

**GEORGE E. BROWN, JR. NETWORK
FOR EARTHQUAKE ENGINEERING SIMULATION**

NEES

**2004-2014
A DECADE OF EARTHQUAKE
ENGINEERING RESEARCH**



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Photo opposite: Education, Outreach, and Training event at the NEES at Buffalo site.

A Decade of Earthquake Engineering Research



Julio Ramirez
NEES Chief Officer
and NEEScomm Center Director

In November 1998, the National Science Board approved construction of the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) with funds totalling \$82 million from the National Science Foundation (NSF) Major Research Equipment and Facilities Construction appropriation.

Construction occurred during the period 2000-2004. As part of its contribution to the National Earthquake Hazards Reduction Program, the NSF funded NEES operations as well as many of the research projects that were conducted in NEES facilities.

In the ten years since officially opening its doors in 2004, NEES has provided a vibrant collaboratory consisting of unique experimental facilities and a cyberinfrastructure as its collaboration platform, NEEShub, representing hundreds of millions of dollars of investment. The NEES collaboratory has served tens of thousands of users from over 210 nations.

In 2009, Purdue University replaced NEES Consortium, Inc. (NEESinc) as manager of the network of 14 advanced laboratories and its supporting cyberinfrastructure. The NEES Community and Communications Center (NEEScomm) was established in West Lafayette, IN.

Participating universities included: University of California, Berkeley; University at Buffalo, State University of New York; Cornell University; University of California, Davis; University of Illinois, Urbana-Champaign; Lehigh University; University of California, Los Angeles; University of Minnesota; University of Nevada, Reno; Oregon State University;

Rensselaer Polytechnic Institute; University of California, San Diego; University of California, Santa Barbara; University of Texas at Austin.

Each of these university-based laboratories enabled researchers to explore a different aspect of the complex way that soils and structures behave in response to earthquakes and tsunamis. The laboratories were available not just to researchers at the universities where they are located, but to investigators throughout the United States who were awarded grants through NSF's annual NEES Research (NEESR) Program and other NSF programs. In fact, researchers located at colleges or universities remote from the NEES sites have led 80% of NEESR projects. The laboratories have also been used for research conducted or funded by other federal, state, and local agencies, by private industry, and by international researchers under the partnerships that NEES has cultivated with research facilities and agencies in Japan, Taiwan, Canada, and China.

In July 2010, NEEScomm released the first version of the NEEShub, the collaboration platform for NEES researchers. Linking the NEES experimental facilities to each other, to NEEScomm, and to off-site users, this unique cyberinfrastructure has enabled researchers participating on-site or remotely to collect, view, process, and store data from NEES experiments at the NEES-curated central repository, also known as the Project Warehouse. Using the NEES cyberinfrastructure, researchers conduct numerical simulation studies and perform hybrid (combined experimental and numerical) testing involving one or more NEES equipment sites.

At the heart of this system is NEEShub, a platform designed to facilitate information exchange and collaboration among earthquake engineering researchers, educators, students, practitioners, and stakeholders. Accessed via the NEES website, NEEShub is powered by HUBzero software developed at Purdue University.

Earthquakes and tsunamis can be devastating not only to the infrastructure of a society, but also to families, the community, and people's sense of security. To reduce the impact of these events, and to save lives, the NEES network originated as a national research infrastructure to enable innovation in earthquake and tsunami loss reduction, to create an educated workforce in hazard mitigation, and to conduct broad outreach and lifelong learning activities.

This mission for NEES aligns with the larger plan from the National Earthquake Hazards Reduction Program for earthquake and tsunami risk reduction. Research at NEES facilities has contributed to the advancement of understanding of seismic phenomena, such as the characteristics and effects of tsunamis and the potential for soil liquefaction. It has also strengthened our knowledge of how the built environment responds to earthquakes. NEES investigators have studied the responses of a variety of structures, from reinforced concrete columns used in buildings and bridges to wind turbines and port container cranes.

NEES projects have validated the improved seismic performance of bridge piers made with innovative polymer materials; of base-isolated designs for steel structures; of reinforced masonry shear-wall structures; and of retrofit techniques for nonductile, reinforced concrete frames with infill walls. New design methods have been developed for mid-rise wood-framed buildings, metal building systems, precast concrete floors, and reinforced concrete wall systems. NEES research has also produced new simulation tools and fragility data for nonstructural building systems.

