PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

PEER Annual Report 2020-2021

Khalid M. Mosalam
Amarnath Kasalanati

Pacific Earthquake Engineering Research Center
University of California, Berkeley

PEER Report No. 2021/11

Pacific Earthquake Engineering Research Center
Headquarters at the University of California, Berkeley
December 2021

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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, 2020 to June 30, 2021. PEER staff, in particular Grace Kang, Erika Donald, Claire Johnson, Christina Bodnar-Anderson, Arpit Nema and Zulema Lara, helped in preparation of this report.

Despite the remote work during the pandemic, the Center was active on many fronts, such as Research activities (Major projects, Requests-for-Proposals, Research Committee), Educational or Technology Transfer activities (PEER Annual Meetings, Workshops), Outreach activities (Business-Industry-Partnership, PEER reports, Email reach of 2000+ people, Prediction contests), Organizational activities (Core members, Strategic plan, Bylaws, Event calendar), and New initiatives. Key activities of the past academic year include the following:

1. Requests for Proposal: PEER issued a Request for Proposal (RFP) in the Fall of 2020 for the Transportation Systems Research Program (TSRP) and received 34 proposals. Based on three independent reviews of each project, 12 projects were funded comprising a total funding of $600,000. Since the resumption of the RFP process in Fall of 2017, TSRP funds have supported 54 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–Bridge Program: In 2020, Caltrans awarded a $4.5 million, 36-month contract to PEER for the new PEER–Bridge Program. This streamlined framework of Caltrans research program has a single master contract and funds several new contracts each year, with a duration of 2 to 3 years for each new project. Problem statements are chosen from seven priority topics and selection is through a PEER-administered request-for-proposal (RFP) process.

3. Researchers' Workshop: This forum for in-progress reporting of PEER-funded projects, was conducted online in August 2020. With 30 presentations spread over 2 days and ample time for discussion, this workshop identified interaction between several projects and participating researchers provided constructive feedback to on-going work.

4. PEER-DOE Workshop: In May 2021, PEER along with Department of Energy, sponsored a workshop organized by the University of Nevada, Reno, on large-scale shake table testing for seismic safety of DOE facilities. This online two-day event featured over 90 invited attendees including DOE, industry and academics.

5. Pacific Rim International Forum: In June 2021, PEER sponsored the Pacific Rim International Forum organized by the University of Nevada, Reno, on "Regional-scale Simulations for Earthquake Ground Motions and Infrastructure Response for Performance-Based Earthquake Engineering." This online international workshop featured nearly 50 speakers over 2 days and was attended by over 250 people.

6. PEER Committees: Three PEER committees took on their charges in early 2020. These are: 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 have been active with several meetings in 2021. In addition, a new committee, PEER Student Committee was formed in May 2021, to facilitate interaction and engagement of students from all core institutions.
7. Review of the Center: The College of Engineering (CoE) at UC Berkeley initiated a review of PEER Center in November 2020. The review was intended to evaluate the current successes, assess future challenges and explore the long-term needs of the Center, with the benefit of external advice. The composition of the committee provided different perspectives: internal (UCB) faculty, Institutional Board members, an industry partner, and an external reviewer in natural hazard engineering community. The committee recommended Director Mosalam for a second term and commended PEER Center for continuing to be an internationally visible organization with widely used tools and products. Further, the committee provided several suggestions and recommendations for the future growth of the Center.

In the upcoming year, PEER plans to continue holding focused workshops, leverage the new committees' activities, and draw on existing experience on PBE to systematically move towards Resilient Design for Extreme Events (RDEE).

Keywords: Earthquake Engineering, Seismic, PBEE, PEER-Bridge, TSRP, Lifelines

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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 needed to draw on existing resources and formed a new committee structure. The following committees help PEER achieve these strategic objectives:

1. The Institutional Board (IB): 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. The Research Committee (RC): 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.
5. PEER Student Committee (PSC): In May 2021, PEER Student Committee was formed to facilitate student interaction and engagement in PEER activities, while enhancing student education in earthquake engineering & related fields. This committee is planning on several initiatives such as making PEER Student Videos, preparing Student Highlights, making videos of PEER Institution Lab Tours, conducting PEER Student Meetings, and bridging the gap between industry partners and students involved in research, including empowering PEER students with opportunities for the future workforce.

Since 2017 Fall, PEER has funded 54 project through the RFP process, and 11 projects outside the RFP process in 2016-2017. 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. 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 have been developing the sense of 'PEER-community' for a new cohort of researchers and have been instrumental in maintaining PEER's position as a leading research center.

1.4 REVIEW OF THE CENTER

The College of Engineering (CoE) at UC Berkeley initiated a review of PEER Center in November 2020. The review was intended to evaluate the current successes, assess future challenges and explore the long-term needs of the Center, with the benefit of external advice. The consisted of the following to provide different perspectives: (i) a member of COE leadership team, (ii) two faculty members from UCB, (iii) two representatives from the PEER Institutional Board (IB), (iv) a member of PEER Business & Industry Partnership (BIP), and (v) an external reviewer in natural hazard engineering community.

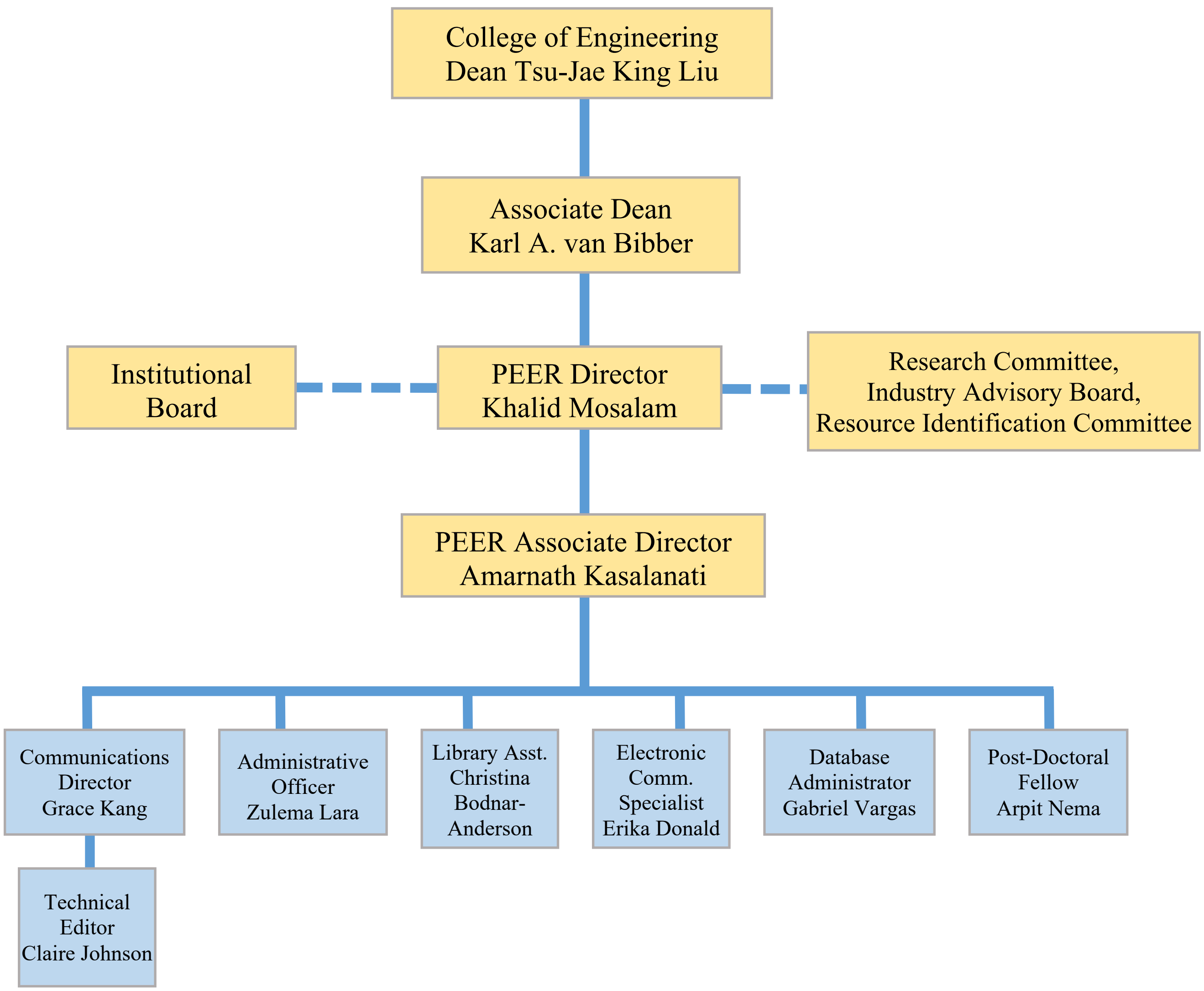
PEER Headquarters prepared and provided a self-study report to the review committee. This report included the Center's mission, activities & accomplishments over the past 5 years, current funding information, an assessment of strengths, opportunities & challenges, and a plan for the next five years.

The review was completed in June 2021. The committee endorsed PEER's mission and commended the Center for continuing to be an internationally visible organization with widely used tools & products. In addition, the committee recommended that Director Mosalam be appointed for a second term. Further, the review committee provided several suggestions for the future growth of the Center, grouped into four categories: (a) broad research objectives, (b) funding opportunities, (c) outreach items, and (d) specific items of interest. PEER Headquarters will work with committees (RC, IAB and RIC) to implement these suggestions.

1.5 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 staff members. In addition, several other Research Engineers, Project Scientists, and Graduate Student Researchers help with PEER activities.

The organizational structure of PEER is shown here for the period of July 1, 2020 through June 30, 2021. More details of PEER's key personnel, IB members, and PEER resources are presented in Section 6 of this report.



2 Major Research Programs & Projects

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

A total of 65 projects were funded from the TSRP program, with a combined total of nearly $5.8 million of total funding, since Prof. Mosalam became the Director of the Center in January 2016. Of these, 54 projects were funded through the RFP process since reinstating this process in the Fall of 2017. In 18 months prior to that, there were 11 other projects that were funded outside of the RFP or were continuing projects. 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.

Year	Proposals	Funded	Solicited	Funded
2016 NoRFP	-	7	$ 577,572	$ 577,572
2017 PreRFP	-	4	$ 444,703	$ 444,703
2017 RFP	47	17	$ 4,801,433	$1,498,723
2018 RFP	47	11	$ 5,279,057	$1,471,309
2019 RFP	44	14	$ 4,953,596	$1,210,466
2020 RFP	34	12	$ 1,722,841	$ 594,449
Total	**183**	**65**	**$17,779,202**	**$5,797,222**

Research highlights from projects of the last year are presented in Chapter 3. Appendix A provides statistics of distribution of funding among institutions across different topics of research. Appendix B lists the names of funded projects. Detailed information about project titles, PI's, proposed research summary and reports of these projects are available at the TSRP website.

2.2 PEER-BRIDGE PROGRAM

Caltrans awarded a $4.5 million, 36-month contract to PEER for the new PEER-Bridge research program. Caltrans has had an established bridge research program, which was expanded greatly in response to the 1989 Loma Prieta earthquake. The new PEER-Bridge Research Program is a streamlined framework of Caltrans bridge research program. A single master contract is established between Caltrans and PEER, and different projects are executed as Task Orders under the master contract. This new program covers the following seven priority topics:

1. Maintenance/Sustainability
2. New Materials
3. Bridge Modeling & Analysis
4. Accelerated Bridge Construction
5. Performance-Based Earthquake Engineering (PBEE)/Bridge & System Reliability
6. Foundations & Walls
7. Intelligent Design Tools/Bridge Design Aids

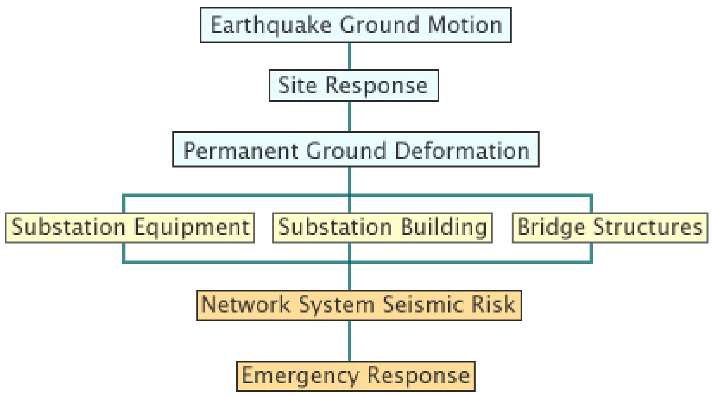
Project topics or detailed problem statements are selected by Caltrans. PEER administers a request-for-proposal (RFP) for each of these problem statements. Caltrans and PEER will review the proposals and make a decision on final selection(s). Selected proposals will be executed as Task Order agreement, and PEER will issue a subaward to the Principal Investigator's university.

According to the Master Agreement between the funding agency and the University of California, Berkeley, for this RFP, only public universities are eligible to submit proposals. That is, the Principal Investigator (PI) must be affiliated with one of the following universities: UC Berkeley, UC Davis, UC Irvine, UC Los Angeles, UC San Diego, Oregon State University, University of Nevada – Reno, and University of Washington.

Since the beginning of the program in August 2020, four projects are funded through the PEER-Bridge program. These projects are listed in Appendix B and on the program website.

2.3 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.

2.4 NEXT GENERATION LIQUEFACTION PROJECT

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.

2.5 SEISMIC RISK ASSESSMENT OF NATURAL GAS INFRASTRUCTURE

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. The project is currently in the second year of its multi-year term and researchers are developing 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.

Professor Jonathan Bray of UC Berkeley is the Principal Investigator of the project. 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.

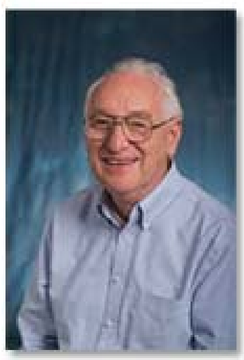
3 Research Highlights and PEER Reports

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

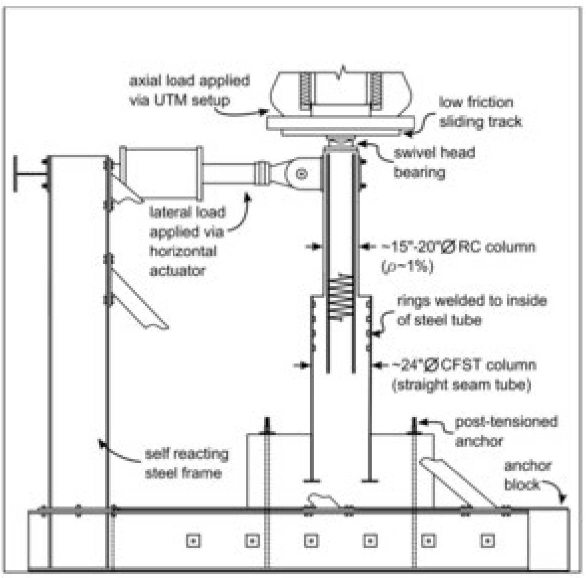
The Project Principal Investigators are Dawn Lehman, Civil & Environmental Engineering, University of Washington, and Charles Roeder, Civil & Environmental Engineering, University of Washington. The research team includes Zhao Muzi, Ph.D. Candidate.

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

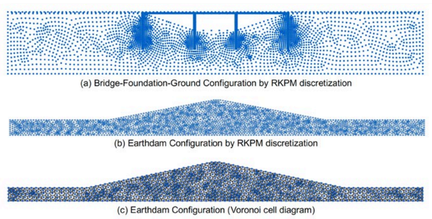
Ahmed Elgamal

Details of the PEER funded research project, "Meshfree Large-Strain Framework for Seismic Response of Ground-Structural Systems: Development and Open Source Tool" are highlighted below. The project Principal Investigator (PI) is 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

An effort is proposed 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



RKPM representations of Soil and Soil structure Systems

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.

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


Domniki Asima**ki**

Details a PEER funded research project “Reduced-Order Models for Dynamic Soil-Structure Interaction Analyses of Buried Structures” are highlighted below. 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).

In this project, we propose to 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 non-linear, frequency-dependent ROM by comparison to 3D FEM of soil and buried structures; and potentially will validate it using published experimental results, if available. We will lastly use the ROM to study the effects of asynchronous excitation on the performance of an idealizedcir cular tunnel in a homogeneous half-space and a sedimentary basin.

RESEARCH IMPACT

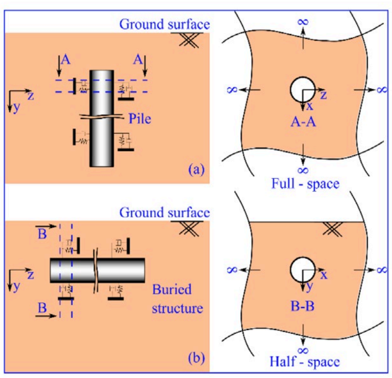


Figure 1: Schematic of full-space and half-space problems

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 benefit this problem two-fold: (i) the 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 (ii) the proposed OpenSEES uniaxial material model that will account for the frequency-dependence of nonlinear SIF will provide a robust and versatile tool to improve the analysis of buried structures under seismic excitation, while maintaining computational efficiency. This in turn will benefit performance-based earthquake engineering methods by providing a physics-based model to account for the effects of spatial variability and incoherency in the seismic demand of extended structures.

3.4 TEXT ANALYTICS ON SOCIAL MEDIA FOR RESILIENCE-ENABLED EXTREME EVENTS RECONNAISSANCE (TAR)

Laurent El Ghaoui

Details a PEER funded research project "Text Analytics on Social Media for Resilience-Enabled Extreme Events Reconnaissance (TAR)" are highlighted below. The project Principal Investigator (PI) is Laurent El Ghaoui, Professor of Electrical Engineering and Computer Science, UC Berkeley. The research team includes Selim Günay, Project Scientist, UC Berkeley, Alicia Yi-Ting Tsai, Graduate Student Researcher, UC Berkeley, Chenglong Li, Graduate Student Researcher, UC Berkeley, and Minjune Hwang, Undergraduate, UC Berkeley.

ABSTRACT

This project aims to apply Natural Language Processing (NLP) techniques to news and social media posts after an extreme event. Natural language processing (NLP) is a subfield of linguistics, computer science, and artificial intelligence concerned with the interactions between computers and human (natural) languages, with the objective of processing and analyzing large amounts of natural language data. In the context of reconnaissance for earthquakes and other natural hazards, it is used here for three purposes: 1) Automated data (news & social media) collection hosted at the Pacific Earthquake Engineering Research (PEER) Center server, 2) Automatic summarization for reconnaissance report generation, and 3) Use of social media to extract information related to earthquake consequences, such as recovery time. The images below illustrate the concept of recovery time, and they show that measuring the intensity of Twitter conversations over time helps develop a sensible recovery measure.

RESEARCH IMPACT

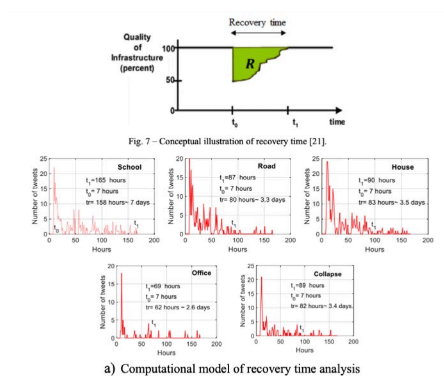


Fig. 7 – Conceptual illustration of recovery time [21].

a) Computational model of recovery time analysis

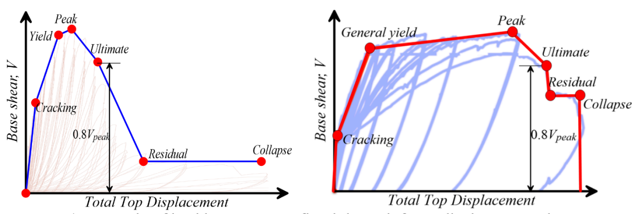
The significant worldwide population growth and urbanization of the past century resulted in an era of global development and infrastructure construction on a massive scale, including buildings and other critical infrastructure systems. Recognizing the associated growth, the National Academy of Engineering has identified "restore and improve urban infrastructure" as one of the Engineering Grand Challenges of the 21st century. On a positive note, the major advancements made in sensor and communication technologies, artificial intelligence algorithms, and science-based understanding of natural hazards, taken in combination, provide a foundation for developing methods of advanced monitoring, maintenance, and reconnaissance of infrastructure. Moreover, the mass adoption of mobile internet-enabled devices, paired with wide-spread use of social media platforms for communication and coordination, has created new opportunities to better understand human responses to extreme events. These methods have the potential to tackle the above-mentioned grand challenge and achieve resilient communities following natural hazards. Being aware of the existing challenges and opportunities, this project presents the tools and methods aiming to achieve resilient communities through reconnaissance efforts. The project develops methods and software to collect news and social media posts after an extreme event to: a) create automatically generated new summaries for immediate report writing after an event, b) to extract key information, such as the recovery time, the most affected regions and infrastructure, and to relate these to the magnitude of the event, socio-economic consequences facing the community, etc. Application of this tool to several recent earthquakes are demonstrated and potential use of the tool along with extreme event reconnaissance networks can be further established.

3.5 A COMPREHENSIVE DATABASE OF RC COLUMN TESTS

John W. Wallace

Details of a PEER funded research project "A Comprehensive Database of RC Column Tests" are highlighted below. The project Principal Investigator (PI) is John W. Wallace, Professor, UCLA, Department of Civil and Environmental Engineering. The research team includes Saman Abdullah, Postdoctoral Researcher, UCLA.

ABSTRACT



a) Example of backbones curves fitted through force-displacement plots

The PEER Column Database was developed in the mid-2000s, and there have since been limited efforts to update the database. Although other databases have been developed, these efforts have not been comprehensive, i.e., test results limited to specific geographic regions (e.g., Japan)or to narrowly focused issues (e.g. high-strength rebar). Furthermore, existing databases (e.g., PEER, ACI Committee 369, and SERIES column Databases) lack detailed information about test geometry, materials, test setup, loading protocol, reinforcement details, experimental results, and analytical results to enable more systematic studies on how particular variables impact column behavior. Also, a significant number of column tests have been conducted over the last several years that are not typically included in these databases. Lastly, most databases do not include test results for retrofitted and repaired columns. Given these issues, this project will focus on updating, expanding, and replacing the PEER Column Database to enable development of new design provisions for bridge and building columns for stiffness, strength (primarily shear strength), and deformation capacity. The primary goals are to: 1) improve the database structure and interface to enable a more efficient use of the database, 2) add more metadata (more parameterized details about the specimens, test setup, loading protocols, and test results, e.g., backbone curves) for the existing tests in the database, 3) add more column data from recent tests, including retrofitted and repaired columns, and 4) include computed and analytical data (e.g., the degree to which the test columns satisfy code detailing provisions, computed strengths, demands relative to these strengths, neutral axis depths at nominal moment strength, moment-curvature analysis). The database will be used to evaluate Caltrans, ACI 318, and ASCE 41 provisions using traditional approaches (e.g., correlation) and machine learning approaches, given that the expanded database will allow more detailed assessments.

RESEARCH IMPACT

1. Reevaluate Caltrans Seismic Design Criteria to improve design provisions (e.g., lateral stiffness and shear strength, as well as statistical information) of bridge columns for new and existing construction.
2. Provide experimental data on retrofitted and repaired columns that could be used to develop updated design provisions and modeling parameters.
3. Assess the newly introduced one-way and two-way column shear strength equations in ACI 318-19 and address potential issues associated with seismic design.
4. The expanded database should also provide data for extending and validating existing fiber-based modeling approaches implemented in OpenSees for coupled axial-bending (P-M) and shear (V) responses of RC columns.
5. Provide the structural/earthquake engineering community with a comprehensive column database. It is expected that the new database would be widely used by both researchers and practitioners.

3.6 OPENSEES IMPLEMENTATION OF 3D EMBEDDED PILE ELEMENT FOR ENHANCED SOIL-PILE INTERACTION ANALYSIS OF BRIDGE SYSTEMS SUBJECT TO LIQUEFACTION AND LATERAL SPREADING

Pedro Arduino

Details of a PEER funded research project "OpenSees Implementation of 3D Embedded Pile Element for Enhanced Soil-pile Interaction Analysis of Bridge Systems Subject to Liquefaction and Lateral Spreading" are highlighted below. The project Principal Investigator (PI) is Pedro Arduino, Professor of Civil & Environmental Engineering, University of Washington.

ABSTRACT

With the current growth in computational power, numerical modeling of seismic events has become a viable tool used in the structural design of bridge systems. Events like the Maule earthquake in Chile (2010), where several bridges collapsed partly or completely due to forces exerted by lateral spreading of the soil prove that soil-structure interaction continues to be an important aspect to consider in numerical analyses of bridge systems. The interaction between the soil and pile foundation is highly nonlinear and inherently complex in nature. Several factors contribute to this nonlinearity including the constitutive behavior of the surrounding soil, constitutive behavior of the pile itself, geometrical nonlinearities of the pile structure, and the interface behavior between the soil and the pile. One-dimensional springs (p-y springs), representing the nonlinear response of both the soil and interface, are commonly used and are available in OpenSees. These elements rely heavily on empirical data and are validated mostly against static or quasi-static experimental data; in general using simple foundation configurations. Their use in large foundation models where the soil is represented by 2D and 3D finite elements

is questionable; since these elements cannot represent the complete 3D soil-pile domain and geometry. More advanced contact models based on node-to-node and node-to-solid contact formulations have been proposed and several of such elements are implemented in OpenSees. In particular, the author proposed and implemented in OpenSees a beam-to- solid contact element that greatly simplifies the representation of structural components using 1D beam elements. In this element the contact between the soil and pile surface imposes the impenetrability geometrical condition at nodes and introduces singular point loads to impose the constraint. Although computationally expensive, these elements have proven very effective for static and quasi-static analyses. For complex geometries, however, discretization of the model to incorporate such elements is cumbersome. This problem is exacerbated in dynamic analyses of complete infrastructure systems (e.g. complete bridge) that include pile groups with many piles and/or drilled shafts. To address (alleviate) this problem, in this proposal an embedded beam element formulation is proposed to be implemented in OpenSees. The element formulation is based on the early work of Turello (2016) as modified by Ghofrani (2018). A schematic of embedded elements showing a regular FEM grid, beam elements, and contact interface surfaces is shown in Figure 1. This formulation imposes interaction constraints between 1D beam elements embedded inside a regular 3D solid element over an explicitly defined interface surface. By imposing the constraints in a weak sense along an imaginary interface surface, a uniform contact pressure can be generated. In contrast to other contact formulations, in this case the soil domain can be uniformly discretized as the new embedded element removes any dependency on discretization. Interface behavior is attained using traditional contact mechanics such that the impenetrability condition is satisfied in a weak sense along the interaction surface and elasto-plastic behavior is used to represent the near-field soil behavior. This formulation eliminates the need to discretize the soil surrounding the pile to match the pile geometry and greatly simplifies mesh generation and post-processing. This is most important, in dynamic analysis of large and complicated systems where the response of the foundation is not the only aspect to be considered.

