fully validated simulated broadband records to represent the site-specific demand on the structural systems with associated probability of occurrence and structural systems models that include uncertainties. The proposed research addresses a topic of high interest to the scientific and engineering community and can inform infrastructure design and evaluation on a risk-informed basis.



a) Geophysics model of the San Francisco Bay Area b) Representative long-period bridge
c) Demonstrative model results for the evaluation of seismic risk variability

3.10 A PACIFIC RIM FORUM ON REGIONAL-SCALE SIMULATIONS OF EARTHQUAKE GROUND MOTIONS AND INFRASTRUCTURE RESPONSE FOR PBEE OF TRANSPORTATION SYSTEMS

David McCallen

The Project Principal Investigator is David McCallen, University of Nevada, Reno. The research team includes Norman Abrahamson, Adjunct Professor, UC Berkeley, and Floriana Petrone, Assistant Professor, University of Nevada, Reno.

ABSTRACT

Rapid advancements in high-performance-computing platforms and state-of-the-art computational ecosystems, coupled with new understanding of the physics of earthquake processes, are creating an ability to realistically simulate earthquake ground motions and associated infrastructure response at a regional scale. A computational capability to augment sparse observational data and inform the site-dependent, spatial variation of future earthquake ground motions and the complex manner in which earthquake wave forms interact with major infrastructure systems can support major advances in performance-based design of distributed transportation systems. This timely workshop will bring together multidisciplinary experts from structural and geotechnical engineering, and the earth sciences, to share recent research and state-of-practice advancements and apprise both the research and practitioner communities of recent developments. An additional focus will include critical discussions on the opportunities and appropriate pathway to bring high-performance simulations into broader research efforts and PBEE practice.

RESEARCH IMPACT

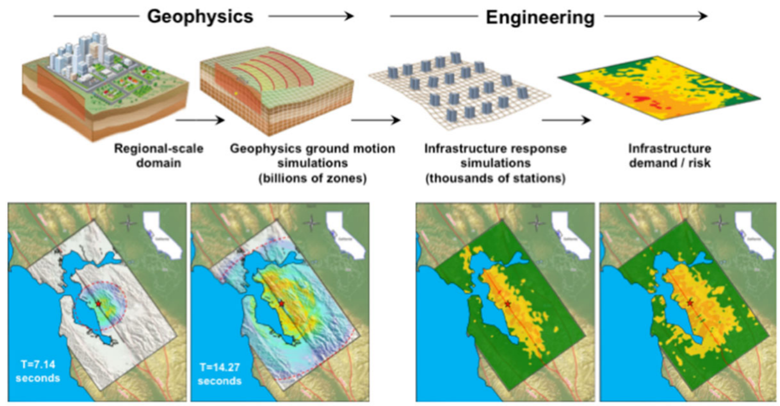


Figure 1. Regional-scale, fault-to-structure simulations with the U.S. Department of Energy supported EarthQuake Simulation (EQSIM) framework.

The ability to realistically and accurately simulate the complex end-to-end phenomenon of earthquake processes would provide a transformational capability for the economical and safe design of transportation systems. Advanced simulations offer a pathway to evaluate phenomenon that cannot easily be experimentally observed at full-scale in the field, increasing the insight and understanding necessary to address key transportation system design issues. This workshop will provide an opportunity for PEER to engage and organize the broader PEER community in an area that is rapidly developing and evolving, with significant potential to have a positive and profound impact on performance-based earthquake engineering over the next decade. Specific benefits of the workshop will include:

1. Informing the broad earthquake engineering community on the rapid developments and emerging capabilities in regional-scale simulations and the workflow and methodologies for coupling geophysics and engineering simulation models;
2. Deep-dive technical presentations on the most recent developments in regional-scale simulations as they pertain to engineering evaluations and PBEE (see. e.g., Figure 1 and recent regional simulation model development for the San Francisco Bay Area);
3. Identification of remaining consensus key knowledge or computational gaps that should be addressed with priority for regional-scale simulations to be fully integrated into PBEE of transportation systems; and
4. Generate discussion and follow-on interest in PEER's research road-mapping activities to define the appropriate path for development of advanced, regional-scale simulations in PBEE practice for transportation as well as other distributed infrastructure systems.

3.11 MESH-FREE LARGE-STRAIN FRAMEWORK FOR SEISMIC RESPONSE OF GROUND-STRUCTURAL SYSTEMS: DEVELOPMENT AND OPEN-SOURCE TOOL

Ahmed Elgamal

Jiun-Shyan Chen

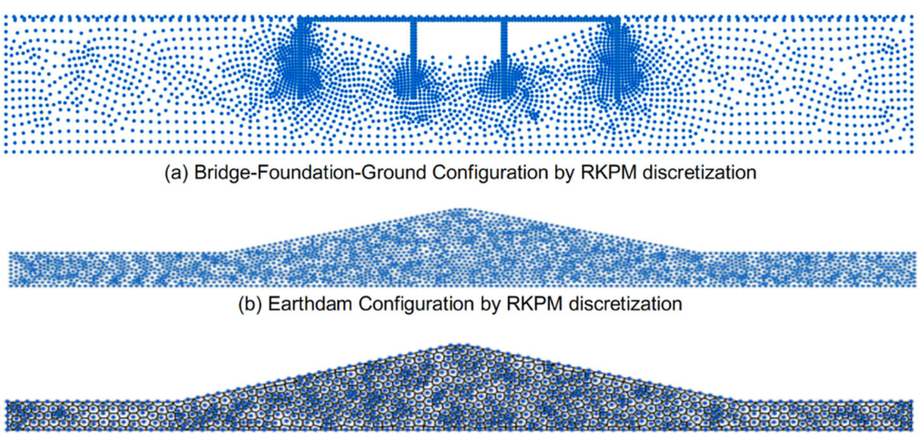
The Project Principal Investigators are Ahmed Elgamal, Professor, UC San Diego and Jiun-Shyan (JS) Chen, Professor, UC San Diego. The research team includes Zhijian Qiu, Graduate Student Researcher, UC San Diego.

ABSTRACT

The goal of this research is to bring the capabilities and advantages of the meshfree method within a dedicated open-source framework for use in earthquake engineering applications. Meshfree method, such as the Reproducing Kernel Particle Method (RKPM), is a class of numerical methods designed to inherit the main advantages of the finite-element method (FEM), while at the same time overcoming the main disadvantages caused by mesh dependency. As such, RKPM allows for capabilities such as large deformations, high gradients and strain localization, crack propagation, and multi-scale strain localization phenomena, all being mechanisms of much relevance to PBEE assessment frameworks under conditions of strong excitation. As the main deliverable, an open source MATLAB-based RKPM code will be provided, with the extended capabilities of dynamic (seismic) analysis, large-strain formulation, and components of the OpenSees geotechnical seismic soil modeling capabilities.

RESEARCH IMPACT

A wide range of practical applications will benefit greatly from this initial effort and potential future developments. The meshfree RKPM approach widens the user-base and horizon of applications for large-displacement and/or large-strain seismic response. Facilitated by the RKPM large-displacement and deformation response characteristics, more accurate consequences of strong shaking are paramount for performance-based engineering (PBE) assessments.



(a) Bridge-Foundation-Ground Configuration by RKPM discretization

(b) Earthdam Configuration by RKPM discretization

(c) Earthdam Configuration (Voronoi cell diagram)

RKPM representations of Soil and Soil structure Systems

3.12 REDUCED-ORDER MODELS FOR DYNAMIC SOIL-STRUCTURE INTERACTION ANALYSES OF BURIED STRUCTURES

Domniki Asimaki

The project Principal Investigator (PI) is Domniki Asimaki, Professor of Mechanical and Civil Engineering, Caltech. The Co-Principal Investigator is Elnaz Esmaeilzadeh Seylabi, Assistant Professor, University of Nevada, Reno. The research team includes Kien T. Nguyen, Postdoctoral Researcher, Caltech.

ABSTRACT

We propose to develop a reduced-order-model (ROM) for dynamic soil-buried structure interaction (SbSI) to evaluate the seismic performance of circular buried structures, such as tunnels, pipelines, and culverts. State-of-the-art SbSI models of buried structures are based on the theory of beam on nonlinear Winkler foundation (BNWF), where the soil surrounding the structure is replaced by a set of springs and dashpots (aka. soil impedance functions, SIF) formulated to represent its macroscopic reaction to differential deformations between soil and structure. Most, if not all, of these models, however, ignore the dynamic nature of seismic loading, and resort to frequency-independent SIFs that cannot account for transient differential strains induced by wave passage effects (e.g. surface waves from basin effects). Recent studies, however, have showed that in SSI problems of buried structures, frequency dependency of SIF is more important than in the case of either shallow or deep foundations, because the free surface distorts the path of radiated energy away from the vibrating tunnel or pipeline (cf. Figure 1).

This project will perform a systematic study on the effects of frequency in seismic SSI analyses of buried structures. We will specifically use high-fidelity finite-element models (FEM) to investigate the frequency-dependency of SIFs and the conditions under which this dependency cannot be ignored, and we will derive analytical expressions that can be incorporated in PBE methodologies for the design of buried structures. The proposed ROM will need to simultaneously consider the frequency- and deformation-dependency of SIFs. To our knowledge, such a model has not yet been developed.

We will develop the model for a homogeneous (or weakly heterogeneous) half-space, and we will extend it to study SbSI effects of a buried tunnel crossing a basin (cf. Figure 2). We will verify the proposed nonlinear, frequency-dependent ROM by comparison to a 3D FEM of soil and buried structures for validation of this method using published experimental results if available. We will lastly use the ROM to study the effects of asynchronous excitation on the performance of an idealized circular tunnel in a homogeneous half-space and a sedimentary basin.

RESEARCH IMPACT

The frequency-dependency of SIF for the design of shallow and deep foundations has been established and widely accepted by the profession. However, there are no equivalent methods to account for the frequency-dependence of SIF in the case of horizontally oriented buried structures. Our recently published and ongoing work has shown that the response of these structures to dynamic loading is both strongly nonlinear (as opposed to the bilinear state-of-the-art assumptions) and strongly frequency dependent. The proposed research will have a twofold benefit: (1) a community database of dynamic SbSI functions (springs and dashpots) will be generated in a and strongly frequency dependent. The proposed research will have a twofold benefit: (1) a community database of dynamic SbSI functions (springs and dashpots) will be generated in a tabulated or graphical form to enable their use by practitioners who are interested in selecting the most appropriate values of springs and dashpots for this class of problems; and (2) the proposed OpenSees uniaxial material model will account for the frequency-dependence of nonlinear SIF, providing a robust and versatile tool to improve the analysis of buried structures under seismic excitation while maintaining computational efficiency. This in turn will benefit PBEE methods by providing a physics-based model to account for the effects of spatial variability and incoherency in the seismic demand of extended structures.

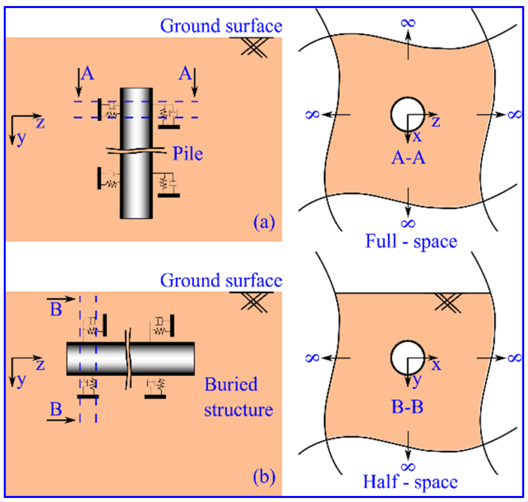


Figure 1: Schematic of full-space and half-space

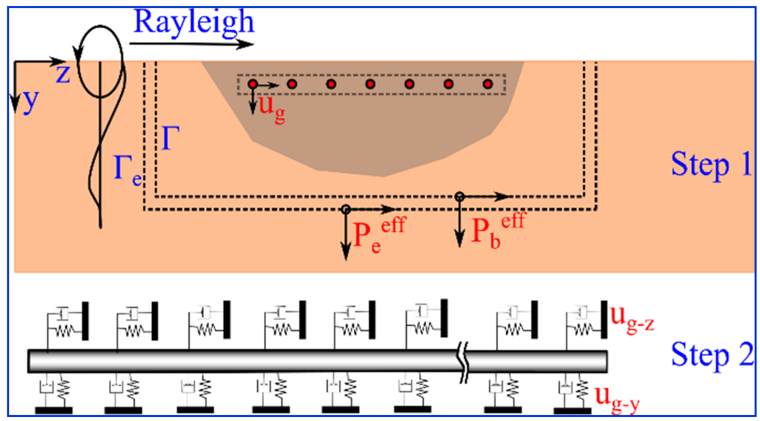


Figure 2: Two-step analysis for tunnel crossing a basin

Projects Funded in 2018-2019

3.13 SHAKE TABLE TESTS ON SHALLOW-FOUNDATIONS IN LIQUEFIED SOILS SUPPORTED ON HELICAL PILES

Ramin Motamed

The Project Principal Investigator is Ramin Motamed, Associate Professor, University of Nevada, Reno. The research team includes Milad Jahed Orang, Graduate Research Assistant, University of Nevada, Reno and Professor Ahmed Elgamal, Collaborator, UCSD

ABSTRACT

This study aims at evaluating the performance of helical piles as a cost-effective mitigation measure against liquefaction-induced settlement of shallow foundations. As a part of this research, two series of large-scale shaking table tests will be conducted at the UCSD's Powell Laboratory. The first series of tests was recently completed, which focused on the behavior of shallow foundations in liquefied soils without any mitigation measures, serving as a benchmark test. The next series will evaluate the efficiency of helical piles to mitigate the liquefaction effects on shallow foundations. Figure 1 illustrates the large-size laminar box at UCSD's Powell Laboratory, which is utilized to perform the large-scale shaking table tests. Figure 2 shows the benchmark model prior to the shaking. The large-scale tests are planned after an extensive series of medium-sized shaking table tests at UNR. This project is a collaborative research between UNR and UCSD with Professor Ahmed Elgamal.

Laminar Soil Box at UCSD's Powell Laboratory

RESEARCH IMPACT

Post-disaster reconnaissance of areas affected by earthquakes, such as the 2010 and 2011 earthquakes in New Zealand, has documented extensive damage to residential homes and low-story structures founded on shallow foundations within liquefaction-prone areas. Such buildings are widespread throughout California, and liquefaction has been extensively observed in its urban areas such as during the 1989 Loma Prieta earthquake.

Foundations are integral to earthquake resistant structures in soils susceptible to liquefaction in seismic events. Continuing research into the performance of foundations in seismic conditions is vital to ensure that public safety is maintained. Where existing structures are to be seismically upgraded, research is needed to provide guidelines to properly design underpinning systems. Helical piles are a type of deep foundation system used regularly to underpin both new and existing structures. Research into their performance in liquefiable soils is the purpose of this study. Current practice lacks offering a cost-effective yet robust solution for underpinning residential buildings and low-story structures. Therefore, this study tries to address this knowledge gap using 1*g* shaking table tests.

3.14 NGL: NEXT GENERATION LIQUEFACTION DATABASE DEVELOPMENT AND IMPLICATIONS FOR ENGINEERING MODELS

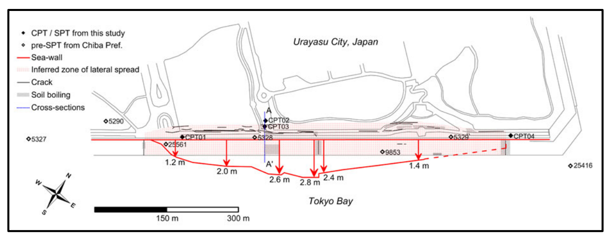
Jonathan Stewart

Steven L. Kramer

The project Principal Investigators are Jonathan P. Stewart, Professor, University of California, Los Angeles and Steven L. Kramer, Professor, University of Washington. The research team includes Paolo Zimmaro, Project Scientist, University of California, Los Angeles; Scott J. Brandenberg, Professor and Associate Dean for Diversity and Inclusion, University of California, Los Angeles; Dongyoup Kwak, Assistant Professor, Hanyang University; John Stamatakos, Director of Special Programs, SWRI, San Antonio, Texas; Thomas Weaver, Nuclear Regulatory Commission, Rockville, Maryland; Onder Cetin, Professor, Middle Eastern Technical University, Turkey; Kevin W. Franke, Assistant Professor, Brigham Young University; Robb E.S. Moss, Professor, Cal Poly San Luis Obispo; and Yousef Bozorgnia, Professor, University of California, Los Angeles.

ABSTRACT

Procedures for engineering assessment of liquefaction hazards are typically empirical or semi-empirical because they are based on the interpretation of field performance information from sites that have or have not experienced ground failure attributable to liquefaction. However, the number of case histories supporting liquefaction procedures is remarkably small. As a result, existing databases are incomplete, meaning they cannot constrain important components of engineering predictive models. In this project, this situation is being addressed with substantial increase in the size and quality of field performance data sets available for model development.



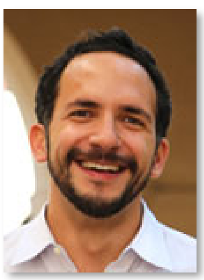
The Next-Generation Liquefaction (NGL) project is developing a transparent, open-source, community database of liquefaction case histories. The NGL case history database is accessible via a web interface where registered users can upload, view, and download data. The database was developed using the My Structured Query Language relational database management system. The NGL database contains data from recent earthquakes (the last 20 years) in California, Chile, Italy, Japan, New Zealand, Taiwan, and Turkey, which caused a great deal of damage attributable to liquefaction and its effects, but which is not considered in most of the currently used models. Also included in the database are legacy case-histories that were used in the development of existing semi-empirical models.

RESEARCH IMPACT

The Next-Generation Liquefaction project has three broad objectives: (1) substantially improve the quality, transparency, and accessibility of case-history data related to ground failure; (2) provide a coordinated framework for supporting studies to augment case-history data for conditions important for applications but poorly represented in empirical databases; and (3) provide an open, collaborative process for model development in which developer teams have access to common resources and share ideas and results during model development, so as to reduce the potential for mistakes and to mutually benefit from best practices. This approach is motivated in part by the success of the Next-Generation of Attenuation (NGA) models for ground-motion prediction, which has followed this approach and has had substantial global buy-in and broad application.

This project is contributing towards the database element of NGL. The project as a whole is anticipated to have substantial impact on the profession, dramatically improving the quality and consistency of models that are available to assess liquefaction susceptibility, triggering, and effects.

3.15 MICRO-INSPIRED CONTINUUM MODELING USING VIRTUAL EXPERIMENTS



José E. Andrade

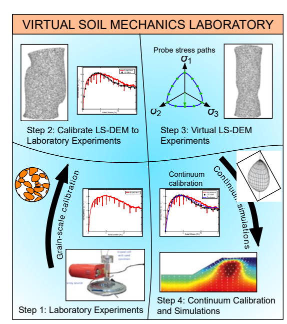
The project Principal Investigator is José E. Andrade, George W. Housner Professor of Civil & Mechanical Engineering, Caltech. The research team includes John Harmon, Graduate Research Assistant, Caltech.

ABSTRACT

The objective of the proposed project is to develop new hardening rules for the most common plasticity constitutive models by using accurate micromechanical simulations that can capture the main features of granular behavior under cyclic loading—a crucial feature for earthquake engineering applications.

RESEARCH IMPACT

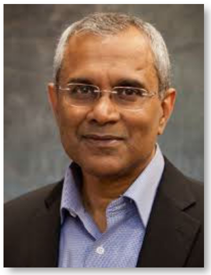
The LS-DEM work builds on 10 years of collaboration between the geomechanics group and the University of Grenoble Alps. Efforts have been supported by the National Science Foundation, the Defense Threat Reduction Agency (DTRA), and others. This work has been focused on the development of the LS-DEM tool and its potential application to monotonic loading. The work proposed herein is the first attempt to use the tool beyond monotonic loading and consider different stress paths, including cyclic loading. New experimental results demonstrate the ability of the LS-DEM technique to capture cyclic loading.