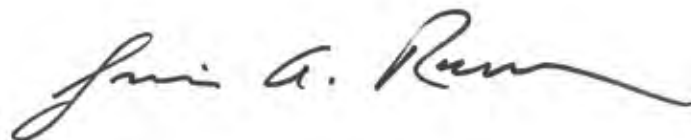
The impact of the NEES network has been felt on the development of future earthquake engineering researchers as well as practicing engineers. The network has supported the efforts of educators to build the workforce necessary to discover and implement research findings. NEES students learn earthquake engineering through involvement in research projects, undergraduates through NEES' annual Research Experiences for Undergraduates program, and graduate students by directly working with NEES investigators. In a recent survey, NEEScomm found that at least 559 graduate students, including 191 PhD candidates, have been trained through participation in NEES research.

Many of the projects conducted in the NEES laboratories have prompted, or laid the groundwork for, improvements in building codes, evaluation and design guidelines, and construction practices, enhancing societal resilience to earthquakes and tsunamis.

Many of those receiving PhDs now hold faculty positions at major research universities worldwide.

The community of NEES researchers, educators, and students encompasses a large group of universities, industry partners, and research institutions in the United States and abroad. This publication is meant as a sample of the breadth of the impact of the activities of researchers, students, educators, and practitioners collaborating in NEES. Already, more than 4,000 citations of NEES work bear testimony to the efforts of the NEES community. To date, more than 400 multi-year, multi-investigator projects have been completed or are in progress at NEES sites. These projects have produced a wealth of valuable experimental data and continue to produce transformational research and outcomes that impact engineering practice from analytical models to design guidelines and codes.

We invite you to explore some of the outcomes and impacts of a decade of earthquake engineering research and to try to envision the future impacts that these works may have yet to achieve.



Julio Ramirez
NEES Chief Officer and NEEScomm Center Director

“The most important step in the progress of every science is the measurement of quantities. Those whose curiosity is satisfied with observing what happens have occasionally done service by directing the attention of others to the phenomena they have seen; but it is to those who endeavor to find out how much there is of anything that we owe all the great advances in our knowledge.”

--James Clerk Maxwell, Scottish Physicist, 19th Century

As was elegantly stated by James Clerk Maxwell, experimentation and accompanying data sets have always been essential in research for the validation of models and theories, the identification of structural performance, and the improvement and development of systems and components.

A less obvious but perhaps more important reason for the growing significance of scientific data is the evolving multi-disciplinary nature of research. Advances in one discipline become critical for research in another area, and data are the mechanism to make those linkages quantitatively. Society benefits from an improved understanding of the performance of the built environment, which enables a better quality of life. Specifically, advances in earthquake engineering secure economies, protect human lives, and contribute to the resilience and sustainability of our communities.

For the past decade, the double focus of the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) has been simulation – physical, numerical and hybrid – and preservation of the resulting data.

This publication provides a window into the vibrant collaborative milieu in which dedicated researchers, educators, and professional staff endeavored to produce and preserve high-impact research. Review boards consisting of researchers and practicing engineers examined information about the hundreds of research projects conducted over the past ten years. After careful evaluation, the review boards selected the projects now presented in each section. We wish to express our deepest appreciation for the dedicated work of the members of the review boards, listed on the next page.

It is also our great pleasure to specially recognize the Principal Investigators who contributed to the project descriptions included in the publication. Each project description received approval by the corresponding project PI.

It is important to note that, for a given investigation, it typically takes years for impacts to be felt. As the advances in earthquake engineering continue, the influence of the entire NEES community will be recognized for decades to come, and undoubtedly, other, ongoing NEES projects will join the numbers of those described in these pages.