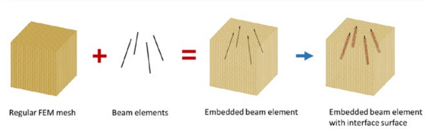


Figure 1: Schematic of embedded element.

RESEARCH IMPACT

The main objective of the proposed work is to facilitate representation of SSI by embedding elements in regular FEM meshes. In this way, embedded beam elements can be used to perform relatively fast and straightforward analysis of seismic and aseismic numerical simulations of foundation systems. They can be used for analysis and design of bridge pile foundations subject to axial and lateral loads, seismic excitations, lateral spreading and liquefaction flow failures. The proposed elements can also be used for validation and verification of current design methodologies as well as analysis of complicated engineering problems. Their application to practice is natural and in sync with other efforts in commercial codes like FLAC and PLAXIS.

The proposed work complements other PEER research efforts related to OpenSees implementation and validation of constitutive models for soils and of structural elements. Soil structure Interaction (SSI) is the obligatory link necessary to connect the geotechnical and structural domains. This works aims to improve current functionality in OpenSees to facilitate dynamic analysis of pile foundation systems.

3.7 SEISMIC EVALUATION OF THE CALIFORNIA HIGH SPEED RAIL SYSTEM

Details of a PEER funded research project “Seismic Evaluation of the California High Speed Rail System” are highlighted below. The project Principal Investigator (PI) is John Stanton, Professor of Civil Engineering, University of Washington. The Research Team includes Marc Eberhard, Professor of Civil Engineering, University of Washington and Michelle Chang, Graduate Research Assistant, University of Washington.

ABSTRACT

John Stanton

The work originally proposed for this project concerned the evaluation of different structural systems for use in the California High Speed Rail (CAHSR) system. After the project was awarded, the funding for the CAHSR was indefinitely postponed, so the research was re-directed, with agreement from PEER, to investigate structural systems that would be of use in either the HSR system or in highway bridges. Those systems concerned bridge substructures, because the superstructures for HSR and highway bridges differ in both their requirements and their typical configurations.

Deep foundations, and primarily drilled shafts, are being used for transportation infrastructure with increasing frequency today, and the transition region from the shaft to the column is a critical region for which behavioral models and design details have not yet been fully developed. “Type 2”shafts are larger in diameter than the columns that they support, and they are widely used because they allow some tolerance in the column location after the body of the shaft has been cast. However, they necessarily depend on non-contact splices between the shaft and column bars. If the development length provisions from the AASHTO LRFD Specifications for such splices are used without modification, the transition region becomes long, the splices become expensive, and the construction crew members face additional safety hazards working at depth. The purpose of this project is to develop, by physical experiment and structural analysis, models for the behavior of the non-contact splice in the transition region that will allow transition regions to be designed that are more compact, more economical and safer to build.

RESEARCH IMPACT

Fig 1. Specimen construction

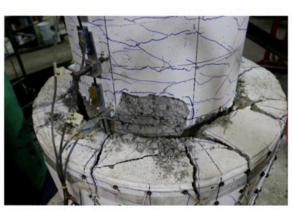


Fig 2. After testing. (Note the separation between column and shaft)

Highway bridges in California constitute one of the most important components of the transportation system. When construction of the High Speed Rail system resumes, it is expected to play a similar role. The capital cost of that infrastructure is much too high to accept the need for replacement after a severe earthquake, so the components, and especially those in locations that are hard to access and repair, must be designed to be both reliable and economical. This can only be achieved by developing a full understanding of the structural properties and behavior of those components. In reinforced concrete, “Disturbed Regions” such as connections and non-contact splices, are some of the least well understood elements. The research described here is expected to have a significant impact on the safety and reliability of drilled shafts and the associated columns.

3.8 PREDICTION OF SEISMIC COMPRESSION OF UNSATURATED BACKFILLS

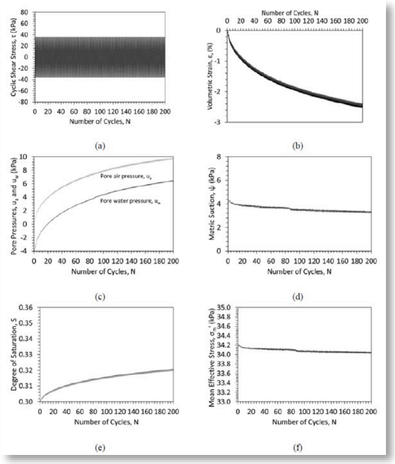
John McCartney

Details of a PEER funded research project "Prediction of Seismic Compression of Unsaturated Backfills" are highlighted below. The project Principal Investigator (PI) is John McCartney, Professor and Department Chair, Department of Structural Engineering, UC San Diego. The Research Team includes Wenyong Rong, Post-doctoral Researcher, UC San Diego.

ABSTRACT

This study will develop, implement and validate a new effective stress-based elasto-plastic constitutive model to predict the evolution in seismic compression of unsaturated backfill soils in transportation systems (e.g., highway embankments, bridge abutments, earth retention systems, etc.). This study seeks to depart from commonly-used semi-empirical approaches for seismic compression prediction by developing an effective stress-based elasto-plastic constitutive model that can capture the impacts of initial degree of saturation and density on the deformation response. Although the model development will build upon concepts from established elasto-plastic constitutive models (e.g., UBCSand), new developments will include a poro-mechanics approach to consider the generation in pore air and pore water pressures during cyclic shearing, an approach to consider changes in the shape of the soil-water retention curve (SWRC) on the effective stress state, and an approach to consider the coupled evolution in soil dynamic properties with effective stress and volumetric contraction. Interaction between each of these new developments is also expected in the model. Data from cyclic simple shear tests on unsaturated sands under different densities will be used to calibrate the new constitutive model in terms of the evolution in volumetric strain, degree of saturation, pore air and pore water pressures, matric suction, effective stress, and dynamic soil properties with cycles of shearing. This study will focus on unsaturated granular backfill soils in the funicular saturation regime (i.e., initial degrees of saturation between 20%and 60%), where the largest volumetric contractions are expected during earthquake loading but liquefaction is not expected.

RESEARCH IMPACT



Seismic compression is defined as the accrual of permanent contractive volumetric strains in soils during earthquakes and has been recognized as a major cause of seismically-induced damage in earth structures. Although backfill soils are typically in an initially dense state and are expected to have minimal settlement under static or traffic loading, they may still experience volumetric contraction during earthquakes. Even small backfill settlements can have a negative impact on the functionality of transportation systems and can lead to high repair costs. Most approaches for seismic compression prediction are semi-empirical, which have been shown to result in variable predictions, and do not necessarily consider the impacts of unsaturated conditions. Accurate predictions are challenging for unsaturated soils, as the degree of saturation and matric suction (the difference between pore air and water pressures) will change during volumetric contraction and will affect the effective stress and dynamic soil properties (e.g., the shear modulus, damping ratio). Generation of pore air and water pressures depend on the bulk fluid modulus and on the initial degree of saturation in the soil.

3.9 REFINED BRIDGE DECK DESIGN AND ANALYSIS

Lijuan “Dawn” Cheng

Details of a PEER funded research project “Refined Bridge Deck Design and Analysis” are highlighted below. The project Principal Investigator (PI) is Lijuan “Dawn” Cheng, Professor of Civil and Environmental Engineering, UC Davis. The Research Team includes Xun “Clay” Wang, Graduate Student Researcher, UC Davis.

ABSTRACT

Since the 1960’s, bridge live loads (design axle loads) and truck volume have been continuously increasing. The truck loads and wheel configurations that the bridge decks are designed for according to the AASHTO LRFD Bridge Design Specifications no longer reflect the modern trucks, not mentioning the use of larger permit vehicles (e.g., P-15) and new vehicle configurations mandated or allowed by federal or state programs such as special hauling vehicles (SHV) and emergency vehicles (EV) in the design. The approximate analysis method in the AASHTO LRFD specification that the current bridge deck design procedure is based on was initially developed in the 1930’s and the accuracy is of concern due to simplified assumptions and approximations in the procedure. In addition, the California Amendments to AASHTO does not permit the empirical design of reinforced concrete decks and overhangs due to concerns associated with durability of such members under high average daily truck traffic applications. Laboratory and in-situ testing of concrete bridge decks designed by the empirical method have also demonstrated concrete cracking and potential reinforcement corrosion in such members, as well as insufficiency in the

empirical reinforcement to resist shrinkage stresses. Therefore, a more accurate, safe and reliable bridge deck design procedure needs to be developed that considers all the impacts in order to ensure the safety and adequate load-carrying capacity of the bridge to meet the growing traffic demand. The *objective* of this research is to develop an updated LRFD-based bridge deck design procedure based on refined analysis methods that consider modern vehicle configurations, dynamic loads, flexural and shear demands, and fatigue of concrete and steel reinforcements. The developed procedure will feature two design tiers: (1) a rigorous and refined analysis incorporating the use of a computer code; and (2) a streamlined chart-based procedure suitable for production design.

RESEARCH IMPACT

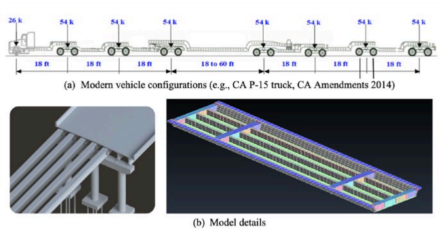


Figure 1 Refined bridge deck analysis

The work in this research will provide an updated LRFD-based bridge deck design procedure based on refined analysis that considers the modern vehicle configurations, dynamic (rolling) loads, flexural and shear demands, and concrete fatigue. The potential broad impacts of this work in the engineering design and evaluation of our nation's infrastructure include: (1) Increased cost savings by going beyond use of approximate, simplistic and conservative design methods in the existing specs; (2) Improved structural safety by more rigorous assessment of required modern loads and accurate modeling of system/local behavior; (3) Enhanced safety evaluation by full consideration of deck flexural, shear, torsion and fatigue; (4) Accomplishing sustainability by more frequent salvaging of existing infrastructures; and (5) Promoting a fundamental change in the practice of bridge engineering and industry from use of simplistic design formulae to achieve more optimal design solutions via innovation development. Therefore, the final product of this work is of particular interest to industry, Caltrans and other State DOT design engineers, bridge maintenance personnel, contractors, and specialty subcontractors such as inspection and repair crews.

3.10 ADVANCED GUIDELINES FOR STABILITY DESIGN OF SLENDER REINFORCED CONCRETE BRIDGE COLUMNS


Michael H. Scott

Details of a PEER funded research project "Advanced Guidelines for Stability Design of Slender Reinforced Concrete Bridge Columns" are highlighted below. he project Principal Investigator (PI) is Michael H. Scott, Professor, Oregon State University. The Co-Principal Investigator is Mark D. Denavit, Assistant Professor, University of Tennessee, Knoxville.

ABSTRACT

The AASHTO approximate method for the design of slender reinforced concrete (RC) bridge columns was adopted from building design codes. Accordingly, the AASHTO method applies to a certain range of parameters and configurations based on floor framing stiffness, building story

heights, material properties, and reinforcing ratios. While some analogies carry over to bridge columns, the superstructure stiffness and unbraced column lengths can be quite different for bridge systems compared to buildings. As a result, bridge engineers typically make very conservative assumptions on the strength of slender RC bridge columns. Although engineers can obtain more efficient designs using refined analysis, this is rarely used in practice due to computational effort and model uncertainty. This project will evaluate the AASHTO approximate moment magnification method using advanced second order inelastic analyses. Parametric studies will be conducted on single column models and common Caltrans bridge types. The impact of major parameters, e.g., slenderness, out of plumb, and superstructure stiffness, on structural behavior according to both the approximate method and advanced analysis will be quantified and refinements to the approximate method will be developed where these methods differ substantially.

RESEARCH IMPACT

Through the development of design recommendations, this project will help engineers design more efficient slender RC columns in bridge structures when compared to approximate methods in AASHTO. Design recommendations will be based on inelastic second order finite element analyses performed using the OpenSees software framework. A new approach for modeling the time-dependent effects of creep and shrinkage in slender RC columns will be developed and validated against published experimental data. Effective stiffness and effective length factors will be assessed along with design limitations and guidance for second order analysis of RC bridge columns. To increase confidence in and applicability of analysis results, modeling recommendations based on OpenSees analyses will be further validated using CSiBridge. Integration of slender RC column experimental data with current PEER databases for cyclic loading of RC columns will be explored and will facilitate the sharing of information and further refinements of second order analysis and design methodologies for bridge structures.

3.11 PERFORMANCE-BASED ECONOMIC LOSS ASSESSMENT DUE TO A HYPOTHETICAL LARGE SOUTHERN CALIFORNIA EARTHQUAKE BASED ON THE DISRUPTION AND RECOVERY OF PORT OF LOS ANGELES FREIGHT TRAFFIC

Ertugrul Taciroglu

Details of a PEER funded research project "Performance-Based Economic Loss Assessment Due to a Hypothetical Large Southern California Earthquake Based on the Disruption and Recovery of Port of Los Angeles Freight Traffic" are highlighted below. The project Principal Investigator (PI) is Ertugrul Taciroglu, Professor of Civil Engineering, UC Los Angeles. The Co-Principal Investigator is Kenichi Soga, Professor of Civil Engineering, UC Berkeley. The Research Team includes Barbaros Cetiner, Postdoctoral Researcher, UC Los Angeles; Bingyu Zhao, Postdoctoral Researcher, UC Berkeley; Michael Virtucio, Graduate Student Researcher, UC Berkeley; and Renjie Wu, Graduate Student Researcher, UC Berkeley.

ABSTRACT

This project develops a novel approach that couples an image-based structure-and-site-specific bridge fragility generation methodology with regional-scale travel demand and economic loss prediction models. The established framework is being applied to real-life bridge networks of

crucial importance, including the highway network surrounding the Port of Los Angeles, to assess resilience and economic losses at a high resolution. Due to its data-intensive nature, the proposed approach will capture and incorporate many details that are usually omitted in traditional analyses (e.g., HAZUS). It, therefore, promises to yield significantly improved accuracy in estimating economic losses and recovery after a major scenario event and the discovery of finer metrics of seismic resilience for transportation networks.

RESEARCH IMPACT

Nonlinear structural models for 1,000 bridges within the immediate periphery of the Ports of Los Angeles and Long Beach were established. The fragility functions for these bridges were computed for slight, moderate, extensive, and complete damage states. Using a GMPE-based approach, the expected 1-second spectral accelerations at each bridge site were determined for an Mw7.3 Palos Verdes Fault scenario event, 2 miles off the port islands. Based on these intensity measure levels, expected damage probabilities and functionality levels and the time required for recovery of these bridges were determined. Figure 1 shows one of the many damage map predictions obtained using the proposed approach. A physics-based simulation of the same scenario earthquake is currently underway.

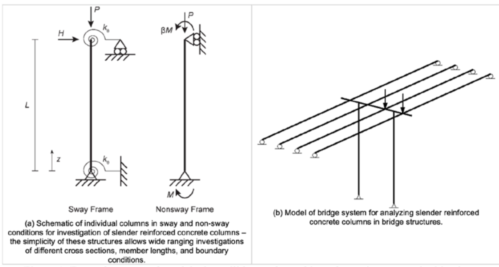


Figure 1: Example structural models that will be used to achieve the project research objectives.

On the traffic side, the road network data for six counties in Southern California represented by the Southern California Association of Governments (SCAG) has been gathered from OpenStreetMap (OSM). The network is converted into a graph representation consisting of 1.4 million edges and 0.6 million nodes. In addition, the travel demand in normal situations (i.e., without earthquake damage) has been obtained from the SCAG and is being processed to the required format. A Python-based traffic assignment module is currently being used, which computes sub-hourly road-usage changes through an interactive assignment process with residual demand. A faster version of the traffic simulation that can better leverage High-Performance Computing (HPC) capabilities is currently being developed.

3.12 IMPLEMENTATION OF FREQUENCY-DEPENDENT IMPEDANCE FUNCTIONS IN OPENSEES


Jian Zhang

Details of a PEER funded research project "Implementation of Frequency-Dependent Impedance Functions in OpenSees" are highlighted below. The project Principal Investigator (PI) is Jian Zhang, Professor of Civil & Environmental Engineering, UCLA. The Research Team includes S. Farid Ghahari, Project Scientist, UCLA and Ertugrul Taciroglu, Professor and Chair of Civil & Environmental Engineering, UCLA (Senior Collaborator).

ABSTRACT

To accurately analyze structures, Soil-Structure Interaction (SSI) effects must be taken into account. One approach to analyze SSI effects is to create and analyze a complete Finite Element Model (FEM) of the full system wherein the soil medium is represented as a semi-infinite domain. This so-called "direct" method approach is frequently adopted in research studies. But, it is typically avoided in engineering practice due to the labor-intensive finite element model development, and the high computational cost. In practice, SSI analysis is mostly carried out through a substructure approach as shown in Figure 1. In this approach, the superstructure is usually modeled through a very detailed FE model and is placed on a soil-foundation substructure which is represented by a system called Impedance Function (IF). Then, the entire system is analyzed under Foundation Input Motions (FIMs) obtained from Free-Field Motions (FFMs) considering Kinematic Interaction (KI) effects. While the method is theoretically designed for linear-elastic behavior due to superposition assumption, the substructure method can be partially applied to nonlinear systems for which the condensation process is performed only on the viscous elastic soil-foundation.

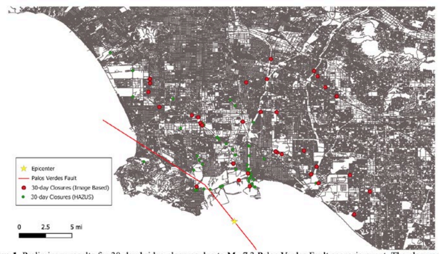


Figure 1. Preliminary results for 30-day bridge closures due to M_w 7.3 Palos Verdes Fault scenario event. The closures were computed using the approach developed for this project (denoted in red) and HAZUS (denoted in green).

Although IFs for various soil and foundation configurations can be obtained from analytical, numerical, or experimental analyses, their implementation in the time-domain is not trivial because they are frequency-dependent with unlimited bandwidth. A simple solution for this problem has been to convert these IFs to some lumped-parameter physical models with frequency-independent components, but there is no straightforward way to connect these components. More importantly, the coefficients of these components could be non-physical parameters that cannot be modeled in FE software like OpenSEES or the final lumped model could be unstable. To resolve the aforementioned problems with the physical models, the IFs can be represented through rational polynomial approximation or equivalently recursive discrete-time filters. An example of such time-domain approximation is shown in Figure 2 for the rocking IF of a rigid disk on elastic half-space. While the implementation of this solution in OpenSEES looks simple, the stability of the entire system is not guaranteed even if the IF filter is itself stable. In this project, we propose to implement any analytically or numerically calculated frequency-dependent IF through recursive filters in OpenSEES and such that the dynamic analysis of the entire structural system with SSI can be stable.

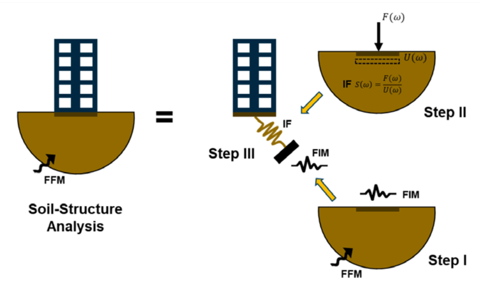


Figure 1. Substructure method

RESEARCH IMPACT

The dynamic nonlinear time-history analysis plays a critical role in PEER Performance-Based Engineering (PBE). While nonlinear behavior of the structures can be modeled with relatively good accuracy, the soil-foundation subsystem is still highly uncertain. One of the sources of the uncertainties is the frequency-dependent behavior of the soil-foundation impedance function. Current FE modeling software are not capable of including frequency-dependency in the time domain unless IF is modeled through physical lumped parameter models. However, there is no unique and general way to develop such lumped models for any IF. Also, there is no solution to guarantee the stability of the entire system. This project will provide engineers and researchers with an extended version of the OpenSEES by which they can carry out more accurate nonlinear time-history analysis while frequency-dependent soil-structure interaction effects are taken into account.

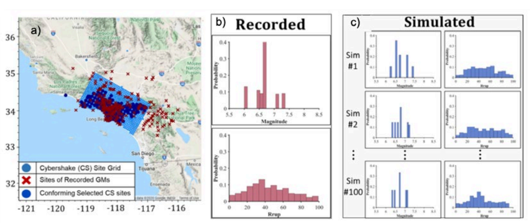
3.13 VALIDATION AND UTILIZATION OF PHYSICS-BASED SIMULATED ROUND MOTIONS FOR BRIDGE PERFORMANCE ASSESSMENT

Farzin Zareian

Details of a PEER funded research project "Validation and Utilization of Physics-based Simulated Ground Motions for Bridge Performance Assessment" are highlighted below. The project Principal Investigator (PI) is Farzin Zareian, Associate Professor, UC Irvine. The Research Team includes Mayssa Dabaghi, Co-PI, American University of Beirut, Jawad Fayaz, Graduate Student Researcher, UC Irvine, and Sarah Azar, Graduate Student Researcher, American University of Beirut.

ABSTRACT

The overarching goal of this research is to develop and apply a methodology to validate synthetic ground motions obtained from physics-based simulation models intended for performance assessment and design of bridge structures. The main objective is to investigate if such synthetic motions lead to a bridge response that is consistent with the response obtained using statistically conforming recorded ground motions. The validation methodology will provide technical feedback to ground motion modelers on needed model enhancement, and bridge engineers on best utilization practices. The validation methodology is founded on comparing conforming groups of ground motion waveforms from recordings and simulations and their effect on a collection of structures that represent the engineering practices and application. The comparison considers the statistics of earthquake scenarios at the level of the seismic event and site parameters, the resulting waveform characteristics, and the subsequent structural responses. Regression models are developed at three levels (between structural responses and waveform characteristics, structural responses and event and site parameters, and waveform characteristics and event and site parameters). The validation process is guided by a statistical comparison of the models obtained from groups of recorded and simulated ground motions. The validation methodology is applied to CyberShake (ver. 15.12) simulations in the southern California region and estimates the column drift ratio of a representative set of bridge structures.



RESEARCH IMPACT

The mainstream approach for designing and assessing structures to withstand impacts of seismic hazard is to utilize a set of selected and modified ground motions from past global recordings of seismic events. Such an approach does not allow the opportunity to embrace the advancements in ground motion simulation, resulting in waveforms tailored for the structures' location. A validated ground motion simulation method opens significant research opportunities to investigate seismic events' regional impact on essential components of distributed systems (e.g., highway bridges in a transportation system). The main hurdle in using simulated motions is the lack of consensus on the acceptable accuracy of the computed structural responses. Validation methods for simulated ground motions can be categorized into three main types. Type I validation methods are based on historic events; they show if ground motion waveforms obtained from replicating a single event at their respective recording stations have the same central value of response as their corresponding recordings. Type II validation methods focus on the similarity of trends in important parameters representing ground motion characteristics (e.g., peak ground acceleration, building response) with event and site parameters obtained from simulations and recordings. In contrast with Type I validation, Type II validation may utilize a population of past events to form the trends in ground motion parameters. Type III validation methods find the equivalency between simulated and recorded ground motions using established structural/earthquake engineering principles and statistical tools; similarity of response spectra is the cornerstone of such equivalency checks. The methodology presented in this research is of the Type II validation approach. The suggested validation methodology's main contribution resides in its ability to be tailored for the target simulation method and engineering application while founded on a set of established engineering principles and statistical tools.

3.14 GROUND IMPROVEMENT-BASED PROTECTION OF TRANSPORTATION INFRASTRUCTURE: VALIDATION OF PBE VIA CENTRIFUGE AND NUMERICAL MODELING

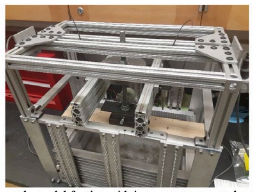

Tara Hutchinson

Details of a PEER funded research project "Ground Improvement-Based Protection of Transportation Infrastructure: Validation of PBE via Centrifuge and Numerical Modeling" are highlighted below. The project Principal Investigator (PI) is Tara Hutchinson, Professor of Structural Engineering, UC San Diego. The Co-Principal Investigator is John McCartney, Professor of Structural Engineering, UC San Diego. The Research Team includes Jeffrey Newgard, Research Assistant, UC San Diego.