MICROMECHANICALLY-INSPIRED CONTINUUM MODELS

The potential impact on practice is large since this work could enable better predictions of soil behavior and help model challenging problems such as liquefaction instabilities.

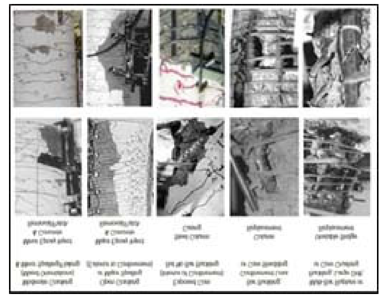
3.16 CALTRANS PEER WORKSHOP ON CHARACTERIZING UNCERTAINTY IN BRIDGE COMPONENT CAPACITY LIMIT STATES



Sashi Kunnath

The Project Principal Investigator is Sashi Kunnath, Professor, UC Davis. The research team includes Jin Zhou, Graduate Student Researcher, UC Davis.

ABSTRACT



The goal of the workshop is to leverage and extend an ongoing Caltrans-funded project on developing component capacity limit state (CCLS) models for performance-critical bridge columns. The emphasis will be on the synthesis, discussion, refinement, and publication of expert opinions focused on characterizing uncertainty in the full distribution of Engineering Demand Parameter (EDP) values (e.g., 10th, 50th, and 90th percentile) which may be assigned to CCLS models. The workshop aims to use data from expert opinions to capture quantitative CCLS uncertainty for a range of component designs (e.g., brittle, strength-degrading, and ductile columns having both regular and wide sections) over a range of damage states. It will also qualitatively explore possible additional factors (e.g., scale and shape effects) that may influence CCLS-value selections.

RESEARCH IMPACT

The broad topic of seismic fragility-model development is an active research pursuit with contributions involving various methodologies, scales, and applications. However, no current work or documented references is available that systematically capture community perspectives regarding optimal CCLS models or the uncertainty associated with differing perspectives. Thus, the proposed survey and workshop documentation is expected to serve as a central community resource. In terms of downstream application, there is growing adoption of the ShakeCast platform as a primary means for implementing organization-specific earthquake-damage alerting and loss estimation strategies for both live emergency situations and for pre-event planning. Multiple state DOT's have already adopted ShakeCast, and others are committing to a Transportation Pooled Fund project (*http://www.pooledfund.org/Details/Solicitation/1406*). Fragility models developed for state DOT's may vary due to differences in the composition of the local bridge inventory, thus affecting the PSDM's for local classes. However, establishing a benchmark framework for characterizing uncertainty in CCLS models will serve each of these model-development efforts.

The results of the workshop will have both immediate and long-term impact on practice. Immediately, the expert views and consensus results will be used as guidance for the specification of CCLS models being incorporated into Caltrans' emerging fragility models to be deployed within ShakeCast. Over the longer term, workshop documentation will serve as a benchmark of expert views that can be referenced in comparable studies and used to characterize and communicate this critical source of fragility-model uncertainty.

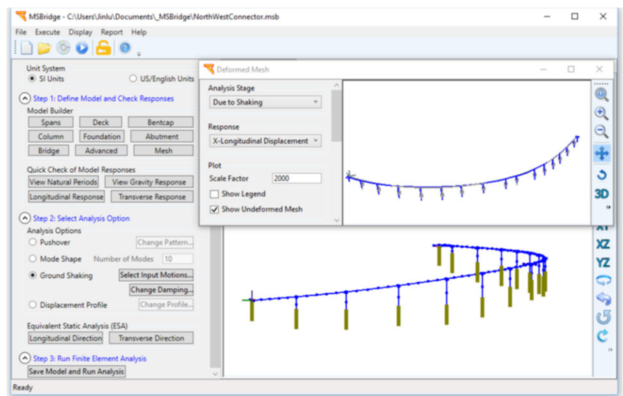
3.17 A SYSTEMATIC COMPUTATIONAL FRAMEWORK FOR MULTI-SPAN BRIDGE PBEE APPLICATIONS

Ahmed Elgamal

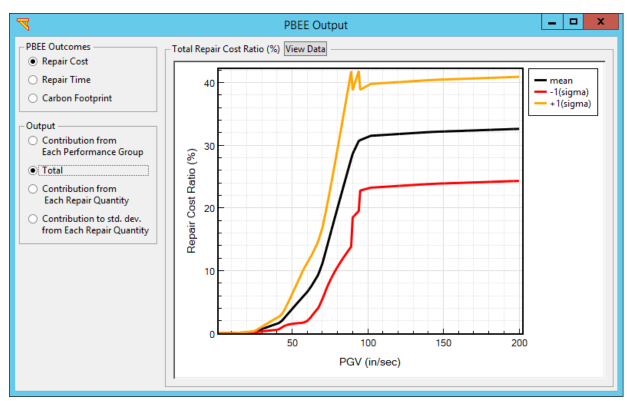
The project Principal Investigator (PI) is Ahmed Elgamal, Professor, Department of Structural Engineering, UC San Diego. The research team includes Jinchi Lu, Associate Project Scientist, UC San Diego and Abdullah S. Almutairi, Graduate Student Researcher, UC San Diego.

ABSTRACT

This project will develop an integrated computational framework to combine nonlinear Time History Analysis (THA) of multi-span bridge systems with an implementation of the PEER PBEE methodology that estimates the probabilistic repair cost and repair time. In addition, the carbon footprint of repair will be included as a sustainability metric in this framework. This research builds on previous efforts, including a PBEE assessment tool BridgePBEE (developed by the PI and co-workers under an earlier PEER-funded project) and the THA multi-span bridge-foundation framework, MSBridge (using OpenSees, developed under a Caltrans-funded project, as shown in the first Project Image)). In nonlinear THA, bridge columns/piers are modeled using force-based beam–column elements with a nonlinear fiber section. Advanced abutment models considering bearing pads and shear keys are also included. Bridge columns/piers, superstructure, abutments, and foundation response mechanisms are integrated within a unified framework. Systematic evaluation of the global system response is conducted under a wide range of earthquake input shaking scenarios. The analysis options available in the new user interface MSBridge include: (1) pushover analysis; (2) mode-shape analysis; (3) single and multiple 3D base input acceleration analysis; and (5) full PBEE analysis (the second Project Image). All stages of the involved analyses including the PBEE assessment are executed in a systematic fashion, allowing the end user to conveniently conduct extensive parametric investigations.



An important feature of the new interface is that the PBEE analysis can be executed sequentially: (1) ground-motion selection (2) THA; (3) loss (repair cost, time and carbon emission) modeling; and (5) calculation of hazard curves. Once the time history results are computed, the user can view the PBEE results against any Intensity Measure (IM) and perform what-if scenarios by changing any parameter of the intermediate probabilistic models without recomputing the time history results.



RESEARCH IMPACT

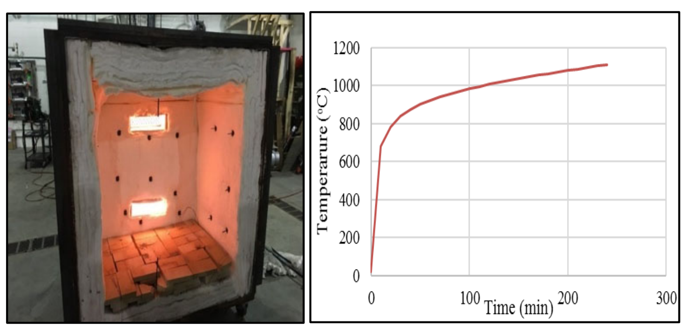
Seismic response and failure mechanisms of highway bridges, which are critical lifelines in a transportation network, continue to receive much research attention. Tools and guidelines that allow bridge engineers to use nonlinear THA as well as PBEE for design/assessment of ordinary bridges will improve safety and mobility across California and enhance the performance of bridges in seismic events. This project will develop an integrated computational framework for combining nonlinear THA of multi-span bridge systems with PBEE assessments that estimate the probabilistic repair cost and repair time. In addition, the carbon footprint of repair will be included as a sustainability metric. The integrated computational tool will allow bridge engineers to efficiently conduct nonlinear THA studies with PBEE assessments for a wide range of multi-span bridge configurations within a seamless integrated simulation environment. Bridge engineers can compare the effectiveness of different bridge design options and evaluate the performance of bridges. In addition, this research project will provide stakeholders with a valuable tool that contributes to economic-based and environment-based decision making. The project builds on prior PEER research to integrate research outcomes into robust next generation seismic computational assessment tools for bridge systems. The framework can also incorporate the latest research outcomes from other related PEER work when available (e.g., an advanced abutment/shear-key model, or an updated PBEE-type framework).

3.18 HOW THE WATER/BINDER RATIO AND VOIDS AFFECT THE PERFORMANCE OF HARDENED CONCRETE SUBJECTED TO FIRE

Kamran M. Nemati

The Project Principal Investigator is Kamran M. Nemati, Associate Professor, University of Washington. The research team includes Alessandro P. Fantilli, Associate Professor, Polytechnic University of Turin, Italy, and Nicholas A Dembsey, Professor, Worcester Polytechnic Institute, Massachusetts.

ABSTRACT



Fire simulation temperature

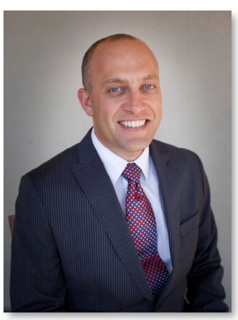
Post-earthquake fire (PEF) is a relatively frequent disaster, but its damage on concrete is complicated and is usually affected by uncertain factors. Considering the risk of fire either locally within buildings or conflagrations after an earthquake, the effects of seismic damage on the fire resistance of structural members need to be better understood for resilient structural design. To increase the efficiency of concrete structures, the use of high-strength concrete is desirable, especially in bridges, tall buildings, and concrete tunnel linings. However, high-strength concrete exhibits very brittle behavior in compression and is prone to spalling in case of fire. The presence of fibers can increase the fracture toughness (or the ductility) in compression and reduce the risk of fire spalling. Several types of concrete with different water/binder ratios and porosities have been investigated previously. This research had demonstrated that the strength of concrete (i.e., the quality of

concrete) increases when air content and/or w/c decreases, regardless of the fiber content. Conversely, material ductility decreases with air content, but increases with w/c. Contrary to the common opinion, mass loss does not decrease as air voids increase, and the lower w/c, the lower the mass loss. Mass loss in concrete subjected to fire can be predicted only by means of uniaxial compression tests, as the experiments clearly indicate that mass loss decreases with increasing strength and increases with ductility, and both of these parameters are measured through the uniaxial compression test. Artificial voids can substitute the polypropylene fiber in reducing the mass loss after fire. Mass loss is mainly related to the mechanical properties of concrete rather than the content of polypropylene fibers. Concrete with the highest strength and the lowest ductility will best perform if subjected to fire.

RESEARCH IMPACT

Previous experimental studies to determine the response of concrete to fire are scarce in the technical literature. Parameter of interest include: (a) the strength of concrete; (2) its resistance to spalling; and (3) the fracture toughness in compression. To our knowledge, this detailed study dealing with the effect produced by the water/binder ratio and by porosity on the mechanical performances in compression and fire spalling is the first of its kind and a welcome addition to the literature. Through the use of uniaxial compression tests, lowering the water/binder ratio, and the amount of artificial voids and polypropylene fibers can be optimized to prevent spalling of concrete in the event of a fire.

3.19 ANALYSIS OF FINE-GRAINED SOIL FAILURE IN CHIBA DURING 2011 TOHOKU EARTHQUAKE, AND DEVELOPMENT OF COMMUNITY LAB TEST DATABASE



Scott J. Brandenberg

Jonathan P. Stewart

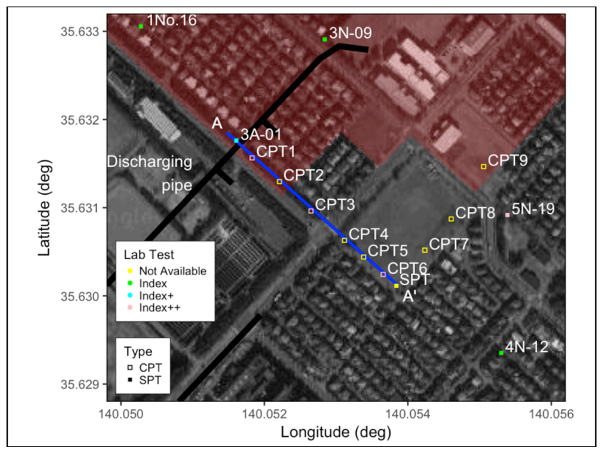
The project Principal Investigators are Scott J. Brandenberg, Professor and Associate Dean, Department of Civil and Environmental Engineering, UCLA and Jonathan P. Stewart, Professor, Department of Civil and Environmental Engineering, UCLA. The research team includes Claudia Rangel, Graduate Student Researcher, UCLA, and Paolo Zimmaro, Project Scientist, UCLA.

ABSTRACT

Liquefaction susceptibility of fine-grained soils remains an important unresolved issue in geotechnical earthquake engineering. During recent earthquakes, ground failure and associated structural damage has been observed at many sites consisting of fine-grained soils. Traditional liquefaction triggering procedures developed for sands are inappropriate for analyzing fine-grained soils with moderate plasticity, and recently developed suitable alternative have not yet been validated with adequate field performance data. This project will document and analyze the Mihama Ward case history in Chiba, Japan, which exhibited various levels of ground failure during the 2011 Tohoku earthquake. Mihama Ward was composed by sluicing fill material through pipes

such that coarse grained sediments tended to deposit close to the pipes, while fine grained sediments were deposited further away. The result is a gradual gradient in plasticity characteristics. Ground performance observations indicated a gradient in ground failure characteristics that are correlated with plasticity. We will study available boring logs and cone penetration test results, and we will perform cyclic and monotonic direct simple shear tests on samples of soil from Mihama Ward. These test data will be performed on soils with a range of plasticity characteristics, and the laboratory findings will form an integral part of the case history interpretation. This project will also develop a relational database consisting of laboratory test data on fine grained soils. This database will be implemented as part of the Next-Generation Liquefaction (NGL) project, and it is envisioned as a community resource that will continue to grow with time. All of the laboratory tests performed as part of this project will be curated in the database and available as a public resource.

RESEARCH IMPACT



There will be two primary benefits to practice that result from the proposed work. First, the Mihama Ward case history is very valuable and will shed light on liquefaction susceptibility and triggering evaluation procedures for fine-grained soils. This is currently an area of confusion among practice due to disagreements regarding the plasticity characteristics that render a soil susceptible to liquefaction triggering. The Mihama Ward case history is unique due to the range of plasticity characteristics present at the site and the manner in which damage observations map spatially in relation to those plasticity characteristics.

Second, the proposed database will be a very useful resource for practitioners. Many projects lack the budget for cyclic laboratory testing, even though researchers agree that laboratory testing is currently the best way to assess cyclic strength loss potential for fine-grained soil. We anticipate the database will grow over time and ultimately become a community resource. Practitioners will undoubtedly benefit from this resource, enabling them to make better decisions regarding strength loss potential for the soils they encounter in their projects.

3.20 CITY SCALE MULTI-INFRASTRUCTURE NETWORK RESILIENCE SIMULATION TOOL

Kenichi Soga

The project Principal Investigator is Kenichi Soga, Professor, UC Berkeley. The research team includes Claudia Rangel, Graduate Student Researcher, UCLA, and Paolo Zimmaro, Project Scientist, UCLA. Renjie Wu, Graduate Student Researcher, UC Berkeley, Zhenxiang Su, Graduate Student Researcher, UC Berkeley, Bingyu Zhao, Visiting Researcher, UC Berkeley, and Miki Komatsu, Visiting Researcher, UC Berkeley.

ABSTRACT

The goal of this project is to deliver graph-parallel distributed network simulation tools that can quantify the performance of the transportation network and water pipeline network at the city scale under different ground-motion scenarios. In this project, a large-scale traffic network analysis model for the San Francisco Bay Area road network, and a pipeline network analysis model for the entire EBMUD water distribution is developed. The main research objective is to demonstrate a unified network model capable of simulating the interactions between the two networks in the cases of normal operational and various earthquake damage scenarios. To interrogate the connections and serviceability loss of these two systems after earthquakes, these two models are run independently and jointly with feedback exchange. The meso-scale traffic simulation model serves as a tool to understand the complex behaviors of the entire transportation system and to evaluate various performance metrics (e.g., traffic flow, delay, accessibility) in a large-scale hazard event. Traffic is simulated as movements and interactions between large numbers of individual vehicles. The development includes an optimized and scalable shortest path routing algorithm, which allows distribution of the computational demand across hundreds of threads on high-performance computing clusters to achieve the desired simulation speed. The entire EBMUD network model is modeled using a newly developed hydraulic network simulator that has been optimized to conduct large-scale (city scale) water pipeline network simulations. Water distribution change under many earthquake damage scenarios is explored all at once. By coupling the two city-scale simulations, the functionality dynamics of the damaged traffic and water distribution networks after an earthquake are examined by considering their interdependence.

RESEARCH IMPACT

The ultimate aim of this project is to provide tools that enable city-scale resilience planning for infrastructure planners in the Bay Area. The loss of accessibility due to damages/closures of the transportation network can greatly affect the rescue and recovery of a city after natural disasters. Transport asset managers need to know the route availability, traffic distribution, reduction in speed, and reconstruction resources required under disaster scenarios to evaluate the impacts and plan for relief measures. The proposed tool can potentially be used for analysis in real-time and enables probabilistic analysis through multiple runs for different recovery scenarios after an earthquake. Both HPC-based network simulation tools are available under the open source MIT license on GitHub (*https://github.com/cb-cities*). The web-based visualization engine is also available under MIT license on GitHub (*https://github.com/cb-cities/sierra-charlie*). This tool will allow visualization of transport network performance regarding traffic volume, speed, route closure, and estimated recovering time under different damage scenarios in an earthquake.

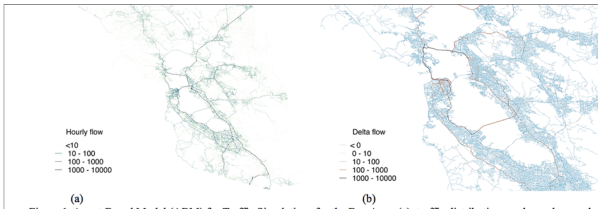


Figure 1. Agent-Based Model (ABM) for Traffic Simulations for the Bay Area. (a): traffic distributions under undamaged network. (b): Additional traffic distributions under damaged network (Bay Bridge closure scenario).

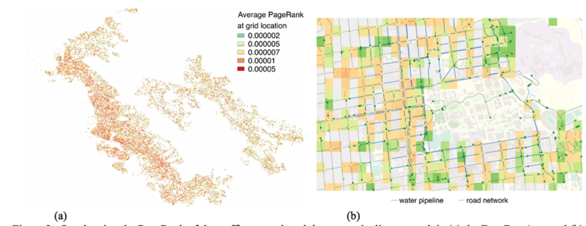


Figure 2. Overlapping the PageRank of the traffic network and the water pipeline network in (a) the East Bay Area and (b) Berkeley area. Red/Orange means the mean PageRank from the two networks are high in a grid cell, indicating areas where important traffic intersections meet important pipe joints.