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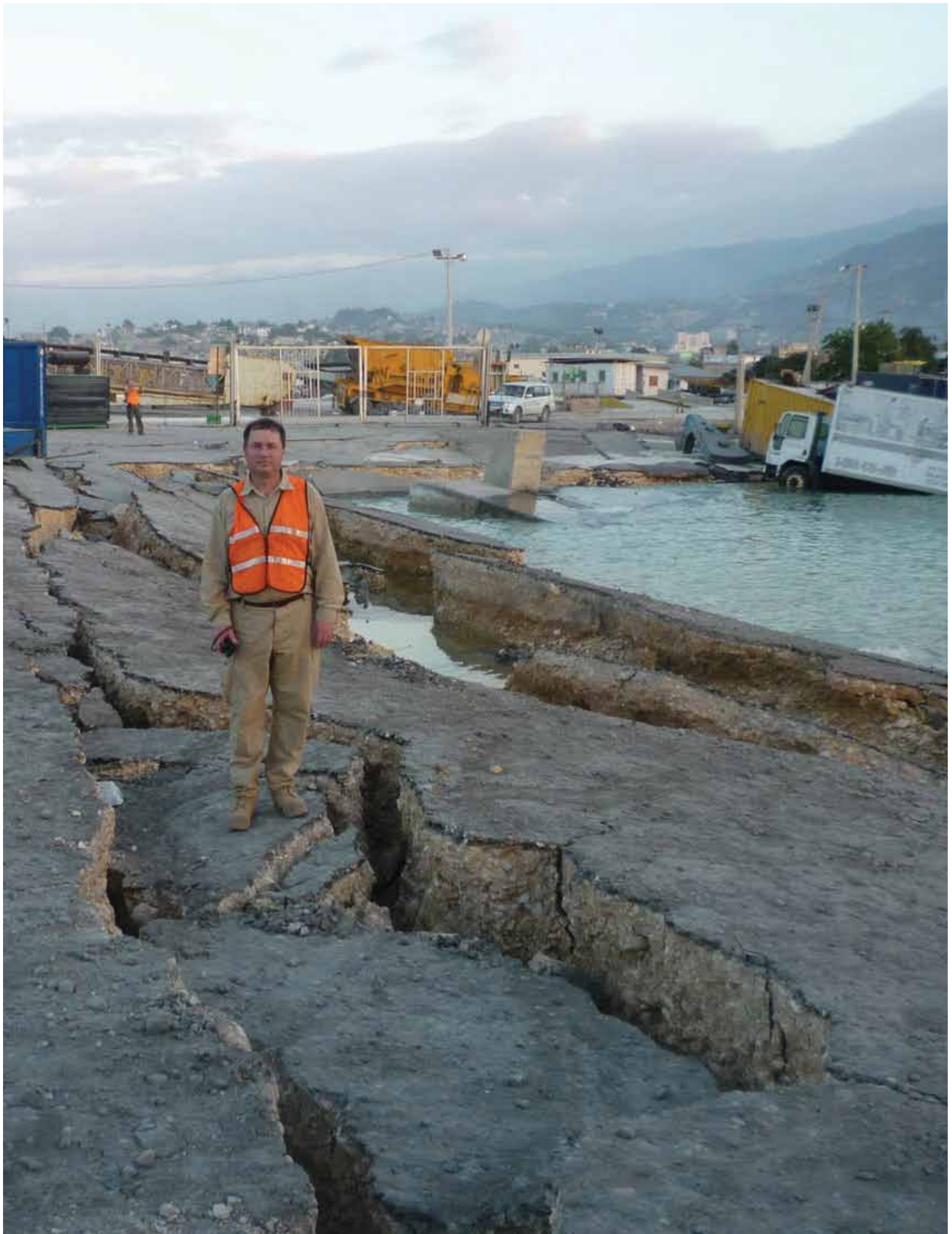
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1. GRAND CHALLENGES

In the 10 years since NEES officially opened its doors, the National Science Foundation has funded three NEESR Grand Challenge projects. Each of these projects focused on a compelling national infrastructure challenge in earthquake hazard mitigation that could only be addressed through significant use of NEES resources.

The Grand Challenge projects featured in this section have taken a comprehensive systems approach and engaged investigators from a range of disciplines to advance knowledge, innovation, and technology-transfer for earthquake hazard mitigation. This work addresses three critical areas of our infrastructure—port systems, vulnerable reinforced concrete buildings, and nonstructural systems.

The extensive use of NEES facilities and cyberinfrastructure resources allowed these researchers to test and collaborate in ways not possible before NEES. The projects involved significant and successful participation from external advisory boards of practicing engineers that helped formulate the research and technology-transfer strategy to expeditiously improve the resilience of our infrastructure.