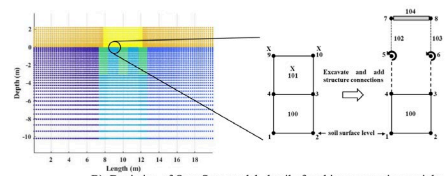
ABSTRACT

This study builds upon previous research illuminating the propensity of rocking footings to dissipate energy into the ground and re-center themselves during and following an earthquake – thereby protecting the superstructure from sustaining undue damage. Essentially, to induce rocking the footing must be under-designed, that is, sized smaller with a lower safety factor against bearing failure. However, a consequence of allowing the footing to rock is that it may exhibit undesirable

deformations, including large transient rotations and residual settlements during and following shaking, respectively. Strategically designed ground improvement beneath the foundation can control such detrimental kinematics. To refine the best ground improvement strategies, a numerical model in the OpenSees platform (detail of the model shown in Project Image B) was assembled and validated against centrifuge experiments conducted at UC Davis. Next the numerical model will be used to design our own centrifuge test program in the coming months.



A) Centrifuge-ready model footing with instruments mounted on laminar container



B) Depiction of OpenSees model, detail of rocking connection at right

This testing program is geared around resolving unanswered questions, including the appropriate balance between enhanced energy dissipation and acceptable residual settlement, and the level of ground improvement needed to reach that balance. After corresponding with practicing engineers (including James Gingery and Lisheng Shao) the primary ground improvement method to be tested is soil-cement columns owing to their prevalence in local practice. A relatively heavily loaded footing will undergo shaking with and without the improvement in sand samples carefully curated with an air pluviator designed to fill a flexible laminar container, to be mounted on the centrifuge's shaking table. The laminar container (Project Image A) has been assembled with instrumentation needed to monitor its orientation during shaking. The footing is loaded with a static mass (rather than a load actuator) for simplicity and to ensure constant vertical load during shaking. While the numerical model is complete, centrifuge tests are expected to begin by April of 2021.

RESEARCH IMPACT

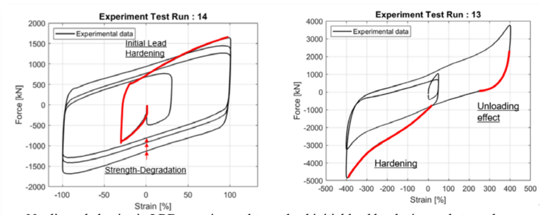
By developing a strategy to control the detrimental kinematics of plastic hinging foundations, practice can move and embrace a natural, cost-effective solution withits implementation in PBE of transportation infrastructure. The proposed approach, via implementation of ground improvement strategies below rocking foundations, supports use of readily accepted concepts in geotechnical practice. We anticipate these concepts will be readily accepted in practice with sufficient experimental and numerical evidence. It is noted that the use of ground improvement strategies is also readily extensible to retrofit design and thus when the additional rocking and/or energy dissipative benefits of an existing transportation structure foundation support system are needed to enhance seismic performance, coupling with ground improvement to control deformations offers a feasible option. Ultimately, adaption of this concept will reduce risk to infrastructure in the event of severe earthquakes, limiting potential service disruptions and costly repairs to transportation systems.

3.15 SEISMIC PERFORMANCE OF ISOLATED BRIDGES UNDER EXTREME SHAKING

Gilberto Mosqueda

Details of a PEER funded research project “Seismic Performance of Isolated Bridges under Extreme Shaking” are highlighted below. The project Principal Investigator (PI) is Gilberto Mosqueda, Professor, Department of Structural Engineering, UC San Diego.

ABSTRACT



Nonlinear behavior in LRB experimental tests: lead initial lead hardening and strength degradation, rubber hardening and unloading effects

Seismic isolation is a proven strategy for protecting critical infrastructure, such as signature bridges and high-speed elevated rail, from the damaging effects of design-level earthquake ground shaking. While the performance of seismically isolated transportation infrastructure under design level ground motions has been widely verified, the risk posed under beyond design basis shaking requires more refined modeling of bearing models for prediction of isolator displacements and assessment of failure modes including pounding or deck unseating. Most past studies have relied on bilinear models of bearings under design level motions. Recent experimental studies have shown that lead rubber bearings (LRB) widely used in bridges have strength degradation from heating of the lead that can substantially increase isolator displacements especially for long duration shaking. LRB can also exhibit strain hardening of the rubber at large strains. Various bearing models have been proposed to capture these and other nonlinear characteristics of LRB, however, a review of existing models showed that one model is notable to capture all dominant characteristics observed in experimental measurements of bearing to large strains.

This study aims to develop improved bearing models for bridges to more accurately predict displacements. The use of restrainers and supplemental damping will be considered for mitigation of pounding or unseating, and to limit demands on bearings, expansion joints, rails and other components that cross the isolation interface. Models of bridge and elevated railway structures with advanced bearing models and contact interface will be used to examine the structural response sensitivity in terms of isolation gap and isolation system modeling parameters.

RESEARCH IMPACT

PBEE for the evaluation of new and existing seismically isolated transportation infrastructure considering beyond design basis earthquakes will require more accurate modeling of bearing models for prediction of isolator displacements and assessment of failure modes including pounding or deck unseating. Past studies for seismically isolated structures have mainly considered the response for design level shaking for which simplified bearing models are adequate. In light of recent studies demonstrating unacceptable risk of collapse for seismically isolated buildings designed to current standards, the probability of failure of isolated transportation infrastructure needs to be further investigated. These structures require high confidence in seismic responses given the low level of redundancy that makes them vulnerable to modeling uncertainty. Large displacements at expansion joints are of concern while pounding between decks or deck to abutment and unseating has been cited as a major source of damage to bridges leading to catastrophic failure. Further, restrainers and deck pounding can result in a large transfer of forces between decks and/or substructure, negating the isolation effect. State of the art models of seismically isolated bridges and elevated rail considering the isolation system behavior is necessary to capture these potential failure models. This study will focus on modeling of LRB including restrainers and contact models for the consideration of pounding. Complete bridge and elevated railway models will be developed to assess the reliability of seismically isolated transportation infrastructure under extreme shaking and propose effective mitigation measures.

3.16 A SYSTEM-LEVEL STUDY TO EVALUATE THE ROLE OF SOIL GRADATION ON SEISMICALLY INDUCED EMBANKMENT DEFORMATIONS

Jason T. DeJong

Details of a PEER funded research project "A System-Level Study to Evaluate the Role of Soil Gradation on Seismically Induced Embankment Deformations" are highlighted below. The project Principal Investigator (PI) is Jason T. DeJong, Professor, UC Davis.

ABSTRACT

The overarching goal is to realize a step-change in the prediction accuracy of earthquake induced embankment deformations that will result in increased societal safety and significant reductions in economic impacts. More specifically, the project objectives are to (1) evaluate how and why the seismic deformations of embankments constructed of well graded soils, as is typical in practice, can be significantly less than for embankments constructed of poorly graded soils, which is the basis for industry standard analyses, and (2) develop guidance on how to incorporate the project results into nonlinear deformation analyses (NDA) so that excessive and unknown conservatism does not continue to be incorporated into engineering analyses of earthen embankments. The project is planned around a 9m radius centrifuge test comprised of two side-by-side embankments constructed with a soil representative of field embankment conditions and prepared at relative densities of 40% and 65%. High speed cameras (HSC) using Particle Image Velocimetry (PIV), LiDAR, and accelerometers will be used for detailed deformation analysis. All methods, data, and personnel capabilities that have been developed for an ongoing NSF project (CMMI #1916152) will be leveraged to accelerate productivity, magnify impact, and bridge the knowledge generated from the NSF project to conditions routinely present in constructed embankments.

RESEARCH IMPACT

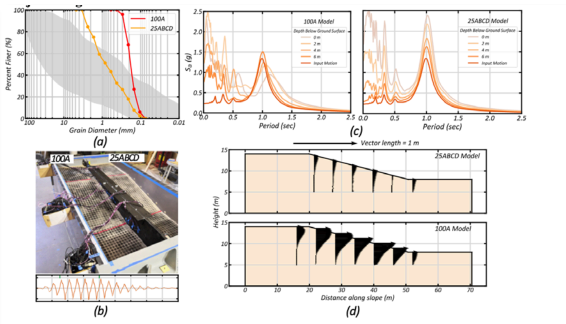


Figure: (a) Grain size distribution of tested soils (colored lines) and typical gradations in constructed embankments (gray zone); (b) photo of divided centrifuge model and input motion; (c) response spectrum of accelerometer data; (d) permanent deformations of slopes following shaking from HSC-PIV analysis.

Industry NDA analyses to predict the seismic induced deformations are based, at its origin, on constitutive models developed for and calibrated to poorly graded sands. Knowledge on how soil properties and behaviors change with gradation is severely limited (even though gradation is always known), and hence routine practice defaults to the (incorrect) assumption that well graded soils behave similarly to poorly graded sands. The NSF leveraged results (in Project Image below) show that embankment deformations comprised of well graded soils can be 20% of poorly graded sands when subject to the same loading conditions. This implies that current industry practice may be excessively conservative. Large embankment dams routinely undergo re-evaluation, and due to recent increases in seismic hazard estimates, it often leads to remediation measures, typically at the cost of $50-$500M per embankment. If the project hypothesis is true, and well-graded soils deform only a fraction of poorly graded soils, retrofit measures may not be necessary or could be more modest in many cases, which could lead to significant savings for dam owners (and rate payers).

3.17 PEER REPORTS 2020–2021

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.

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 MCER 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.

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

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 (VS30), 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.

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

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 (VS30), 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, Φ ; (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 VS30-dependent for distances less than 200 km, decreasing for softer soils with VS30 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)].

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

This report presents a summary of the development, evaluation, and comparison of a new subduc-tion 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 in-traslab 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 esti-mates. 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. Fur-thermore, the Bayesian approach used to develop the model will facilitate update of this innovative GMM as new data become available.

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

Conditional models for the horizontal and vertical peak ground velocity (PGV), given the pseudospectral acceleration [PSA(T)] values, are developed for active crustal regions. The period of the PSA(T) used in the conditional model, TPGV, 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.

2020/06 *Development of NGA-Sub Ground-Motion Model of 5%-Damped Pseudo-Spectral Acceleration Based on Database for Subduction Earthquakes in Japan.* Hongjun Si, Saburoh Midorikawa, Tadahiro Kishida.

Presented within is an empirical ground-motion model (GMM) for subduction-zone earthquakesin Japan. The model is based on the extensive and comprehensive subduction database of Japanese earthquakes by the Pacific Engineering Research Center (PEER). It considers RotD50 horizontal components of peak ground acceleration (PGA), peak ground velocity (PGV), and 5%-damped elastic pseudo-absolute acceleration response spectral ordinates (PSA) at the selected periods ranging from 0.01 to 10 sec. The model includes terms and predictor variables considering tectonic setting (i.e., interplate and intraslab), hypocentral depths (D), magnitude scaling, distance attenuation, and site response. The magnitude scaling derived in this study is well constrained by the data observed during the large-magnitude interface events in Japan (i.e., the 2003 Tokachi-Oki and 2011 Tohoku earthquakes) for different periods. The developed ground-motion prediction equation (GMPE) covers subduction-zone earthquakes that have occurred in Japan for magnitudes ranging from 5.5 to as large as 9.1, with distances less than 300 km from the source.

2020/07 *Comparison of NGA-Sub Ground-Motion Models.* Nicholas Gregor, Kofi Addo, Linda Al Atik, Gail M. Atkinson, David M. Boore, Yousef Bozorgnia, Kenneth W. Campbell, Brian S.-J. Chiou, Zeynep Gülerce, Behzad Hassani, Tadahiro Kishida, Nico Kuehn, Saburoh Midorikawa, Silvia Mazzoni, Grace A. Parker, Hongjun Si, Jonathan P. Stewart, Robert R. Youngs.

Ground-motion models (GMMs) for subduction earthquakes recently developed as part of the NGA-Subduction (NGA-Sub) project are compared in this report. The three models presented in this comparison report are documented in their respective PEER reports. Two of the models are developed for a global version and as well regionalized models. The third model is developed based on earthquakes contain in the NGA-Sub dataset only from Japan and as such is applicable for Japan. As part of the comparisons presented in this report, deterministic calculations are provided for the global and regional cases amongst the models. The digital values and additional plots from these deterministic comparisons are provided as part of the electronic supplement for this report. In addition, ground-motion estimates are provided for currently published subduction GMMs. Two example probabilistic seismic hazard analysis calculations are also presented for two sites located in the Pacific Northwest Region in the state of Washington. Based on the limited comparisons presented in this report, a general understanding of these new GMMs can be appreciated with the expectation that the implementation for a specific seismic hazard study should incorporate similar and additional comparisons and sensitivity studies similar to the ones presented in this report.

2020/08 *PEER Activities 2018—2020.* Khalid Mosalam, Amarnath Kasalanati.

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).

2020/09 *Blind Prediction of Shaking Table Tests of a New Bridge Bent Design.* Selim Günay, Fan Hu, Khalid Mosalam, Arpit Nema, Jose Restrepo, Ádam Zsarnoczay, Jack Baker.

Considering the importance of the transportation network and bridge structures, the associated seismic design philosophy is shifting from the basic collapse prevention objective to maintaining functionality on the community scale in the aftermath of moderate to strong earthquakes (i.e., resiliency). In addition to performance, the associated construction philosophy is also being modernized, with the utilization of accelerated bridge construction (ABC) techniques to reduce impacts of construction work on traffic, society, economy, and on-site safety during construction.

Recent years have seen several developments towards the design of low-damage bridges and ABC. According to the results of conducted tests, these systems have significant potential to achieve the intended community resiliency objectives. Taking advantage of such potential in the standard design and analysis processes requires proper modeling that adequately characterizes the behavior and response of these bridge systems.

To evaluate the current practices and abilities of the structural engineering community to model this type of resiliency-oriented bridges, the Pacific Earthquake Engineering Research Center (PEER) organized a blind prediction contest of a two-column bridge bent consisting of columns with enhanced response characteristics achieved by a well-balanced contribution of self-centering, rocking, and energy dissipation.

The parameters of this blind prediction competition are described in this report, and the predictions submitted by different teams are analyzed. In general, forces are predicted better than displacements. The post-tension bar forces and residual displacements are predicted with the best and least accuracy, respectively. Some of the predicted quantities are observed to have coefficient of variation (COV) values larger than 50%; however, in general, the scatter in the predictions amongst different teams is not significantly large.

Applied ground motions (GM) in shaking table tests consisted of a series of naturally recorded earthquake acceleration signals, where GM1 is found to be the largest contributor to the displacement error for most of the teams, and GM7 is the largest contributor to the force (hence, the acceleration) error. The large contribution of GM1 to the displacement error is due to the elastic response in GM1 and the errors stemming from the incorrect estimation of the period and damping ratio. The contribution of GM7 to the force error is due to the errors in the estimation of the base-shear capacity. Several teams were able to predict forces and accelerations with only moderate bias. Displacements, however, were systematically underestimated by almost every team. This suggests that there is a general problem either in the assumptions made or the models used to simulate the response of this type of bridge bent with enhanced response characteristics. Predictions of the best-performing teams were consistently and substantially better than average in all response quantities. The engineering community would benefit from learning details of the approach of the best teams and the factors that caused the models of other teams to fail to produce similarly good results.

Blind prediction contests provide: (1) very useful information regarding areas where current numerical models might be improved; and (2) quantitative data regarding the uncertainty of analytical models for use in performance-based earthquake engineering evaluations. Such blind prediction contests should be encouraged for other experimental research activities and are planned to be conducted annually by PEER.

2020/10 *Low Seismic Damage Columns for Accelerated Bridge Construction.* Arpit Nema, José Restrepo.

This report describes the design, construction, and shaking table response and computation simulation of a Low Seismic-Damage Bridge Bent built using Accelerated Bridge Construction methods. The proposed bent combines precast post-tensioned columns with precast foundation and bent cap to simplify off- and on-site construction burdens and minimize earthquake-induced damage and associated repair costs. Each column consists of reinforced concrete cast inside a cylindrical steel shell, which acts as the formwork, and the confining and shear reinforcement. The column steel shell is engineered to facilitate the formation of a rocking interface for concentrating the deformation demands in the columns, thereby reducing earthquake-induced damage. The precast foundation and bent cap have corrugated-metal-duct lined sockets, where the columns will be placed and grouted on-site to form the column–beam joints. Large inelastic deformation demands in the structure are concentrated at the column–beam interfaces, which are designed to accommodate these demands with minimal structural damage. Longitudinal post-tensioned high-strength steel threaded bars, designed to respond elastically, ensure re-centering behavior. Internal mild steel reinforcing bars, debonded from the concrete at the interfaces, provide energy dissipation and impact mitigation.

2020/11 *Hybrid Simulations for the Seismic Evaluation of Resilient Highway Bridge Systems.* Yingjie Wu, Selim Günay, Khalid Mosalam.

Bridges often serve as key links in local and national transportation networks. Bridge closures can result in severe costs, not only in the form of repair or replacement, but also in the form of economic losses related to medium- and long-term interruption of businesses and disruption to surrounding communities. In addition, continuous functionality of bridges is very important after any seismic event for emergency response and recovery purposes. Considering the importance of these structures, the associated structural design philosophy is shifting from collapse prevention to maintaining functionality in the aftermath of moderate to strong earthquakes, referred to as "resiliency" in earthquake engineering research. Moreover, the associated construction philosophy is being modernized with the utilization of accelerated bridge construction (ABC) techniques, which strive to reduce the impact of construction on traffic, society, economy and on-site safety. This report presents two bridge systems that target the aforementioned issues. A study that combined numerical and experimental research was undertaken to characterize the seismic performance of these bridge systems.

The first part of the study focuses on the structural system-level response of highway bridges that incorporate a class of innovative connecting devices called the "V-connector,", which can be used to connect two components in a structural system, e.g., the column and the bridge deck, or the column and its foundation. This device, designed by ACII, Inc., results in an isolation surface at the connection plane via a connector rod placed in a V-shaped tube that is embedded into the concrete. Energy dissipation is provided by friction between a special washer located around the V-shaped tube and a top plate. Because of the period elongation due to the isolation layer and the limited amount of force transferred by the relatively flexible connector rod, bridge columns are protected from experiencing damage, thus leading to improved seismic behavior. The V-connector system also facilitates the ABC by allowing on-site assembly of prefabricated structural parts including those of the V-connector.

A single-column, two-span highway bridge located in Northern California was used for the proof-of-concept of the proposed V-connector protective system. The V-connector was designed to result in an elastic bridge response based on nonlinear dynamic analyses of the bridge model with the V-connector. Accordingly, a one-third scale V-connector was fabricated based on a set of selected design parameters. A quasi-static cyclic test was first conducted to characterize the force-displacement relationship of the V-connector, followed by a hybrid simulation (HS) test in the longitudinal direction of the bridge to verify the intended linear elastic response of the bridge system. In the HS test, all bridge components were analytically modeled except for the V-connector, which was simulated as the experimental substructure in a specially designed and constructed test setup. Linear elastic bridge response was confirmed according to the HS results. The response of the bridge with the V-connector was compared against that of the as-built bridge without the V-connector, which experienced significant column damage. These results justified the effectiveness of this innovative device.

The second part of the study presents the HS test conducted on a one-third scale two-column bridge bent with self-centering columns (broadly defined as "resilient columns" in this study) to reduce (or ultimately eliminate) any residual drifts. The comparison of the HS test with a previously conducted shaking table test on an identical bridge bent is one of the highlights of this study. The concept of resiliency was incorporated in the design of the bridge bent columns characterized by a well-balanced combination of self-centering, rocking, and energy-dissipating mechanisms. This combination is expected to lead to minimum damage and low levels of residual drifts. The ABC is achieved by utilizing precast columns and end members (cap beam and foundation) through an innovative socket connection. In order to conduct the HS test, a new hybrid simulation system (HSS) was developed, utilizing commonly available software and hardware components in most structural laboratories including: a computational platform using Matlab/Simulink [MathWorks 2015], an interface hardware/software platform dSPACE [2017], and MTS controllers and data acquisition (DAQ) system for the utilized actuators and sensors. Proper operation of the HSS was verified using a trial run without the test specimen before the actual HS test.

In the conducted HS test, the two-column bridge bent was simulated as the experimental substructure while modeling the horizontal and vertical inertia masses and corresponding mass proportional damping in the computer. The same ground motions from the shaking table test, consisting of one horizontal component and the vertical component, were applied as input excitations to the equations of motion in the HS. Good matching was obtained between the shaking table and the HS test results, demonstrating the appropriateness of the defined governing equations of motion and the employed damping model, in addition to the reliability of the developed HSS with minimum simulation errors. The small residual drifts and the minimum level of structural damage at large peak drift levels demonstrated the superior seismic response of the innovative design of the bridge bent with self-centering columns. The reliability of the developed HS approach motivated performing a follow-up HS study focusing on the transverse direction of the bridge, where the entire two-span bridge deck and its abutments represented the computational substructure, while the two-column bridge bent was the physical substructure. This investigation was effective in shedding light on the system-level performance of the entire bridge system that incorporated innovative bridge bent design beyond what can be achieved via shaking table tests, which are usually limited by large-scale bridge system testing capacities.

2020/12 *Project Technical Summary, a report for the "Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings" Project.* Evan Reis, Reis Consulting in collaboration with Yousef Bozorgnia, Henry Burton, Kelly Cobeen, Gregory G. Deierlein, Tara Hutchinson, Grace S. Kang, Bret Lizundia, Silvia Mazzoni, Sharyl Rabinovici, Brandon Schiller, David P. Welch, and Farzin Zareian.

This report is one of a series of reports documenting the methods and findings of a multi-year, multi-disciplinary project coordinated by the Pacific Earthquake Engineering Research Center (PEER) and funded by the California Earthquake Authority (CEA). The overall project is titled *"Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings,"* henceforth referred to as the *"PEER-CEA Project."*

The overall objective of the PEER–CEA project is to provide scientifically based information (e.g., testing, analysis, and resulting loss models) that measure and assess the effectiveness of seismic retrofit to reduce the risk of damage and associated losses (repair costs) of wood-frame houses with cripple wall and sill anchorage deficiencies as well as retrofitted conditions that address those deficiencies. Tasks that support and inform the loss-modeling effort are: (1) collecting and summarizing existing information and results of previous research on the performance of wood-frame houses; (2) identifying construction features to characterize alternative variants of wood-frame houses; (3) characterizing earthquake hazard and ground motions at representative sites in California; (4) developing cyclic loading protocols and conducting laboratory tests of cripple wall panels, wood-frame wall subassemblies, and sill anchorages to measure and document their response (strength and stiffness) under cyclic loading; and (5) the computer modeling, simulations, and the development of loss models as informed by a workshop with claims adjustors.

This report is a product of Working Group 7: Reporting and is a summary of the PEER–CEA Project work performed by Working Groups 1–6. This report does not present new information apart from the rest of the project, and its purpose is to serve as a reference for researchers and catastrophe modelers wishing to understand the objectives and key findings of the project. The key overall findings of the PEER–CEA Project are summarized in Chapters 8 and 10, which describe the efforts of the WG5 and WG6 Working Groups. The reader is referred to the individual reports prepared by the Working Groups for comprehensive information on the tasks, methodologies, and results of each.

2020/13 *Development of Index Buildings,* a report for the "Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings" Project. Evan Reis.

This report is one of a series of reports documenting the methods and findings of a multi-year, multi-disciplinary project coordinated by the Pacific Earthquake Engineering Research Center (PEER and funded by the California Earthquake Authority (CEA). The overall project is titled *"Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings,"* henceforth referred to as the *"PEER–CEA Project."*

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This report is a product of Working Group 2: *Development of Index Buildings* and focuses on the identification of common variations and combinations of materials and construction characteristics of California single-family dwellings. These were used to develop "Index Buildings" that formed the basis of the PEER–CEA Project testing and analytical modeling programs (Working Groups 4 and 5). The loss modeling component of the Project (Working Group 6) quantified the damage-seismic hazard relationships for each of the Index Buildings.

2020/14 *Probabilistic Seismic Hazard Analysis and Selecting and Scaling of Ground-Motion Records,* a report for the "Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings" Project. Silvia Mazzoni, Nicholas Gregor, Linda Al Atik,Yousef Bozorgnia, David P. Welch, Gregory G. Deierlein.

This report is one of a series of reports documenting the methods and findings of a multi-year, multi-disciplinary project coordinated by the Pacific Earthquake Engineering Research Center (PEER) and funded by the California Earthquake Authority (CEA). The overall project is titled *"Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings,"* henceforth referred to as the *"PEER–CEA Project."*

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This report is a product of Working Group 3 (WG3), Task 3.1: *Selecting and Scaling Ground-motion records*. The objective of Task 3.1 is to provide suites of ground motions to be used by other working groups (WGs), especially Working Group 5: Analytical Modeling (WG5) for Simulation Studies. The ground motions used in the numerical simulations are intended to represent seismic hazard at the building site. The seismic hazard is dependent on the location of the site relative to seismic sources, the characteristics of the seismic sources in the region and the local soil conditions at the site. To achieve a proper representation of hazard across the State of California, ten sites were selected, and a site-specific probabilistic seismic hazard analysis (PSHA) was performed at each of these sites for both a soft soil (V_{s30} = 270 m/sec) and a stiff soil (V_{s30}=760 m/sec). The PSHA used the UCERF3 seismic source model, which represents the latest seismic source model adopted by the USGS [2013] and NGA-West2 ground-motion models. The PSHA was carried out for structural periods ranging from 0.01 to 10 sec.

At each site and soil class, the results from the PSHA—hazard curves, hazard deaggregation, and uniform-hazard spectra (UHS)—were extracted for a series of ten return periods, prescribed by WG5 and WG6, ranging from 15.5–2500 years. For each case (site, soil class, and return period), the UHS was used as the target spectrum for selection and modification of a suite of ground motions. Additionally, another set of target spectra based on "Conditional Spectra" (CS), which are more realistic than UHS, was developed [Baker and Lee 2018]. The Conditional Spectra are defined by the median (Conditional Mean Spectrum) and a period-dependent variance. A suite of at least 40 record pairs (horizontal) were selected and modified for each return period and target-spectrum type. Thus, for each ground-motion suite, 40 or more record pairs were selected using the deaggregation of the hazard, resulting in more than 200 record pairs per target-spectrum type at each site. The suites contained more than 40 records in case some were rejected by the modelers due to secondary characteristics; however, none were rejected, and the complete set was used.