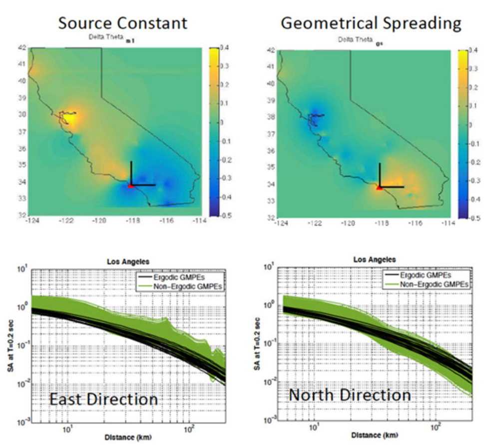
3.21 A NON-ERGODIC GROUND-MOTION MODEL FOR CALIFORNIA

Norman Abrahamson

The project Principal Investigator is Norman Abrahamson, UC Berkeley. The research team includes Grigorios Lavrentiadis, Graduate Student Researcher UC Berkeley and Tessa Williams, Graduate Student Researcher UC Berkeley

ABSTRACT

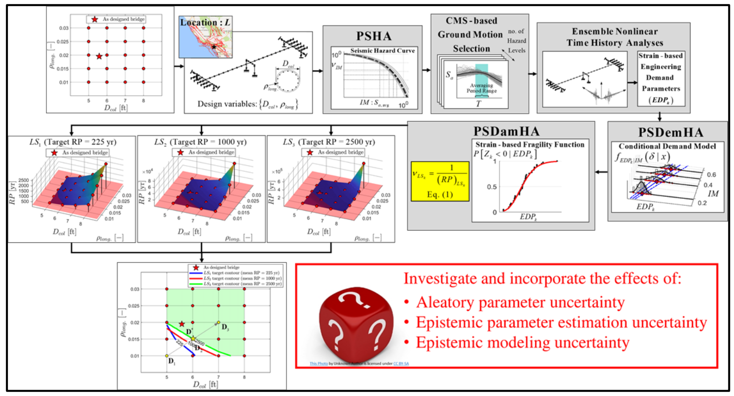
As ground-motion datasets have grown, it has become clear that there are strong systematic effects in the source, path, and site effects for specific site/source pairs that are not captured by the average magnitude, distance, and V_{S30} scaling in traditional ergodic GMPEs. While we have known of this limitation of ergodic models for decades, the size of the effect is much larger than originally thought: recent data show that about 60% of the variance in ergodic GMPEs is due to repeatable source, path, and site effects. These systematic effects are incorrectly characterized as randomness that can occur at any site in the ergodic approach. To address this limitation, we will develop a complete non-ergodic GMPEs for California, with the coefficients of the GMPE that depend on the longitude and latitude of the earthquake and the site.



The empirically-based non-ergodic model will include the epistemic uncertainty in both the base scaling (how the GMPEs extrapolate to large magnitudes and short distances) and in the non-ergodic terms (how well the regional variations in the ground motion are constrained). The non-ergodic GMPE will include the same 21 spectral periods between 0.01 and 10 sec given in the Abrahamson et al. (2014) NGA-West2 GMPE.

RESEARCH IMPACT

Properly accounting for the systematic source, path, and site effects using non-ergodic GMPEs can have a large effect on the ground motion for a given scenario. These new GMPEs will greatly increase the accuracy of the hazard in regions with adequate ground-motion data. In regions with limited ground-motion data, the new GMPEs will show that the epistemic uncertainty is large.



An example comparing the ergodic and non-ergodic distance scaling of $T = 0.2$ sec spectral acceleration for **M**6 earthquakes is shown in Figure 1. In the non-ergodic GMPE, the geometrical spreading coefficient (upper right) and the source constant (upper left) vary depending on the location of the earthquake. This results in a direction-dependent attenuation with distance. For a site in Los Angeles, the attenuation along the east direction (lower left) differs from the attenuation along the north direction (lower right).

The transition from ergodic to non-ergodic hazard codes will lead to the largest changes (improvements) in estimated hazard in California since the change to include the standard deviation of the ground motion occurred in the 1980s. At a given site in California, the ground motion for a return period of 2500 years may increase or decrease by up to a factor of 2 relative to the current hazard based on ergodic GMPEs. Due to the steep slopes of hazard curves in California, the risk of collapse of structures may increase or decrease by up to factor of 8 as we begin to incorporate non-ergodic GMPEs.

3.22 INCLUSION OF MODELING UNCERTAINTY, PARAMETER UNCERTAINTY AND PARAMETER ESTIMATION UNCERTAINTY IN PBSD OF ORDINARY STANDARD RC BRIDGES

Joel P. Conte

The project Principal Investigator is Joel P. Conte, Professor of Structural Engineering, UC San Diego. The research team includes Angshuman Deb, Graduate Student Researcher, UC San Diego, and Jose I. Restrepo, Professor of Structural Engineering, UC San Diego.

ABSTRACT

The current research is intended to complement and extend the PI's recent work on the development of a simplified, yet rigorous, framework for risk-targeted performance-based seismic design (PBSD) of Ordinary Standard Bridges (OSBs) in California. The design framework developed based on the PEER probabilistic performance-based earthquake engineering (PBEE) assessment methodology considers explicitly the following basic sources of uncertainty in its formulation: (1) the seismic hazard associated with the seismic intensity measure and ground motion record-to-record variability; and (2) the uncertainty in the structural capacity against various damage/limit-

states. At the heart of the PBEE methodology is the explicit quantification of pertinent sources of uncertainties and their propagation through the various steps of the analysis methodology.

The project aims at significantly enhancing the previous work by the inclusion, quantification, and propagation of the following additional sources of uncertainty in the PBSD framework developed: (1) the aleatory uncertainty associated with finite-element (FE) model parameters (e.g., constitutive material model parameters, damping model parameters); (2) the epistemic parameter estimation uncertainty associated with using finite datasets to estimate the parameters of the aleatory probability distributions characterizing the FE model parameters and especially the fragility functions for the various limit-states considered; and (3) the epistemic modeling uncertainty characterizing the overall numerical modeling of the bridges considered, resulting from the inability of idealized (due to numerous simplifying assumptions) numerical models of bridge systems to predict exactly their actual seismic response. The analytical and computational frameworks previously assembled will be extended via a modular incorporation of these additional sources of uncertainty. Bridge testbeds and their risk-targeted redesigned versions will be analyzed with and without these additional sources of uncertainty to evaluate their significance. Their contributions to the seismic performance of OSBs will be accounted for in the PBSD framework and the resulting simplified PBSD procedure developed.

RESEARCH IMPACT

The targeted additional sources of uncertainty considered are commonly omitted or neglected in PBEE by invoking that the earthquake ground motion uncertainty is the predominant source of uncertainty. However, recent studies have shown that these sources of uncertainty can or are likely to be significant and must be included for a comprehensive seismic performance assessment of structures. Modeling uncertainty is expected to have highly significant effects on PBSD in light of the results of recent blind studies. To our knowledge, a comprehensive PBSD analytical and computational framework accounting explicitly for all pertinent sources of uncertainty is not currently available for bridge structures. Only components and portions of such an integrated framework that includes the targeted three sources of uncertainty in addition to the uncertainties in the seismic input and limit-state capacities (i.e., fragility functions) are available for building structures. Although some analytical treatment of the aleatory uncertainty of FE model parameters already exists as part of the PEER–PBEE methodology, the proposed research will focus on the investigation and quantification of the effects of this source and other two sources of uncertainty on the PBSD of OSBs. The proposed research will contribute to the extension and further development of the PEER–PBEE framework and resulting PBSD methodology for OSBs by providing a more comprehensive account and treatment of the pertinent sources of uncertainty contributing to the quantification of structural seismic performance.

3.23 TSUNAMI-BORNE DEBRIS LOADING ON BRIDGES

Ian Buckle

The project Principal Investigator is Ian Buckle, Foundation Professor, University of Nevada, Reno. The research team includes Denis Istrati, Research Assistant Professor, UNR, Seddigheh (Anis) Hasanpour, Graduate Assistant, UNR, and Michael Scott, Oregon State University, Corvallis.

ABSTRACT

Widespread damage to coastal bridges in recent tsunamis (Indian Ocean, 2004, and East Coast Japan, 2011) have shown the vulnerability of these structures to tsunami overtopping and the crippling socioeconomic impact of their loss on both emergency response and long-term recovery of the affected communities. Developing design guidelines for coastal bridges subject to tsunami overtopping has therefore become a priority, and large-scale experimental and numerical simulations have been conducted to develop and validate tsunami design equations. But this work has been limited to clear-water conditions. The goal of the present effort is to study the effect of tsunami-borne debris on design loads for bridges using the Large-Wave Flume at Oregon State University in Corvallis. This work will be informed by high-end numerical simulations. Experimentally-validated tsunami debris load equations will then be developed including adjustment factors for debris, and these will be used to evaluate (a) available simplified equations for debris loading on buildings (ASCE 7, FEMA P-646), and (b) the simplified debris loading equations for bridges recently developed using engineering judgment in the PEER pooled-fund, design guideline project for coastal bridges [TPF-5(307)]. Major deliverable will be a set of validated adjustment factors for use in design load equations for bridges to include the effect of tsunami-borne debris.

Tsunami from Great East Japan Earthquake coming ashore near Sendai, Japan, March 2011. Photo source: Mark Yashinsky

RESEARCH IMPACT

Widespread damage to coastal bridges in recent tsunamis (Indian Ocean, 2004, and East Coast Japan, 2011) have shown the vulnerability of these structures to tsunami overtopping and the crippling socioeconomic impact of their loss on both emergency response and long-term recovery of the affected communities. Developing design guidelines for coastal bridges subject to tsunami overtopping has therefore become a priority and large-scale experimental and numerical simulations have been conducted to develop and validate tsunami design equations. But this work has been limited to clear-water conditions. The goal of the present effort is to study the effect of tsunami-borne debris on these design loads using the Large-Wave Flume at Oregon State University in Corvallis. This work will be informed by high-end numerical simulations. In particular, the objectives of this study are to:

1. Understand the two-fold effect of debris: (a) impact and (b) damming on bridges, for (i) small-size debris objects such as construction material, and (ii) large-size debris objects such as containers and ships.
2. Examine the effect of multi-object debris, which is a more realistic case than single-object debris.
3. Decipher (a) debris-wave interaction during debris transport, and (b) debris-wave-bridge interaction during the tsunami inundation of two types of bridges, a T-girder and a box-girder bridge. Although both types of bridges are expected to sustain the same impact force, the damming force could change, especially for small-to-moderate sized debris trapped between the girders of a T-girder bridge.
4. Develop a high-quality experimental database to be used by PEER and other research teams around the world for development and validation of numerical tools, to advance PBTE for coastal bridges.
5. Develop and test possible countermeasures for new and existing bridges against debris loading.
6. Contribute to the development, calibration, and validation of the particle finite element method (PFEM) in OpenSees for simulating the tsunami debris impact on bridges.
7. To the extent possible, compare results mesh-based (FEM), particle-based (SPH) and hybrid particle-mesh based method (PFEM) numerical methods for simulating (a) debris transport, (b) debris impact, and (c) debris damming, and identify the limitations of each method.
8. Evaluate (a) available simplified equations for debris loading on buildings (*ASCE 7*, and *FEMA P-646*), and (b) the simplified debris loading equations for bridges recently developed using engineering judgment in the PEER pooled-fund, design guideline project for coastal bridges [TPF-5(307)].

3.24 PEER REPORTS 2018–2020

PEER 2020/01 *Modeling Viscous Damping in Nonlinear Response History Analysis of Steel Moment-Frame Buildings: Design-Plus Ground Motions*. Xin Qian, Anil K. Chopra, and Frank McKenna. September 2020.

This report investigates the question: can seismic demands on steel moment-frame buildings due to Maximum Considered Earthquake (MCE_R) design-level ground motions [2% probability of exceedance (PE) in 50 years] be estimated satisfactorily using linear viscous damping models or is a nonlinear model, such as capped damping, necessary? This investigation employs two models of a 20-story steel moment-frame building: a simple model and an enhanced model with several complex features. Considered are two linear viscous damping models: Rayleigh damping and constant modal damping; and one nonlinear model where damping forces are not allowed to exceed a pre-defined bound.

Presented are seismic demands on the building due to two sets of ground motions (GMs): MCE_R design-level GMs (2% PE in 50 years) and rarer excitations (1% PE in 50 years); and even more intense GMs. Based on these results, we do not recommend Rayleigh damping for use in nonlinear response history analysis (RHA) of buildings. Recommended instead is constant modal damping, which also is available in commercial computer codes. Although satisfactory for estimating seismic demands for MCE_R design-level motions and even more intense GMs, this damping model may not be appropriate for extreme motions that deform the structure close to collapse.

PEER 2020/02 *Data Resources for NGA-Subduction Project.* Yousef Bozorgnia (NGA-Sub PI) and Jonathan P. Stewart (Report Editor). June 2020.

The NGA-Subduction (NGA-Sub) project is one in a series of Next Generation Attenuation (NGA) projects directed towards database and ground-motion model development for applications in seismic-demand characterization. Whereas prior projects had targeted shallow crustal earthquakes, active tectonic regions (NGA-West1 and NGA-West2), and stable continental regions (NGA-East), NGA-Sub is the first to address specifically subduction zones, which are a dominant source of seismic hazard in many regions globally, including the Pacific Northwest region of the United States and Canada.

This report describes the development of data resources for the NGA-Sub project. Agreements were formed with many owners and providers of ground-motion data and metadata worldwide to support data collection. Prior NGA projects organized the data collected into a series of spreadsheets. The enormous amount of the collected data for NGA-Sub required abandoning that strategy and ultimately the data was organized into a relational database consisting of 23 tables containing various data, metadata, and outputs of various codes required to compute desired quantities (e.g., intensity measures, distances, etc.). A schema was developed to relate fields in tables to each other through a series of primary and foreign keys. As with prior NGA projects, model developers and others largely interact with the data through flatfiles specific to certain types of intensity measures (e.g., pseudo-spectral accelerations at a certain oscillator damping level); such flatfiles are a time-stamped output of the database.

The NGA-Sub database contains 70,107 three-component records from 1880 earthquakes from seven global subduction zone regions: Alaska, Central America and Mexico, Cascadia, Japan, New Zealand, South America, and Taiwan. These data were processed on a component-specific basis to minimize noise effects in the data and remove baseline drifts. Component-specific usable period ranges are identified. Various ground-motion intensity measures (IMs) were computed including peak acceleration, peak velocity, pseudo-spectral accelerations for a range of oscillator periods and damping ratios, Fourier amplitudes, Arias intensity, significant durations, and cumulative absolute velocity-parameters.

Source parameters were assigned for earthquakes that produced recordings. Some of the 1880 earthquakes were screened out because of missing magnitudes or hypocenter locations, which decreased the number of potentially usable earthquakes to 1782. Further screening to remove events without an assigned event type (e.g., interface, intraslab, etc.) or distances reduced the number of events to 976. For those 976 events, source parameters of two general types are assigned: those related to the focus (including moment tensors) and those related to finite-fault representations of the source. A series of source-to-recording site distances and other parameters are provided using finite-fault representations of seismic sources. Finite-fault models of sources were developed from literature where available and from a simulation procedure otherwise. As part of the NGA-Sub project, the simulation procedure was revised and more fully documented.

In addition, all events are reviewed to assign event types, event classes (mainshock, aftershock, etc.), and event locations relative to volcanic arcs.

Quality assurance (QA) of ground-motion data and source/path metadata was an important component of NGA-Sub. For ground motions, QA procedures included visual checks of records prior to processing, checks of records from each network that recorded each earthquake to check for systematic outliers (perhaps indicative of gain problems), and checks of limiting distances beyond which data sampling for a given event is likely to be biased by data approaching noise thresholds. Source/path QA procedures largely involved checking that information in database fields accurately reflects source documents.

Site metadata was compiled into a site table containing time-averaged shear-wave velocities in the upper 30 m of sites (V_{S30}), basin depths, and related uncertainties. Major efforts were undertaken during the project to develop shear-wave velocity profile databases and to use those data to develop regional predictive models for site parameters when site-specific measurements are unavailable. Many of those predictive relations were published in journal or conference papers over the course of the NGA-Sub project (i.e., for Alaska, Cascadia, Chile, and Taiwan); those results are reviewed only briefly. Rather, emphasis in this report has been placed on procedures used for other regions. In addition to site parameters, all sites are also assigned a location relative to local volcanic arcs.

PEER 2020/03 *NGA-Subduction Global Ground-Motion Models with Regional Adjustment Factors.* Grace A. Parker, Jonathan P. Stewart, David M. Boore, Gail M. Atkinson, and Behzad Hassani. September 2020.

Next Generation Attenuation Subduction (NGA-Sub) is a multi-year, multidisciplinary project with the goal of developing an earthquake ground-motion database of processed time series and ground-motion intensity measures (IMs), as well as a suite of ground-motion models (GMMs) for global subduction zone earthquakes. The project considers interface and intraslab earthquakes that have occurred in Japan, Taiwan, New Zealand, Mexico, Central America, South America, Alaska, and Cascadia. This report describes one of the resulting GMMs, one important feature of which is its ability to describe differences in ground motions for different event types and regions.

We use a combination of data inspection, regression techniques, ground-motion simulations, and geometrical constraints to develop regionalized models for IMs for peak ground acceleration, peak ground velocity, and 5%-damped pseudo-spectral acceleration at 26 oscillator periods from 0.01 to 10 sec. We observe significant differences in ground-motion scaling for interface and intraslab events; therefore, the model terms for source and path effects are developed separately. There are complex distance-scaling effects in the data, including regional variations and forearc and backarc effects. No differences in site effects between the event types were observed; therefore, a combined site term is developed that is taken as the sum (in natural log units) of a linear term conditioned on the time-averaged shear-wave velocity in the upper 30 m (V_{S30}), and an empirically constrained nonlinear term. Basin sediment depth terms are developed for Cascadia and Japan that are conditioned on the depth to the 2.5 km/sec shear-wave velocity horizon ($Z_{2.5}$).

Our approach to model development was to first constrain a path term capturing the observed effects, then to subsequently investigate magnitude scaling, source-depth scaling, and site effects. Regionalized components of the GMM include the model amplitude, anelastic attenuation, magnitude-scaling corner, V_{S30}-scaling, and sediment depth terms.

Aleatory variability models are developed that encompass both event types, with different coefficients for each IM. Models are provided for four components of ground-motion variability: (1) between-event variability, τ; (2) within-event variability, ϕ ; (3) single-station within-event variability, ϕ_{SS} ; and (4) site-to-site variability, ϕ_{S2S}. The aleatory variability models are magnitude independent. The within-event variability increases with distances beyond 200 km due to complexities in path effects at larger distances. Within-event variability is V_{S30}-dependent for distances less than 200 km, decreasing for softer soils with V_{S30} less than 500 m/sec. These reductions are attributed to soil nonlinearity. An ergodic analysis should use the median GMM and aleatory variability computed using the between-event and within-event variability models. An analysis incorporating non-ergodic site response (i.e., partially non-ergodic) should use the median GMM at the reference-rock shear-wave velocity (760 m/sec), a site-specific site amplification model, and aleatory variability computed using the between-event and single-station within-event variability models. Epistemic uncertainty in the median model is represented by standard deviation terms on region-dependent model constant terms, which facilitates scaled-backbone representations of model uncertainty in hazard analyses.

Model coefficients are available in the electronic supplement to this report (Tables E1–E4), and coded versions of the model are available in Excel, MatLab, R, and Python from Mazzoni et al. [2020(b)].

PEER 2020/04 *Partially Non-Ergodic Ground-Motion Model for Subduction Regions using the NGA-Subduction Database.* Nicolas Kuehn, Yousef Bozorgnia, Kenneth W. Campbell, and Nicholas Gregor. September 2020.