Among the many impacts from the Grand Challenge projects, it is worth noting the invaluable contribution to workforce development through the training of more than 50 undergraduate and 50 graduate students.

These projects have also created a wealth of experimental data and metadata. This data is available to the public in the Project Warehouse at nees.org.

The following projects are profiled in this section.

First-Ever Seismic Risk-Assessment for Seaport Systems12

NEESR-GC: Seismic Risk Mitigation for Port Systems,
Glenn Rix, Georgia Institute of Technology

Research Identifies Killer Concrete Structures in Los Angeles.....14

NEESR-GC: Mitigation of Collapse Risk in Vulnerable Concrete Buildings,
Jack Moehle, University of California, Berkeley

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NEESR-GC: Simulation of the Seismic Performance of Nonstructural Systems,
Emmanuel Maragakos, University of Nevada, Reno

First-Ever Seismic Risk-Assessment for Seaport Systems

Comprehensive model examines losses based on property damage and business interruption

NEESR-GC: Seismic Risk Mitigation for Port Systems, Glenn Rix, Georgia Institute of Technology Research Corporation, NSF #0530478, NEEShub Project Warehouse #86, [2005]

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Educational Impact

Post-doctoral researchers: 2
Graduate research assistants: 25
High school students: 6
High school science teachers: 2
Undergraduate research assistants: 8

SELECTED RESEARCH PUBLICATIONS

Varun, Assimaki, D., and Gazetas, G.. "A simplified model for the lateral response of large diameter caisson foundations," *Soil Dynamics and Earthquake Engineering*, v.29, 2009, p. 268.

Taylor, C.E., Rix, G.J. and Liu, F.. "Exploring financial decision-making approaches for use in earthquake risk decision processes for ports," *Journal of Infrastructure Systems*, v.15, 2009, p. 406.

Jacobs, L.D., Kosbab, B.D., Leon, R.T., and DesRoches, R.. "Seismic behavior of a jumbo container crane including uplift," *Earthquake Spectra*, v.27, 2011, p. 745.

Gregory, R., Harstone, M., Rix, G. J., and Bostrom, A. "Seismic risk mitigation decisions at ports: multiple challenges, multiple perspectives," *Natural Hazards Review*, v.13, 2012, p. 88.

Howell, R., Rathje, E., Kamai, R., and Boulanger, R.. "Centrifuge modeling of prefabricated vertical drains for liquefaction remediation," *Journal of Geotechnical and Geoenvironmental Engineering*, v.138, 2012, p. 262.

Because seaports concentrate high commercial activity into such a small geographic area, these transportation hubs are particularly vulnerable to natural hazards. Damage caused by a natural or man-made disasters and the resulting business interruption has devastating and long-lasting economic consequences, as seen in Japan's Port of Kobe. After the 1995 earthquake, the port fell from the sixth largest container port in the world to the 55th in 2007.

IMPACTS

This NEES Grand Challenge project developed the first systematic and practical approach for managing seismic risk for container ports.

Specifically, Georgia Institute of Technology research engineer Glenn Rix and his multi-institutional research team built a comprehensive seismic risk analysis model that examines losses based on property damage and business interruption. The team's performance-based model allows port stakeholders to evaluate the benefit-cost analyses for investments in alternative seismic design and mitigation strategies, to prioritize port construction projects, to estimate losses from a seismic event, and draft new emergency response operations procedures. The model also can be used to assess non-seismic natural hazards and terrorism threats.

Importantly, the team thoroughly investigated and modeled how uplift response affects the seismic demands on port structures such as jumbo container cranes. The resulting computational model now serves as a foundation for practitioners to design and evaluate cranes based on seismic performance objectives.

Data from the project experiments were used to develop procedures to evaluate the seismic capacity and performance expectations of existing wharves. In addition, the research resulted in guidelines for port managers to determine the need for seismic retrofit or replacement of existing wharves.

Use of this new, real-time decision support model for ports minimizes the impact of natural and man-made disasters on American port systems. The data gathered is assisting in the development of new guidelines for the building and retrofitting of port systems.

OUTCOMES

Among the study's findings, wharf pile sections are found to be the components most vulnerable to extensive damage, typically caused by large deformation demands on the piles at the interface of loose and dense sand layers. Somewhat surprisingly, the wharf's landside rail is susceptible to slight and moderate, not catastrophic, damage.