For the case of UHS as the target spectrum, the selected motions were modified (scaled) such that the average of the median spectrum (RotD50) [Boore 2010] of the ground-motion pairs follow the target spectrum closely within the period range of interest to the analysts. In communications with WG5 researchers, for ground-motion (time histories, or time series) selection and modification, a period range between 0.01–2.0 sec was selected for this specific application for the project. The duration metrics and pulse characteristics of the records were also used in the final selection of ground motions. The damping ratio for the PSHA and ground-motion target spectra was set to 5%, which is standard practice in engineering applications.

For the cases where the CS was used as the target spectrum, the ground-motion suites were selected and scaled using a modified version of the conditional spectrum ground-motion selection tool (CS-GMS tool) developed by Baker and Lee [2018]. This tool selects and scales a suite of ground motions to meet both the median and the user-defined variability. This variability is defined by the relationship developed by Baker and Jayaram [2008]. The computation of CS requires a structural period for the conditional model. In collaboration with WG5 researchers, a conditioning period of 0.25 sec was selected as a representative of the fundamental mode of vibration of the buildings of interest in this study. Working Group 5 carried out a sensitivity analysis of using other conditioning periods, and the results and discussion of selection of conditioning period are reported in Section 4 of the WG5 PEER report entitled *Technical Background Report for Structural Analysis and Performance Assessment*.

The WG3.1 report presents a summary of the selected sites, the seismic-source characterization model, and the ground-motion characterization model used in the PSHA, followed by selection and modification of suites of ground motions. The Record Sequence Number (RSN) and the associated scale factors are tabulated in the Appendices of this report, and the actual time-series files can be downloaded from the PEER Ground-motion database Portal (https://ngawest2.berkeley.edu/).

2020/15 *Development of Testing Protocol for Cripple Wall Components,* a report for the "Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings" Project. Farzin Zareian, Joel Lanning.

This report is one of a series of reports documenting the methods and findings of a multi-year, multi-disciplinary project coordinated by the Pacific Earthquake Engineering Research Center (PEER) and funded by the California Earthquake Authority (CEA). The overall project is titled *"Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings,"* henceforth referred to as the *"PEER–CEA Project."*

The overall objective of the PEER–CEA project is to provide scientifically-based information (e.g., testing, analysis, and resulting loss models) that measure and assess the effectiveness of seismic retrofit to reduce the risk of damage and associated losses (repair costs) of wood-frame houses with cripple wall and sill anchorage deficiencies as well as retrofitted conditions that address those deficiencies. Tasks that support and inform the loss-modeling effort are: (1) collecting and summarizing existing information and results of previous research on the performance of wood-frame houses; (2) identifying construction features to characterize alternative variants of wood-frame houses; (3) characterizing earthquake hazard and ground motions at representative sites in California; (4) developing cyclic loading protocols and conducting laboratory tests of cripple wall panels, wood-frame wall subassemblies, and sill anchorages to measure and document their response (strength and stiffness) under cyclic loading; and (5) the computer modeling, simulations, and the development of loss models as informed by a workshop with claims adjustors.

This report is a product of Working Group 3.2 and focuses on *Loading Protocol Development for Component Testing*. It presents the background, development process, and recommendations for a quasi-static loading protocol to be used for cyclic testing of cripple wall components of wood-frame structures. The recommended loading protocol was developed for component testing to support the development of experimentally informed analytical models for cripple wall components. These analytical models are utilized for the performance-based assessment of wood-frame structures in the context of the PEER–CEA Project.

The recommended loading protocol was developed using nonlinear dynamic analysis of representative multi-degree-of-freedom (MDOF) systems subjected to sets of single-component ground motions that varied in location and hazard level. Cumulative damage of the cripple wall components of the MDOF systems was investigated. The result is a testing protocol that captures the loading history that a cripple wall may experience in various seismic regions in California.

2020/16 *Cripple Wall Small-Component Test Program: Wet Specimens I,* a report for the "Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings" Project. Brandon Schiller, Tara Hutchinson, Kelly Cobeen.

This report is one of a series of reports documenting the methods and findings of a multi-year, multi-disciplinary project coordinated by the Pacific Earthquake Engineering Research Center (PEER and funded by the California Earthquake Authority (CEA). The overall project is titled *"Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings,"* henceforth referred to as the *"PEER–CEA Project."*

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This report is a product of *Working Group 4*: Testing and focuses on the first phase of an experimental investigation to study the seismic performance of retrofitted and existing cripple walls with sill anchorage. Paralleled by a large-component test program conducted at the University of California [Cobeen et al. 2020], the present study involves the first of multiple phases of small-component tests conducted at the UC San Diego. Details representative of era-specific construction, specifically the most vulnerable pre-1960s construction, are of predominant focus in the present effort. Parameters examined are cripple wall height, finish materials, gravity load, boundary conditions, anchorage, and deterioration. This report addresses the first phase of testing, which consisted of six specimens. Phase 1 including quasi-static reversed cyclic lateral load testing of six 12-ft-long, 2-ft high cripple walls. All specimens in this phase were finished on their exterior with stucco over horizontal sheathing (referred to as a “wet” finish), a finish noted to be common of dwellings built in California before 1945. Parameters addressed in this first phase include: boundary conditions on the top, bottom, and corners of the walls, attachment of the sill to the foundation, and the retrofitted condition. Details of the test specimens, testing protocol, instrumentation; and measured as well as physical observations are summarized in this report. In addition, this report discusses the rationale and scope of subsequent small-component test phases. Companion reports present these test phases considering, amongst other variables, the impacts of dry finishes and cripple wall height (Phases 2–4). Results from these experiments are intended to provide an experimental basis to support numerical modeling used to develop loss models, which are intended to quantify the reduction of loss achieved by applying state-of-practice retrofit methods as identified in *FEMA P-1100, Vulnerability-Base Seismic Assessment and Retrofit of One- and Two-Family Dwellings*.

2020/17 *Cripple Wall Small-Component Test Program: Dry Specimens,* a report for the "Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings" Project. Brandon Schiller, Tara Hutchinson, Kelly Cobeen.

This report is one of a series of reports documenting the methods and findings of a multi-year, multi-disciplinary project coordinated by the Pacific Earthquake Engineering Research Center (PEER) and funded by the California Earthquake Authority (CEA). The overall project is titled *“Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings,”* henceforth referred to as the *“PEER–CEA Project.”*

The overall objective of the PEER–CEA Project is to provide scientifically based information (e.g., testing, analysis, and resulting loss models) that measures and documents seismic performance of wood-frame houses with cripple wall and sill anchorage deficiencies as well as retrofitted conditions that address those deficiencies. Three primary tasks support the earthquake loss-modeling effort. They are: (1) the development of ground motions and loading protocols that accurately represent the diversity of seismic hazard in California; (2) the execution of a suite of quasi-static cyclic experiments to measure and document the performance of cripple wall and sill anchorage deficiencies to develop and populate loss models; and (3) nonlinear response history analysis on cripple wall-supported buildings and their components.

This report is a product of Working Group 4: Testing, whose central focus was to experimentally investigate the seismic performance of retrofitted and existing cripple walls. This present report focuses on non-stucco or "dry" exterior finishes. Paralleled by a large-component test program conducted at the University of California, Berkeley (UC Berkeley) [Cobeen et al. 2020], the present report involves two of multiple phases of small-component tests conducted at University of California San Diego (UC San Diego). Details representative of era-specific construction–specifically the most vulnerable pre-1960s construction–are of predominant focus in the present effort. Parameters examined are cripple wall height, finish style, gravity load, boundary conditions, anchorage, and deterioration. This report addresses all eight specimens in the second phase of testing and three of the six specimens in the fourth phase of testing. Although conducted in different testing phases, their results are combined here to co-locate observations regarding the behavior of all dry finished specimens. Experiments involved imposition of combined vertical loading and quasi-static reversed cyclic lateral load onto eleven cripple walls. Each specimen was 12 ft in length and 2-ft or 6-ft in height. All specimens in this report were constructed with the same boundary conditions on the top, bottom, and corners of the walls. Parameters addressed in this report include: dry exterior finish type (shiplap horizontal lumber siding, shiplap horizontal lumber siding over diagonal lumber sheathing, and T1-11 wood structural panels), cripple wall height, vertical load, and the retrofitted condition. Details of the test specimens, testing protocol (including instrumentation), and measured as well as physical observations are summarized. Results from these experiments are intended to support advancement of numerical modeling tools, which ultimately will inform seismic loss models capable of quantifying the reduction of loss achieved by applying state-of-practice retrofit methods as identified in FEMA P-1100 Vulnerability-Base Seismic Assessment and Retrofit of One- and Two-Family Dwellings.

2020/18 *Cripple Wall Small-Component Test Program: Wet Specimens II,* a report for the "Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings" Project. Brandon Schiller, Tara Hutchinson, Kelly Cobeen.

This report is one of a series of reports documenting the methods and findings of a multi-year, multi-disciplinary project coordinated by the Pacific Earthquake Engineering Research Center (PEER and funded by the California Earthquake Authority (CEA). The overall project is titled *"Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings,"* henceforth referred to as the *"PEER–CEA Project."*

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This report is a product of Working Group 4 (WG4): Testing, whose central focus was to experimentally investigate the seismic performance of retrofitted and existing cripple walls. This report focuses stucco or "wet" exterior finishes. Paralleled by a large-component test program conducted at the University of California, Berkeley (UC Berkeley) [Cobeen et al. 2020], the present study involves two of multiple phases of small-component tests conducted at the University of California San Diego (UC San Diego). Details representative of era-specific construction, specifically the most vulnerable pre-1960s construction, are of predominant focus in the present effort. Parameters examined are cripple wall height, finish style, gravity load, boundary conditions, anchorage, and deterioration. This report addresses the third phase of testing, which consisted of eight specimens, as well as half of the fourth phase of testing, which consisted of six specimens where three will be discussed. Although conducted in different phases, their results are combined here to co-locate observations regarding the behavior of the second phase the wet (stucco) finished specimens. The results of first phase of wet specimen tests were presented in Schiller et al. [2020(a)]. Experiments involved imposition of combined vertical loading and quasi-static reversed cyclic lateral load onto ten cripple walls of 12 ft long and 2 or 6 ft high. One cripple wall was tested with a monotonic loading protocol. All specimens in this report were constructed with the same boundary conditions on the top and corners of the walls as well as being tested with the same vertical load. Parameters addressed in this report include: wet exterior finishes (stucco over framing, stucco over horizontal lumber sheathing, and stucco over diagonal lumber sheathing), cripple wall height, loading protocol, anchorage condition, boundary condition at the bottom of the walls, and the retrofitted condition. Details of the test specimens, testing protocol, including instrumentation; and measured as well as physical observations are summarized in this report. Companion reports present phases of the tests considering, amongst other variables, impacts of various boundary conditions, stucco (wet) and non-stucco (dry) finishes, vertical load, cripple wall height, and anchorage condition. Results from these experiments are intended to support advancement of numerical modeling tools, which ultimately will inform seismic loss models capable of quantifying the reduction of loss achieved by applying state-of-practice retrofit methods as identified in *FEMA P-1100,Vulnerability-Base Seismic Assessment and Retrofit of One- and Two-Family Dwellings.*

2020/19 *Cripple Wall Small-Component - Test Program: Comparisons,* a report for the "Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings" Project. Brandon Schiller, Tara Hutchinson, Kelly Cobeen.

This report is one of a series of reports documenting the methods and findings of a multi-year, multi-disciplinary project coordinated by the Pacific Earthquake Engineering Research Center (PEER) and funded by the California Earthquake Authority (CEA). The overall project is titled *"Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings,"* henceforth referred to as the *"PEER–CEA Project."*

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This report is a product of Working Group 4 (WG4): Testing, whose central focus was to experimentally investigate the seismic performance of retrofit and existing cripple walls. Amongst the body of reports from WG4, in the present report, a suite of four small cripple wall test phases, in total 28 specimens, are cross compared with varied exterior finishes, namely stucco (wet) and non-stucco (dry) exterior finishes. Details representative of era specific construction, specifically the most vulnerable pre-1960s construction are of predominant focus in the present effort. Experiments involved imposition of combined vertical loading and quasi-static reversed cyclic lateral load onto cripple walls of 12 ft in length and 2 ft or 6 ft in height. All specimens in this report were constructed with the same boundary conditions and tested with the same vertical load. Parameters addressed in this report include: wet exterior finishes (stucco over framing, stucco over horizontal lumber sheathing, and stucco over diagonal lumber sheathing); and dry exterior finishes (horizontal siding, horizontal siding over diagonal sheathing, and T1-11 wood structural panels) with attention towards cripple wall height and the retrofit condition. The present report provides only a brief overview of the test program and setup; whereas a series of three prior reports present results of test groupings nominally by exterior finish type (wet versus dry). As such, herein the focus is to cross compare key measurements and observations of the in-plane seismic behavior of all 28 specimens.

2020/20 *Large-Component Seismic Testing for Existing and Retrofitted Single-Family Wood-Frame Dwellings,* a report for the "Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings" Project. Kelly Cobeen, Vahid Mahdavifar, Tara Hutchinson, Brandon Schiller, David P. Welch, Grace S. Kang, Yousef Bozorgnia.

This report is one of a series of reports documenting the methods and findings of a multi-year, multi-disciplinary project coordinated by the Pacific Earthquake Engineering Research Center (PEER and funded by the California Earthquake Authority (CEA). The overall project is titled *"Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings,"* henceforth referred to as the *"PEER–CEA Project."*

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Quantifying the difference of seismic performance of un-retrofitted and retrofitted single-family wood-frame houses has become increasingly important in California due to the high seismicity of the state. Inadequate lateral bracing of cripple walls and inadequate sill bolting are the primary reasons for damage to residential homes, even in the event of moderate earthquakes.

Physical testing tasks were conducted by Working Group 4 (WG4), with testing carried out at the University of California San Diego (UCSD) and University of California Berkeley (UCB). The primary objectives of the testing were as follows: (1) development of descriptions of load-deflection behavior of components and connections for use by Working Group 5 in development of numerical modeling; and (2) collection of descriptions of damage at varying levels of peak transient drift for use by Working Group 6 in development of fragility functions. Both UCSD and UCB testing included companion specimens tested with and without retrofit.

This report documents the portions of the WG4 testing conducted at UCB: two large-component cripple wall tests (Tests AL-1 and AL-2), one test of cripple wall load-path connections (Test B-1), and two tests of dwelling superstructure construction (Tests C-1 and C-2). Included in this report are details of specimen design and construction, instrumentation, loading protocols, test data, testing observations, discussion, and conclusions.

2020/21 *Comparison of the Response of Small- and Large-Component Cripple Wall Specimens Tested under Simulated Seismic Loading,* a report for the "Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings" Project. Brandon Schiller, Tara Hutchinson, Kelly Cobeen.

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This report is a product of *Working Group 4:* Testing, whose central focus was to experimentally investigate the seismic performance of retrofitted and existing cripple walls. Two testing programs were conducted; the University of California, Berkeley (UC Berkeley) focused on large-component tests; and the University of California San Diego (UC San Diego) focused on small-component tests. The primary objectives of the tests were to develop descriptions of the load-deflection behavior of components and connections for use by Working Group 5 in developing numerical models and collect descriptions of damage at varying levels of drift for use by Working Group 6 in developing fragility functions. This report considers two large-component cripple wall tests performed at UC Berkeley and several small-component tests performed at UC San Diego that resembled the testing details of the large-component tests.

Experiments involved imposition of combined vertical loading and quasi-static reversed cyclic lateral load on cripple wall assemblies. The details of the tests are representative of era-specific construction, specifically the most vulnerable pre-1945 construction. All cripple walls tested were 2 ft high and finished with stucco over horizontal lumber sheathing. Specimens were tested in both the retrofitted and unretrofitted condition. The large-component tests were constructed as three-dimensional components (with a 20-ft × 4-ft floor plan) and included the cripple wall and a single-story superstructure above. The small-component tests were constructed as 12-ft-long two-dimensional components and included only the cripple wall. The pairing of small- and large-component tests was considered to make a direct comparison to determine the following: (1) how closely small-component specimen response could emulate the response of the large-component specimens; and (2) what boundary conditions in the small-component specimens led to the best match the response of the large-component specimens.

The answers to these questions are intended to help identify best practices for the future design of cripple walls in residential housing, with particular interest in: (1) supporting the realistic design of small-component specimens that may capture the response large-component specimen response; and (2) to qualitatively determine where the small-component tests fall in the range of lower- to upper-bound estimation of strength and deformation capacity for the purposes of numerical modelling. Through these comparisons, the experiments will ultimately advance numerical modeling tools, which will in turn help generate seismic loss models capable of quantifying the reduction of loss achieved by applying state-of-practice retrofit methods as identified in FEMA P-1100Vulnerability-Base Seismic Assessment and Retrofit of One- and Two-Family Dwellings. To this end, details of the test specimens, measured as well as physical observations, and comparisons between the two test programs are summarized in this report.

2020/22 *Technical Background Report for Structural Analysis and Performance Assessment,* a report for the "Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings" Project. David P. Welch, Gregory G. Deierlein.

This report outlines the development of earthquake damage functions and comparative loss metrics for single-family wood-frame buildings with and without seismic retrofit of vulnerable cripple wall and stem wall conditions. The underlying goal of the study is to quantify the benefits of the seismic retrofit in terms of reduced earthquake damage and repair or reconstruction costs. The earthquake damage and economic losses are evaluated based on the *FEMA P-58* methodology, which incorporates detailed building information and analyses to characterize the seismic hazard, structural response, earthquake damage, and repair/reconstruction costs. The analyses are informed by and include information from other working groups of the Project to: (1) summarize past research on performance of wood-frame houses; (2) identify construction features to characterize alternative variants of wood-frame houses; (3) characterize earthquake hazard and ground motions in California; (4) conduct laboratory tests of cripple wall panels, wood-frame wall subassemblies and sill anchorages; and (5) validate the component loss models with data from insurance claims adjustors. Damage functions are developed for a set of wood-frame building variants that are distinguished by the number of stories (one- versus two-story), era (age) of construction, interior wall and ceiling materials, exterior cladding material, and height of the cripple walls. The variant houses are evaluated using seismic hazard information and ground motions for several California locations, which were chosen to represent the range seismicity conditions and retrofit design classifications outlined in the *FEMA P-1100* guidelines for seismic retrofit.

The resulting loss models for the Index Building variants are expressed in terms of three outputs: *Mean Loss Curves* (damage functions), relating expected loss (repair cost) to ground-motion shaking intensity, Expected Annual Loss, describing the expected (mean) loss at a specific building location due to the risk of earthquake damage, calculated on an annualized basis, and *Expected RC250 Loss*, which is the cost of repairing damage due to earthquake ground shaking with a return period of 250 years (20% chance of exceedance in 50 years). The loss curves demonstrate the effect of seismic retrofit by comparing losses in the existing (unretrofitted) and retrofitted condition across a range of seismic intensities.

The general findings and observations demonstrate: (1) cripple walls in houses with exterior wood siding are more vulnerable than ones with stucco siding to collapse and damage; (2) older pre-1945 houses with plaster on wood lath interior walls are more susceptible to damage and losses than more recent houses with gypsum wallboard interiors; (3) two-story houses are more vulnerable than one-story houses; (4) taller (e.g., 6-ft-tall) cripple walls are generally less vulnerable to damage and collapse than shorter (e.g., 2-ft-tall) cripple walls; (5) houses with deficient stem wall connections are generally observed to be less vulnerable to earthquake damage than equivalent unretrofitted cripple walls with the same superstructure; and (6) the overall risk of losses and the benefits of cripple wall retrofit are larger for sites with higher seismicity. As summarized in the report, seismic retrofit of unbraced cripple walls can significantly reduce the risk of earthquake damage and repair costs, with reductions in Expected RC250 Loss risk of up to 50% of the house replacement value for an older house with wood-frame siding at locations of high seismicity. In addition to the reduction in repair cost risk, the seismic retrofit has an important additional benefit to reduce the risk of major damage that can displace residents from their house for many months.

2020/23 *Earthquake Damage Workshop,* a report for the "Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings" Project. Kylin Vail, Bret Lizundia, David P. Welch, Evan Reis.

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This report is a product of Working Group 6 (WG6): Interaction with Claims Adjustors & Catastrophe Modelers and focuses on a damage workshop effort undertaken to provide repair estimates of representative damaged single-family wood-frame case study buildings to compare the differences in costs between houses with and without retrofits to cripple walls and sill anchorage. At the request of the CEA, 11 experienced claims adjustors from insurance companies volunteered to provide the estimates. Electronic cost estimation files for each case study building were developed by the PEER–CEA Project Team using the Verisk Xactware Xactimate X1 platform and provided to the claims adjustors to complete their estimates. These adjustor estimates served as the baseline for comparison against the *FEMA P-58* [FEMA 2012] methodology used on the project for loss estimation. The term "damage workshop effort" is used to emphasize that the scope of work included not just a successful workshop meeting, but the broader development of a damage description package describing case studies and associated Xactimate descriptions before the workshop meeting and revisions after it, two rounds of estimates and survey question responses by adjustors, interpretation and clarification of the estimates for consistency, and synthesizing of estimate findings and survey responses into conclusions and recommendations.

Three building types were investigated, each with an unretrofitted and a retrofitted condition. These were then assessed at four levels of damage, resulting in a total of 24 potential scenarios. Because of similarities, only 17 scenarios needed unique Xactimate estimates. Each scenario was typically estimated by three to five adjustors, resulting in a final total of 74 different estimates.

2020/24 *Seismic Performance of Single-Family Wood-Frame Houses: Comparing Analytical and Industry Catastrophe Models,* a report for the "Quantifying the Performance of

Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings" Project. Evan Reis.

This report is one of a series of reports documenting the methods and findings of a multi-year, multi-disciplinary project coordinated by the Pacific Earthquake Engineering Research Center (PEER and funded by the California Earthquake Authority (CEA). The overall project is titled *"Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings,"* henceforth referred to as the *"PEER–CEA Project."*

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This report is a product of Working Group (WG) 6: *Catastrophe Modeler Comparisons* and focuses on comparing damage functions developed by the PEER–CEA Project with those currently contained in modeling software developed by the three largest insurance catastrophe modelers: RMS, CoreLogic and AIR Worldwide. A semi-blind study was conducted in collaboration with the modeling companies to compare damage estimates for a selection of the Index Buildings developed in the PEER–CEA Project Study. The WG6 Project Team conducted several meetings with these modeling companies to gather feedback on the structure of and assumptions made by the PEER–CEA Project. The comparative results are evaluated and presented herein.

2020/25 *Regionalized Ground-Motion Models for Subduction Earthquakes Based on the NGA-SUB Database.* Norman Abrahamson, Zeynep Gülerce.

A set of global and region-specific ground-motion models (GMMs) for subduction zone earthquakes is developed based on the database compiled by the Pacific Earthquake Engineering Research Center (PEER) Next Generation Attenuation - Subduction (NGA-SUB) project. The subset of the NGA-SUB database used to develop the GMMs includes 3914 recordings from 113 subduction interface earthquakes with magnitudes varying between 5 and 9.2 and 4850 recordings from 89 intraslab events with magnitudes varying between 5 and 7.8. Recordings in the back-arc region are excluded, except for the Cascadia region. The functional form of the model accommodates the differences in the magnitude, distance, and depth scaling for interface and intraslab earthquakes. The magnitude scaling and geometrical spreading terms of the global model are used for all regions, with the exception of the Taiwan region which has a region-specific geometrical spreading scaling. Region-specific terms are included for the large distance (linear R) scaling, V_{S30} scaling, $Z_{2.5}$ scaling, and the constant term. The nonlinear site amplification factors used in Abrahamson et al. (2016) subduction GMM are adopted. The between-event standard deviation piece of the aleatory variability model is region and distance independent; whereas, the within-event standard deviations are both region and distance dependent. Region-specific GMMs are developed for seven regions: Alaska, Cascadia, Central America, Japan, New Zealand, South America, and Taiwan. These region-specific GMMs are judged to be applicable to sites in the fore-arc region at distances up to 500 km, magnitudes of 5.0 to 9.5, and periods from 0 to 10 sec. For the Cascadia region, the region-specific model is applicable to distances of 800 km including the back-arc region. For the sites that are not in one of the seven regions, the global GMM combined with the epistemic uncertainty computed from the range of the regional GMMs should be used.

2020/26 *Long-Term Monitoring of Bridge Settlements using Vision-Based Embedded System.* Henry L. Teng, Khalid M. Mosalam.

The State of California is highly seismic, capable of generating large-magnitude earthquakes that could cripple the infrastructure of several large cities. Yet the annual maintenance of the State's bridges, such as highway overpasses, is not robust due to budget and staff constraints. Over 1000 bridges were not inspected according to the California Department of Transportation's (Caltrans) 2015 Maintenance Plan. To help engineers monitor infrastructure conditions, presented within is a device recently developed that employs modern sensing, computing, and communication technologies to autonomously measure and remotely report vertical settlements of bridges, such as highway overpasses. Given the limitations of existing measurement devices, we propose a novel vision-based method that employs a camera to take a picture of a projected laser beam. This new device is referred to as the Projected Laser Target Method (PLTM).

This report documents the embedded system design and development of two prototypes. The first prototype implements communication over a local WIFI network using synchronous code to measure distance over time; this PLTM is deployed in a laboratory setting. The second device under study implements communication over a Bluetooth Low Energy system using asynchronous code and communication over 2G cellular networks using synchronous code, with the aim of determining its accuracy in the field. This report evaluates the performance of the field-suitable system in terms of its system reliability, measurement accuracy and precision, power consumption, and its overall system performance.