This report presents a summary of the development, evaluation, and comparison of a new subduction ground-motion model (GMM), now known as Kuehn-Bozorgnia-Campbell-Gregor (KBCG20) model. This GMM was developed as part of the Next Generation Attenuation for Subduction Regions (NGA-Sub) program using a comprehensive compilation of subduction interface and intraslab ground-motion recordings and metadata compiled in the NGA-Sub database. The KBCG20 model includes ground-motion scaling terms for magnitude, distance, site amplification, and basin amplification. Some of these terms are adjustable to accommodate differences between interface and intraslab earthquakes, and differences among seven subduction-zone regions for which data were compiled as part of the NGA-Sub program. These regions include Alaska (AK), Central America and Mexico (CAM), Cascadia (CASC), Japan (JP), New Zealand (NZ), South America (SA), and Taiwan (TW). Some of these regions are further divided into sub-regions to account for differences in anelastic attenuation between the subduction forearc and backarc, and differences in breakpoint magnitude (the magnitude at which magnitude scaling rate decreases) between segments of a larger subduction zone.

This study uses an innovative Bayesian regression approach to incorporate informative prior distributions of model coefficients and formally estimate the uncertainty in their posterior estimates. The posterior distributions of coefficients together with their co-variance matrix can be used to estimate epistemic uncertainty in the median ground-motion predictions for a given earth-quake scenario. Partial non-ergodicity was achieved by accounting for the regional differences in overall amplitude (constants) of prediction, anelastic attenuation, linear site amplification, and basin amplification. Because of the expanded database and innovative regression approach that includes median, aleatory variability, and epistemic uncertainty models, this new GMM represents a significant improvement in the understanding and prediction of subduction ground motion. Furthermore, the Bayesian approach used to develop the model will facilitate update of this innovative GMM as new data become available.

PEER 2020/05 *Conditional Ground-Motion Model for Peak Ground Velocity for Active Crustal Regions*. Norman A. Abrahamson and Sarabjot Bhasin. October 2020.

Conditional models for the horizontal and vertical peak ground velocity (*PGV*), given the pseudo-spectral acceleration [*PSA*(*T*)] values, are developed for active crustal regions. The period of the *PSA*(*T*) used in the conditional model, *T*(*PGV*), is magnitude dependent, which captures the effect of the magnitude dependence of the earthquake source corner frequency on the *PGV*. Conditional models can be used to estimate the *PGV* given a design spectrum and are applicable for magnitudes between 3.0 and 8.5, and for distances up to 200 km. The conditional *PGV* models can also be combined with appropriate GMMs for *PSA*(*T*) to develop traditional GMMs for *PGV* that are consistent with the more complex scaling included in the *PSA*(*T*) model. Unlike previous conditional *PGV* models, the slope on the *ln*[*PSA*(*T*)] term is allowed to be different from unity. With this feature, an appropriate aleatory standard deviation of the resulting *ln*(*PGV*) can be computed, avoiding the over-prediction of the aleatory standard deviation of the *PGV* seen in previous conditional *PGV* models.

PEER 2019/01 *Flow-Failure Case History of the Las Palmas, Chile, Tailings Dam.* R.E.S. Moss, T.R. Gebhart, D.J. Frost, and C. Ledezma. March 2019.

This report documents the flow failure of the Las Palmas tailings dam that was induced by the 27 February 2010 Maule Chile M8.8 earthquake. The Las Palmas site is located in Central Chile in Region VII near the town of Talca. Construction of the tailings dam occurred between 1998 as part of a gold mining operation and was no longer in active use. The ground shaking from the earthquake induced liquefaction of the saturated tailings material and resulted in a flow failure that ran out upwards of 350 m, flowing downslope in two directions. This report is broken into three sections: 1. A summary of the construction and flow failure of the Las Palmas tailings dam; 2. Details on the field investigations at the site, including the 2010 GEER reconnaissance, 2011 litigation support [DICTUC 2012], and the recent PEER–NGL-funded 2017 investigation; and 3. Back-analysis of the flow failure by Gebhart [2016] to estimate the residual strength. The goal of this work is to provide a "high-quality" flow-failure case history to augment the existing database. The existing database is composed of roughly thirty case histories of varying quality (e.g., Weber et al. [2015] and Kramer and Wang [2015]). Herein, the term "high-quality" means that the *in situ* measurements were made in a controlled and repeatable manner, and that the back-analysis of the residual strength was performed considering static and dynamic effects of the slide mass. The results from this research indicate that the median back-analyzed residual strength of the liquefied material is ~8.3 kPa (~173 psf) at a pre-earthquake vertical effective stress of 2 atm (~200 kpa or 4000 psf), which is correlated to a median SPT blow count of N1,60~2.5, a median CPT tip resistance of qc1~1.3 MPa, and a median shear-wave velocity of V_{S1}~172 m/sec. The back analyzed residual strength has a nominal coefficient of variation of 5.5% determined using a sensitivity analysis.

PEER 2019/02 *Direct-Finite-Element Method for Nonlinear Earthquake Analysis of Concrete Dams Including Dam–Water–Foundation Rock Interaction.* Arnkjell Løkke and Anil Chopra. March 2019.

Evaluating the seismic performance of concrete dams requires nonlinear dynamic analysis of two- or three-dimensional dam–water–foundation rock systems that include all the factors known to be significant in the earthquake response of dams. Such analyses are greatly complicated by interaction between the structure, the impounded reservoir and the deformable foundation rock that supports it, and the fact that the fluid and foundation domains extend to large distances. Presented in this report is the development of a direct finite-element (FE) method for nonlinear earthquake analysis of two- and three-dimensional dam–water–foundation rock systems. The analysis procedure applies standard viscous-damper absorbing boundaries to model the semi-unbounded fluid and foundation domains, and specifies at these boundaries effective earthquake forces determined from a ground motion defined at a control point on the ground surface.

This report is organized in three parts, with a common notation list, references, and appendices at the end of the report. Part I develops the direct FE method for 2D dam–water–foundation rock systems. The underlying analytical framework of treating dam–water–foundation rock interaction as a scattering problem, wherein the dam perturbs an assumed "free-field" state of the system, is presented, and by applying these concepts to a bounded FE model with viscous-damper boundaries to truncate the semi-unbounded domains, the analysis procedure is derived. Step-by-step procedures for computing effective earthquake forces from analysis of two 1D free-field systems are presented, and the procedure is validated by computing frequency response functions and transient response of an idealized dam–water–foundation rock system and comparing against independent benchmark results.

This direct FE method is generalized to 3D systems in Part II of this report. While the fundamental concepts of treating interaction as a scattering problem are similar for 2D and 3D systems, the derivation and implementation of the method for 3D systems is much more involved. Effective earthquake forces must now be computed by analyzing a set of 1D and 2D systems derived from the boundaries of the free-field systems, which requires extensive book-keeping and data transfer for large 3D models. To reduce these requirements and facilitate implementation of the direct FE method for 3D systems, convenient simplifications of the procedure are proposed and their effectiveness demonstrated.

Part III of the report proposes to use the direct FE method for conducting the large number of nonlinear response history analyses (RHAs) required for performance-based earthquake engineering (PBEE) of concrete dams, and discusses practical modeling considerations for two of the most influential aspects of these analyses: nonlinear mechanisms and energy dissipation (damping). The findings have broad implications for modeling of energy dissipation and calibration of damping values for concrete dam analyses. At the end of Part III, the direct FE method is implemented with a commercial FE program and used to compute the nonlinear response of an actual arch dam. These nonlinear results, although limited in their scope, demonstrate the capabilities and effectiveness of the direct FE method to compute the types of nonlinear engineering response quantities required for PBEE of concrete dams.

PEER 2019/03 *Ground-Motion Directivity Modeling for Seismic Hazard Applications.* Jennifer L. Donahue, Jonathan P. Stewart, Nicolas Gregor, and Yousef Bozorgnia. May 2019.

Executive Summary: We reviewed five models for modifying the natural log mean and within-event standard deviation of ground-motion models (GMMs) to account for directivity effects in the near-fault environment. We found broad consistency for strike–slip ruptures, with positive and negative directivity effects for cases of rupture towards and away from a site of interest, respectively. We found substantial divergence among directivity models for reverse slip, with some providing maximum directivity for sites positioned to experience the peak alignment of rupture direction with the fault-slip direction (this occurs in the up–dip direction), while others optimize directivity based on the amount of fault rupture towards the site (even if the azimuth of rupture propagation does not align with the fault-slip direction).

We found four of five NGA-West2 GMMs to be centered on a condition of null directivity. Therefore, we consider those GMMs suitable for use in combination with similarly centered directivity models.

We present two deterministic methods for adjusting ground-motion hazard results for the effects of directivity: one modifies ground motions for a specified hazard level based on location-specific (relative to fault) changes in mean and standard deviation; and the second produces a directivity-compatible conditional mean spectra. We also provide recommendations for incorporating directivity effects into calculations within the hazard integral by either (1) modifying the mean and standard deviation of ground motion to approximately account for the effect of variable hypocenter location; (2) integrating over a location-specific distribution of the directivity parameter, which also indirectly accounts for variable hypocenter location; or (3) integrating directly over alternate hypocenter locations.

PEER 2019/04 *Aftershock Seismic Vulnerability and Time-Dependent Risk Assessment of Bridges.* Sujith Mangalathu, Mehrdad Shokrabadi, and Henry V. Burton. May 2019.

The time-dependent seismic risk of bridges is assessed while account accounting for the effect of aftershocks and the uncertainty in the damage state after a mainshock event. To achieve this, a Markov risk-assessment framework is adopted to account for the probabilistic transition of the bridge structure through different damage states and time-dependent aftershock hazard. The methodology is applied to three typical California bridge configurations that differ only based on their era of design and construction. Era 11, Era 22, and Era 33 designations are used for the three bridges, which are designed and detailed to reflect pre-1971, 1971–1990 and post-1990 construction. In addition to mainshock-only evaluations (used as a benchmark to quantify the additional risk posed by aftershocks), pre-mainshock (to account for the uncertainty in the occurrence of mainshock and aftershock events) and post-mainshock (which are based on a conditioning mainshock event and bridge damage state) seismic risk assessments are performed. To support these assessments, a set of 34 pairs of ground motions from as-recorded mainshock–aftershock sequences is assembled. Sequential nonlinear response history analyses (including incremental dynamic analyses) are used to obtain the response demands when the structural models of all bridges are subjected to mainshock-only records or mainshock–aftershock record-pairs. Physical damage in both the mainshock and mainshock–aftershock environments is defined using the following mutually exclusive and collectively exhaustive limit states: Intact, Slight, Moderate, Extensive, and Complete. For both the pre- and post-mainshock assessments, the additional risk caused by aftershock hazard is found to be higher for the older bridges (i.e., Era 11 and Era 22) and more severe conditioning damage states. A direct correlation between the bridge's age and the increase in seismic risk due to aftershock hazard was also observed for the pre-mainshock assessment. It is suggested that the proposed methodology be used to make informed decisions regarding the appropriateness and timing of bridge closures (partial and complete) following a seismic event while considering aftershock hazard.

PEER 2019/05 *Expected Earthquake Performance of Buildings Designed to the California Building Code (California Alfred E. Alquist Seismic Safety Commission Publication 19-01),* Grace S. Kang, Sifat Muin, Jorge Archbold, Bitanoosh Woods, and Khalid Mosalam. July 2019.

The brochure explains the intent of the California Building Code, the expected performance of code-compliant new buildings when they are subjected to moderate and large earthquakes, possible consequences to residents, businesses, and communities, and initial proactive actions that can be taken.

"This publication combines information from the earthquake engineering community as well as policy and community officials, and it incorporates input from SSC's commissioners and staff, whose valuable feedback reflected their diverse range of expertise and experience," said Grace Kang, PEER Director of Communications. "The brochure is an educational tool intended to raise public awareness and provide basic information for decision-makers. It can be used to initiate and catalyze discussion."

The Alfred E. Alquist Seismic Safety Commission engaged the Pacific Earthquake Engineering Research Center (PEER) to develop and prepare the brochure to raise awareness and offer guidance on immediate and longer-term actions that can be taken by residents, businesses, and local and State representatives impacted by earthquakes.

Shaking from earthquakes is a fact of life. At least half of California's largest cities are at moderate or high risk of a major earthquake. The recent Ridgecrest Earthquake Sequence near Searles Valley is a wake-up call. The magnitude 6.4 foreshock and magnitude 7.1 main earthquakes produced the strongest shaking California has had in decades.

"The SSC believes it is critical to clarify what California building standards are and are not intended to provide in the way of life safety and building resiliency. California's standards are intended to reduce building collapse and provide life safety. The codes are not intended to ensure a building will be useable or even repairable after strong shaking. The SSC and its partners are starting this awareness program with buildings and the code, even though earthquake recovery involves many additional considerations," said Mike Gardner, SSC Chairman.

The brochure is a basic educational tool and is a synthesis of information from numerous sources including the earthquake engineering community, policy and community officials, SSC staff, and PEER.

PEER 2019/06 *Fluid-Structure Interaction and Python-Scripting Capabilities in OpenSees.* Minjie Zhu and Michael H. Scott. October 2019.

Building upon recent advances in OpenSees, the goals of this project are to expand the framework's Python scripting capabilities and to further develop its fluid–structure interaction (FSI) simulation capabilities, which are based on the particle finite-element method (PFEM). At its inception, the FSI modules in OpenSees were based on Python scripting. To accomplish FSI simulations in OpenSees, Python commands have been added for a limited number of pre-existing element and material commands, e.g., linear-elastic triangle elements and beam–column elements with `Concrete01/Steel01` fiber sections. Incorporation of hundreds of constitutive models and element formulations under the Python umbrella for FSI and general OpenSees use remain to be done. Although the original scripting language, Tcl, in OpenSees is string based, powerful, and easy to learn, it is not suitable for mathematical computations. Recent trends in scripting languages for engineering applications have embraced more general, scientific languages such as Python, which has evolved to a large community with numerous libraries for numerical computing, data analysis, scientific visualization, and web development. These libraries can be utilized with the FSI simulation for tsunami analysis. Extending OpenSees to Python will help OpenSees keep pace with new scripting developments from the scientific computing community and make the framework more accessible to graduate students, who likely have learned Python as undergraduates.

PEER 2019/07 *PEER Hub ImageNet (ϕ-Net): A Large-Scale Multi-Attribute Benchmark Dataset of Structural Images.* Yuqing Gao and Khalid M. Mosalam. March 2019.

In this data explosion epoch, data-driven structural health monitoring (SHM) and rapid damage assessment after natural hazards have become of great interest in civil engineering research. This report introduces deep-learning (DL) approaches and their application to structural engineering, such as post-disaster structural reconnaissance and vision-based SHM. Using DL in vision-based SHM is a relatively new research direction in civil engineering. As researchers begin to apply these concepts to structural engineering concerns, two critical issues remain to be addressed: (1) the lack of a uniform automated detection principle or framework based on domain knowledge; and (2) the lack of benchmark datasets with well-labeled large amounts of data.

To address the first issue, an automated and hierarchical framework has been proposed: the PHI-Net or *Ø*-Net for the PEER Hub Image-Net. This framework consists of eight basic benchmark detection tasks based on current domain knowledge and past reconnaissance experience. The second area of concern is based on the *Ø*-Net framework; a large number of structural images was collected, preprocessed, and labeled to form an open-source online large-scale multi-attribute image dataset, namely, the *Ø*-Net dataset. At the time of this writing, this dataset contains 36,413 images with multiple labels.

This report introduces herein three deep convolutional neuronal networks (CNN): VGG-16, VGG-19, and ResNet-50. The architecture design and network properties, etc., are described and discussed. For benchmarking purposes, a series of computer experiments are conducted. Multiple factors are considered in comparison studies under a fair setting of hyper-parameters and training approaches, i.e., using affine data augmentation (ADA) and transfer learning (TL). All experimental results are reported and discussed, which provide benchmark and reference values for future studies by other researchers developing new algorithms. These results reveal the great potential of using DL in vision-based SHM.

Finally, the first image-based challenge in structural engineering was held by the Pacific Earthquake Engineering Research (PEER) Center during the Fall of 2018. This challenge, designated as the Ø-Net Challenge, served as a pre-event prior to the open sourcing of the Ø-Net dataset and attracted worldwide attention and participation from researchers from around the globe.

PEER 2019/08 *Influence of Vertical Ground Motion on Bridges Isolated with Spherical Sliding Bearings.* Rushil Mojidra and Keri L. Ryan. February 2019.

The motivation for this project developed from testing of a full scale building isolated with triple friction pendulum bearings on the E-defense shake table in Japan. The test demonstrated experimentally that the vertical component of ground motion can amplify both the base shear and the story acceleration in the isolated building. Vertical shaking introduced high-frequency variation in the axial force of the bearings, and, consequently, a high-frequency component in the bearing lateral force, which excited higher structural modes in the building. Since vertical bridges are flexible in the vertical direction because of long spans, similar effects may be observed in bridges.

The objectives of this study are to develop a physical understanding of the amplification of responses and develop a simplified method to predict amplification of base shear in three-dimensional (3D) shaking relative to two-dimensional (2D) shaking, for bridges isolated with spherical sliding bearings. A series of ground motions with a wide range of vertical shaking intensity were applied to 3D models of bridges isolated with triple pendulum bearings (TPBs), both excluding the vertical component (2D motion) and including the vertical component (3D motion). This enabled the comparison of the bridge response under 2D and 3D shaking such that the direct effect of vertical shaking could be investigated. The selected ground motions were fit to target spectra in the horizontal and vertical directions, and divided into three groups based on vertical peak ground acceleration (PGAv). Multi-span concrete box girder bridges were selected for this study, as they are a prominent bridge type in California, and are suitable for seismic isolation. Models were developed for a 3-span, 45-ft wide, multi-column Base Model bridge; various superstructure and isolation-system parameter variations were implemented to evaluate the effect of these variations on the amplification of base shear. Response histories were compared for a representative motion from each ground-motion group under 2D and 3D shaking. Modal and spectral analyses were conducted to understand dynamic properties and behavior of the bridge under vertical motion. Based on simplified theory, a method to estimate the amplification of base shear due to vertical shaking was developed. The accuracy of the simplified method was assessed through a base shear normalized error metric, and different amplification factors were considered.

Response history analysis showed significant amplification of base shear under 3D motion implying that exclusion of vertical component could lead to under estimation of demand shear forces on bridge piers. Deck acceleration spectral response at different locations revealed that a transverse-vertical modal coupling response was present in the Base Model bridge, which led to amplification of deck accelerations in addition to base shear due to excitation of the superstructure transverse mode. The simplified method predicted that in addition to the peak vertical ground acceleration base shear amplification depended on the isolation-system period (radius of curvature) and friction coefficient. The error in the simplified method was approximately constant across the range of isolation-system parameters. Variations in the bridge superstructure or substructure modeling parameters had only a minor effect on the base shear since the deck acts as a single mass sliding on isolators; therefore, the simplified method can be applied to a range of bridge models. The simplified method includes an amplification factor that indirectly represents the dynamic amplification of vertical acceleration from the ground to the isolation system. An amplification factor of 1.0 was found to be sufficiently conservative to estimate the base shear due to 3D shaking. The lack of apparent dynamic amplification could mean that the peak vertical acceleration is out-of-phase with the base shear. The simplified method is more likely to be unconservative for high-intensity vertical ground motions due to the complexities associated with uplift and pounding. Further investigation is recommended to determine the threshold shaking intensity limit for the simplified method.

PEER 2019/09 *Seismic Behavior of Special Concentric Braced Frames under Short- and Long-Duration Ground Motions.* Ali Hammad and Mohamed A. Moustafa. March 2019.