Lastly, the fragility curves of the 3D wharf model exhibited larger probabilities of failure compared to the corresponding 2D model. Although not surprising, this finding demonstrates the usefulness of 3D port modeling, which includes longitudinal and torsional responses of the wharf and enables an accurate gauge of the port's responses.

RESEARCH METHODOLOGY

The seismic risk analysis framework comprised three steps. First, seismic hazard models were used to estimate ground motions at all port terminals. Next, the team used component fragility models to estimate the cost and time of port repair or reconstruction. Lastly, port operations models were used to calculate the system's fragility in terms of business interruption, the loss or delay in shipping traffic.

Large-scale earthquake simulation experiments were conducted at four NEES equipment sites: UC Davis, University of Texas at Austin, University at Buffalo and University of Illinois, Urbana-Champaign.

Pile-supported marginal wharves. Seismic activity can induce liquefaction under pile sections where loose and dense sand interface, a major cause of wharf damage. Field and centrifuge tests revealed that soils treated with colloidal silica effectively reduced pore pressure response and the shear strains induced when subjected to large dynamic loads. In addition, data showed that the installation of prefabricated vertical drains were highly effective in dissipating the excess pore water pressures.

Research on the seismic performance of precast/prestressed concrete pile-to-wharf connections at the University of Washington and University of Illinois, Urbana-Champaign resulted in alternative connection concepts and construction practices.

Container cranes. At the NEES at Buffalo facility, the team tested the seismic behavior of container cranes. Two large-scale experiments provided data confirming that a simple tipping analysis is sufficient to predict when derailment of a crane will occur, as well as indicating that torsional



1/20th scale crane on the shake table at the NEES at Buffalo facility.

responses seen in 3D models has little effect on the overall response of a jumbo container crane.

Unfortunately, the study's fragility models indicate that existing container cranes are not expected to achieve the seismic performance objectives of many ports. The team has developed performance-based design recommendations that enable practitioners to conveniently design for reliable achievement of seismic performance objectives.

Port operations. Using an optimization-based heuristic scheduling technique, the decision-making of terminal operators was simulated to determine how specific operations took place during periods of infrastructure disruption. Mitigation options that reduced repair times have the greatest effect in decreasing costs.

Decision-making under uncertainty. The team surveyed chief engineers at 126 North American seaports. Survey results showed that risk management and governance methods vary widely. Further, the majority of respondents at high-seismic-hazard ports say they have only informal or no seismic mitigation plans, and many report having no plans for conducting an assessment of seismic vulnerability.

Research Identifies Killer Concrete Structures in Los Angeles

Project improves seismic rehabilitation standards for concrete buildings constructed prior to 1976 and creates tools to support communities in developing mitigation strategies

NEESR-GC: Mitigation of Collapse Risk in Vulnerable Concrete Buildings, Jack Moehle, University of California, Berkeley, NSF #0618804, NEEShub Project Warehouse #637, [2006]

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 Julio Ramirez, Purdue University
 Santiago Pujol, Purdue University