2021/01 *Fire-Induced Structural Collapse on Pier 45 at Fisherman's Wharf, San Francisco, California, May 23, 2020.* Mohammadreza Eslami, Khalid Mosalam, Ankit Agrawal, Amarnath Kasalanati.

On May 23, 2020, a severe fire resulted in progressive collapse of a processing and storage warehouse structure located at Pier 45, Fisherman's Wharf, in San Francisco, California. This incident provided a unique opportunity to study the performance of structural systems exposed to large open-compartment fires resulting in progressive collapse. Subsequently, a post-fire investigation was conducted to collect data pertinent to both fire severity and key structural characteristics, which were made available to the Pacific Earthquake Engineering Research Center (PEER) at the University of California, Berkeley. The collected information in conjunction with engineering judgment is used to qualitatively and, to the extent possible, quantitatively describe the fire-induced failure modes and damage observed in the structural members. Further, a simplistic sequence of eventsl eading to the fire-induced progressive collapse is hypothesized. Preliminary analysis, based on available fire resistance verification methods, is carried out to qualify this hypothesis. Findings from this report and data available through PEER will contribute towards improving the collective understanding of best practices in performance-based structural fire engineering.

2021/02 *Implementation, Verification, and Validation of the PM4Sand Model in OpenSees.* Long Chen, Pedro Arduino.

Human and economic losses caused by earthquake-induced soil liquefaction underscore the importance of assessing liquefaction hazards, both by determining whether a soil is likely to liquefy and by estimating consequences these events may cause. Numerical simulations have proven to be useful for these purposes. Reliable numerical analysis requires that constitutive models represent the *in situ* soil behavior as well as general loading and drainage conditions. For this purpose, comprehensive verification and validation studies of material models are imperative for successful deployment of advanced numerical tools. In this context, the main objective of this research is to implement, verify, and validate a newly developed constitutive model, PM4Sand (Boulanger and Ziotopoulou, 2017), using the finite-element platform

OpenSees (OpenSees, 2007). This model was developed for earthquake engineering applications and can achieve reasonable approximations of desired behavior (including pore pressure generation and dissipation, limiting strains, and cyclic mobility) using a straight-forward calibration process. After implementing PM4Sand in OpenSees, a parametric study was carried out to shed light on the model's general behavior and calibration process. Next, a verification study was performed to compare the response of the model implemented in three different frameworks, OpenSees, FLAC, and PLAXIS, using point, element, and one-dimensional model analyses. Lastly, a few well known case histories were considered to validate and demonstrate the model's ability to capture realistic soil behavior.

2021/03 *Effective Stress Analysis of Liquefaction Sites and Evaluation of Sediment Ejecta Potential.* Daniel Hutabarat, Jonathan D. Bray.

Sediment ejecta mechanism contributes significantly to the severity of liquefaction-induced ground failure (e.g., excessive land subsidence). Estimating the amount of ejected sediment is a key step to assess the severity of ground failure; however, procedures to quantify it are currently lacking. Sediment ejecta is a post-shaking phenomenon resulting from the migration and redistribution of excess-pore-water-pressure (ue) generated during earthquake shaking. The dissipation process of residual ue can trigger high-gradient upward seepage, which can exploit cracks in the upper non-liquefiable crust layer. Once cracks in the crust layer are fully formed and there is sufficient artesian water pressure, the seepage flow can produce artesian flow above the ground surface while ejecting the fluidized sediment to the ground surface. As more sediment is transported to the ground surface, additional ground subsidence is produced.

The characteristics of liquefiable sites that did and did not produce sediment ejecta manifestation after the 2010–2011 Canterbury earthquake sequence in Christchurch, New Zealand, remain unclear. The severity of liquefaction-induced ejecta manifestation for the 2010–2011 Canterbury earthquakes was overestimated or underestimated using liquefaction-induced ground failure indices, such as the Liquefaction Potential Index (LPI) or Liquefaction Severity Number (LSN), at several sites in Christchurch. By capturing the sediment ejecta mechanism, it is possible to have a reliable estimate of ground failure severity and prevent costly or unconservative ground improvement designs in mitigating liquefaction hazards. This research proposes a new way to quantify the quantity of sediment ejecta and hence the severity of post-shaking liquefaction consequences due to sediment ejecta for level ground.

2021/04 *Towards Multi-Tier Modeling of Liquefaction Impacts on Transportation Infrastructure.* Brett W. Maurer, Mertcan Geyin, Alex J. Baird.

Semi-empirical models based on in situ geotechnical tests have been the standard-of-practice for predicting soil liquefaction since 1971. More recently, prediction models based on free, readily available data have grown in popularity. These "geospatial models" rely on satellite remote sensing to infer subsurface traits without in situ tests. While the concept of such an approach is not new, the recent models of Zhu et al. [2015; 2017] are arguably the most rigorously formulated and well-trained to date. The use of such models is appealing for a range of applications, but these models have not been evaluated using independent datasets, nor have they been tested against more established geotechnical methods. These independent evaluations are important for community acceptance and for identifying pathways to improve the models via future research. In other words, when the geospatial models perform poorly, what do they miss that geotechnical models do not? Moreover, the physical damage and monetary loss from liquefaction are arguably more important than the probability of liquefaction occurring. The extension of geospatial models to predict the consequences from liquefaction is both enticing and consistent with the objectives of PEER. Accordingly, the presented study has two main components.

First, using 15,222 liquefaction case histories from 24 earthquakes, the performance of 23 models based on geotechnical or geospatial data are assessed using standardized metrics. Uncertainty due to finite sampling of case histories is accounted for and used to establish statistical significance. Geotechnical predictions are found to be significantly more efficient worldwide, yet successive models proposed over the last twenty years show little or no demonstrable improvement. In addition, geospatial models outperform geotechnical models for large subsets of the data—a provocative finding given the relative time and cost requirements underlying these predictions. Comparisons between geotechnical predictions versus geospatial models provide key insights into improving geospatial models.

2021/05 *City-Scale Multi-Infrastructure Network Resilience Simulation Tool.* Kenichi Soga, Renjie Wu, Bingyu Zhao, Chaofeng Wang.

The goal of this project is to deliver a coherent framework of simulation tools that can quantify the performance of the water distribution network (WDN) and the transportation network at the city scale under different ground-motion scenarios. In addition to tool development, this project also investigates the potential interactions between structural and infrastructure systems in the case of normal operational and various earthquake damage scenarios. A multi-threaded, high-performance computing (HPC) scalable semi-dynamic traffic simulation model has been developed to understand the complex behaviors of the entire transportation system and to evaluate various performance metrics (e.g., traffic flow, delay, accessibility, etc.) in a large-scale hazard event. An efficient, multi-threaded C++ program, HydrauSim, has been created to understand the hydraulic behavior of WDNs after a disruptive hazard event such as an earthquake. Equipped with advanced linear system solvers, HydrauSim solves hydraulic parameters for a city-scale WDN al-most instantaneously, allowing the water distribution change under many earthquake damage scenarios to be determined in a short time. To support a framework of holistic assessment of regional performance after earthquakes, multiple existing tools are integrated, including the ground-motion generation software from Stanford University and the building damage assessment tool rWhale from the SimCenter.

Earthquake scenarios (M7.05 Hayward fault) in the San Francisco Bay Area are studied to evaluate the infrastructure networks' hazard response using the developed tools. In collaboration with the East Bay Municipal Utility District (EBMUD), the WDN hydraulic responses on the EBMUD gravity feed zone (65,700 distribution pipes with a total length of 7,223,217 ft) under various ground movement conditions have been studied. The SimCenter building damage estimation tool, rWhale, is used to simulate building damage states for 1.8 million buildings across the Bay Area. On the traffic side, 2 million agents' movements on the full San Francisco Bay Area's road network (224,224 nodes with 549,009 links) has been simulated to understand potential traffic re-distributions after major hazard events. Interactions between these three infrastructure systems under the Hayward fault earthquake scenarios are explored in the study.

2021/06 *F-Rec Framework: Novel Framework for Probabilistic Evaluation of Functional Recovery of Building Systems.* Vesna Terzic, Peny K. Villanuev, Daniel Saldana, Dong Y. Yoo.

Earthquakes are one of the most destructive natural disasters with potentially devastating consequences on communities and the supporting infrastructure. To mitigate the effects of earthquakes on communities and infrastructure, the recovery process of building systems should be considered during the design of the building as it is essential for continued operation. This study presents a novel, probabilistic, building-level framework for modeling and evaluating the entire recovery process (F-Rec Framework), including a building's post-earthquake functionality along with duration and path of functional recovery. The proposed framework considers all structural and nonstructural building components/systems. It consists of three novel and integrated methods for evaluation building's post-earthquake functionality, mobilization time, and repair time. The framework—in line with the probabilistic performance-based earthquake engineering methodology—uses FEMA P-58 damage/performance assessment results to evaluate the recovery process. With its modular structure, this framework is extendable and lends itself to the additional of new components.

The method for evaluating a building's post-earthquake functionality utilizes FEMA P-58 damage assessment results in conjunction with fault trees of complex building systems to provide a probabilistic estimate about the percent of the inaccessible functional area within a building and to identify building components that impair its functionality. To facilitate functionality analysis, the research proposes a fault tree for a complex building system and introduces user-defined probabilistic limit state functions of individual building components that define the damage thresholds for partial (local) and full loss of the building functionality.

2021/07 *Shake Table Tests on a Shallow Foundation on Liquefiable Soils Supported on Helical Piles.* Milad Jahed Orang, Ramin Motamed.

Extensive damage to buildings and infrastructure observed during past earthquakes resulting from the liquefaction of shallow saturated soil deposits underneath structures has demonstrated the necessity for further research in the area of liquefaction-induced ground movement effects. This study explores utilizing helical piles as a countermeasure to reduce liquefaction-induced foundation settlement and investigates their seismic performance in liquefiable grounds. Two large-scale shake table test series, one without any mitigation measures and one using helical piles, were conducted using the shake table facility at the University of California, San Diego. During each test series, the soil and superstructure models were extensively instrumented and subjected to two consistently applied shaking sequences. The model ground included a shallow liquefiable layer aimed at replicating the subsurface ground conditions observed in the past earthquakes in New Zealand, Japan, and Turkey.

Liquefaction-induced foundation settlement mechanisms are broadly categorized as follows: (1) shear-induced, (2) volumetric-induced, and (3) ejecta-induced. In the first test series (referred to as the Baseline test hereafter), all these three components were realistically reproduced, while in the second test series (referred to as the Helical Pile test hereafter) the volumetric and ejecta-induced mechanisms were mainly mitigated, resulting in significant reductions in the foundation settlement. Results from the first test series (i.e., Baseline test) indicated that the flow velocity due to the hydraulic transient gradient displayed an upward flow in the loose layer, which explains the observed sand ejecta.

This series of shake table tests resulted in an average total foundation settlement of 28 cm and 42.7 cm during two shaking sequences. The measured foundation settlements were compared to the estimated foundation settlement obtained from Liu and Dobry [1997] and Bray and Macedo's [2017] simplified procedures. The observed foundation settlements generally were higher than the estimated values. In the second large-scale test series, an identical test setup to the first test series was used except for a group of four helical piles were attached to the shallow foundation to mitigate liquefaction-induced settlements. In this series of tests, a reduced excess pore-water pressure generation around the group of helical piles was observed and is mainly attributed to the increased relative density around their zone of influence as a result of installation. The foundation supported on helical piles underwent almost no differential settlement and tilt. A significant reduction in the total foundation settlement was achieved during the Helical Pile test series compared to the Baseline test series.

2021/08 *Seismic Design and Detailing of Bridge Columns to Account for Ground-Motion Duration.* S. Mojtaba Alian Amiri, Mohamed A. Moustafa, David H. Sanders.

Devastating, long-duration earthquakes such as 2011 Tohoku, Japan, earthquake, and 2010 Maule, Chile, earthquake have proved the importance of considering the duration of ground motion in conducting a seismic demand assessment. This research focuses on using both analytical and experimental methods to study the effect of different design details—confinement spacing ratio and longitudinal bar debonding—and different reinforcement strategies—conventional and high-strength reinforcement—on the seismic response of reinforced concrete (RC) bridge columns under long-duration ground motions. In this study, six large-scale RC bridge column specimens were designed, constructed, and tested in two phases on the shake table at the University of Nevada, Reno.

The first phase included three specimens designed using conventional Grade 60 ASTM 706 reinforcing bars tested under a sequence of long-duration earthquakes (2011 Tohoku earthquake). All three columns had the same longitudinal reinforcement ratio. Column #2 had a different confinement spacing ratio compared to Column #1. In contrast, Column #3 considered debonding of longitudinal reinforcement at the footing interface. Columns #4, 5, and 6 tested in the second phase were reinforced longitudinally with high-strength grade 100 ASTM A1035 MMFX steel. These columns were tested under short- and long-duration motions to study the cyclic deterioration of high-strength reinforcement and quantify the response of bridge columns under seismic events. Presented herein are the pre-test analyses, design, and construction of the specimens, the results of the shake table tests, and a comparison of the global and local seismic response of the six columns tested. The global responses include the force and displacement capacities and mode of failure. Local responses include the strain in both transverse and longitudinal rebars and the curvature of the columns within the plastic hinge zone. The experimental results demonstrate that although both the higher concrete confinement (i.e., smaller tie spacings) and longitudinal bars debonding are effective in improving the performance of columns subjected to long-duration earthquakes, the smaller tie spacings is more effective.

2021/09 *Use of Corridors for Decision Making in Transportation Networks in Seismic Regions.* Rodrigo I. Silva-Lopez, Jack W. Baker.

This report presents the results of the study that proposes a retrofitting strategy to manage seismic risk via identification of what constitutes "Corridors" in transportation networks. We define a Corridor as a set of bridges that work together to ensure connectivity and traffic flow between areas of a region. We propose using a Markov clustering algorithm to detect Corridors, whereby it selects sets of bridges that correspond to highway and main road segments that are effective in reducing disruption when jointly retrofitted. We then use a two-stage stochastic optimization to identify corridors that can be retrofitted to efficiently reduce seismic risk. This two-stage stochastic optimization couples retrofitting actions over bridges in a Corridor with repair actions to damaged bridges after an earthquake. We observe that this Corridors-supported optimization approach yields better relative performance than retrofitting approaches that consider bridges as individual entities or rank them using PageRank. We also propose techniques for selecting parameters in the corridor selection step that perform well in the retrofit optimization.

This content is currently under review for publication in an archival journal. It is being submitted here also as a technical project report, per the requirements of the PEER Transportation Systems Research Program.

2021/10 *Seismic Performance of Column-to-Drilled-Shaft Connections in Reinforced Concrete Bridges.* Michelle Chang, John Stanton, Marc Eberhard.

Drilled shaft foundations are often used to support reinforced concrete bridge columns founded in soft soils or in locations where a small footprint is desired. Increasingly, the shaft is being built with a diameter larger than that of the column, to allow tolerance in the column placement and to facilitate plastic hinge formation in the column rather than in the shaft. The column–shaft connection, which involves a noncontact splice between the column and shaft bars, is a key component in this structural system. However, there is limited research on the behavior of these connections under seismic loads. In order to understand the force-transfer mechanism of column–shaft connections under seismic loading, one quasi-static cyclic experimental test was conducted on a column–shaft subassembly. Measured results were compared with those from three previous experiments performed at the University of Washington and others conducted at the University of California San Diego.

The study found that the amount of shaft transverse reinforcement in the connection region was critical in determining the failure mode of the connection. In specimens with relatively low amounts of transverse reinforcement, including the specimen tested during this study and a previous specimen tested at the University of Washington, the connection failed through a shaft prying failure mode; the specimens developed large vertical cracks between the confined column core and the annular shaft transition region, and the shaft transverse reinforcement eventually fractured at large drift ratios. Therefore, three methodologies for detailing the shaft transverse reinforcement were evaluated, and a new analysis procedure using a strut-and-tie model was proposed. It is consistent with the measured and observed performances of the tested connections and is applicable to shafts supporting either precast or cast-in-place columns. The new procedure allows engineers to (a) more accurately predict the behavior of a column–shaft connection and (b) prevent an undesirable below-ground failure in the shaft transition region. Lastly, a set of design equations based on the strut-and-tie findings and existing design models is proposed for use in practice.

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.

4.1 2020 PEER RESEARCHERS' WORKSHOP

The PEER Researchers' Workshop was held online on August 17-18, 2020, due to the Covid-19 pandemic. The meeting was well attended with approximately 50 participants and colleagues from PEER core institutions and from the PEER BIP Program. 20 PEER-funded projects were presented, and 4 projects with collaborative organizations were also presented. The Researchers' Workshop provided a forum for in-progress reporting of PEER-funded projects. The comments and discussion between presenters and the audience provided an 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 CEA-PEER RESEARCH FORUM

The California Earthquake Authority (CEA) teamed up with PEER to host the 2020 Research Forum on Residential Seismic Retrofits, held online October 26 and 27, 2020.

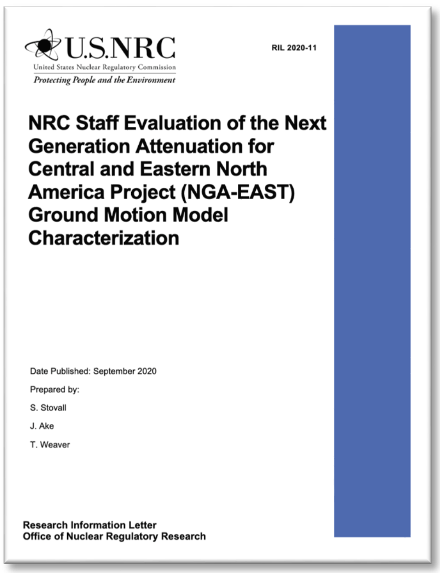
This year's Research Forum featured the multi-year project *"Quantifying the Performance of Retrofit of Cripple Walls and Sill Plate Anchorage in Single-Family Wood-frame Buildings"* (PEER-CEA Project).

Key findings of the PEER-CEA Project were presented by members of the project team comprised of academic and practicing experts with unique and 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.

Additional topics at the Research Forum included:

- Current understanding of seismic risk for wood-frame single-family residential (SFR) structures and the tools available
- Implications of SFR earthquake risks
- Identifying remaining gaps in research and potential research programs

4.3 NGA-EAST GROUND MOTION MODELS VALIDATED BY U.S. NUCLEAR REGULATORY COMMISSION


U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

RIL 2020-11

NRC Staff Evaluation of the Next Generation Attenuation for Central and Eastern North America Project (NGA-EAST) Ground Motion Model Characterization

Date Published: September 2020
Prepared by:
S. Stovall
J. Ake
T. Weaver

Research Information Letter
Office of Nuclear Regulatory Research

The United States Nuclear Regulatory Commission (NRC) released a report in September 2020 that concluded that the NGA-East Ground Motion Characterization Model is robust, captures epistemic uncertainty, and provides regulatory stability for siting evaluations of nuclear facilities in the central and eastern United States (CEUS).

The report "NRC Staff Evaluation of the Next Generation Attenuation for Central and Eastern North America Project (NGA-East) Ground Motion Model Characterization" is a Research Information Letter (RIL) issued by NRC's Office of Nuclear Regulatory Research to the NRC regulatory and regional offices. RIL documents typically summarize, synthesize, and/or interpret significant research information relevant to a given technical area, provide new or revised information, and discuss how that information may be used in regulatory activities. This RIL 2020-11 specifically provides a detailed description of the NGA-East Ground Motion Characterization Model development, highlights the sensitivity analyses performed by the NRC technical staff, validates the unique approaches used in the development of the NGA-East ground motion models, and advises on the stability of the model.

The NGA-East project was a 10-year multidisciplinary project started in 2008, coordinated by PEER. and jointly sponsored by the U.S. NRC, U.S. Department of Energy, the Electric Power Research Institute, and the U.S. Geological Survey. Dr. Yousef Bozorgnia was the Principal Investigator of the project and Dr. Christine Goulet was the chair of the Technical Integration team. This multidisciplinary project team included over 55 researchers and practicing professionals. The project went through an extensive external review process as formalized under the SSHAC Level 3 framework.

4.4 PEER-CEA PROJECT PRESENTATIONS AT SEAOC CONVENTION

The project "Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings," (PEER-CEA Project), coordinated by PEER and sponsored by the CEA, was featured in two presentations at the Structural Engineers Association of California (SEAOC)'s Annual convention(link is external) which was held online on December 2-4, 2020.

Greg Deierlein delivered the convention's opening plenary presentation "NHERI SimCenter: Computational Modeling and Simulation for Natural Hazards Engineering" about NHERI SimCenter tools that support research in natural hazards engineering. His presentation emphasized the relevance of computational modeling and simulation to the profession of structural engineering, and its role in designing for the future: to inform policy and land-use decisions. He presented an illustrative application of the PEER-CEA project that demonstrated how a large number of computations could be executed in a reasonable amount of time with SimCenter's application tools. The project entailed consideration of building variants that included different configurations and construction materials. Approximately 110,000 non-linear dynamic analyses and millions of FEMA P-58 statistical damage and loss simulations were conducted in a compressed timeframe with high performance computing technology. Refer to the video timestamp starting 23:46. Greg was on the PEER-CEA project leadership team and co-chair of Working Groups 1 (Resources Review), 2 (Index Buildings), 5 (Analytical Modeling), and 6 (Fragility Functions and Loss Assessment).

Brandon Schiller and Kelly Cobeen delivered the presentation "Testing for Multiple Performance Levels: Recent Experiences from the PEER-CEA Project" [search "Schiller" or "Cobeen"]. The session featured the overall objectives of the project and the important role of experimental testing, then focused on the small component testing program conducted at UC San Diego and the large assembly testing program (refer to timestamp starting 26:43) conducted at UC Berkeley. Brandon and Kelly were active in Working Group 4 (Experimental Testing); Brandon worked in the UC San Diego testing program and Kelly led the UC Berkeley testing program.

4.5 PROJECTS AWARDED FROM PEER TSRP RFP 20-02 AND PEER-BRIDGE PROGRAM

In response to Solicitation PEER TSRP 20-02, 34 proposals were received. Each proposal received three independent reviews from the 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, 12 new projects were approved, comprising a total funding of $600,000.

PEER TSRP Funded Projects 2020:

Title: G1: Liquefaction Evaluation of Gravelly Soils: An Integrated Laboratory Testing and Numerical Modeling Approach

PI: Adda Athanasopoulos-Zekkos, UC Berkeley

Title: G1: Advancing the Practice of Cyclic Softening Assessments of Silts and Clays

PI: Armin Stuedlein, Oregon State University

Title: G2: A System-Level Study to Evaluate the Role of Soil Gradation on Seismically Induced Embankment Deformations **PI: Jason DeJong, UCD.** Co-PIs: Mike Beaty (Beaty Engineering) Thomas Westover (Cornforth Consultants)

Title: G2: Prediction of Seismic Compression of Unsaturated Backfills

PI: John McCartney, UC San Diego

Title: M1: Correlation of Ground Motion Duration with Spectral Acceleration and Implications for Expected Bridge Performance

PI: Tracy Becker, UC Berkeley. Co-PI: Jennie Watson-Lamprey

Title: M3: Deep Learning Based Surrogate Modeling for Uncertainty Quantification in Soil-Structure Interaction Problems

PI: Elnaz Seylabi, University of Nevada, Reno

Title: M6: Autonomous Drones for Inspection-Driven Exploration of Structures

PI: Raja Sengupta, UC Berkeley. Co-PI: ZhiQiang Chen

Title: M7: Seismic Performance of Isolated Bridges under Extreme Shaking

PI: Gilberto Mosqueda, UC San Diego

Title: S3: A Critical Examination of Material Strain Limits for Performance-based Seismic Design of Modern Pier and Wharf Structures **PI: Machel Morrison, UC San Diego.** Co-PI: Jose Restrepo

Title: T2: Calibration and Verification of OpenSees Models for Simulating the Response through Collapse of Nonplanar RC Walls **PI: Laura Lowes, University of Washington**

Title: T2: Implementation of Frequency-Dependent Impedance Function in OpenSees

PI: Jian Zhang, UC Los Angeles

Title: T4: Machine Learning for Analysis and Risk Management of Complex Infrastructure Systems

PI: Jack Baker, Stanford

PEER-Bridge program Funded Projects:

Title: An Updated LRFD-Based Design Procedure for Bridge Decks

PI: Lijuan "Dawn" Cheng, UC Davis. Co-PI: Thomas Murphy

Title: Advanced Guidelines for Stability Design of Slender Reinforced Concrete Bridge Columns

PI: Michael Scott, Oregon State University. Co-PI: Mark Denavit

Title: Statistical Variation of Seismic Damage Index (DI) of California Bridges

PI: Farzin Zareian, UC Irvine. Co-PIs: Norm Abrahamson, Saiid Saiidi

The PEER-Bridge Research program is a streamlined framework of the Caltrans bridge research program. A single master contract is established between Caltrans and PEER, and different projects in seven topic areas are executed as Task Orders under the master contract. In 2020, PEER issued two requests for proposals, Solicitation PEER-Bridge 20-02, and Solicitation PEER-Bridge 20-01. Four new projects were funded from PEER-Bridge Program in 2020-21.

4.6 THREE PEER COLLEAGUES ELECTED TO NATIONAL ACADEMY OF ENGINEERING

Three PEER colleagues were honored with election to the National Academy of Engineering (NAE), which is among the highest professional distinctions accorded to an engineer. Election to the NAE honors those who have made outstanding contributions to "engineering research, practice, or education, including, where appropriate, significant contributions to the engineering literature" and to "the pioneering of new and developing fields of technology, making major advancements in traditional fields of engineering, or developing/implementing innovative approaches to engineering education."

Anne S. Kiremidjian, C. L. Peck, Class of 1906 Professor, Department of Civil and Environmental Engineering, Stanford University, Stanford, California. For research and dissemination of probabilistic seismic hazard methods and mentoring. Anne is a member of the PEER Institutional Board and is immediate past-Chair.