Over the past decade, several long-duration subduction earthquakes took place in different locations around the world, e.g., Chile in 2010, Japan in 2011, China in 2008, and Indonesia in 2004. Recent research has revealed that long-duration, large-magnitude earthquakes may occur along the Cascadia subduction zone of the Pacific Northwest Coast of the U.S. The duration of an earthquake often affects the response of structures. Current seismic design specifications mostly use response spectra to identify the hazard and do not consider duration effects. Thus, a comprehensive understanding of the effect of the duration of the ground motion on structural performance and its design implications is an important issue.

The goal of this study was to investigate how the duration of an earthquake affects the structural response of special concentric braced frames (SCBFs). A comprehensive experimental program and detailed analytical investigations were conducted to understand and quantify the effect of duration on collapse capacity of SCBFs, with the goal of improving seismic design provisions by incorporating these effects. The experimental program included large-scale shake table tests, and the analytical program consisted of pre-test and post-test phases. The pre-test analysis phase performed a sensitivity analysis that used OpenSees models preliminarily calibrated against previous experimental results for different configuration of SCBFs. A tornado-diagram framework was used to rank the influence of the different modeling parameters, e.g., low-cycle fatigue, on the seismic response of SCBFs under short- and long-duration ground motions. Based on the results obtained from the experimental program, these models were revisited for further calibration and validation in the post-test analysis.

The experimental program included three large-scale shake-table tests of identical single-story single-bay SCBF with a chevron-brace configuration tested under different ground motions. Two specimens were tested under a set of spectrally matched short and long-duration ground motions. The third specimen was tested under another long-duration ground motion. All tests started with a 100% scale of the selected ground motions; testing continued with an ever-increasing ground-motion scale until failure occurred, e.g., until both braces ruptured. The shake table tests showed that the duration of the earthquake may lead to premature seismic failure or lower capacities, supporting the initiative to consider duration effects as part of the seismic design provisions. Identical frames failed at different displacements demands because of the damage accumulation associated with the earthquake duration, with about 40% reduction in the displacement capacity of the two specimens tested under long-duration earthquakes versus the short-duration one.

Post-test analysis focused first on calibrating an OpenSees model to capture the experimental behavior of the test specimens. The calibration started by matching the initial stiffness and overall global response. Next, the low-cycle fatigue parameters were fine-tuned to properly capture the experimental local behavior, i.e., brace buckling and rupture. The post-test analysis showed that the input for the low-cycle fatigue models currently available in the literature does not reflect the observed experimental results. New values for the fatigue parameters are suggested herein based on the results of the three shake-table tests.

The calibrated model was then used to conduct incremental dynamic analysis (IDA) using 44 pairs of spectrally matched short- and long-duration ground motions. To compare the effect of the duration of ground motion, this analysis aimed at incorporating ground-motion variability for more generalized observations and developing collapse fragility curves using different intensity measures (IMs). The difference in the median fragility was found to be 45% in the drift capacity at failure and about 10% in the spectral acceleration (S_a). Using regression analysis, the obtained drift capacity from analysis was found to be reduced by about 8% on average for every additional 10 sec in the duration of the ground motion.

The last stage of this study extended the calibrated model to SCBF archetype buildings to study the effect of the duration of ground motion on full-sized structures. Two buildings were studied: a three-story and nine-story build that resembled the original SAC buildings but were modified with SCBFs as lateral support system instead of moment resisting frames. Two planer frames were adopted from the two buildings and used for the analysis. The same 44 spectrally matched pairs previously used in post-test analysis were used to conduct nonlinear time history analysis and study the effect of duration. All the ground motions were scaled to two hazard levels for the deterministic time history analysis: 10% exceedance in 50 years and 2% exceedance in 50 years. All analysis results were interpreted in a comparative way to isolate the effect of duration, which was the main variable in the ground-motion pairs. In general, the results showed that the analyzed SCBFs experienced higher drift values under the long-duration suite of ground motions, and, in turn, a larger percentage of fractured braces under long-duration cases. The archetype SCBFs analysis provided similar conclusions on duration effects as the experimental and numerical results on the single-story single-bay frame.

PEER 2018/01 *PEER Annual Report, 2017–2018.* June 2018.

This report was prepared by PEER staff, led by Khalid Mosalam, Amarnath Kasalanati, and Selim Günay. It contains a summary of research, educational and outreach activities at the PEER Center from July 2017 to June 2018. This report presents the activities of the Center over the period of July 1, 2017 to June 30, 2018. PEER staff, in particular Grace Kang, Erika Donald, Claire Johnson, Christina Bodnar-Anderson, and Zulema Lara, helped in preparation of this report. Key activities of the past academic year include the following:

1. Continuation of major projects such as Tall Building Initiative (TBI) and Next Generation Attenuation (NGA) projects, and start of work on the major project funded by the California

Earthquake Authority (CEA). The TBI was completed in 2017, and NGA projects are nearing completion soon.

2. Addition of University of Nevada, Reno (UNR) as a core institution.
3. Re-establishment of the PEER Research Committee.
4. Issuing a Request for Proposal (RFP) from TSRP funds and funding 17 projects as a result of this RFP. Together with the ongoing projects, the total number of projects funded in 2017 is 24.
5. Organization of several workshops focused on Liquefaction, Structural Health Monitoring (SHM), High-Performance Computing (HPC), Bridge Component Fragility Development, Physics-Based Ground Motions, Hybrid Simulation, and Research Needs for Resilient Buildings.
6. Rollout of TBI seminars and HayWired activities as part of outreach.
7. Conducting a blind prediction contest with robust participation and instructive findings on current modeling approaches.
8. Organization of the PEER Annual Meeting with participation of 240 attendees.
9. Continuing participation in board of directors of international organizations such as Global Alliance of Disaster Research Institutes (GADRI) and International Laboratory of Earthquake Engineering (ILEE).

Going forward, PEER aims to hold more focused workshops, form new committees, and draw on existing resources and experience on PBE to systematically move towards Resilient Design for Extreme Events (RDEE).

PEER 2018/02 *Update of the BC Hydro Subduction Ground-Motion Model using the NGA-Subduction Dataset.* Norman Abrahamson, Nicolas Kuehn, Zeynep Gulerce, Nicholas Gregor, Yousef Bozorgnia, Grace Parker, Jonathan Stewart, Brian Chiou, I.M. Idriss, Kenneth Campbell, and Robert Youngs. June 2018.

An update to the BCHydro ground-motion model for subduction earthquakes has been developed using the 2018 PEER NGA-SUB dataset. The selected subset includes over 70,000 recordings from 1880 earthquakes. The update modifies the BCHydro model to include regional terms for the VS30 scaling, large distance (linear R) scaling, and constant terms, which is consistent with the regionalization approach used in the NGA-W2 ground-motion models. A total of six regions were considered: Cascadia, Central America, Japan, New Zealand, South America, and Taiwan. Region-independent terms are used for the small-magnitude scaling, geometrical spreading, depth to top of rupture (Z_{TOR}) scaling, and slab/interface scaling. The break in the magnitude scaling at large magnitudes for slab earthquakes is based on thickness of the slab and is subduction-zone dependent. The magnitude scaling for large magnitudes is constrained based on finite-fault simulations as given in the 2016 BCHydro model. Nonlinear site response is also constrained to be the same as the 2016 BCHydro model. The sparse ground-motion data from Cascadia show a factor of 2–3 lower ground motions than for other regions. Without a sound physical basis for this large reduction, the Cascadia model is adjusted to be consistent with the average from all regions for the center range of the data: M = 6.5, R= 100 km, V_{S30} = 400 m/sec. Epistemic uncertainty is included using the scaled backbone approach, with high and low models based on the range of average ground motions for the different regions. For the Cascadia region, the ground-motion model is considered applicable to distance up to 1000 km, magnitudes of 5.0 to 9.5, and periods from 0 to 10 sec. The intended use of this update is to provide an improved ground-motion model for consideration for use in the development of updated U.S. national hazard maps. This update ground-motion model will be superseded by the NGA-SUB ground-motion model when they are completed

PEER 2018/03 *Probabilistic Seismic Hazard Analysis Code Verification.* Christie Hale, Norman Abrahamson, and Yousef Bozorgnia. July 2018.

Over the past decade, the use of Probabilistic Seismic Hazard Analysis (PSHA) to assess seismic hazards has expanded, leading to the creation of a number of new PSHA computer codes throughout the industry. Additionally, recent seismic source and ground-motion characterization studies have led to more complex source and ground-motion models, which necessitate implementation in PSHA codes. This project was undertaken to update previous PSHA computer code verification efforts by running an expanded set of verification tests on codes currently in use for PSHA calculations. Following an announcement to the community, fifteen owners of PSHA codes from private consulting companies, academic institutions, risk analysis firms, and government agencies participated in the verification project by running verification tests on their own codes. The project included three sets of tests that increased in complexity from the first test in Set 1 to the last test in Set 3. Over the course of the project the group held ten meetings to discuss and finalize the results. Tests were often re-run several times before the results for all codes were finalized. This report documents the specifications and benchmark answers for the verification tests. Common issues and programming errors are also summarized, along with standard modeling approaches and key discussion points from the meetings. Where differences in modeling approaches lead to differences in reported hazard, those different modeling approaches are described. Through participation in the project, code owners verified the primary functions of their codes as benchmark answers were reached. The PSHA codes developed in the future can be verified by running the tests and comparing the results to the benchmark answers documented in this report. Note: the scope of this project is PSHA computer code verification. This project does not make recommendations on how to model earthquake scenarios from the specified source-characterization or ground-motion characterization inputs.

PEER 2018/04 *Capturing Directivity Effects in the Mean and Aleatory Variability of the NGA-West2 Ground-Motion Prediction Equations.* Jennie A. Watson-Lamprey. November 2018.

We expect there to be locations around a rupture that experience both positive and negative directivity effects more than others. The concept was to develop a simple model of additional mean and standard deviation to add to existing published ground motion prediction equations to account for this. The directivity effect predicted by Chiou and Youngs [2014] using the directivity parameter DPP [Spudich et al. 2013] was selected as the basis for the model. A suite of rupture geometries for strike-slip and reverse ruptures was generated and the mean and standard deviation of the change in the 5% damped pseudo-spectral acceleration at sites out to rupture distances of 70 km was calculated. Models are presented for the change in mean and standard deviation for both strike-slip and reverse ruptures that use only simple parameters as inputs.

PEER 2018/05 *Selection of Random Vibration Procedures for the NGA-East Project.* Albert Kottke, Norman A. Abrahamson, David M. Boore, Yousef Bozorgnia, Christine Goulet, Justin Hollenback, Tadahiro Kishida, Armen Der Kiureghian, Olga-Joan Ktenidou, Nicolas Kuehn, Ellen M. Rathje, Walter J. Silva, Eric Thompson, and Xiaoyue Wang. December 2018.

Pseudo-spectral acceleration (PSA) is the most commonly used intensity measure in earthquake engineering as it serves as a simple approximate predictor of structural response for many types of systems. Therefore, most ground-motion models (GMMs, aka GMPEs) provide median and standard deviation PSA using a suite of input parameters characterizing the source, path, and site effects. Unfortunately, PSA is a complex metric: the PSA for a single oscillator frequency depends on the Fourier amplitudes across a range of frequencies. The Fourier amplitude spectrum (FAS) is an appealing alternative because its simple linear superposition allows effects to be modeled as transfer functions. For this reason, most seismological models, i.e., the source spectrum, are developed for the FAS. Using FAS in conjunction with random-vibration theory (RVT) allows GMM developers to superimpose seismological models directly, computing PSA only at the end of the process. The FAS-RVT-PSA approach was first used by the Hollenback et al. team in their development of GMMs for the Next Generation Attenuation Relationships for Central & Eastern North America (NGA-East) project (see Chapter 11 of PEER Report No. 2015/04). As part of the NGA-East project to support the Hollenback et al. team and similar efforts, the current report summarizes a systematic processing algorithm for FAS that minimizes computational requirements and bias that results from the RVT approximation for median GMM development.

PEER 2018/06 *Estimation of Shear Demands on Rock Socketed Drilled Shafts subjected to Lateral Loading.* Pedro Arduino, Long Chen, and Christopher R. McGann. December 2018.

This report presents results of an evaluation study on the applicability of current design procedures(based on p-y curves) to the analysis of large-diameter shafts socketed in rock, and the identification of enhanced moment transfer mechanisms not considered in current design methodologies. For this purpose, simplified models, and possible three-dimensional (3D) finite-element method (FEM) models are studied to shed some light on the response of drilled shafts socketed in rock. A parametric study using p-y and considering a wide range of rock properties and rock-socket depths, different criteria to define the soil and rock p-y curves, different beam theories, and different inter-face frictional resistances are presented and compared with 3D FEM simulations. A new element is discussed to account for the shaft toe and underlain rock interaction, which could provide benefit to reduce shear demands when the socket is shallow.

PEER 2018/07 *An Empirical Model for Fourier Amplitude Spectra using the NGA-West2 Database.* Jeff Bayless and Norman A. Abrahamson. December 2018.

An empirical ground-motion model (GMM) for shallow crustal earthquakes in California and Nevada based on the NGA-West2 database [Ancheta et al. 2014] is presented. Rather than the traditional response spectrum GMM, this model is developed for the smoothed effective amplitude spectrum (EAS) as defined by PEER [Goulet et al. 2018]. The EAS is the orientation-independent horizontal component Fourier amplitude spectrum (FAS) of ground acceleration. The model is developed using a database dominated by California earthquakes, but takes advantage of crustal earthquake data worldwide to constrain the magnitude scaling and geometric spreading. The near-fault saturation is guided by finite-fault numerical simulations and non-linear site amplification is incorporated using a modified version of Hashash et al. [2018]. The model is applicable for rupture distances of 0–300 km, M 3.0 – 8.0, and over the frequency range 0.1–100 Hz. The model is considered applicable for V_{S30} in the range 180–1500 m/sec, although it is not well constrained for V_{S30} values greater than 1000 m/sec. Models for the median and the aleatory variability of the EAS are developed. Regional models for Japan and Taiwan will be developed in a future update of the model. A MATLAB program that implements the EAS GMM is provided as an electronic appendix.

PEER 2018/08 *Central and Eastern North America Ground-Motion Characterization - NGA-East Final Report.* Christine Goulet, Yousef Bozorgnia, Norman Abrahamson, Nicolas Kuehn, Linda Al Atik, Robert Youngs, and Robert Graves. December 2018.

This document is the final project report of the Next Generation Attenuation for Central and Eastern North America (CENA) project (NGA-East). The NGA-East objective was to develop a new ground-motion characterization (GMC) model for the CENA region. The GMC model consists of a set of new ground-motion models(GMMs) for median and standard deviation of ground motions and their associated weights to be used with logic-trees in probabilistic seismic hazard analyses (PSHA).NGA-East is a large multidisciplinary project coordinated by the Pacific Earthquake Engineering Research Center (PEER), at the University of California. The project has two components: (1) a set of scientific research tasks, and (2) a model-building component following the framework of the "Seismic Senior Hazard Analysis Committee (SSHAC) Level 3" (Budnitz et al. 1997; NRC 2012). Component (2) is built on the scientific results of component (1) of the NGA-East project. This report documents the tasks under component (2) of the project. Under component (1) of NGA-East, several scientific issues were addressed, including: (a) development of a new database of ground motion data recorded in CENA; (b) development of a regionalized ground-motion map for CENA, (c) definition of the reference site condition; (d) simulations of ground motions based on different methodologies; and (e) development of numerous GMMs for CENA. The scientific tasks of NGA-East were all documented as a series of PEER reports. The scope of component (2) of NGA-East was to develop the complete GMC. This component was designed as a SSHAC Level 3 study with the goal of capturing the ground motions' center, body, and range of the technically defensible interpretations in light of the available data and models. The SSHAC process involves four key tasks: evaluation, integration, formal review by the Participatory Peer Review Panel (PPRP), and documentation (this report).Key tasks documented in this report include review and evaluation of the empirical ground-motion database, the regionalization of ground motions, and screening sets of candidate GMMs. These are followed by the development of new median and standard deviation GMMs, the development of new analyses tools for quantifying the epistemic uncertainty in ground motions, and the documentation of implementation guidelines of the complete GMC for PSHA computations. Appendices include further documentation of the relevant SSHAC process and additional supporting technical documentation of numerous sensitivity analyses results. The PEER reports documenting component (1) of NGA-East are also considered “attachments” to the current report and are all available online on the PEER website (https://peer.berkeley.edu/).The final NGA-East GMC model includes a set of 17 GMMs defined for 24 ground-motion intensity measures, applicable to CENA in the moment magnitude range of 4.0 to 8.2 and covering distances up to 1500 km. Standard deviation models are also provided for site-specific analysis (single-station standard deviation) and for general PSHA applications (ergodic standard deviation). Adjustment factors are provided for consideration of source-depth effects and hanging-wall effects, as well as for hazard computations at sites in the Gulf Coast region.

4 Events and Outreach Activities

PEER organized several events and was involved in numerous outreach activities in the past two years. PEER researchers were active participants in workshops, RFPs, blind prediction contests, and responded to earthquakes around the world. Several students participated in PEER summer internship program. Highlights of the outreach activities are presented in the following sections.

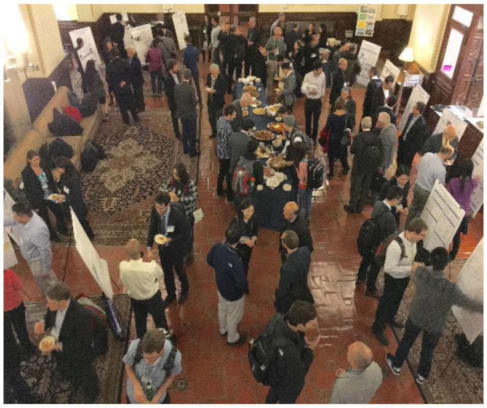
Activities in 2019–2020

4.1 2019 PEER RESEARCHERS' WORKSHOP

The PEER Researchers' Workshop was held on August 26–27, 2019, at UC Berkeley's Richmond Field Station. The meeting was well attended with approximately 50 participants from PEER core institutions and from the PEER BIP program. The meeting was also hosted as a web-conference for researchers who could not attend in person. Twenty PEER-funded projects were presented, and four projects with collaborative organizations were also presented.

The Researchers' Workshop provides a forum for in-progress reporting of PEER-funded projects. The comments and discussion between presenters and the audience created the opportunity to share insight and additional resources available on the research topics. The program ended with a panel and open discussion about research needs and funding sources for large, multi-institutional projects.

4.2 PEER BUSINESS INDUSTRY PARTNERSHIP (BIP) PROGRAM



BIP – Information Exchange

Industry and government partners have been an integral part of the research program at PEER. The PEER Business and Industry Partnership (BIP) Program engages industry members in PEER research and education programs, and provides access to PEER researchers, students, and products. Selected BIP representatives are the members of the Industry Advisory Board (IAB). This board advises PEER on current and future research needs as seen from the industry point-of-view, implementation of research results, and new opportunities to explore. More details of the IAB are provided in Section 6.4.

Over the past few years, PEER has been focusing on increasing the depth and breadth of its BIP program and developing extended ties with the structural firms and state and federal government agencies. Six new members, representing a wide range of expertise, joined the PEER BIP Program in the past year: BART, MIDAS Software, Hinman Engineers, SC Solutions, ARUP, and SLATE Geotechnical Consultants. Below is a listing of current members:

Sponsors:

- State of California
- California Department of Conservation
- California Department of Transportation (Caltrans)
- California Earthquake Authority (CEA)
- California Energy Commission (CEC)
- California Seismic Safety Commission
- College of Engineering, UC Berkeley

Annual Members:

- MIDAS Software
- Degenkolb Engineers
- Forell/Elsesser Engineers, Inc.
- Hinman Engineers
- Holmes Structures
- IHI Corporation
- SC Solutions
- ARUP
- Arx-Pax
- Bechtel Corporation
- Exponent
- FM Global

- Gannett Fleming
- Micron Optics
- SLATE Geotechnical Consultants
- Skidmore, Owings & Merrill LLP
- Walter P Moore
- Wiss, Janney, Elstner Associates, Inc.