Educational Impact

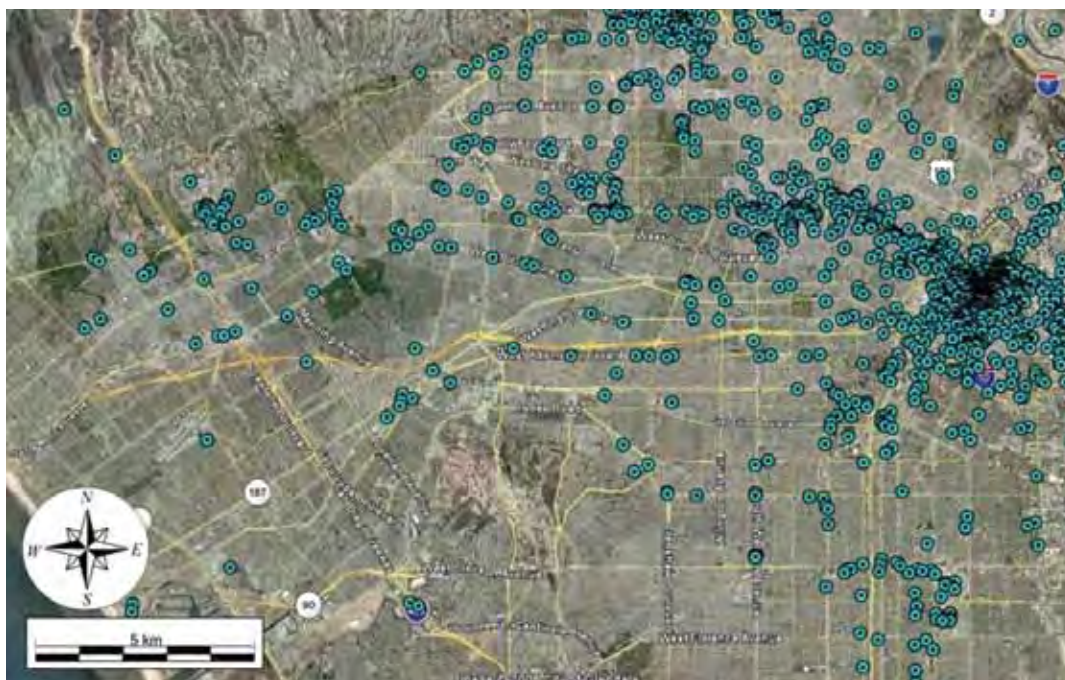
Graduate students: 17
 Undergraduate students: 33

Due to their high potential for collapse, older concrete buildings in urban areas pose one of the greatest risks in the event of an earthquake. Paradoxically, the large number of vulnerable, “killer” buildings means that mitigation costs can be prohibitive, so cities tend to delay instituting protective measures – a risky practice.

This NEES Grand Challenge project aimed to improve seismic rehabilitation standards for concrete buildings constructed prior to 1976 and to create tools to support communities in developing mitigation strategies. Professor Jack Moehle, a civil and environmental engineering researcher at the University of California, Berkeley, along with a multi-institutional team of researchers from San José State, UCLA, UC San Diego, the University of Kansas, Purdue University, the University of Washington, and UC Berkeley, studied the performance of these buildings when subjected to an earthquake.

IMPACTS

After conducting novel field and lab tests and developing innovative computational models, the team devised a practical approach for identifying buildings with a high potential for collapse. In close collaboration with the Applied Technology Council (ATC), the Pacific Earthquake Engineering Research Center (PEER), and the Earthquake Engineering Research Institute (EERI), through the Concrete Coalition, the project has been particularly effective in raising public awareness and prompting communities to evaluate their own risk and start planning for taking action.



Researchers completed an inventory of older concrete buildings in the City of Los Angeles using a variety of public data sets, Internet maps, streetscape technologies, sidewalk surveys and survey input.

Using more than 250 volunteers, the Concrete Coalition of engineers, architects, building owners, and public officials with a common interest in identifying high risk concrete buildings has conducted inventories in more than 30 California communities.

These counts have been combined with a regression model to estimate that there are 16,000-17,000 pre-1980 concrete buildings in the 23 highest seismicity and exposure counties of California. This is an important contribution to raising awareness of the scope of the nonductile concrete building issue.

Proof of the team's success is a detailed inventory of about 1,500 vulnerable buildings in Los Angeles, an outcome that has generated significant discussion and action toward mitigating this threat in our nation's second largest city.

Given the study's findings, Los Angeles' aggressive new plan to investigate earthquake safety has taken on a new urgency. The L.A. City Council is now looking into ways for financing the cost of inspecting and retrofitting at-risk buildings, including bond measures. Several occupied buildings that the team identified, including a school, are slated for immediate retrofitting.

OUTCOMES

The team's experiments, which took place at multiple NEES laboratories, provided valuable new data, innovative models and practical methods for evaluating the performance of concrete buildings.

One surprising finding was the strength of building corner connections – which previously were thought to be vulnerable. The novel joint and beam column models developed by Dr. Moehle and his team provide data on deformations at which shear failure initiates in columns and beam-column joints. Additionally, the research has improved the field's understanding of the drift at which axial failure occurs with these components. This study demonstrated the importance of modeling shear and axial failure, and presented a practical method for doing so.