James O. Malley, group director and senior principal, Structural Engineering, Degenkolb Engineers, San Francisco. For leadership in improving seismic design. Jim is an active member of PEER. In the Tall Buildings Initiative, Jim led the working group that developed guidance for nonlinear modeling of tall buildings and acceptance values. He was in the working group for both editions of the TBI Seismic Design Guidelines, most recently released in 2017. Degenkolb Engineers is a member of the PEER Business and Industry Partnership Program, and Jim is Chair of the PEER Industry Advisory Board.

Mark Peter Sarkisian, partner, Structural and Seismic Engineering, Skidmore Owings and Merrill LLP, San Francisco. For innovation in efficient and aesthetic design of tall buildings and structures. Skidmore Owings and Merrill is a member of the PEER Business and Industry Partnership Program.

4.7 MOEHLE DELIVERS 2021 FAZLUR R. KHAN DISTINGUISHED LECTURE

Jack Moehle, Professor of the Graduate School at UC Berkeley, was selected to deliver a 2021 Fazlur R. Khan Distinguished Lecture at Lehigh University on March 11, 2021. The Fazlur R. Khan Distinguished Lecture Series honors Dr. Fazlur Rahman Khan, one of the foremost structural engineers of the 20th century who ushered in a renaissance in skyscraper construction during the second half of the 20th century.

Jack Moehle

Professor Moehle's lecture, "Performance-based Seismic Design of Tall Buildings", reviewed the development of performance-based seismic design of tall buildings, documented a typical design application, and summarized results of over a decade of experience in tall building designs.

Professor Moehle was the PI of the PEER Tall Buildings Initiative, founding director of PEER, and is currently an active member of the PEER Institutional Board.

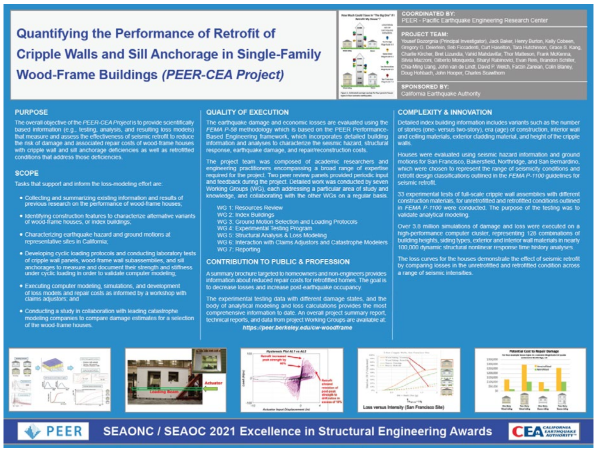
4.8 BUCKLE RECEIVES 2021 REGENTS' RESEARCHER AWARD

Ian Buckle

Ian Buckle, a Foundation Professor in the Department of Civil and Environmental Engineering at University of Nevada Reno and an active member of the PEER Institutional Board, is the recipient of the "2021 Regents' Researcher Award - Distinguished" by the Nevada System of Higher Education. This award is bestowed upon faculty members with a substantial record of accomplishments, including a significant amount of research and scholarly work with recognition, clear evidence of the national and/or international stature of the research, and in the case of grants and contracts, must have been competitive on a national or international level.

Professor Buckle's research interests include improving the seismic performance of highway bridges, design and retrofit criteria for bridges, earthquake protective systems for bridges including the theory, hardware, and applications of seismic isolation, tsunami loads on bridges, and soil-structure-interaction for bridges with deep foundations such as those with long spans. In addition to teaching graduate courses in these topics, he participates in short courses for design professionals in the seismic design of new bridges, retrofitting of existing bridges and the seismic isolation of new and existing bridges.

4.9 PEER-CEA PROJECT RECEIVES 2021 SEAONC EISE AWARD



The research project "Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings *(PEER-CEA Project)*" received an Award of Merit in the Research Category from the 2021 Structural Engineers Association of Northern California Excellence in Structural Engineering Awards (EiSE) Program. Awards in this category are for "outstanding achievement in the development of structural engineering practice, standards, research documents or design guidelines."

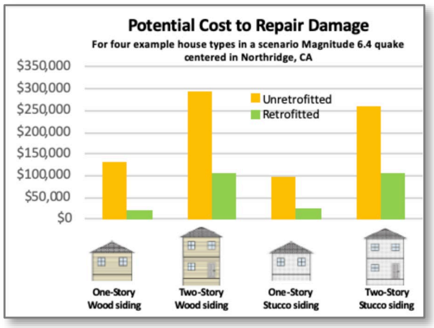
The Awards Committee stated that "the jurors were impressed with the amount of collaboration that was required between all of the contributors and the number of working groups. They also thought that the ability to compute so much data and run so many analyses was innovative, as the team expected the computing to take [years] but they were able to accomplish it in weeks. Additionally, because the end product is designed for home owners and non-engineers to promote retrofitting of single family homes, this project has a significant contribution to the public."

Yousef Bozorgnia, project Principal Investigator, noted that "we appreciate this award that recognizes the collaborative work of the project team of over two dozen academic researchers and expert practitioners for the past four years. The data and information gained from the project will be impactful beyond the project itself."

Grace Kang, project coordinator and PEER Communications Director, said that "on behalf of the project team and PEER, we are delighted to receive this award and the recognition for the project team's work. A complex problem was tackled by the expertise in each working group, with the groups working collaboratively to show that a simple retrofitting investment today can save significant costs in repairing damage that would be caused by a future major earthquake. The findings of this project affects not just northern California, but all homeowners in California."

Project abstract: In California and many other states, inadequate bracing and anchoring is a major cause of earthquake damage in older wood-frame houses that have a first floor above a crawlspace. Past quakes have caused varying levels of damage in these homes, resulting in costly repairs even if the houses did not collapse. Many homeowners may not have enough financial resources to cover such repairs. Hence, understanding how older, wood-frame houses benefit from earthquake retrofitting is important.

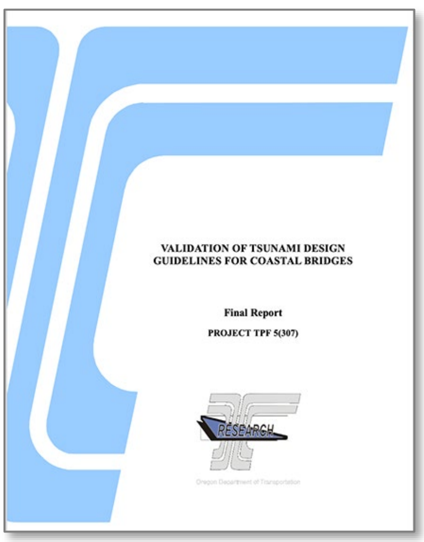
The objective of the project "Quantifying the Performance of Retrofit of Cripple Walls and Sill Anchorage in Single-Family Wood-Frame Buildings (PEER-CEA Project)" is to provide scientifically based information (e.g., testing, analysis, and resulting loss models) that measure and assess the effectiveness of seismic retrofit to reduce the risk of damage and associated repair costs of wood-frame houses with cripple wall and sill anchorage deficiencies as well as retrofitted conditions that address those deficiencies.



To understand how retrofitting reduces earthquake damage and repair costs, project researchers first identified different characteristics or "variants" of home types, such as the number of stories (one- or two-story), era or age of construction, interior wall and ceiling materials, exterior cladding material, and height of the cripple walls. Experimental tests of full-scale cripple wall assemblies with different construction materials, for unretrofitted and retrofitted conditions, were conducted in order to validate analytical modeling. State-of-the-art modeling and analysis was conducted to estimate how retrofits can reduce losses in vulnerable housing styles in California. Workshops with experts generated realistic repair cost data.

A brochure targeting the non-engineering audience summarizes the benefits of retrofit in terms of potential savings of repair costs in the event of a major earthquake. This document, as well as the research methods and data can be viewed at: https://www.peer.berkeley.edu/cw-woodframe.

4.10 TSUNAMI DESIGN GUIDELINES FOR NEW BRIDGES RELEASED



The PEER research project to develop bridge design guidelines for tsunami loads concluded and released three reports summarizing the project methodology, investigations, and findings. The project was a multi-campus, multi-disciplinary research program that spanned five years, and it was funded through PEER by a Transportation Pooled-Fund that included Alaska, California, Hawaii, Oregon (lead state), Washington, and the Federal Highway Administration. The Cascadia subduction zone poses a direct threat for a major tsunami that could impact the coastlines of these of these five states.

The purpose of the project was to develop the necessary probabilistic tsunami wave heights in coastal areas of the western states, followed by design guidelines for new bridges to withstand tsunami loads.

For this project, a map of probabilistic offshore tsunami wave-heights at the 1000-year recurrence interval was created using a Green's function summation approach. This approach enables the integration over a wide range of source zones and magnitudes and the inclusion of epistemic uncertainties that describe our incomplete knowledge and understanding of natural processes, and aleatory variability, which expresses the randomness in natural processes. The methodology is similar to the common approach in Probabilistic Seismic Hazard Analysis (PSHA). Both methods use an integration over a range of earthquake magnitudes and locations. While PSHA uses Ground Motion Prediction Equations (GMPEs) to compute the ground motion amplitude at a site, the PTHA approach uses numerical models to predict the wave- heights and inundation areas.

The overview report, "**Validation of Tsunami Design Guidelines for Coastal Bridges**," was authored by Patrick Lynett - University of Southern California; Hong Kie Thio – AECOM; Michael Scott - Oregon State University; Tom Murphy - Modjeski & Masters; Tom Shantz – CalTrans; and Jian-Dzwan Shen – FHWA. (Oregon Department of Transportation, Report No.

FHWA-OR-RD-21-09.January2021.)
https://www.oregon.gov/odot/Programs/ResearchDocuments/TsunamiFinal.pdf

Abstract: This paper details a Transportation Pooled Fund Study, TPF-5(307), that included Alaska, California, Hawaii, Oregon (lead state), Washington, and the Federal Highway Administration. The research goal was to update guidelines as a foundation for review by the respective AASHTO sub-committee(s). This report focused on bridges for the Western United States. Five major efforts were completed:

Updated probabilistic tsunami hazard mapping to include wave-heights, velocities, and inundation levels at the 1000-year recurrence interval. This was completed for all aforementioned states at varying detail (10m through 60m);

Uncertainties and bias between models were examined to find areas where they agree and potential areas where the study could identify conservative estimates for optimization.

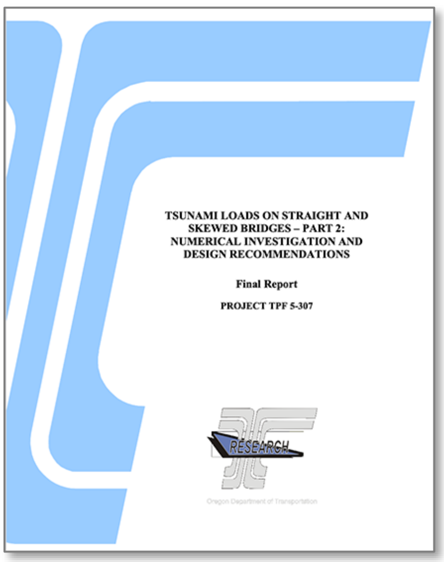
Analysis of site-specific tsunami hazards was developed. Two methods (level 1 and level 2) are presented to detail local tsunami hydrodynamics;

Loading are detailed and recommendations for equations presented based on research findings. Three load cases, including conditions showing upward lift were modeled and equated. Bridge skew, slope, and super-elevation were examined. Debris was considered. Geotechnical considerations were also discussed.

"**Tsunami Loads on Straight and Skewed Bridges – Part 1: Experimental Investigation and Design Recommendations**," authored by Denis Istrati and Ian G. Buckle, Department of Civil and Environmental Engineering, University of Nevada, Reno. (Oregon Department of Transportation, Report No. FHWA-OR-RD-21-12. February 2021.)

Abstract: This report presents the results of a large-scale experimental investigation of tsunami impact on straight and skewed bridges. The 1:5 scale specimens had realistic structural components and dynamic properties, and were subjected to a range of simplified unbroken solitary waves and more realistic bores. The unique experimental data revealed: (a) the complexity of the tsunami inundation mechanism of bridges and the overloading of the offshore bearings and columns, due to the large overturning moment (OTM) generated by the wave slamming the offshore girder and overhang, (b) the significant difference between the effects introduced by simplified unbroken solitary waves and more realistic bores, (c) the major role of structural dynamics and fluid-structure interaction for the estimation of design forces, and the possibility of dynamic amplification when the bridge is impacted by a bore, (d) the increase of both the total uplift forces and the OTM in bridges with diaphragms due to the airentrapment, (e) the dependence of the tsunami loads on the bridge type, with box-girder bridges witnessing on average uplift forces 134% higher than those in I-girder bridges, (f) the modification of the hydrodynamic flow caused by solid rails, which increases both the horizontal and downward tsunami loads, and (g) the promising use of air-vents in the deck as a mitigation strategy against tsunamis, in which both the number and the location of the venting holes are optimized in order to maximize the air release. Based on the above findings, the authors developed two simplified methods that can be used for the tsunami design of bearings and other structural components necessary for the survival of straight bridges. While the above findings are applicable to straight bridges, skewed ones witness more complex loads, including significant roll and yaw moments, which should be considered in their design. These moments lead to non-uniform distribution of the tsunami loads to the two supports of the deck and the individual bearings with (i) one abutment having to sustain up to 96% of the total horizontal force, and the other one up to 146% of the total uplift, and (ii) the bearings of the offshore obtuse corner attracting 95% of the total deck uplift.

"**Tsunami Loads on Straight and Skewed Bridges – Part 2: Numerical Investigation and Design Recommendations**," authored by Denis Istrati and Ian G. Buckle, Department of Civil and Environmental Engineering, University of Nevada, Reno. (Oregon Department of Transportation, Report No. FHWA-OR-RD-21-13.March 2021.)



Abstract: Despite the documented vulnerability of coastal bridges in recent tsunami events, no formal guidance exists to date for the tsunami design of such structures. To contribute to the development of such guidelines, this report presents the results of a numerical investigation into tsunami-induced loads on bridges. Following extensive validation of an incompressible hydrodynamic solver, three existing bridges owned by the Oregon Department of Transportation, are investigated, including open-girder and box- girder superstructures. These analyses revealed that when a bore impacts a straight bridge, large impulsive horizontal (Fx) and uplift (Fy) loads together with an overturning moment about the longitudinal axis of the bridge (Mz) are simultaneously applied to the bridge, increasing the likelihood for severe damage. As the angle of skew increases the magnitude of the impulsive component of these loads decreases, leading to a decreasing trend in Fx, Fy and Mz. On the other hand these structures are also subject to (i) a force normal to the direction of wave propagation, and (ii) moments about the y- and z-axes. The Fz force and the yaw moment My can have a detrimental effect on bridge performance because they generate out-of- plane horizontal loads that can result in unseating of the deck, while the roll moment Mx can overload the structural components (bearings and shear keys) at one end of a skewed deck. Another important finding is that while a tsunami wave that strikes a straight bridge at an oblique angle generates significant three- dimensional effects similar to skewed bridges, such a wave can lead to more severe deck loads due to the interaction of the wave with the bridge abutments and a subsequent channeling effect. Finally, to assist bridge designers, the report presents a simplified methodology for the tsunami design of skewed bridges, and performance criteria for bridges in tsunami-prone areas, based on (i) two tsunami levels, (ii) three bridge operation categories, and (iii) three performance levels to quantify the criteria.

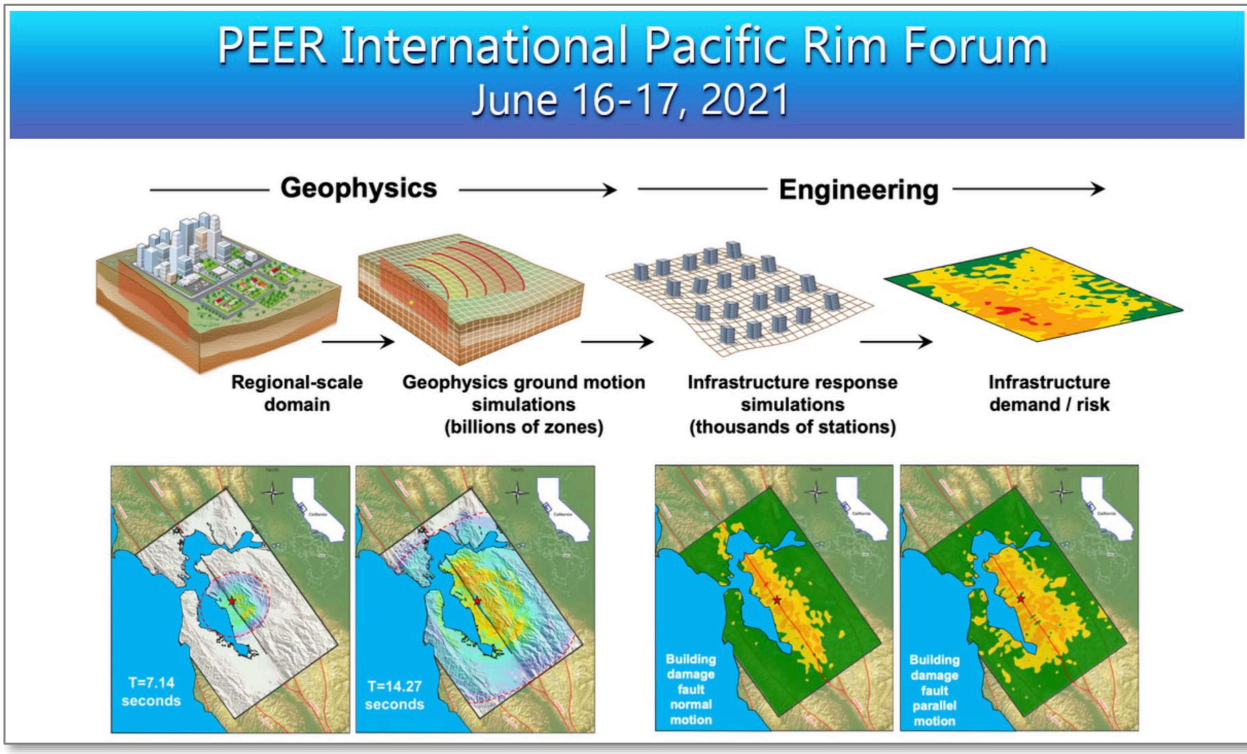
4.11 PEER DOE WORKSHOP: MAY 17-18, 2021

This workshop, which was held virtually during May 17-18 2021, brought together a group of international experts from the research and practitioner communities in the U.S. and Japan, to discuss state-of-the-art experimental techniques and emerging instrumentation technologies for large-scale SSI experiments that can produce unique experimental data to advance knowledge in natural hazards. The generated experimental data followed by research and development activities will ultimately result in updates to the technical standards and design guides, and build confidence in advanced nonlinear simulation techniques.

The workshop included presentations in the following areas within the common theme of "large-scale shake table tests" to study:

- R&D activities related to resiliency of nuclear facilities against natural phenomenon hazards
- Probabilistic Risk Assessment (PRA) advancements
- Soil-foundation-structure system analysis considering interaction
- Advanced simulations and validations
- Assessment of areas of uncertainty and quantification
- State-of-the-art experimental techniques
- Emerging instrumentation technologies
- Large scale shake table facilities, design basis and performance objectives, experimental capabilities, example recent projects
- Technical standard developments
- Other areas related to large-scale shake table testing

4.12 PEER INTERNATIONAL PACIFIC RIM FORUM: JUNE 16-17, 2021



This latest in a series of PEER Pacific Rim Forums brought together multidisciplinary experts from structural and geotechnical engineering and the earth sciences to share recent research results as well as state-of-practice advancements and applications of regional-scale fault-to-structure simulations. Special attention was also focused on the identification of key knowledge and capability gaps providing barriers to realizing the full potential of regional-scale simulations.

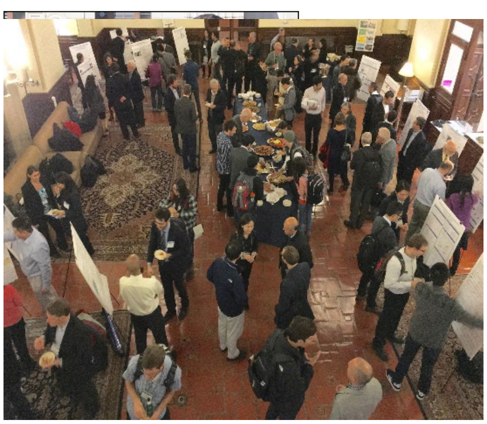
Given the continuing pandemic challenges to travel and large meetings, the Forum was entirely web-based. Researchers, practitioners and students all benefited from attendance at this Forum. The presentations and discussions provided broad coverage of key topics for this rapidly advancing domain.

4.13 MEET THE PEER STUDENTS – PRESENTED BY THE PEER STUDENT COMMITTEE

The PEER Student Committee presented their first spotlighted researcher in the "Meet the PEER Students" Series in June, 2021. The series features students and postdoctoral researchers who conduct exciting research projects, engage in leadership activities, and perform exceptional work. In June 2021, they met Dr. Maha Kenawy, a postdoctoral scholar in the Department of Civil and Environmental Engineering at the University of Nevada, Reno.

Dr. Maha Kenawy is a postdoctoral scholar in the Department of Civil and Environmental Engineering at the University of Nevada, Reno. She specializes in advancing the nonlinear modeling methods of reinforced concrete structures, and characterizing the risks of earthquakes to civil structures. Dr. Kenawy holds a Ph.D. in Civil and Environmental Engineering from the University of California, Davis, and a M.Sc. and B.Sc. in Construction Engineering from the American University in Cairo (AUC), Egypt. She is the recipient of the ASCE O.H. Ammann Research Award in Structural Engineering, the NHERI Summer Institute Grant for early-career researchers in natural hazard risk reduction from NSF, and the Laboratory Instruction Graduate Fellowship from AUC. Dr. Kenawy has been invited to give technical talks at several U.S. institutions and conferences. She has also held leadership positions in the earthquake engineering community, including a chair of the EERI Younger Members Committee.

4.14 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 two years: 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.

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.

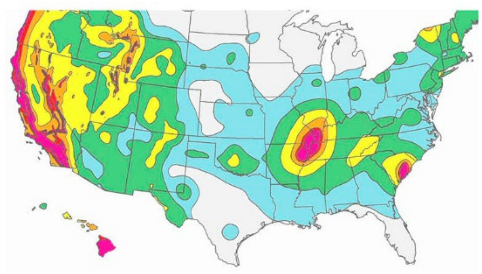
UniaxialMaterial: *ConcreteD, ConcreteCM, SteelMPF*, and *BilinearOilDamper*

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.



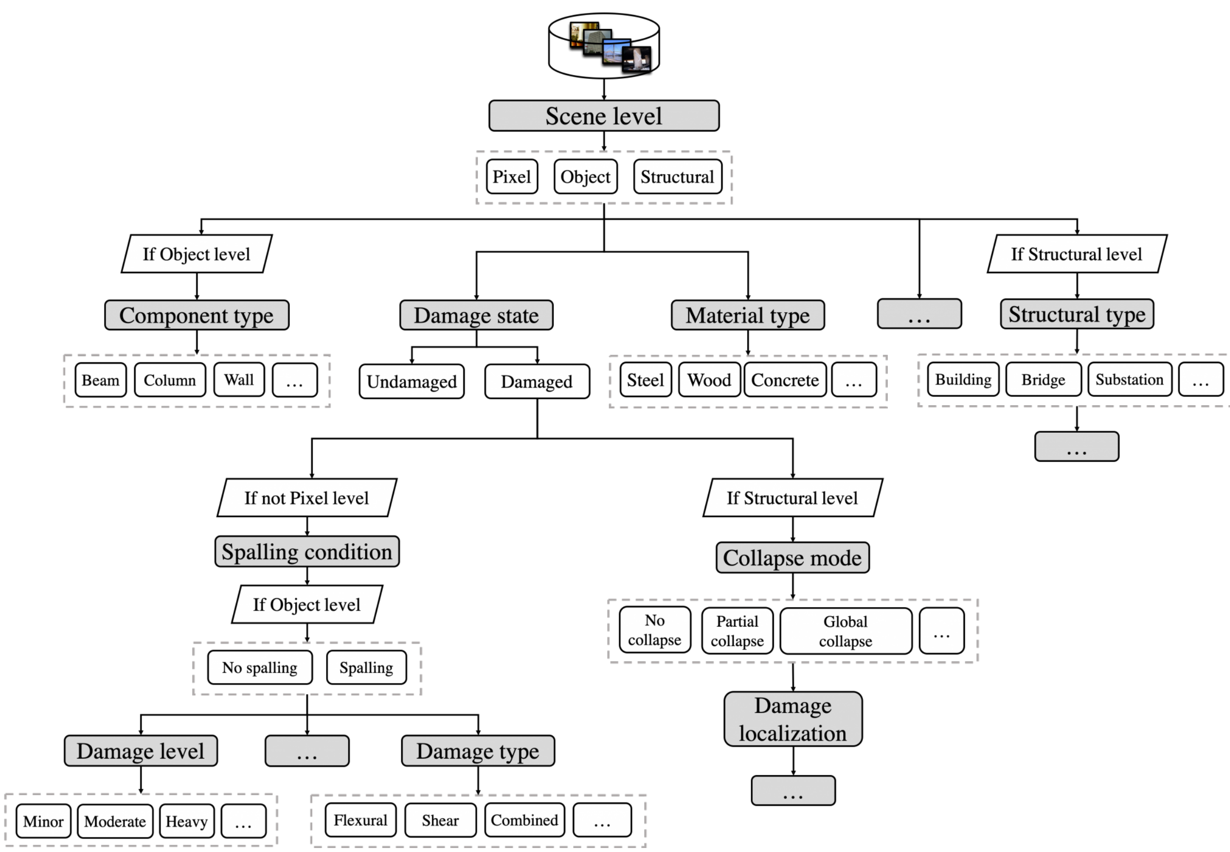
5.2.2 PEER Hub Imagenet (PHI-Net or Φ-Net)

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.