The BIP program is a gift-based program. Funds are used to support PEER's outreach, technology transfer efforts, and to waive student registration fees for the Annual Meeting. The tiered membership program is designed to fit every firm's interests and budget, and is outlined on the attached PEER BIP Program website.

4.3 REQUEST FOR PROPOSAL: SOLICITATION TSRP-PEER 19-01

PEER has continuing funding from the State of California related to the seismic performance of transportation systems. This funding supports the Transportation Systems Research Program (TSRP)[1], the purpose of which is to lessen the impacts of earthquakes on the transportation systems of California, including highways and bridges, port facilities, high-speed rail, airports, and other related structures. In September 2019, PEER issued a request for proposals, Solicitation PEER TSRP 19-01[2] , for one- and two-year projects aligned with the current TSRP research priorities and vision.

In response to Solicitation PEER TSRP 19-01, 44 proposals were received. Each proposal received at least two independent reviews from a pool of more than two dozen reviewers. Based on the priorities of the pre-set TSRP vision, pre-defined evaluation criteria specified in the RFP and factors such as the level of engagement with the PEER core institutes; 14 new projects were approved, comprising a total funding of $1.2 million, with the first-year funding at nearly $740,000.

The following is a list of the 14 funded projects, including six multi-institution collaborative projects. PEER thanks all of the PIs who submitted proposals and also thanks the efforts and detailed feedback from the reviewers.

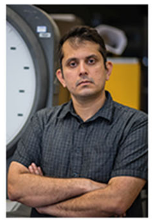
[1] *https://peer.berkeley.edu/research/transportation-systems*.
[2] *https://peer.berkeley.edu/research/transportation-systems/request-proposals*.

Title: A3: Fire Performance of Steel-Frame Buildings using OpenSees
PI: Erica Fisher, OSU

Title: A3: Leveraging Leading Indicators for Wildfire Risk Reduction **PI:** Rune Storesund, UC Berkeley **Co-PIs:** Karlene Roberts, UC Berkeley

Title: M1: Probabilistic Simulation-Based Evaluation of the Effect of Near-Field Spatially Varying Ground Motions on Distributed Infrastructure Systems
PI: Floriana Petrone, UNR, **Co-PIs:** Norm Abrahamson, UC Berkeley; David McCallen, UNR

Title: M2: A Pacific Rim Forum on Regional-Scale Simulations of Earthquake Ground Motions and Infrastructure Response for PBEE of Transportation Systems, **PI:** David McCallen, UNR, **Co-PIs:** Norm Abrahamson, UC Berkeley; Floriana Petrone, UNR



Title: S1, T2, T5: Fracture of Deficient Steel Details in Pre-Northridge Transportation Infrastructure Structures
PI: Amit Kanvinde, UC Davis
Collaborators: James Malley and Robert Pekelnicky, Degenkolb

Title: S2: Ground Improvement-Based Protection of Transportation Infrastructure: Validation of PBE via Centrifuge and Numerical Modeling
PI: Tara Hutchinson, UC San Diego, **Co-PI:** John McCartney, UC San Diego

Title: S3: Performance Based Economic Loss Assessment Due to a Hypothetical Large Southern Earthquake based on the Disruption and Recovery of Port of Los Angeles Freight Traffic
PI: Ertugrul Taciroglu, UC Los Angeles, **Co-PI:** Kenichi Soga, UC Berkeley

Title: T1, T2: Workshop of Pre- and Post-processing Tools for OpenSees
PI: Frank McKenna, UC Berkeley
Co-PIs: Filip Filippou, UC Berkeley; Joel Conte, UC San Diego

Title: T1: A Comprehensive Database of RC Column Tests
PI: John Wallace, UC Los Angeles

Title: T1: Text Analytics on Social Media for Resilience-Enabled Extreme Events Reconnaissance
PI: Laurent El Ghaoui, UC Berkeley

Title: T2: Meshfree Large-Strain Framework for Seismic Response of Ground-Structural Systems: Development and Open Source Tool
PI: Ahmed Elgamal, UC San Diego **Co-PI:** Jiun-Shyan Chen, UC San Diego

Title: T2: OpenSees Implementation of 3D Embedded Pile Element for Enhance Soil-Pile Interaction Analysis of Bridge Systems Subject to Liquefaction and Lateral Spreading
PI: Pedro Arduino, UW

Title: T2: Reduced-Order Models for Dynamic Soil-Structure Interaction Analyses of Buried Structures
PI: Domniki Asimaki, Caltech
Co-PI: Elnaz Seylabi, UNR

Title: T4: Identification of Transportation Network Corridors, for Enhancing Network Resilience
PI: Jack Baker, Stanford

4.4 2020 PEER ANNUAL MEETING

The PEER Annual Meeting 2020 with the theme of "The Future of Performance-Based Natural Hazards Engineering" was held on January 16 and 17, 2020. Tsu-Jae King Liu, Dean of Engineering at UC Berkeley, opened the meeting highlighting the contributions of PEER since its inception 23 years ago. PEER Director Khalid Mosalam presented an overview of the Center's activities to lead off the opening plenary "Future of PBE for Community Resilience" moderated by Jonathan Bray. Subsequently, Norman Abrahamson, Saiid Saiidi, and Ron Klemencic discussed the future of Geo-Hazards, Transportation Systems and Tall Buildings respectively.

The second plenary "Emerging Technologies for Future Cities" was moderated by Gregory Deierlein and featured presentations by Richard Allen, Susan Owen, and Brian Strong. These speakers focused on early earthquake warning systems, use of satellite radar imagery for disaster response, and programs for a resilient San Francisco, respectively. The first day's lunch special presentation was by Judith Mitrani-Reiser on Disaster Measurement Science.

The afternoon of Day 1 focused on Modeling & Simulation. Plenary 3 "Modeling of Distributed Systems" was moderated by Tom Shantz and featured presentations that looked beyond individual facilities to systems and regional-scale applications. Bruce Johnson discussed State DOT seismic resiliency programs and Maha Kenawy presented on regional collapse risk. Two complementary talks on resiliency by Jack Baker and Božidar Stojadinović focused on regional post-earthquake recovery and interdependent infrastructure systems.

Plenary 4 was on "Simulation Platforms" moderated by Keri Ryan. Michael Scott put forward an argument for using Python to enhance simulation and Arthur Rodgers discussed the future of ground motion simulation. Sanjay Govindjee outlined the SimCenter tools, and Jong Sung Lee provided details of IN-CORE.

After the session, the winners of Rocking Column Blind Prediction Contest (Chiyun Zhong and Constantin Christopoulos) were announced. Subsequently, poster session featuring work of 45 students was held at the University Club at the California Memorial Stadium.

Tom Shantz, Caltrans, 2020 PEER Annual Meeting Moderator

Arthur Rodgers, Lawrence Livermore National Lab, 2020 PEER Annual Meeting Presenter

Blind Prediction Contest Winners: Chiyun Zhong and Constantin Christopoulos

Day 2 started with Plenary 5 "Resilience by Reconnaissance" moderated by Khalid Mosalam and focused on a variety of hazards. StEERteam leaders Tracy Kijewski-Correa, David Prevatt, and David Roueche summarized the benefits of coordinated reconnaissance for several recent events. Venkatesh Kodur provided a look at condition assessment of fire damaged structures, and Patrick Lynett focused on building resilience against tsunami hazard.

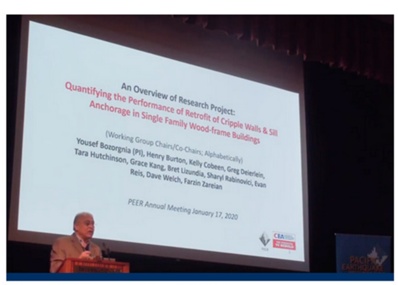
Three concurrent sessions followed this plenary. Concurrent session C1 was on Geo-Hazards moderated by Norman Abrahamson and Tom Shantz, and featured presentations by Norman Abrahamson, Nicholas Sitar, Ahmed Elgamal, and Yousef Bozorgnia. Topics included non-ergodic ground-motion model for California, DEM modeling of influence of depositional fabric using XRT data, shake-table tests to investigate soil-pile-interaction during liquefaction, and the NGA subduction zone project.

Concurrent session C2 was on Bridges & Transportation moderated by Ian Buckle and had presentations by John Stanton, Denis Istrati, Amit Kanvinde, and Farzin Zareian. Presentations included seismic evaluation of California high-speed rail systems, tsunami loads on skewed bridges, base connections for moment-frame structures, and physics-based ground motions.

Concurrent session C3 was a focused session on the PEER-CEA wood-frame project moderated by Janiele Maffei with presentations by Yousef Bozorgnia, Evan Reis, David Welch, and Sharyl Rabinovici. They covered different aspects the project: an overview, comparison with insurance loss models, numerical simulations, and communicating brace & bolt benefit of the CEA program .

Day 2 lunch presentation was by Thomas O'Rourke on change agents for resilient infrastructure.

Tracy Kijewski-Correa, University of Notre Dame



Yousef Bozorgnia, UCLA

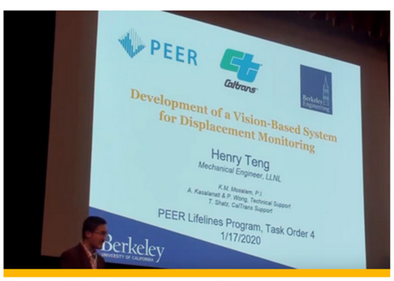
Lunch Presentation, Thomas O'Rourke, Cornell University

The afternoon of the second day began with Concurrent Session C4 on Geo Hazards moderated by Scott Brandenberg, and featured presentations by Paolo Zimmaro, Daniel Hutabarat and Jonathan Bray, Ramin Motamed, and Adda Athanasopoulos-Zekkos. Topics included next generation liquefaction: a community discussion, effective stress analysis to evaluate ejecta severity and sand and silty sites, large-scale shake table testing on the effectiveness of helical piles to mitigate liquefaction-induced building settlements, and recent advances in the liquefaction assessment of gravelly soils.

Concurrent Session C5 was on Structures - Experimental Methods moderated by Sashi Kunnath and had presentations by Ian Buckle, Daniel Miller and Diego De la Mora, Mohamed Moustafa, and Khalid Mosalam. Presentations included pre-test planning for experimental studies on tsunami-borne debris loads on bridges, behavior of bridge arches under high axial loads, shake table tests of RC bridge columns with conventional and high-strength steel under long duration earthquakes, and system level performance evaluation of new designs of bridge bents using hybrid simulation.

Concurrent Session C6 focused on Sensors & Data Interpretation and was moderated by Farzin Zareian with presentations by Eduardo Miranda, Henry Teng, Ertugrul Taciroglu, and Matt DeJong. Topics included instrumented structures an opportunity to learn about seismic response and to validate our models, laser-based displacement sensors for settlement monitoring, on the use of digital twins for structural health and performance monitoring and rapid post-event assessment, and fiber optic monitoring of building settlement and bridge degradation.

The 2020 PEER Annual Meeting concluded with Plenary 6 moderated by Mason Walters and featured presentations on the future direction of PEER. David McCallen discussed advancements in high performance computing and opportunities for applications in the PEER research community, while Charles Scawthorn offered a new perspective on risk analysis. Greg Deierlein provided the final technical presentation on opportunities and challenges in high-fidelity simulation of disaster recovery and Karl Van Bibber offered the closing remarks on PEER Annual Meeting 2018.



Henry Teng, Lawrence Livermore National Laboratory


Ian Buckle, UNR

David McCallen, UNR and LBNL

The Steering Committee of the 2020 PEER Annual Meeting consisted of: Gregory Deierlein, Grace Kang, Amarnath Kasalanati, Dawn Lehman, Khalid Mosalam, Keri Ryan, and Tom Shantz. Presentations and videos from the PEER Annual Meeting are posted at *https://peer.berkeley.edu/news-and-events/2020-peer-annual-meeting/program*.

4.5 2019 PEER BLIND PREDICTION COMPETITION

Chiyun Zhong (center), of University of Toronto, receiving the first-place award from Selim Günay (left) and PEER Director Khalid Mosalam (right).

PEER organized a blind prediction contest[3] to predict the maximum bi-directional response of a four-column rocking podium structure excited by 200 artificial ground motions on a shaking table. The structure was designed by an ETH Zurich team led by Professor Michalis Vassiliou and Professor Bozidar Stojadinovic. The tests were conducted using the six degree-of-freedom shaking table located at the Earthquake and Large Structures Laboratory at the University of Bristol.

Daniele Malomo (center) of UC Berkeley, receiving the second-place award from Prof. Bozidar Stojadinovic (left) and Prof. Michalis Vassiliou (right).

Tests were supervised by Professor George Mylonakis and Professor Anastasios Sextos under the SERA transnational access project "3DROCK: Statistical Verification and Validation of 3D Seismic Rocking Motion Models." The PEER organizing team included Selim Günay, UC Berkeley. Thirteen teams with contestants from 10 different countries submitted entries by November 20, 2019. Competition winners were announced at the 2020 PEER Annual Meeting, January 16–17, 2020. Based on the contest criteria, the team of Chiyun Zhong and Constantin Christopoulos of University of Toronto, Department of Civil & Mineral Engineering, was recognized for having the best overall prediction. The second-place team was Daniele Malomo, Anjali Mehrotra, and Matthew DeJong of UC Berkeley, Department of Civil and Environmental Engineering.

4.6 2019 SUMMER INTERNSHIP PROGRAM

The Pacific Earthquake Engineering Research Center is pleased to offer exciting opportunities for students to explore new directions in earthquake engineering studies and research. Last summer, the PEER Internship Program provided a unique opportunity for two outstanding undergraduate students from the Universidad del Norte (UNINORTE) to participate in state-of-the-art research. Internship participants are paired with a faculty advisor and a graduate student mentor. Students learned how to conduct independent research and had the opportunity to participate as a member

[3] *https://peer.berkeley.edu/news-and-events/2019-blind-prediction-contest.*

Veronica Jesus Abuchar Soton
Pedro Javier Gonzalez Prado

of a research team. PEER welcomed 2019 Summer Interns Veronica Jesus Abuchar Soton and Pedro Javier Gonzalez Prado.

Veronica worked on a project to fit the typology of reinforced concrete frames with unreinforced masonry infill walls into the PEER performance-based engineering methodology. She worked with Jorge Archbold, Ph.D. candidate, and Professor Khalid Mosalam. She also received training on a PEER lab ballistic apparatus and worked on a safety protocol document.

Pedro investigated the behavior of small-scale concrete beams with minimum shear reinforcement. He tested specimens in the civil engineering laboratory, while working with Margaret Stack, Ph.D. candidate, and Professor Jack Moehle. The results of his work will be used as the experimental research program on this topic continues in the future.

Activities in 2018-2019

4.7 2018 PEER RESEARCHERS' WORKSHOP

PEER-funded researchers convened at the UC Berkeley Richmond Field Station on August 7 & 8, 2018, to provide information about their projects with one other. Over 45 participants from PEER Core Institutions shared in-progress findings about projects funded by the PEER TSRP and Lifelines Programs. The goal of the workshop was to disseminate information about PEER-funded research that is on-going, and to develop interaction between similar projects and across disciplines.

PEER Director Mosalam noted that "in addition to project-specific topics, overarching discussions about interactions between different projects, the role of industry collaborations in enhancing projects, advantages of multi-campus collaborations, and relevant future research topics were identified."

The workshop presentations and videos are posted at: *https://peer.berkeley.edu/peer-researchers-workshop*.

Researchers' Workshop attendees at the Richmond Field Station, August 2018

4.8 PEER HUB IMAGENET (PHI) CHALLENGE

PEER organized the first image-based structural damage recognition competition, namely, the PEER Hub ImageNet (PHI) Challenge[6], held at the end of Summer 2018. The goal of the PHI challenge was to evaluate algorithms for structural image classification using a large-scale dataset based on service conditions and past reconnaissance efforts and laboratory experiments for conditions of extreme events. For the PHI Challenge, PEER provided a large image dataset relevant to the field of structural engineering and designed several detection tasks, which have contributed to the establishment of automated vision-based structural health monitoring.

The state-of-the-art algorithms tested in the PHI challenge have also enhanced the accuracy and the generalization of vision-based approaches. These approaches aided the construction of a large structural image dataset to solve societal-scale problems of structural health monitoring and assessment of the built environment. Winners were recognized at the 2019 PEER Annual Meeting.

4.9 2018 BLIND PREDICTION CONTEST

PEER announced the 2018 Blind Prediction Competition on the numerical simulation of a recently completed large-scale liquefaction shaking table experiment. As a part of this PEER-funded project, a large-scale shaking table test was conducted at UCSD’s Powell Structures Lab using a 2.9-m-tall soil laminar box that was the basis for this blind prediction competition. The experiment focused on the response of shallow foundations in liquefied soils. Both researchers as well as practicing engineers were encouraged to participate in the exciting competition. This blind prediction is a class B prediction that compares analytical response “predictions” with those measured during experimental testing. Each participant was required to predict permanent settlements at multiple locations. The project team planned follow-up activities for class C numerical predictions by making some of the experimental data available to the predictors. The closest predictions to the test results were announced at the 2019 PEER Annual Meeting.

4.10 REQUEST FOR PROPOSAL: SOLICITATION TSRP PEER 18-01

In response to Solicitation PEER TSRP 18-01, 47 outstanding proposals were received, covering 18 of 19 available topics in the broad domains of Geotechnical Engineering (G), PBEE of Bridge and Other Transportation Systems (S), PBEE Methodology (M), PBEE Tools (T), and Areas of Application (A). Each proposal received three reviews from a pool of more than a dozen

[6] *https://apps.peer.berkeley.edu/phichallenge/.*

4.10 REQUEST FOR PROPOSAL: SOLICITATION TSRP PEER 18-01

In response to Solicitation PEER TSRP 18-01, 47 outstanding proposals were received, covering 18 of 19 available topics in the broad domains of Geotechnical Engineering (G), PBEE of Bridge and Other Transportation Systems (S), PBEE Methodology (M), PBEE Tools (T), and Areas of Application (A). Each proposal received three reviews from a pool of more than a dozen independent reviewers. Based on the priorities of the pre-set TSRP vision, pre-defined evaluation criteria specified in the RFP, and factors such as the level of engagement with the PEER core institutes; 11 new projects were approved, comprising a total funding of nearly $800,000.

Awarded projects are listed on the PEER-TSRP website.

4.11 PEER RESPONSE TO ALASKA EARTHQUAKE: REPORT

A M7.0 earthquake struck Anchorage, Alaska, on November 30, 2018, 8:29 AM local time. PEER was engaged with the Structural Extreme Events Response (StEER) network and the EERI Learning From Earthquakes (LFE) Program in the hours ensuing after the earthquake. More information can be found on the PEER Earthquake Briefings website[7].

PEER Director, Khalid Mosalam (co-PI), serves as StEER Associate Director for Seismic Hazards, leading StEER's Pacific Regional node and as primary liaison to the earthquake engineering community. The Structural Extreme Events Reconnaissance (StEER) Network completed a Preliminary Virtual Assessment Team (P-VAT)[8] report that includes overviews of the hazard characteristics of the 2018 Alaska Earthquake, the regulatory context and emergency response, the impacts of this earthquake, and current conditions by gathering publicly-reported information. This Preliminary Virtual Assessment Team (P-VAT) Report represents the first product of StEER's larger coordinated response to this event, informing and supporting other research teams seeking to learn from this disaster.

4.12 2019 PEER ANNUAL MEETING

The 2019 PEER Annual Meeting was held on January 17–18, 2019, at the UCLA Mong Auditorium. "Seismic Resilience 25 Years after Northridge: Accomplishments & Challenges" featured the role of multi-disciplinary performance-based engineering with seismic and related natural hazards to achieve community resiliency.