Also, the lab and field tests of soil-foundation-structure-interaction (SFSI) provided new insights into the mechanisms controlling soil-structure interaction, insights that the ATC 83-10 project has drawn on in developing guidelines for integrating SFSI into analysis procedures for buildings.

In parallel with physical tests, the team developed and validated shear strength models that they used to make a progressive collapse analysis of existing nonductile concrete buildings. With data gleaned, the team has been able to confirm ASCE 41 standard recommendations as well as propose that the standard implement the study's shear strength and axial capacity models.

In collaboration with NIST (the ATC 76-5 Nonductile Concrete project) and FEMA (the ATC 78 Nonductile Concrete project) researchers began the effort to develop an improved class of fragility models for older-type concrete buildings, as well as a practical methodology for identifying collapse-prone buildings – which will enable cities to prioritize damage mitigation expenses.

Moehle's team completed a detailed inventory of about 1,500 older concrete buildings in the City of Los Angeles. The research team provided the list and a loss-estimate to the city, which directly led to an agreement between Los Angeles and the USGS for developing a mitigation program for the city's older concrete buildings.

RESEARCH METHODOLOGY

To develop their novel criteria for concrete building collapse risk, the team performed a series of large-scale experiments on building nonductile concrete components and subsystems reflective of construction practices prior to the mid 1970s.

Experiments looked into the seismic vulnerability of beam-column joints without transverse reinforcement, the collapse risk of reinforced concrete building columns, the response of concrete columns as they underwent cyclical lateral loads, and the performance of multi-panel beam-slab subsystems. Data from these experiments were used to inform the development of models to simulate the shear strength and flexibility of unreinforced beam-column joints.

In addition, researchers created a 1/5-scale test structure to represent a simple spread footing system and tested it under three different soil conditions to study how each soil type interacts with the structure. The first study was on a fixed base on the strong floor at the UCLA structures laboratory, the second used very soft soil on a poured slab at the NEES at UCSB Wildlife Array field site, and the third used soft soil on a poured slab at the NEES at UCSB Garner Valley field site.

Continued on page 162

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First Steps Toward Securing Resilient Nonstructural Systems

Data from this study about the seismic behaviors of nonstructural systems is leading to the development of new protective technologies and compelling public policy arguments for amending building codes and standards

NEESR-GC: Simulation of the Seismic Performance of Nonstructural Systems, Emmanuel Maragakakis, University of Nevada, Reno, NSF #0721399, NEEShub Project Warehouse #424, [2007]

Principal Investigator

Manos Maragakakis, University of Nevada, Reno

Co-Principal Investigators

André Filiatrault, University at Buffalo, SUNY
Steven French, Georgia Institute of Technology
Tara Hutchinson, University of California, San Diego
Bob Reitherman, CUREE

When we drop an electronic device, it might appear unhurt. But if we shake it and hear an unaccustomed rattle, we know it has suffered internal damage.

Similarly, after an earthquake, offices and other large buildings often remain structurally intact. However, in the United States, fully three-quarters of the earthquake-caused losses are due to damage in non-structural systems in buildings, components such as interior sprinkler pipes, wall partitions, and suspended ceiling systems. Nonstructural damage can render buildings unusable for weeks or months – leading to still more economic losses.

This NEES Grand Challenge is the first systems-level study designed to address this costly problem of nonstructural damage. A team at University of Nevada, Reno, led by E. “Manos” Maragakakis, Dean of Engineering at UNR, adopted an integrated approach in which both subsystem and system-level experiments were tested together in order to understand their interactions.



The capstone test at the NEES at University of Nevada, Reno facility. A full-scale, 2 story building filled with nonstructural components was subjected to earthquake motions.

IMPACTS

New data from this study about the seismic behaviors of nonstructural systems is leading to the development of new protective technologies, including isolation and damping devices that dissipate seismic input and protect the nonstructural components. The outcome of this project could lead to the use of small protective devices that are connected directly between the nonstructural and structural components as potential solutions. In piping systems these protective devices may be fluid viscous, viscoelastic, shape-memory-alloy, and wire-rope bracing struts.

Furthermore, the study provides compelling public policy arguments for amending building codes and standards. Data from the study, for example, prove that the cost of earthquake losses due to nonstructural damage is much larger than the cost of retrofitting existing nonstructural systems or implementing new design methods to reduce the damage.