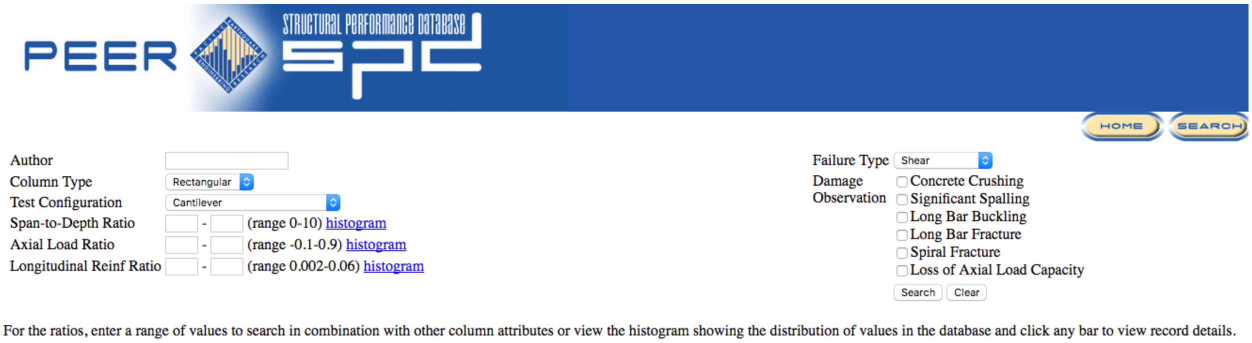
Both AI and machine learning (ML) technologies have developing rapidly in recent decades, especially in the application of deep learning (DL) in computer vision (CV). The objective of ML and DL implementation is to have computers perform labor-intensive repetitive tasks while simultaneously "learning" 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:

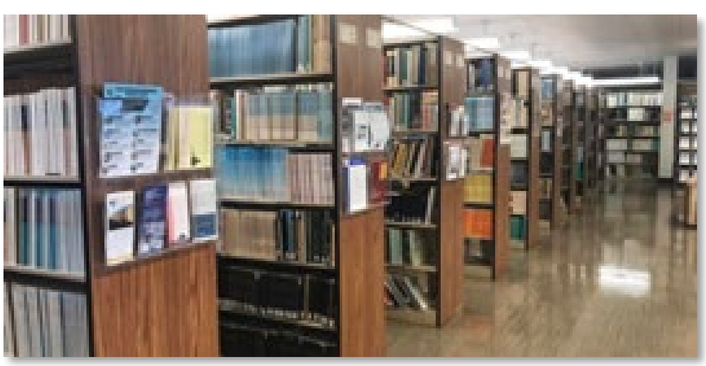
- spiral or circular hoop-reinforced columns (with circular, octagonal, or rectangular cross sections)
- rectangular reinforced columns
- columns with or without splices

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

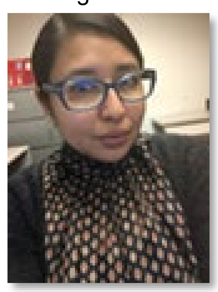
6.1 KEY PERSONNEL (HEADQUARTERS)

Khalid Mosalam
Director

Amarnath Kasalanati
Associate Director for Operations & Strategic Initiatives

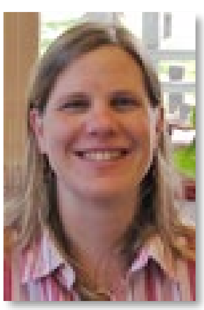
Grace Kang
Communications Director

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

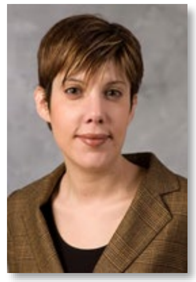
Charles Scawthorn
Visiting Scholar

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

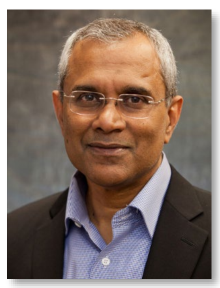
Ian Buckle
University of Nevada, Reno

Jose Restrepo
University of California, San Diego

Rakesh Goel
Educational Affiliate Representative
CalPoly

Patrick Lynett
University of Southern California

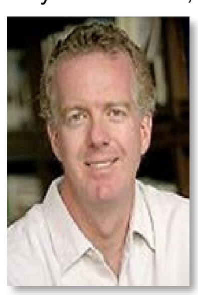
Anne Kiremidjian
Stanford University



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, Anhdan Le, Eduardo Miranda, and Ertugrul Taciroglu. In addition, Norman Abrahamson (Leader of PEER Lifelines Research Program) Amarnath Kasalanati (PEER Associate Director), and Khalid Mosalam (PEER Director) serve as Ex-Officio members on all committees.

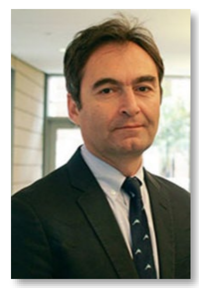
Pedro Arduino
University of Washington

Tara Hutchinson
UC San Diego

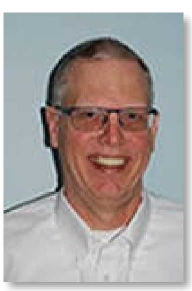
Amit Kanvinde
UC Davis

Anhdan Le
Caltrans

Eduardo Miranda
Stanford University



Ertugrul Taciroglu
UC Los Angeles



Norm Abrahamson
UC Berkeley / Davis
PEER Lifelines Leader
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; Gayle Johnson, Simpson, Gumpertz & Hager; Brian Kehoe, Wiss, Janney, Elstner Associates; Peter Lee, Skidmore Owings and Merrill; Steve Marusich, Forell/Elsesser Engineers; Don Scott, PCS Structural Solutions; and Sharon Yen, Caltrans. Norman Abrahamson (Leader of PEER Lifelines Research Program) serves as an Ex-Officio member.

James Malley, Chair
Degenkolb Engineers

Jennie Watson-Lamprey (Vice Chair)
Slate Geotechnical

Matt Bowers
SC Solutions

Gayle Johnson
Simpson, Gumpertz & Hager

Brian Kehoe
Wiss, Janney, Elstner

Peter Lee
Skidmore, Owings & Merrill

Steve Marusich
Forell/Elsesser Engineers

Don Scott
PCS Structural Solutions

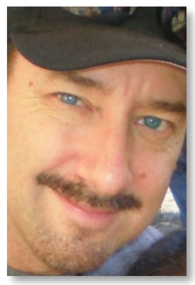
Sharon Yen
Caltrans

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; Chung-Soo Doo, BART; Marc Eberhard, University of Washington; Ahmed ElGamal, University of San Diego; Hamid Haddadi, CGS; David McCallen, University of Reno, Nevada; Farhang Ostadan, Bechtel Corporation; and Toorak Zokaie, Caltrans. Norman Abrahamson (Leader of PEER Lifelines Research Program) serves as an Ex-Officio member.

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

Chung-Soo Doo
BART

Hamid Haddadi
CGS

Toorak Zokaie
Caltrans

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
Karlene Roberts
Nicholas Sitar
David Sunding
Kenichi Soga
Rune Storesund
Adda Athanasopoulos-Zekkos
Dimitrios Zekkos
Tarek Zohdi
Abolhassan Astaneh-Asl
Anil K. Chopra
Mary Comerio
Filip C. Filippou
James M. Kelly
Armen Der Kiureghian
Juan M. Pestana
Raymond B. Seed

California Institute of Technology

Jose Andrade
Domniki Asimaki
James Beck
John Hall
Thomas Heaton

Oregon State University

Scott Ashford
Andre Barbosa
Erica Fischer
Judy Liu
Ben Mason
Michael Olson
Michael Scott
Barbara Simpson
Harry Yeh
Solomon Yim

Stanford University

Jack Baker
Sarah Billington
Gregory Deierlein
Rishee Jain
Anne Kiremidjian
Kincho Law
Michael Lepech
Christian Linder
Eduardo Miranda
Ram Rajagopal
Hae Young Noh

University of California, Davis

Michele Barbato
John Bolander
Ross Boulanger
Rob Y.H. Chai
Dawn Cheng
Jason DeJong
I.M. Idriss
Boris Jeremíc
Amit Kanvinde
Sashi Kunnath
Bruce Kutter
Brian Maroney
Alejandro Martinez
Sabbie Miller
Katerina Ziotopoulou

University of California, Irvine

Joel Lanning
Anne Lemnitzer
Mo Li
Ayman Mosallam
Farzad Naeim
Farzin Zareian

University of California, Los Angeles

Yousef Bozorgnia
Henry Burton
Scott Brandenberg
Ken Hudnut
Jonathan Stewart
Ertugrul Taciroglu
M. Saiid Saiidi
John Wallace
Jian Zhang

University of California, San Diego

Joel Conte
Ahmed Elgamal
Tara Hutchinson
Falko Kuester
J. E. Luco
John McCartney
Machel Morrison
Gilberto Mosqueda
Jose Restrepo
Shabnam Semnani
Pui-Shum Shing
Ingrid Tomac
Chia-Ming Uang
Yael Van Den Einde

University of Nevada, Reno

Ian Buckle
Hamed Ebrahimian
Graham Kent
John Louie
Ramin Motamed
David McCallen
Mohamed Moustafa
Gokhan Pekcan
Floriana Petrone
Keri Ryan
Elnaz Seylabi
Raj Siddharthan

University of Southern California

Gregg Brandow
Roger Ghanem
Tom Jordan
Erik Johnson
Patrick Lynett
Sami Masri
James Moore
Costas Synolakis
Carter Wellford
Qiming Wang

University of Washington

Pedro Arduino
Jeffrey Berman
Paolo Calvi
Marc Eberhard
Michael Gomez
Steve Kramer
Dawn Lehman
Laura Lowes
Peter Mackenzie
Brett Maurer
Michael Motley
Kamran Nemati
Dorothy Reed
Charles Roeder
John Stanton
Travis Thonstad
Richard Wiebe

6.6.2 Faculty Participants (Educational Affiliates)

California Polytechnic State University (Cal Poly), San Luis Obispo

Rakesh Goel

California State University, Los Angeles

Mark Tufenkjian

California State University, Northridge

Nazaret Dermendjian

Carnegie Mellon University

Pei Zhang

Johns Hopkins University
Ben Schafer

Southern Methodist University
Nikos Makris

San Jose State University
Kurt McMullin Thalia Anagnos

University of Alaska, Anchorage
Wael Hassan

University of Hawaii, Manoa
Ian Robertson

6.6.3 Faculty Participants (National and International Institutions)

Auburn University	David Roueche
California State University, Chico	Curt Haselton
California State University, Fullerton	Kristijan Kolozvari
California State University, Long Beach	Lisa Star Vesna Terzic
Eidgenössische Technische Hochschule (ETH) Zürich	Božidar Stojadinović
Florida International University	Atorod Azizinamini Arindam Chowdhury
Lawrence Livermore National Laboratory	Arthur Rodgers Henry Teng
Michigan State University	Venkatesh Kodur
University of California, Santa Barbara	Ralph Archuleta Jamison Steidl
University of Chile, Santiago	Ruben Boroshek
University of Central Florida	Kevin Mackie

University of Illinois, Urbana-Champaign	Paolo Gardoni Jong Sung Lee
University of Florida	Forrest Masters David Prevatt
University of Texas at Austin	Ellen Rathje Kenneth Stokoe
Virginia Tech University	Martin Chapman Adrian Rodriguez-Marek
Western University, Canada	Gail Atkinson

6.6.4 Industry Partners

ARUP	Rob Smith J Ben Shao
Bay Area Rapid Transit (BART)	Chung-Soo Doo Carlos Alberto Rosales
Bechtel	Farhang Ostadan
California Dept. of Conservation	Hamid Haddadi
California Dept. of Transportation	Anhdan Le Tom Ostrom Charles Sikorsky Chris Traina Sharon Yen Toorak Zokaie
California Earthquake Authority	Janiele Maffei
California Energy Commission	Yahui Yang Qing Tian
California High-Speed Rail Authority	Kevin Thompson
California Seismic Safety Commission	Fred Turner Richard McCarthy
Canterbury Earthquake Recovery Authority (CERA)	Roger Sutton
City of San Francisco	Brian Strong

Degenkolb	James Malley Jay Love Stacy Bartoletti Adrian Nakamuli Insung Kim
Exponent	Brian McDonald Ezra Jampole Morgan Griffith
Forell/Elsesser Engineers	Simin Nasseh Mason Walters Steve Marusich Ali Roufegarinejad
FM Global	Hosam Ali
Gannett Fleming, Inc.	Dina Hunt
Hinman	Eve Hinman Mohammadreza Eslami
Holmes Consulting	Bill Tremayne Dion Marriott
IHI	Kensuke Shiomi Teruyoshi Otoyo Takashi Mori
Magnusson Klemencic Associates	Ron Klemencic
MIDAS Software	Angela Kim Daniel Lee Bede Yoo
NIST	Steve Cauffman Judith Mitrani-Reiser
Oregon Dept. of Transportation	Jon Lazarus
Port of San Francisco	Rod Iwashita Steven Reel
Rutherford + Chekene	Bill Holmes Bret Lizundia

SC Solutions	Matt Bowers Farid Nobari
Simpson Gumpertz & Heger	Ron Hamburger Gayle S. Johnson
Skidmore, Owings & Merrill	Peter Lee Mark Sarkisian
Slate Geotechnical Consultants	Jennie Watson-Lamprey
Southern California Edison	Roderick dela Cruz Matthew Muto
TY Lin	Marwan Nader
U.S. Geological Survey	Brad Aaagard Dale Cox Robert Graves Grace Parker
U.S. Resiliency Council	Evan Reis Ron Mayes
Walter P Moore	Bill Andrews Rafael Sabelli
Washington Dept. of Transportation	Bijan Khalegi
Wiss, Janney, Elstner	Kelly Cobeen Brian Kehoe Kent Sasaki

Appendix A   Distribution of TSRP Funding

Transportation Systems Research Program (TSRP)

Pacific Earthquake Engineering Research Center (PEER) is a multi-institutional research and education center with the 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.

PEER receives continuing funding from the State of California to conduct research related to the seismic performance of transportation systems. This funding supports the Transportation Systems Research Program (TSRP), with the goal to reduce the negative impact of earthquakes on California's transportation systems, including highways, bridges, port facilities, high-speed rail, airports and building structures associated with transportation network. 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.

In 2017, PEER revamped the Research Committee and reinstated a Request for Proposal (RFP) process, soliciting the proposals from the researchers of 11 core institutions of PEER. These core institutions are the major research universities in the Western United States and include, UC Berkeley, California Institute of Technology, Oregon State University, Stanford, UC Davis, CU Irvine, UC Los Angeles, UC San Diego, University of Nevada, Reno, University of Southern California and University of Washington. Since reinstating the RFP process, PEER has received 172 proposals and funded 54 projects. Prior to the RFP process, 11 projects were funded in 2016 & 2017, as part of continuation of previous projects or by ad-hoc review by the Research Committee.

The RFP focuses on five broad areas: Geotechnical Engineering (**G**), Structural Engineering (**S**), PBEE Methodology (**M**), PBEE Tools (**T**) and Areas of Application (**A**). Within each of these areas, there are several subtopics, resulting in the following 21 topics:

G.1. Liquefaction Triggering Criteria

G.2. Estimation of Permanent Deformation

G.3. Constitutive Modeling

G.4. Site Characterization

S.1. Development of Fundamental Knowledge: Bridges & Other Transportation Systems

S.2. New Bridge Systems: Cost, Resilience, Durability & Constructability

S.3. Ports, Airports & High-speed Rail

M.1. Ground Motion & Hazard Intensity: Improved Characterization

M.2. Physical Simulation & Physics-based GM Modeling

M.3. Inverse PBEE Analysis, Forward & Backward Uncertainty Quantification

M.4. Hybrid Simulation & Shake Table Tests

M.5. Instrumentation, data collection, use of AI and ML
M.6. Protective Systems

T.1. Visualization, Data Mining and AI Tools
T.2. Highly Non-linear Elements, Materials; Soil-Structure & Fluid-Structure Interaction
T.3. Tools for Incorporating Uncertainties
T.4. Complex Models and Large Networks
T.5. Field Studies and Reconnaissance

A.1. Ports & Bridge Design for Tsunamis
A.2. Development of PBE Basis for New Systems, HSR
A.3. Development of PBE Basis for Other Hazards (Fire) and Multi-Hazards

The following tables and plots show the distribution of TSRP projects across the thrust areas, topics and core institutions.

The TSRP program administered by PEER offers great opportunities for the core institution researchers, with 36% of the projects funded (Table A.1). Three consecutive years of over $1 million per year was provided to fund projects to improve the resiliency of transportation infrastructure.

Table A.1 TSRP Program Funding 2016 - 2020

Year	Proposals	Funded	Percentag	Solicited	Funded	Percentag
2016 NoRFP	7	7	100%	$577,572	$577,572	100%
2017 PreRFP	4	4	100%	$444,703	$444,703	100%
2017 RFP	47	17	36%	$ 4,801,433	$1,498,723	31%
2018 RFP	47	11	23%	$ 5,279,057	$1,471,309	28%
2019 RFP	44	14	32%	$ 4,953,596	$1,210,466	24%
2020 RFP	34	12	35%	$ 1,722,841	$ 594,449	35%
Total	**183**	**65**	**36%**	**$17,779,202**	**$5,797,222**	**33%**

Among the thrust areas, PBEE Methodology (M), PBEE Tools (T) and Structural Engineering (S) received the most number of proposals and were most frequently (Table A.2, Figure A.1 and Figure A.2). It should be noted that many Geotechnical Engineering (G) projects in the past were funded through PEER's Lifelines program (such as NGL), thereby receiving fewer proposals in response to TSRP RFP. Moreover, Areas of Application (A) is an emerging area with expansion to new systems and new hazard, thereby receiving fewer proposals.

Table A.2 Distribution of TSRP funding among thrust areas

Thrust Area	Proposal Applications		Funded Projects	
	Number	Amount	Number	Amount
Geotechnical Engineering (G)	31	$ 2,664,320	10	$ 787,008
Structural Engineering (S)	35	$ 4,177,623	11	$1,457,516
PBEE Methodology (M)	50	$ 5,250,127	17	$1,485,609
PBEE Tools (T)	45	$ 3,648,661	20	$1,397,786
Areas of Application (A)	22	$ 2,038,471	7	$ 669,303
Total	**183**	**$17,779,202**	**65**	**$5,797,222**

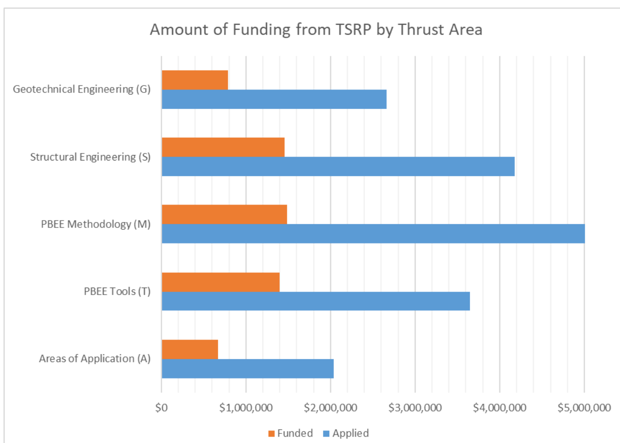


Figure A.1 Funding by thrust area

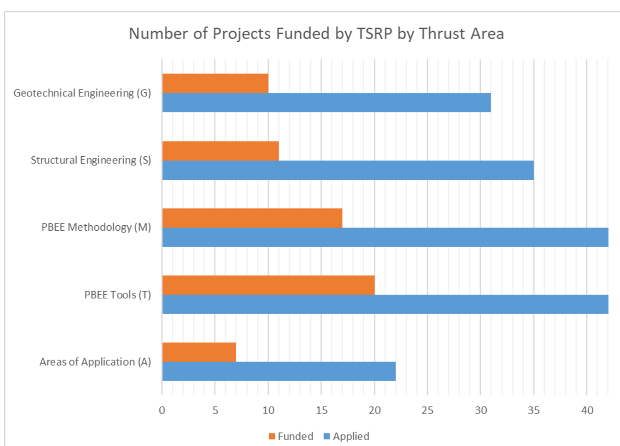


Figure A.2 Projects by thrust area

Looking deeper into the thrust areas, funding was fairly well spread among 20 of the 21 topics (Figures A.3, A4, A5 and A6). The lone exception, G4 – Site Characterization, received no funding because of substantial work being done in the similar field in PEER's Lifelines program.