On Thursday, January 17, plenary sessions included presentations on the following topics:

- Advances and Challenges since Northridge
- Regional PBEE – Lifeline Systems
- Computational Tools for Simulating Natural Hazard Effects and Community Resilience
- Advances in Infrastructure Monitoring and Reconnaissance

[7] *https://peer.berkeley.edu/earthquake-briefings*
[8] *https://www.designsafe-ci.org/data/browser/public/.*

On Friday, January 18, concurrent breakout sessions were formatted for more detailed discussion and engagement of PEER-funded researchers and projects, with the goal of creating a synergy of resources and information. Concurrent discussion topics included:

- Impact of Ground Motions on Bridge Performance and Design
- Geo Hazards
- Computational Simulation of Geotechnical and Structural Systems
- New Trends in Seismic Design of Bridges
- PBEE to Promote Discounts for Single-Family Dwellings

The closing plenary, "Resilient Los Angeles", featured Departmental Chief Resilience Officers from the City of Los Angeles outlining plans for community implementation.

2019 PEER Annual Meeting, January 17-18, 2019
(Photo credit: AP Photo/Mark J. Terrill)

The Steering Committee of the 2019 PEER Annual Meeting consisted of: Craig Davis, Gregory Deierlein, Grace Kang, Amarnath Kasalanati, Steven Kramer, Sashi Kunnath, Khalid Mosalam, Tom Shantz, Ertugrul Taciroglu, John Wallace, and Farzin Zareian. Presentations and videos from the PEER Annual Meeting 2019 are posted on vimeo.com[9].

[9] *https://video.search.yahoo.com/search/video;_ylt=Awr9CJ4cyKVflCcAanhXNyoA;_ylu=Y29sbwNncTEEcG9zAzEEdnRpZAMEc2VjA3Nj?p=peer+2019+annual+meeting+videos+2019&fr=mcafee*

5 Technology Tools and Resources

5.1 OPENSEES

The Open System for Earthquake Engineering Simulation (OpenSees) is a software framework for simulating the seismic response of structural and geotechnical systems. OpenSees has been developed as the computational platform for research in performance-based earthquake engineering at PEER. The goal of the OpenSees development is to improve modeling and computational simulation in earthquake engineering through open-source development.

OpenSees has advanced capabilities for modeling and analyzing the nonlinear response of systems using a wide range of material models, elements, and solution algorithms. The software is designed for parallel computing to allow scalable simulations on high-end computers or for parametric studies.

OpenSees provides beam–column elements and continuum elements for structural and geotechnical models. A wide range of uniaxial materials and section models are available for beam/columns. Nonlinear analysis requires a wide range of algorithms and solution methods, and OpenSees provides a large variety of nonlinear static and dynamic methods, equation solvers, and methods for handling constraints.

As an open-source framework, OpenSees provides a computational environment for researchers from different disciplines and different parts of the world to work together, helping bind the PEER earthquake engineering community together. It is under continual development, so users and developers should expect changes and updates on a regular basis. In this sense, all users are developers, so it is important to register. The OpenSees website provides information about the software architecture, access to the source code, the development process, detailed explanations of the included materials, elements, solution algorithms, etc., along with a large variety of basic and advanced examples. OpenSees fosters development of community-based modeling and simulation methods that have advanced simulation capabilities and integrated structural and geotechnical engineering disciplines. PEER provides support to users through the OpenSees Days workshops and via OpenSees Community message board.

5.1.1 New Functionality to OpenSees

OpenSees continued to grow in the past year with many additions from the community. A full list of contributions can be found at: *http://opensees.berkeley.edu/OpenSees/changeLog.php*. A few examples are indicated below.

Element Modeling: MVLEM, SFI_MVLEM multiple vertical line element models to model shear walls, *ComponentElement2D* to combine *zeroLength* hinges at ends with an elastic element.

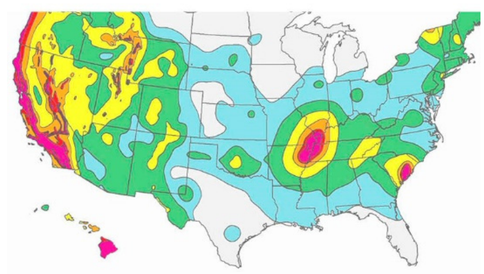
UniaxialMaterial: *ConcreteD, ConcreteCM, SteelMPF*, and *BilinearOilDamper*

Solvers: New GPU solvers, CulaS4 and CulaS5, SimpsonsTimeSeriesIntegrator

5.2 DATABASES

5.2.1 PEER Strong Motion Databases (NGA Databases)

The NGA databases continue to be the premier source of information used by researchers and practitioners worldwide. The new NGA-West 2 database is six times larger than the previous version. It has one of the most comprehensive sets of meta-data, including different distance measures, various site characterizations, and earthquake-source data. Since its release, the PEER Ground Motion database has proved to be very popular among engineers in the earthquake-related disciplines, who are increasingly using it for selection and modification of records to analyze computer models of buildings, bridges, and other facilities. The database is now cited as a primary source of ground motion records in the latest revision of the Building Seismic Safety Councils NEHRP Recommended Provisions. These online ground motion databases are based on the contributions of a significant number of PEER researchers, including junior and senior researchers, post-doctoral fellows, graduate and undergraduate students, and practicing earthquake engineers and scientists.



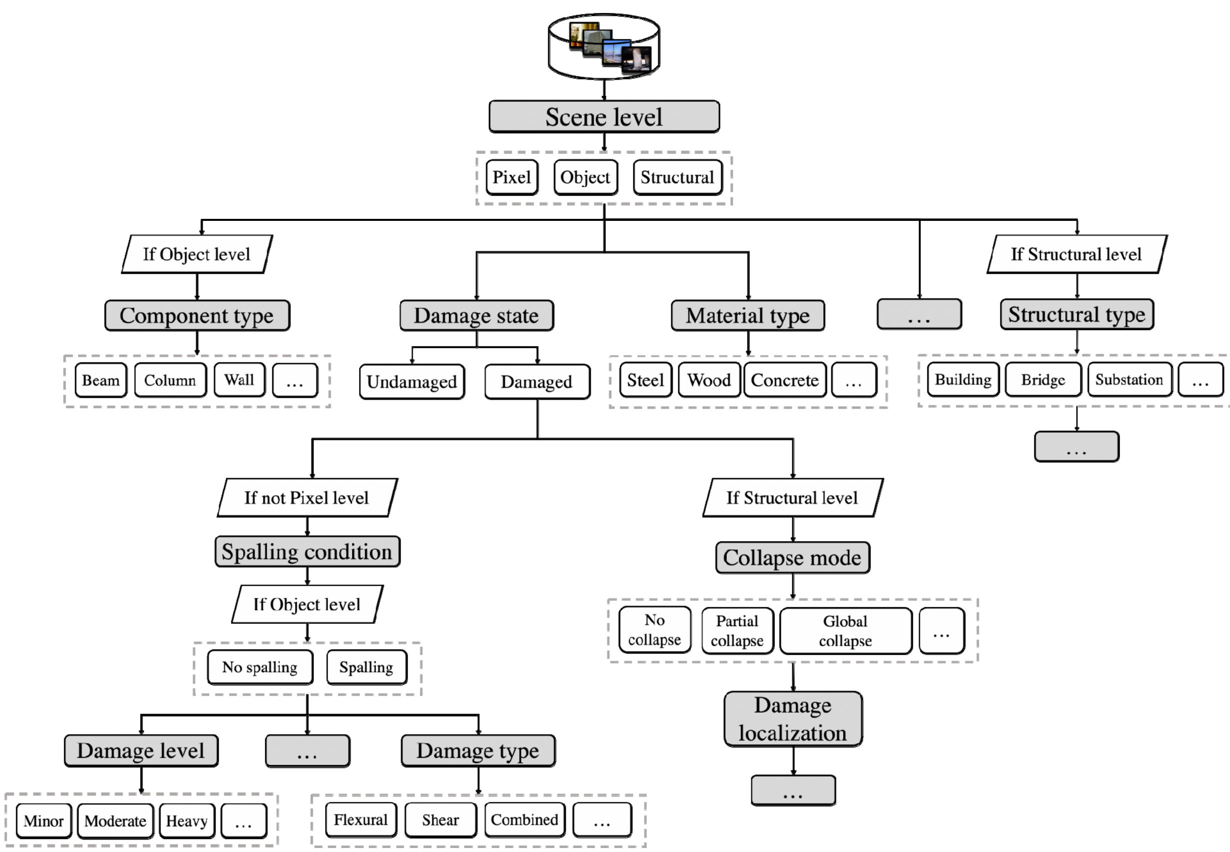
5.2.2 PEER Hub Imagenet (PHI-Net or Φ-Net)

This site (*https://apps.peer.berkeley.edu/phi-net/*) is PEER's new initiative to build a large-scale open-sourced structural image database and contains over 36,000 images with multiple attributes for damage identification.

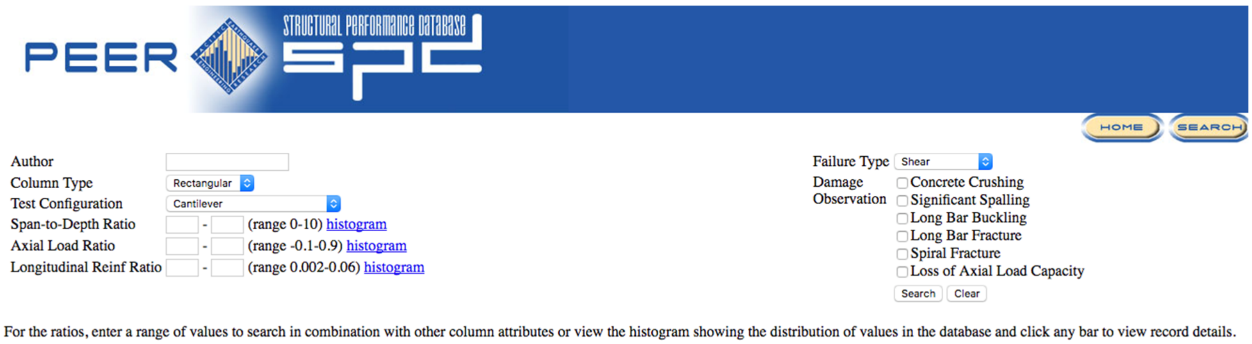
Both AI and machine learning (ML) technologies have developing rapidly in recent decades, especially in the application of deep learning (DL) in computer vision (CV). The objective of ML and DL implementation is to have computers perform labor-intensive repetitive tasks while simultaneously "learning" from those tasks. Both ML and DL fall within the scope of empirical study, where data is the most essential component.

In vision-based Structural Health Monitoring (SHM), using images as data media is currently an active research direction. Structural images obtained from reconnaissance efforts or daily life are playing an increasing role as the success of ML and DL is contingent on the volume of data media available. The expectation is that eventually computers will be able to realize autonomous recognition of structural damage in daily life—under service conditions—or after an extreme event—a large earthquake or extreme wind. Until now, vision-based SHM applications have not fully benefited from the data-driven CV technologies, even as interest on this topic is ever increasing. Its application to structural engineering has been hamstrung mainly due to two factors: (1) the lack of a general automated detection principles or frameworks based on domain knowledge; and (2) the lack of benchmark datasets with well-labeled large amounts of data.

To address the above-mentioned two drawbacks, PEER undertook an effort to build a large-scale open-sourced structural image database: the PEER Hub ImageNet (PHI-Net or Φ-Net). As of November 2019, this Φ-Net dataset contains **36,413** images with multiple attributes for the following baseline recognition tasks: scene level classification, structural component type identification, crack existence check, and damage-level detection. The Φ-Net dataset uses a hierarchy-tree framework for automated structural detection tasks founded on past experiences from reconnaissance efforts for post-earthquakes and other hazards. Through a tree-branch mechanism, each structural image can be clustered into several sub-categories representing detection tasks. This acts as a sort of a filtering operation to decrease the complexity of the problem and improve the performance of the automated applications of the algorithms. To the best of the authors' knowledge, until now there is no open-sourced structural image dataset with multi-attribute labels and this volume of images in the vision-based SHM area. It is believed that this image dataset and its corresponding detection tasks and framework will provide the necessary benchmark for future studies of DL in vision-based SHM.



5.2.3 Structural Performance Database



This site (*nisee.berkeley.edu/spd*) provides the results of over 400 cyclic, lateral-load tests of reinforced-concrete columns. The database describes tests of:

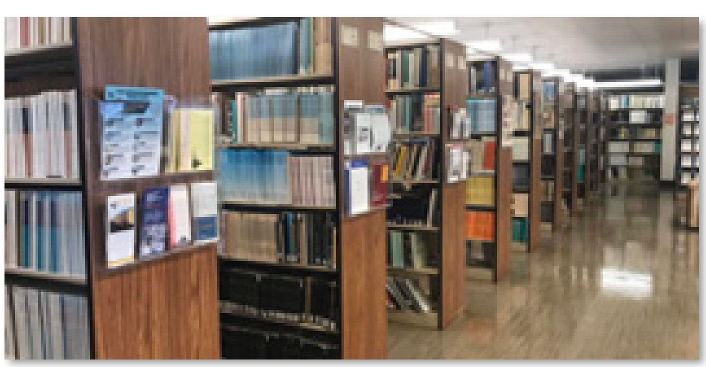
- spiral or circular hoop-reinforced columns (with circular, octagonal, or rectangular cross sections)
- rectangular reinforced columns
- columns with or without splices

5.2.4 Seismic Performance Observatory

The Seismic Performance Observatory (SPO) is an application for storing and searching post-earthquake damage information. The objective of SPO is to

- have a centralized, accessible, and scalable database;
- have information of post-earthquake damage like videos, pictures, data, etc., of structures;
- provide data obtained from earthquakes at magnitudes of 5.5 and up that have occurred since 1900 and linked to structures;
- provide pre-earthquake data for comparison purposes; and
- unify the post-earthquake data collection efforts.

5.3 NISEE / PEER LIBRARY



The National Information Service for Earthquake Engineering (NISEE) /PEER library is an affiliated library of UC Berkeley, specializing in structural engineering, geotechnical engineering, structural dynamics, engineering seismology, and earthquake public safety. In 1971, the NISEE-PEER Library opened its doors at the Richmond Field Station and began its mission of serving the information

needs of the earthquake engineering community. The NISEE-PEER Library houses a large, specialized physical collection of library materials in addition to the NISEE-PEER Online Archive. Researchers worldwide can access this vast database ($25 annual membership) of earthquake, structural, seismology, geotechnical, and public policy engineering research literature, as well as research software, images, and video recordings.

The NISEE–PEER Library originally began in 1971 as a public service project, the National Information Service for Earthquake Engineering (NISEE), with two facilities: one at the Earthquake Engineering Research Center (EERC), University of California, Berkeley, at the Richmond Field Station and another at the Earthquake Engineering Research Laboratory of the California Institute of Technology, Pasadena, California. The physical collection of the library began with the generous contributions of UC Berkeley Professors Ray W. Clough and Joseph Penzien, followed by numerous donations through the years.

Woodcut showing effects of earthquakes Jan Kozak Collection

In 2008, EERC merged with the Pacific Earthquake Engineering Research Center (PEER) becoming the NISEE–PEER Library. Particularly unique to this collection are numerous images donated by UC Berkeley Professors Karl Steinbrugge and Bill Godden, and Geophysicist Jan Kozak, which have been digitized by library staff. Many other image collections have been donated to the library from students, professors, engineers in the community, and Caltrans.

Professor Vitelmo Bertero's tutorial, *An Introduction to Earthquake Engineering*, is also available through the archive, as well as EERC, SEMM, PEER, and UC Berkeley Geotech reports, which include seminal research in earthquake, structural and geotechnical engineering done at UC Berkeley since 1967. Research reports are also available digitally. More information can be found online at *https://nisee.berkeley.edu/elibrary*.

6 People

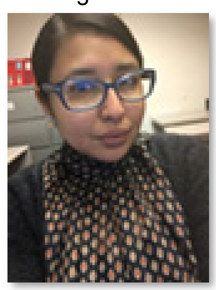
6.1 KEY PERSONNEL (HEADQUARTERS)

Khalid Mosalam
Director

Amarnath Kasalanati
Associate Director for Operations & Strategic Initiatives

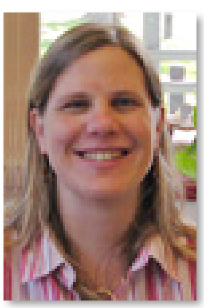
Grace Kang
Communications Director

Gabriel Vargas
Database Specialist



Zulema Lara
Financial Analyst and Subaward Coordinator

Erika Donald
Electronic Communications & Web Specialist



Christina Bodnar-Anderson
Library & Information Services

Claire Johnson
Technical Editor

Selim Günay
Project Scientist

Arpit Nema
Post-Doctoral Fellow

Sifat Muin
Post-Doctoral Fellow

Martin Nuenschawander
Visiting Post-Doctoral Fellow

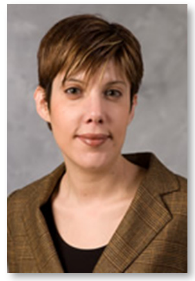
Charles Scawthorn
Visiting Scholar

Frank McKenna
Manager of OpenSees

6.2 INSTITUTIONAL BOARD

The Institutional Board members, listed on the following page, are appointed by the Dean of the College of Engineering or an appropriate Department Chair at the respective core institution and represent PEER researchers at their institution. General duties of the Institutional Board are to provide policy level guidance and oversight for the Center with a goal to help PEER fulfill its mission.

Dawn Lehman Chair, Institutional Board
University of Washington



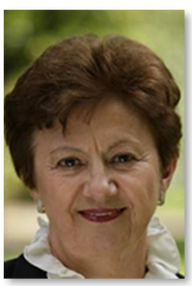
Dominiki Asimaki
California Institute of Technology

Ian Buckle
University of Nevada, Reno

Joel P. Conte
University of California, San Diego

Rakesh Goel
Educational Affiliate Representative
CalPoly

Erik A. Johnson
University of Southern California



Anne Kiremidjian
Stanford University

Sashi Kunnath
University of California, Davis

Jack Moehle
University of California, Berkeley

Michael Scott
Oregon State University

John Wallace
University of California, Los Angeles

Farzin Zareian
University of California, Irvine

6.3 RESEARCH COMMITTEE (RC)

The Research Committee is mainly responsible for setting the general research direction of the Center. It is charged with the following tasks: (1) setting research agenda based on PEER's vision; (2) working with stakeholders and industry partners to identify community needs and integrating them into the research plan; (3) making recommendations for funding grants; (4) developing the topics and timeline for Request for Proposals (RFP), and (5) reviewing and evaluating proposals and/or identifying a pool of reviewers.

The Research Committee consists of the following members: Pedro Arduino, Tara Hutchinson, Amit Kanvinde, Patrick Lynett, Eduardo Miranda, and Ertugrul Taciroglu. In addition, Norman Abrahamson (Leader of PEER Lifelines Research Program) Amarnath Kasalanati (PEER Associate Director), Khalid Mosalam (PEER Director), and Tom Shantz (Manager of PEER funding from Caltrans) serve as Ex-Officio members on all committees.

Pedro Arduino
University of Washington

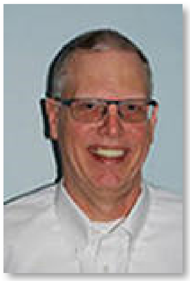
Tara Hutchinson
UC San Diego

Amit Kanvinde
UC Davis

Patrick Lynett
University of Southern California

Eduardo Miranda
Stanford University

Ertugrul Taciroglu
UC Los Angeles



Norm Abrahamson
UC Berkeley / Davis
PEER Lifelines Leader
Ex-Officio Member

Tom Shantz
Caltrans
Ex-Officio Member

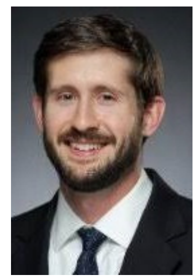
6.4 INDUSTRY ADVISORY BOARD (IAB)

The Industry Advisory Board serves as the bridge between research and practice. Its charge is as follows: (1) identify current and future needs of the profession; (2) advise on industry problems and applications with research potential; (3) provide the bridge between research and industry; and (4) facilitate opportunities for PEER to pursue.

The board consists of the following members: James Malley, Degenkolb Engineers (Chair); Jennie Watson-Lamprey, Slate Geotechnical (Vice-Chair); Matt Bowers, SC Solutions; Eve Hinman, Hinman Consulting; Brian Kehoe, Wiss, Janney, Elstner Associates; Peter Lee, Skidmore Owings and Merrill; and Steve Marusich, Forell/Elsesser Engineers. Norman Abrahamson (Leader of PEER Lifelines Research Program) and Tom Shantz (Manager of PEER funding from Caltrans) serve as Ex-Officio members.

James Malley, Chair
Degenkolb Engineers

Jennie Watson-Lamprey (Vice Chair)
Slate Geotechnical



Matt Bowers
SC Solutions

Eve Hinman
Hinman Consulting

Brian Kehoe
Wiss, Janney, Elstner

Peter Lee
Skidmore, Owings & Merrill

Steve Marusich
Forell/Elsesser Engineers

Norm Abrahamson
UC Berkeley / Davis
PEER Lifelines Leader
Ex-Officio Member

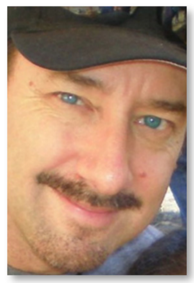
Tom Shantz
Caltrans
Ex-Officio Member

6.5 RESOURCE IDENTIFICATION COMMITTEE (RIC)

The Resource Identification Committee's role is to increase the current funding levels and to realize the Center's vision. Its tasks are as follows: (1) actively identify new sources of funding; (2) pursue extension of existing funding sources; (3) identify and facilitate funding opportunities for PEER leadership to pursue, and (4) provide recommendations and directions to increase chances of securing funding.

The committee consists of senior faculty with strong ties to various funding sources, industry members, and representatives of some of the funding agencies. The members are: Hosam Ali, FM Global; Jeffrey Bachhuber, PG&E; Marc Eberhard, University of Washington; Ahmed ElGamal, University of San Diego; David McCallen, University of Reno, Nevada, and Farhang Ostadan, Bechtel Corporation. Norman Abrahamson (Leader of PEER Lifelines Research Program) and Tom Shantz (Manager of PEER funding from Caltrans) serve as Ex-Officio members.

Hosam Ali
FM Global



Jeffrey Bachhuber
PG & E

Marc Eberhard
University of Washington

Ahmed ElGamal
University of California, San Diego

David McCallen
University of Nevada, Reno

Farhang Ostadan
Bechtel Corporation

Norm Abrahamson
UC Berkeley / Davis
PEER Lifelines Leader
Ex-Officio Member

Tom Shantz
Caltrans
Ex-Officio Member

6.6 FACULTY PARTICIPANTS

6.6.1 Faculty Participants (Core Institutions)

University of California, Berkeley (Headquarters)

Norman Abrahamson
Richard M. Allen
M. Reza Alam
Alexandre M. Bayen
Tracy Becker
Jonathan D. Bray
Matt DeJong
Douglas S. Dreger
Laurent El Ghaoui
Sanjay Govindjee
Peggy Hellweg
Roberto Horowitz
Robert Kayen
Shaofan Li
Dimitrios Konstantinidis
Simo Makiharju
Jack P. Moehle
Khalid M. Mosalam
Paulo J.M. Monteiro
Mark Wilfried Mueller
Claudia P. Ostertag
Michael Riemer
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Henry Burton	Jonathan Stewart	John Wallace
Scott Brandenberg	Ertugrul Taciroglu	Jian Zhang

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Tara Hutchinson	Gilberto Mosqueda	Chia-Ming Uang
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Tom Jordan	James Moore	
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Jeffrey Berman	Laura Lowes	Charles Roeder
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6.6.2 Faculty Participants (Educational Affiliates)

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ARUP	Rob Smith J Ben Shao
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Walter P Moore	Bill Andrews Rafael Sabelli
Washington Dept. of Transportation	Bijan Khalegi
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Appendix A List of Sub-Award Projects (2016–2020)

Fund Source	PI	Institution	Project Title
TSRP	Erica Fischer	OSU	Fire Performance of Steel-Frame Buildings Using OpenSees
TSRP	Rune Storesund	UCB	Wildfire Risk Reduction: Framing Tools and Methods to Facilitate Integration across Organizational Perspectives and System Life Cycles to Confront Complexity of Extreme Events in the Face of Climate Change
TSRP	Floriana Petrone	UNR	Probabilistic Simulation-Based Evaluation of the Effect of Near-Field Spatially Varying Ground Motions on Distributed Infrastructure Systems
TSRP	David McCallen	UNR	A Pacific Rim Forum on Regional-Scale Simulations of Earthquake Ground Motions and Infrastructure Response for PBEE of Transportation Systems
TSRP	Tara Hutchinson	UCSD	Ground Improvement-Based Protection of Transportation Infrastructure: Validation of PBE Via Centrifuge and Numerical Modeling
TSRP	Ertugrul Taciroglu	UCLA	Performance-Based Economic Loss Assessment Due to a Hypothetical Large Southern Earthquake based on the Disruption and Recovery of Port of Los Angeles Freight Traffic
TSRP	Laurent El Ghaoui	UCB	Text Analytics on Social Media for Resilience-Enabled Extreme Events Reconnaissance (TAR)
TSRP	Frank McKenna	UCB	Workshop on Pre- and Post-Processing Tools for OpenSees
TSRP	John Wallace	UCLA	A Comprehensive Database of RC Column Tests
TSRP	Pedro Arduino	UW	OpenSees Implementation of 3D Embedded Pile Element for Enhanced Soil-Pile Interaction Analysis of Bridge Systems Subject to Liquefaction and Lateral Spreading.
TSRP	Domniki Asimaki	Caltech	Reduced-Order Models for Dynamic Soil–Structure Interaction Analyses of Buried Structures
TSRP	Ahmed Elgamal	UCSD	Meshfree Large-Strain Framework for Seismic Response of Ground-Structural Systems: Development and Open Source Tool
TSRP	Jack Baker	Stanford	Identification of Transportation Network Corridors, for Enhancing Network Resilience

Fund Source	PI	Institution	Project Title
TSRP	Amit Kanvinde	UCD	Fracture of Deficient Steel Details in Pre-Northridge Transportation Infrastructure
TSRP	Norm Abrahamson	UC Berkeley	Non-Ergodic Ground-Motion Model for California
TSRP	Scott Brandenberg	UC Los Angeles	Analysis of Fine-grained Soil Failure in Chiba during 2011 Tohoku Earthquake, and Development of Community Lab Test Database
TSRP	Ian Buckle	University of Nevada Reno	Tsunami-borne Debris Loading on Bridges
TSRP	Joel Conte	UC San Diego	Inclusion of Modeling Uncertainty, Parameter Uncertainty and Parameter Estimation Uncertainty in PBSD of Ordinary Standard RC Bridges
TSRP	Sashi Kunnath	UC Davis	Establishing Bridge Column Capacity Limit States through Modeling and Simulation
TSRP	Dawn Lehman	University of Washington	New Seismically Resilient System for HSR, Ports, and Vehicular Transportation Systems: Reducing Downtime, Construction Cost and Post-Earthquake Repair
TSRP	Michael Scott	Oregon State University	Bridge Functionality Instead of Component Damage as a PBEE Metric
TSRP	Nicholas Sitar	UC Berkeley	DEM Modeling of the Influence of Depositional Fabric on the Mechanical Properties of Granular Sediments using XRT Data
TSRP	Kenichi Soga	UC Berkeley	City-Scale Multi-Infrastructure Network Resilience Simulation Tool
TSRP	John Stanton	University of Washington	Seismic Evaluation of the California High-Speed Rail System
TSRP	Farzin Zareian	UC Irvine	Validation and Utilization of Physics-based Simulated Ground Motions for Bridge Performance Assessment
TSRP	Jose Andrade	Cal Tech	Micro-Inspired Continuum Modeling Using Virtual Experiments
TSRP	Brett Maurer	University of Washington	Towards Multi-Tier Modeling of Liquefaction Impacts on Transportation Infrastructure
TSRP	Pedro Arduino	University of Washington	Implementation and Validation of PM4S and in OpenSees
TSRP	Keri Ryan	University of Nevada, Reno	Influence of Vertical Ground Shaking on Design of Bridges Isolated with Friction Pendulum Bearings

Fund Source	PI	Institution	Project Title
TSRP	Minjie Zhu	Oregon State University	Fluid–Structure Interaction and Python Scripting Capabilities in OpenSees
TSRP	Kenichi Soga	UC Berkeley	High-Performance Computing-Based Distributed Multi-Layered City-Scale Transportation Network Tool
TSRP	Jack Baker	Stanford	Modeling Bay Area Transportation Network Resilience
TSRP	Henry Burton	UCLA	Aftershock Seismic Vulnerability and Time-Dependent Risk Assessment of Bridges
TSRP	Ahmed Elgamal	UCSD	A Systematic Computational Framework for Multi-Span Bridge PBEE Applications
TSRP	Erica Fischer	OSU	Post-Earthquake Fire Performance of Industrial Facilities
TSRP	Patrick Lynett	USC	Tsunami Debris: Simulating Hazard and Loads
TSRP	Amit Kanvinde	UCD	Dissipative Base Connections for Moment Frame Structures in Airports and Other Transportation Systems
TSRP	Gregory Deierlein	Stanford	UNR-Stanford Collaboration: Stanford - Accounting for Earthquake Duration in Performance-Based Evaluation and Design of Bridges
TSRP	David Sanders (original PI); Mohamed Moustafa	UNR	Project Title: UNR-Stanford Collaboration: Accounting for Earthquake Duration in Performance-Based Evaluation and Design of Bridges
TSRP	Anne Lemnitzer	UCI	Towards Next Generation P-Y Formulations - Part 2: Statistical Assessment of Uncertainties in Key Components of Soil Resistance Functions
TSRP	Ertugrul Taciroglu	UCLA	Development of a Database and a Toolbox for Regional Seismic Risk Assessment of California's Highway Bridges
TSRP	Jonathan Bray	UCB	Liquefaction Triggering and Effects at Silty Soil Sites
TSRP	Steven L. Kramer	UW	Next Generation Liquefaction: Japan Data Collection
TSRP	Jonathan P. Stewart	UCLA	Next Generation Liquefaction: Japan Data Collection (Task #3k01-Tsrp, Year 2)
TSRP	Jose I. Restrepo	UCSD	Earthquake Resilient Bridge Columns
TSRP	Patrick Lynett	USC	Tsunami Design Guide Specifications for Bridges: Local Tsunami Hazard Assessment

Fund Source	PI	Institution	Project Title
TSRP	Harry Yeh	Oregon State University	Tsunami Engineering: Performance Based Tsunami Engineering
TSRP	Hong Kie Thio	AECOM	Tsunami Engineering: Performance Based Tsunami Engineering
TSRP	Anne Lemnitzer	UCI	Towards Next Generation P-Y Curves - Part 1: Evaluation of the State of the Art and Identification of Recent Research Developments
TSRP	Vesna Terzic	CSU Long Beach	Recovery Model for Commercial Low-Rise Buildings
TSRP	Armen Der Kiureghian	American University of Armenia	Stochastic Modeling and Simulation of Near-Fault Ground Motions for Use in PBEE
TSRP	Kamran M. Nemati	UW	How Water/Biner Ratio and Voids Affect the Performance of Hardened Concrete Subjected to Fire
TSRP	Sanjay Govindjee	UCB	Geometrically Exact Nonlinear Modeling of Multi-Storage Friction
TSRP	Tarek I. Zohdi	UCB	Swarm-Enabled Infrastructure-Mapping for Rapid Damage Assessment following Earthquakes
TSRP	Claudia Ostertag	UCB	Conventional Testing and Hybrid Simulations of Environmentally Damaged Bridge Columns
TSRP	Steve Mahin	UCB	3 Axis Testing of Four PEER Columns (Six Weeks Maximum Shaking Table Occupation and Testing Time)
TSRP	Steve Mahin	UCB	Bridge Column Testing
TSRP	Jonathan D. Bray	UCB	Liquefaction-Induced SFSI Damage Due To the 2010 Chile Earthquake
TSRP	Gregory Deierlein	Stanford University	Effects of Long-Duration Ground Motions on Structural Performance
TSRP	Jose L. Restrepo	UCSD	Advanced Precast Concrete Dual-Shell Steel Columns
TSRP	Joel P. Conte	UCSD	Probabilistic Performance-Based Optimal Seismic Design of Isolated Bridge Structures
TSRP	Claudia P. Ostertag	UCB	Shaking Table Test of Pre-Cast Post-Tensioned Hyfrc Bridge Column
TSRP	Kyle Rollins	Brigham Young University	Supplemental Field Testing of Pile Down Drag Due to Liquefaction
TSRP	Steven L. Kramer	UW	Next Generation Liquefaction: Japan Data Collection

Fund Source	PI	Institution	Project Title
TSRP (Tsunami)	Hong Kie Thio	URS Corporation	Performance Based Tsunami Engineering Methodology (Tsunami Research Program)
TSRP (Tsunami)	Patrick Lynett	USC	Simulation Confidence in Tsunami-Driven Overland Flow (Tsunami Research Program)
TSRP (Tsunami)	Harry Yeh	Oregon State University	Performance Based Tsunami Engineering Methodology (Tsunami Research Program)
TSRP	John W. Wallace	UCLA	Shear-Flexure Interaction Modeling for Reinforced Concrete Structural Walls and Columns Under Cycling Loading
TSRP	Jack Baker	Stanford University	Ground Motions and Selection Tools for PEER Research Program
TSRP	Jonathan P. Stewart	UCLA	Next Generation Liquefaction: Japan Data Collection (Task #3K01-TSRP, Year 2)
TSRP & Validus	Vesna Terzic	CSU Long Beach	Towards Resilient Structures
TSRP	Scott J. Brandenberg	UCLA	Influence of Kinematic SSI on Foundation Input Motions for Bridges on Deep Foundations
TSRP	Ross W. Boulanger	UC Davis	Mitigation of Ground Deformations in Soft Ground
TSRP	Jose I Restrepo	UCSD	Earthquake Resilient Bridge Columns
TSRP	Jonathan D. Bray	UC Berkeley	Next Generation Liquefaction: New Zealand Data Collection
Lifelines	Jonathan P. Stewart	UCLA	NGL: Next Generation Liquefaction Database Development and Implications for Engineering Models
Lifelines	Steven L Kramer	UW	NGL: Next Generation Liquefaction Database Development and Liquefaction Triggering Evaluation
Lifelines	Filip C. Filippou	UCB	PEER-Lifelines Proposal – Non-+Convergence
Lifelines	Sashi Kunnath	UCD	Caltrans-PEER Workshop on Characterizing Uncertainty in Bridge-Component Capacity Limit-States
NC1T01	Steven Day	UCSD	Vertical-Component Basin Amplification Model
NC2Q03	Jason DeJong	UCD	In-Situ Identification and Characterization of Intermediate Soils
NC2S01	Jonathan P. Stewart	UCLA	In-Situ Identification and Characterization of Intermediate Soils

Fund Source	PI	Institution	Project Title
NC2L01	Robert Bachman	Cosmos	Archiving and Web Dissemination of Geotechnical Data, Phase 4a: Production GVDC Using DIGGS Standard
NC1E09	Robert Darragh	Pacific Engineering and Analysis	NGA Processing Update 2
NC10A2	Hong Kie Thio	URS Corporation	Tsunami Hazard Analysis Phase2
NC9K02	Farzin Zareian	UCI	Quantification of Variability in Performance Measures of Ordinary Bridges to Uncertainty in Seismic Loading Directionality and Its Implication in Engineering Practice
NC10B1	Michael H. Scott	Oregon State University	Validation of OpenSees for Tsunami Effects on Bridge Superstructures
NC9M01	Pedro Arduino	UW	Estimation of Shear Demands on Rock-Socketed Drilled Shafts subjected to Lateral Loading
NC4E01	Scott J. Brandenberg	UCLA	Evaluation of Collapse and Non-Collapse of Parallel Bridges Affected by Liquefaction and Lateral Spreading
NC3J01	Steve Kramer	UW	Effects of Liquefaction on Surface Response Spectra
NC2U01	Jonathan P. Stewart	UCLA	Guidelines for Performing Hazard-Consistent 1-D Ground Response Analysis for Ground Motion Prediction
NCBC01	Armen Der Kiureghian	UCB	Synthetic Near-Fault Ground Motion Arrays for PBEE Analysis
NC9N01	Marios Panagiotou	UCB	Three-Dimensional Seismic Demand Model for Bridge Piers Supported on Rocking Shallow Foundations
NC3KL1	Jonathan P. Stewart	UCLA	Next Generation Liquefaction: Japan Data Collection
NC2T01	Scott J. Brandenberg	UCLA	Influence of Kinematic SSI on Foundation Input Motions for Bridges on Deep Foundations
DOE	Robert R. Youngs	AMEC Environment & Infrastructure	NGA-East: SSHAC and TI Seismic Research Review
NRC	Walter J. Silva	Pacific Engineering and Analysis	NGA-East: GMPE Implementation

Fund Source	PI	Institution	Project Title
NRC	Robert R. Youngs	AMEC Environment & Infrastructure	NGA-East: SSHAC and TI Seismic Research Review
DOE	Walter J. Silva	Pacific Engineering and Analysis	Development of Vertical Amplification Factors
DOE	Robert R. Youngs	AMEC Environment & Infrastructure	NGA-East: SSHAC, PPRP and TRC Seismic Research Review
NRC	Martin Chapman	Virginia Tech	NGA-East Path/Source Working Group Tasks
DOE	Martin Chapman	Virginia Polytechnic Institute and State University	NGA-East Path Working Group Tasks
NRC (24669)	Thomas Jordan	USC	Support of the SCEC Broadband Platform for NGA-East Simulations
DOE	Youssef Hashash	University of Illinois at Urbana-Champaign	Geotechnical Working Group Integration Project
CEA	Paul Somerville	URS Corporation	Directivity Corrections for NGA-West GMPE's
CEA	Mark Petersen	USGS	PEER-USGS Collaboration on NGA-WEST 2
CEA	Stanford	Stanford	Directionality Model for NGA West 2
CEA	Jonathan P. Stewart	UCLA	Further Development of Site Responses in NGA Models
CEA	Paul Spudich	USGS	Update of the Spudich and Chiou 2008 Directivity Model for Improved Prediction and Directivity and Directionality
CEA	Robert R. Youngs	AMEC Geomatrix	GMPE Development and Assessment of Epistemic Uncertainty
CEA	Walter J. Silva	Pacific Engineering and Analysis	Update NGA-W Strong Motion Database and Develop Vertical Amplification Factors
FM Global	Walter J. Silva	Pacific Engineering and Analysis	NGA-Subduction Strong Ground Motion

Fund Source	PI	Institution	Project Title
USDI	Jonathan Stewart	UCLA	NGA-Subduction Analysis of Maule Chile and Tohoku Japan Ground Motion Data
TSRP	Steven L. Kramer	UW	Next Generation Liquefaction: Japan Data Collection
TSRP	Jonathan P. Stewart	UCLA	Next Generation Liquefaction: Japan Data Collection (Task #3K01-TSRP, Year 2)

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