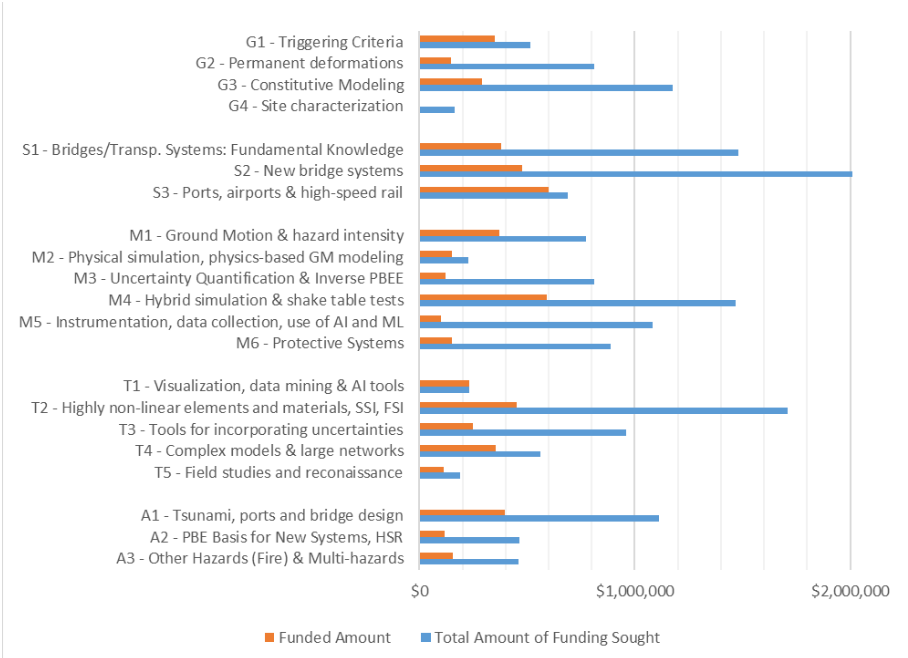


Figure A.3 Amount of funding sought among topics

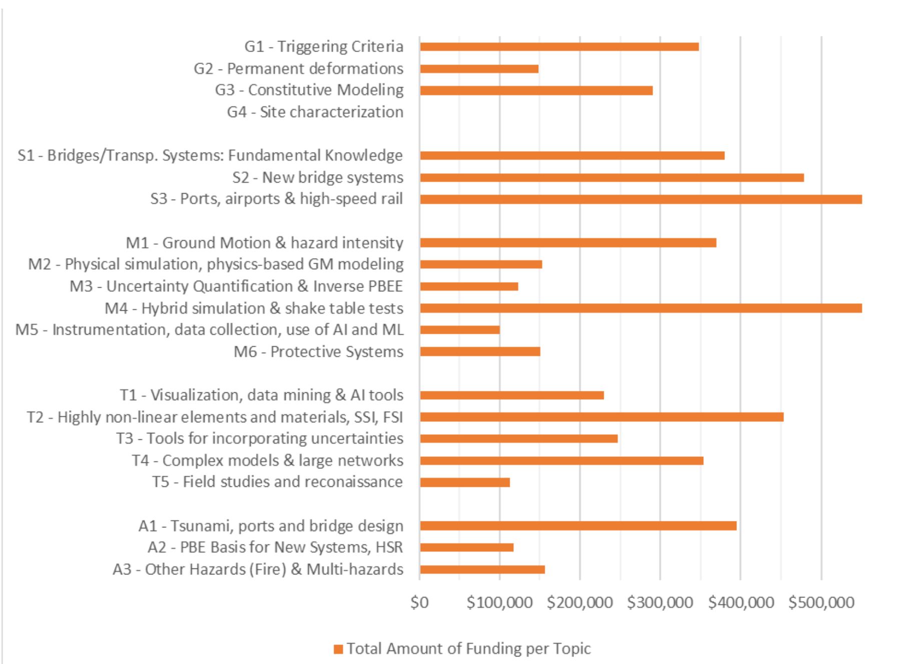


Figure A.4 Amount of funding provided among topics

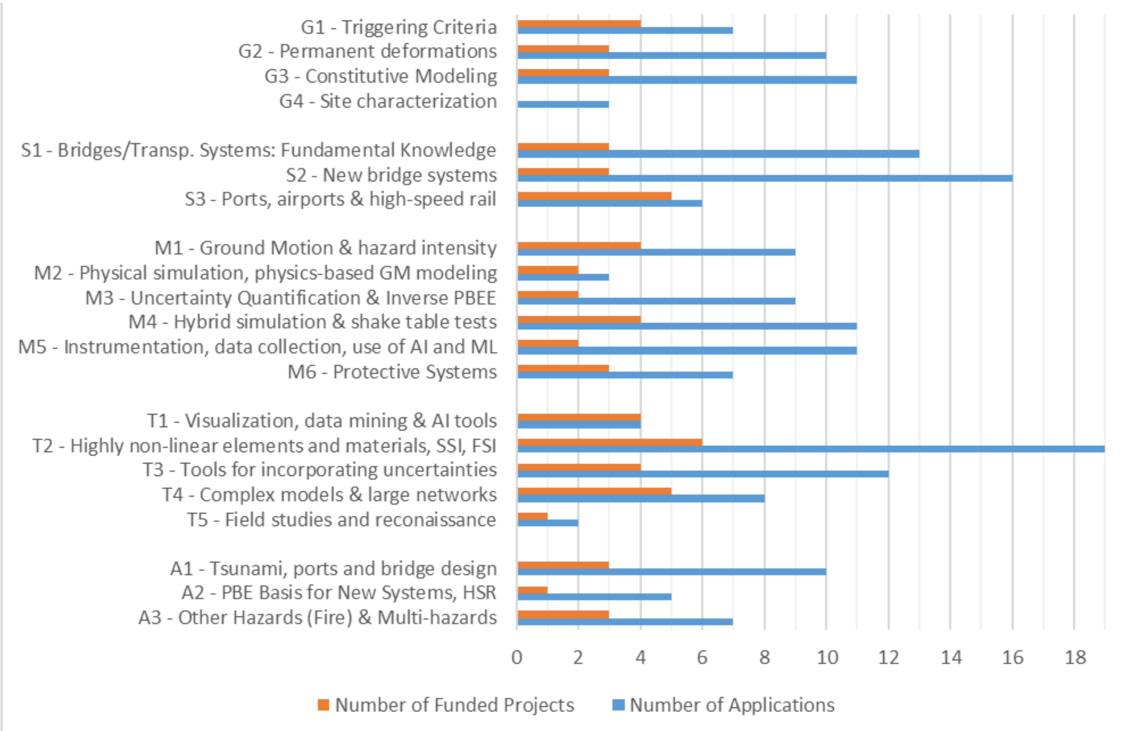


Figure A.5 Number of proposals received for each topic

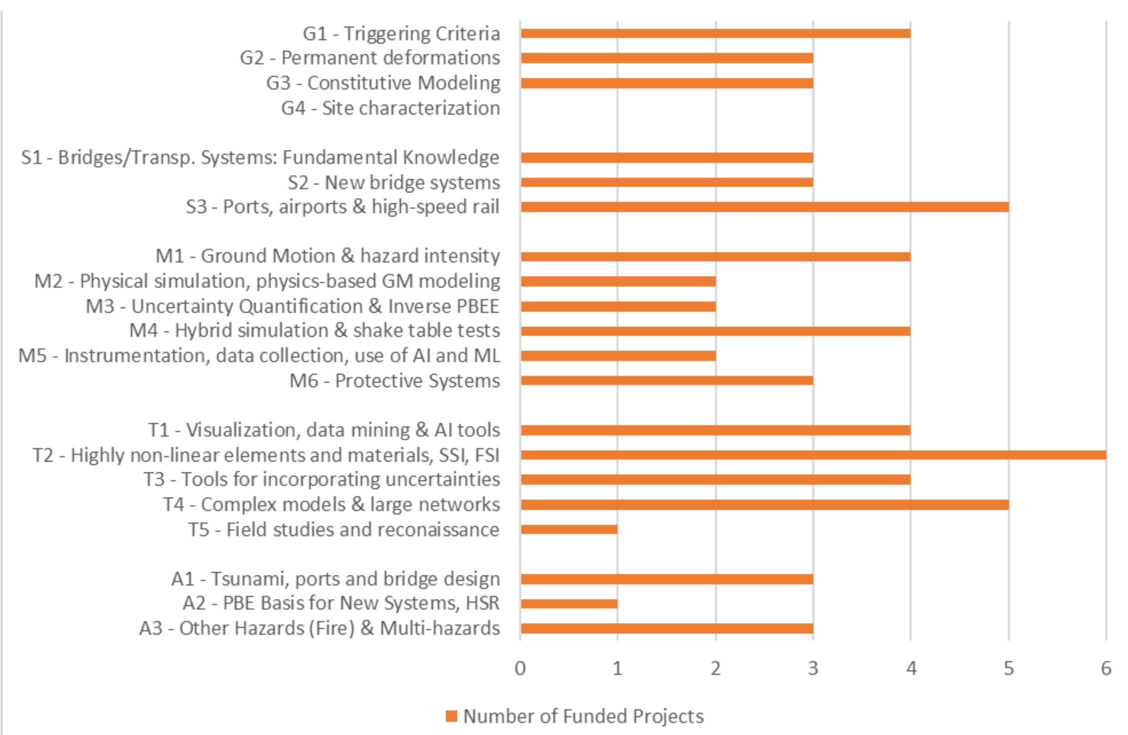


Figure A.6 Number of funded projects for each topic

Since reinstating the RFP in 2017, researchers from all of PEER's 11 core institutions participated in the process (Table A.3, Figures A.7 and A.8). Researchers at UC Berkeley, UNR, UW and UC San Diego have had a large number of proposals well spread across the thrust areas. Institutions with smaller Earthquake Engineering programs have had fewer proposals, focused on specific topics.

Table A.3 TSRP projects among PEER core institutions

Institution	Proposal Applications		Funded Projects	
	Number*	Amount	Number*	Amount
California Institute of Technology	3	$ 245,342	2	$ 154,490
Oregon State University	16	$ 1,492,327	6	$ 554,045
Stanford University	8	$ 719,742	4	$ 357,841
University of Southern California	1	$ 86,697	1	$ 86,697
University of Nevada, Reno	29	$ 3,168,418	7	$ 675,990
University of Washington	20	$ 1,700,224	7	$ 562,426
University of California, San Diego	19	$ 2,258,088	8	$ 789,702
University of California, Los Angeles	17	$ 1,525,866	6	$ 567,523
University of California, Irvine	15	$ 1,500,525	3	$ 259,246
University of California, Davis	14	$ 1,145,769	4	$ 385,369
University of California, Berkeley	39	$ 3,815,364	15	$ 1,283,053
Total for 11 Core Institutions	**181**	**$ 17,658,362**	**63**	**$ 5,676,382**

* Prior to the RFP process, two projects from AUA and CSU-FL were funded

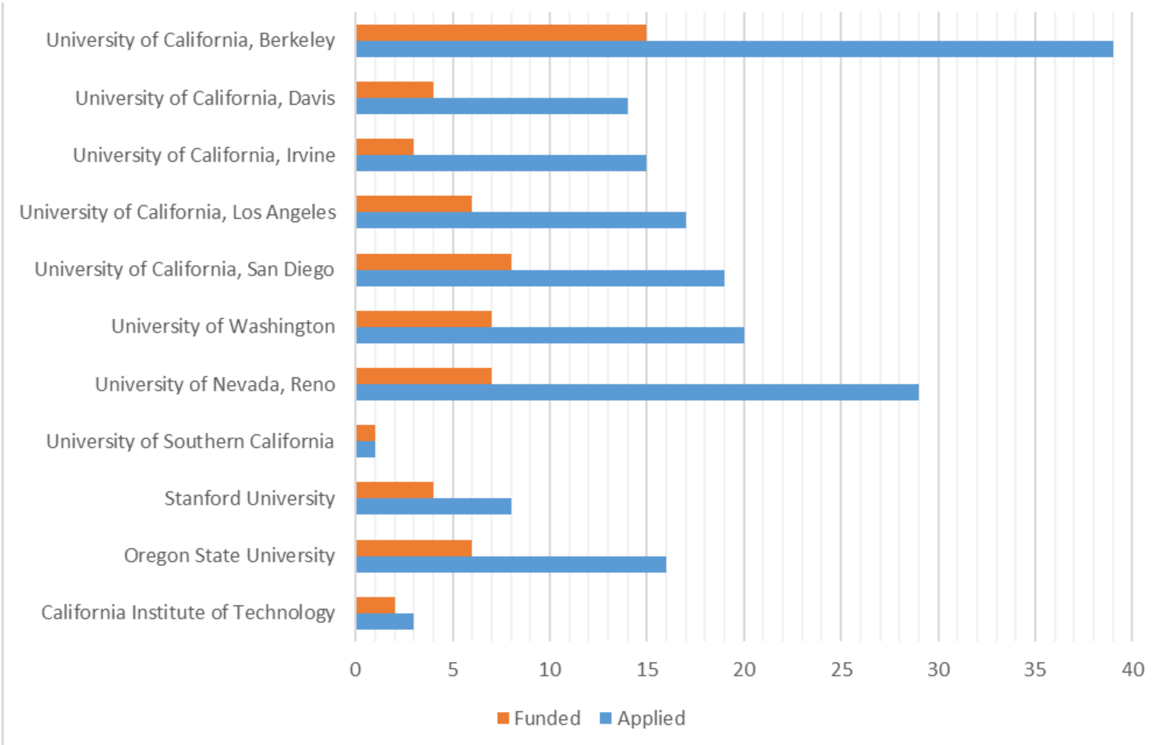


Figure A.7 Number of proposals received from each core institution

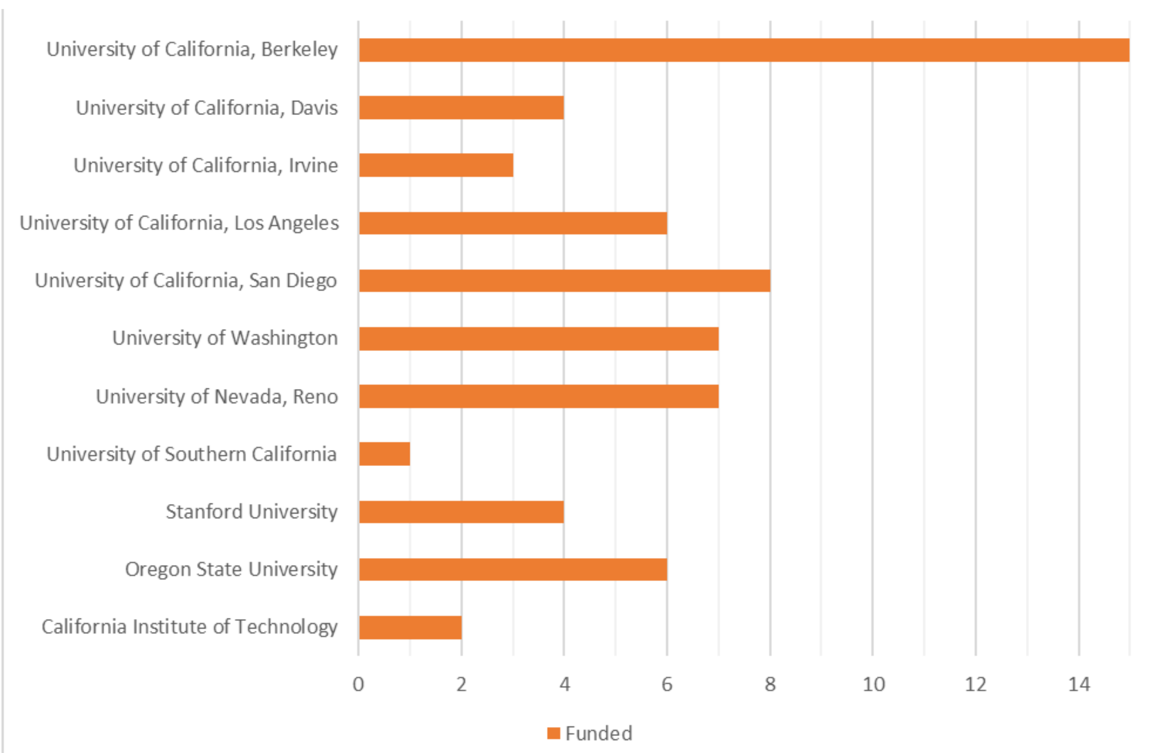


Figure A.8 Number of projects funded at each core institution

Figure A.9 shows the amount of funding sought through all proposals, and actually funded projects, across 21 topics. There is a substantial interest in two topics – new bridge systems and highly nonlinear elements & materials. Topic G4 (Site Characterization) received no funding from TSRP because of substantial work being done in the similar field in PEER's Lifelines program.

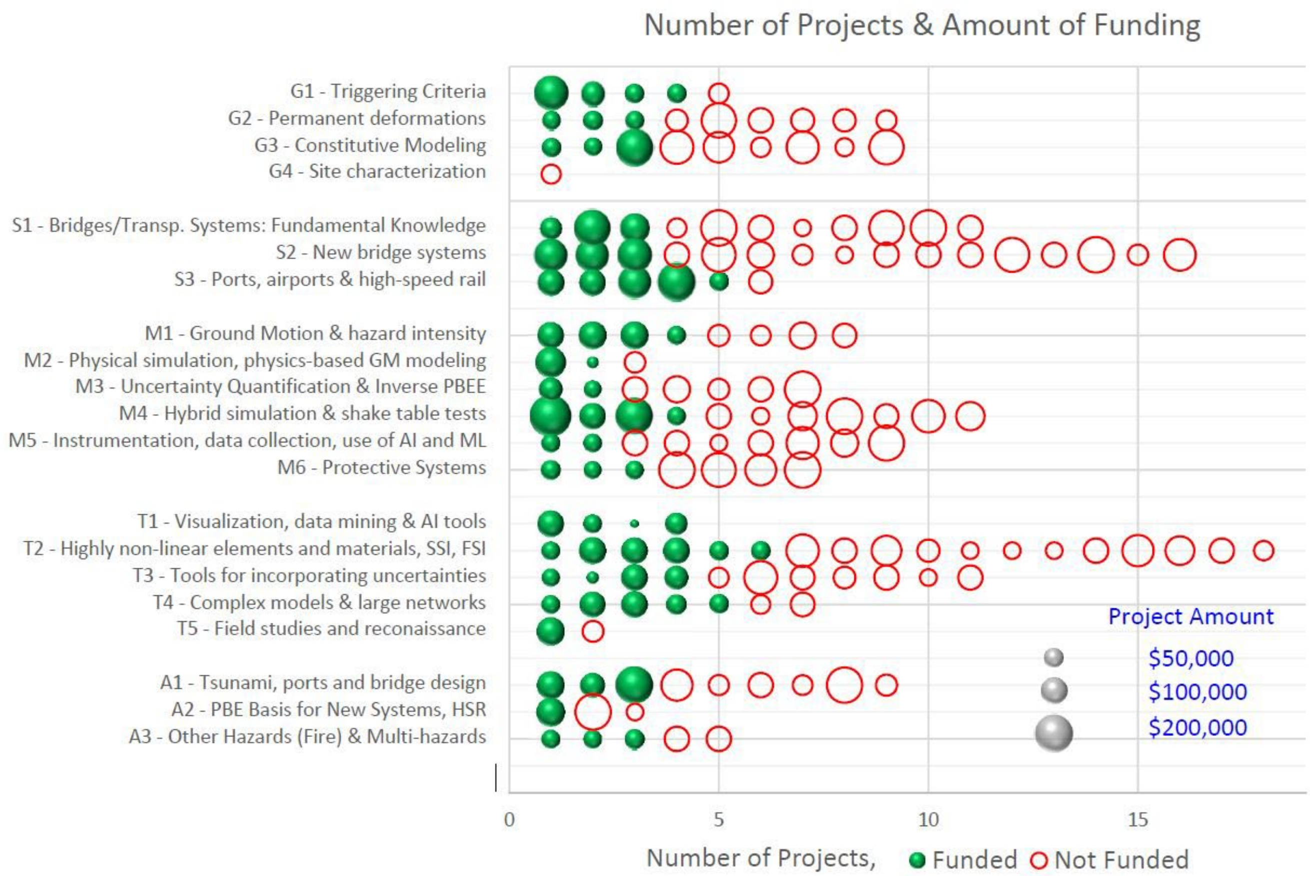


Figure A.9 Number of proposals and funded projects

There are several ways to look at the number of funded projects: by hazard type, by methodology, by infrastructure type, by PBEE phases, by the scale or by the type of uncertainty analysis. The following tables and plots help highlight the emphasis given to different types or projects and determine the gaps for future use.

Because of the Center's focus on Earthquake Engineering, all projects are connected to earthquakes (Table A.4). Of these, over 85% of the projects are directly related to the seismic work, with the rest split evenly between Tsunami research and Fires following the earthquakes.

Table A.4 Distribution of funded amount among different extreme events

Type of Extreme Event	No. of Projects	Amount
Earthquake	57	$5,096,268
Tsunami	4	$ 444,398
Fire Following EQ	4	$ 256,556
Total	**65**	**$5,797,222**

There has been a clear emphasis on the computational projects, followed by experimental in the past 65 funded projects (Table A.5). In recent years, there has been a growth in AI & ML related projects.

Table A.5 Distribution of funded amount among different methodologies

Methodology	No. of Projects	Amount
Theoretical	4	$ 292,941
Computational	39	$ 3,119,427
Experimental	15	$ 1,926,022
Database, Field Data, AI, ML	7	$ 458,832
Total	**65**	**$ 5,797,222**

The PBEE methodology has four phases: hazard, analysis, damage and loss. Of these, a significant amount of work was funded in the analysis phase and moderate funding for the other three phases (Table A.6).

Table A.6 Distribution of funding among different PBEE phases

PBEE Phase	No. of Projects	Amount
Hazard	11	$ 952,806
Analysis	34	$ 3,165,753
Damage	10	$ 843,975
Loss	9	$ 724,688
Total	**64***	**$ 5,687,222**

* One project (PBE for Tsunamis included all four phases

Uncertainty Quantification (UQ) is a primary focus of PEER research. Funded work so far has a near even split between deterministic and probabilistic (forward propagation) methods. Only one project focused on the backward propagation work (Table A.7).

Table A.7 Distribution of projects among UQ categories

Uncertainty Quantification	No. of Projects	Amount
Deterministic	27	$ 2,594,902
Probabilistic - Forward Propagation	37	$ 3,124,516
Probabilistic - Backward Propagation	1	$ 77,804
Total	**65**	**$ 5,797,222**

Because of the core research focus being the transportation resiliency, nearly 70% of the projects focused on bridges (Table A.8). There is a need to study resiliency of tunnels, airports and pipelines.

Table A.8 Distribution of projects among different infrastructure types

Infrastructure Type	No. of Projects	Amount
Building	8	$ 569,569
Bridge	42	$ 3,995,879
Highway	2	$ 145,017
Tunnel	0	$ -
Port	3	$ 360,006
Airport	0	$ -
HSR	2	$ 267,615
Pipelines	1	$ 104,490
Networks	2	$ 149,984
Total	**60***	**$ 5,592,560**

* Five projects (OpenSees, Wildfire, UAVs) span several infrastructure types

PEER Researchers work on a wide range of projects from microscale to regional or city-scale projects. Several projects are at component level, structural level, and regional scale (Figure A.9).

Table A.9 Distribution of projects across scale

Scale	No. of Projects	Amount
Microscale	2	$ 244,251
Material Level	3	$ 149,999
Component Level	12	$ 1,098,268
Structural Level	27	$ 2,445,762
Network	7	$ 520,644
Regional Scale	14	$ 1,338,298
Total	**65**	**$ 5,797,222**

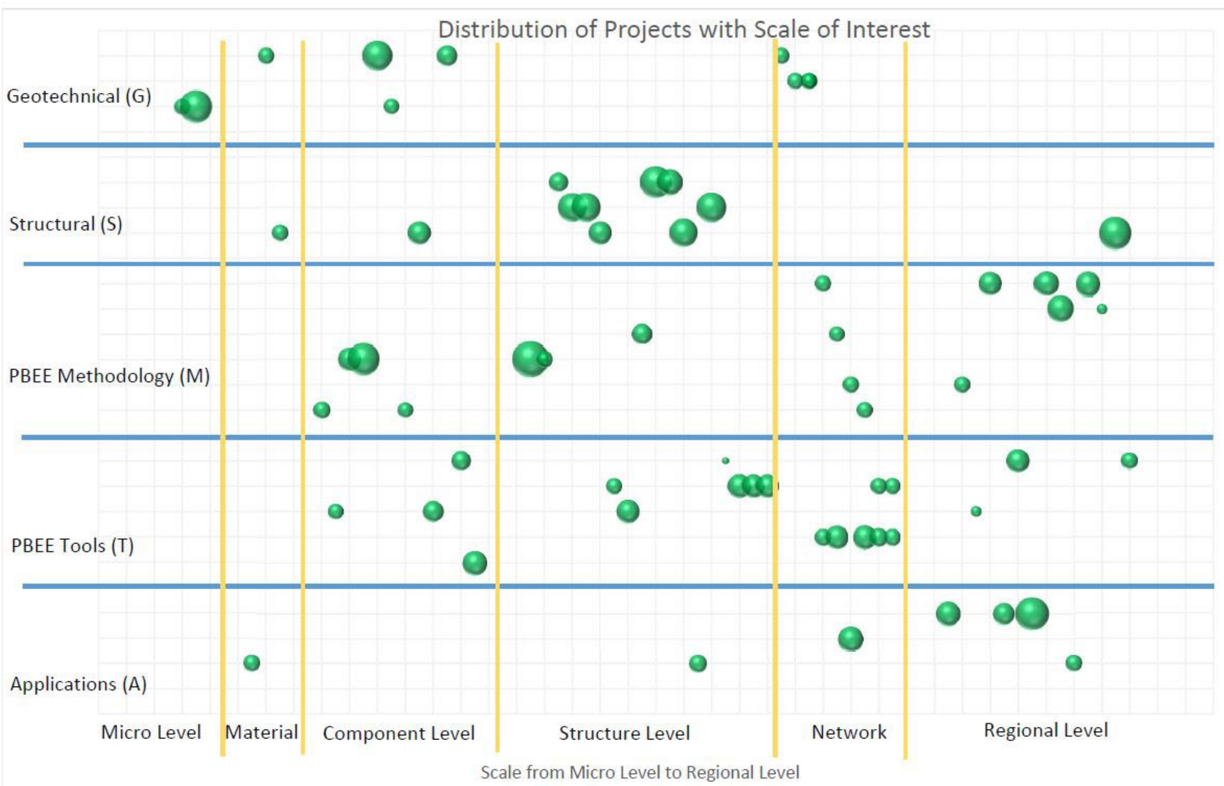


Figure A.10 Distribution of project across scale and thrust areas

As seen from Figure A.10, Structural Engineering (S) projects at Structural Level scale consist of bulk of the projects in number and funding. There is a need for more projects at Network level and Material level.

Reviewers

TSRP proposals are reviewed by three independent reviewers to assess the technical merit and broader impact of proposed research. Reviewers are chosen from a pool of researchers, who are not participating in that cycle of RFP and have no conflict of interest with the proposals they are reviewing. These reviews are vital for maintaining the quality of PEER-funded proposals. Moreover, constructive comments offered by the reviewers have been invaluable in helping PI's with their future proposals. We thank the following researchers for their support of PEER RFP process over the past 5 years.

Amit Kanvinde
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Judy Liu
Kenichi Soga
Koushil Sreenath
Marc Eberhard
Mark Mueller
Martin Neuenschwander
Michael Scott
Minjie Zhu
Mohamed Moustafa
Patrick Lynett
Pedro Arduino
Ramin Motamed
Reza Elsami
Sanjay Govindjee
Sashi Kunnath
Scott Brandenberg
Selim Günay
Shakhzod Takhirov
Sifat Muin
Steve Kramer
Tara Hutchinson
Tom Shantz
Yuqing Gao

Appendix B List of Sub-Award Projects 2016–2020

Fund Source	PI	Institution	Project Title
TSRP	Laura Lowes	UW	Calibration and verification of OpenSees models for simulating the response through collapse of nonplanar RC walls.
TSRP	Jack Baker	Stanford	Machine learning for analysis and risk management of complex infrastructure systems
TSRP	Raja Sengupta	UCB	Autonomous Drones for Inspection-driven Exploration of Structures
TSRP	Laura Lowes	UW	Calibration and verification of OpenSees models for simulating the response through collapse of nonplanar RC walls.
TSRP	Jian Zhang	UCLA	Implementation of Frequency-Dependent Impedance Function in OpenSEES
TSRP	John McCartney	UCSD	Prediction of Seismic Compression of Unsaturated Backfills
TSRP	Jason DeJong	UCD	A System-Level Study to Evaluate the Role of Soil Gradation on Seismically Induced Embankment Deformations
TSRP	Machel Morrison	UCSD	A Critical Examination of Material Strain Limits for Performance-based Seismic Design of Modern Pier and Wharf Structures
TSRP	Elnaz Seylabi	UNR	Deep learning based surrogate modeling for uncertainty quantification in soil-structure interaction problems
TSRP	Armin Stuedlein	OSU	Advancing the Practice of Cyclic Softening Assessments of Silts and Clays
TSRP	Gilberto Mosqueda	UCSD	Seismic performance of isolated bridges under extreme shaking
TSRP	Adda Athanasopoulos-Zekkos	UCB	Liquefaction evaluation of gravelly soils: An integrated laboratory testing and numerical modeling approach
TSRP	Tracy Becker	UCB	Correlation of ground motion duration with spectral acceleration and implications for expected bridge performance
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
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
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
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 (Tsunami)	Hong Kie Thio	URS Corporation	Performance Based Tsunami Engineering Methodology I (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 II (Tsunami Research Program)
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
PEER-Bridge	Khalid Mosalam	UCB	Bridge Rapid Assessment Center for Extreme Events (BRACE2)
PEER-Bridge	Lijuan "Dawn" Cheng	UCD	Refined Bridge Deck Design and Analysis
PEER-Bridge	Farzin Zareian	UCI	Statistical Variation of Seismic Damage Index (DI) of California Bridges
PEER-Bridge	Michael Scott	OSU	Advanced Guidelines for Stability Design of Slender Reinforced Concrete Bridge Columns

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, several consulting companies, and researchers at various state and federal government agencies contribute to research programs focused on performance-based earthquake engineering.

These research programs aim to identify and reduce the risks from major earthquakes to life safety and to the economy by including research in a wide variety of disciplines including structural and geotechnical engineering, geology/seismology, lifelines, transportation, architecture, economics, risk management, and public policy.

PEER is supported by federal, state, local, and regional agencies, together with industry partners.

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California Institute of Technology
Oregon State University
Stanford University
University of California, Davis
University of California, Irvine
University of California, Los Angeles
University of California, San Diego
University of Nevada, Reno
University of Southern California
University of Washington

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