The project's robust fragility database for components and sub-systems of the ceiling-piping-partition system is available for practitioners to use on the NEES cyberinfrastructure platform. Maragakis and his team have been working to incorporate their findings into a performance based framework such as ATC-58, a national rubric for developing modern, performance-based design procedures for new and existing buildings in order to make them more seismically resilient.

OUTCOMES

The team studied response and failure mechanisms of ceiling-piping-partition nonstructural subsystems and identified their limits and interactions. Resulting experimental data now populate a detailed database that will enable the development of reliable simulations of nonstructural components.

Additionally, simulation and visualization tools created by the team – now available on the NEEShub – will provide new methods for 3D modeling for researchers and practitioners.

The researchers have assembled robust fragility data for components and subsystems of the ceiling-piping-partition system, which can be used to characterize the fragility of the building system itself and develop fragility models. Some of the fragility data is expected to be incorporated into a performance based framework such as the ATC-58.

The team also developed recommendations for protective technologies that will greatly reduce seismic damage to nonstructural systems.

RESEARCH METHODOLOGY

In order to address the failures of nonstructural systems, Maragakis and his team conducted a systematic, six-year study of the behavior of ceiling-piping-partition systems during seismic events. They focused on identifying major failure mechanisms, quantifying how the failure affects critical facilities and metropolitan areas, and producing reliable simulation tools for predicting the behavior of nonstructural systems in future earthquakes.

Experimentation took place at the State University of New York at Buffalo and the University of Nevada, Reno—both NEES network sites. A payload project using the E-Defense shake table facility in Miki City, Japan, also took place in coordination with Japanese researchers.

At the Buffalo site, tests employed the facility's shake tables and Nonstructural Component Simulator (NCS). The earthquake simulations revealed several types of subsystem failure, including fractures in CPVC cemented joints and the vertical hanger pull-outs in piping systems, as well as connection failures in ceiling systems.

The capstone experimentation for the project took place at UNR, where a full-scale two-story building, filled with full-scale partitions, suspended ceilings, and sprinkler piping layouts, was subjected to earthquake motions. This set of experiments measured the response of nonstructural components as part of a system under large drifts and accelerations.

The unique facility at UNR allowed for full-scale experiments to be completed, using its three high-performance shake tables simultaneously.

The team developed methods for modeling ceiling, partition, and piping subsystems. Additionally, the team developed and refined a 3D model for ceiling systems using SAP software, and they used OpenSees simulation in order to develop a model of the test-bed structure prior to building it. The capacity to explain and predict the behavior of nonstructural systems in an earthquake using the new modeling systems is a result of comparing the models to data developed from the physical tests.

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2. STRUCTURES

For an earthquake engineer designing a building or bridge, the goal is to design a structure that achieves a specific level of performance following an earthquake.

For most structures, the desired level of performance is “collapse prevention,” such that building occupants are not injured and can safely evacuate the structure. However, for many buildings such as hospitals, fire stations, and other buildings that house emergency responders, and for bridges that are critical links in the transportation network, the desired level of performance following the earthquake is complete functionality.

Using laboratory testing and computer modeling, researchers seek to discover why structures fail and to establish limits of performance so as identify how best to improve design to prevent failures, reduce economic loss, and in special cases maintain service in the future. The following projects are profiled in this section.

Smart Materials Boost Seismic Performance of Bridges 20 NEESR-SG: Seismic Performance of Bridge Systems with Conventional and Innovative Materials, Mehdi Saiidi, University of Nevada, Reno	Impacts of Combined Loading on Bridge-Column and System Response..... 30 NEESR-SG: Seismic Simulation and Design of Bridge Columns under Combined Actions, and Implications on System Response, David Sanders, University of Nevada, Reno
Watershed Data Describes the Seismic Behavior of Concrete Walls 22 NEESR-SG: Seismic Behavior, Analysis and Design of Complex Wall Systems, Laura Lowes, University of Washington	Toward Seismically Safe Masonry: How the Data Stacks Up..... 32 NEESR-SG: Performance-Based Design of New Masonry Structures, Richard Klingner, University of Texas at Austin
New, Seismically Sound Foundation for Precast Concrete Buildings 24 GOALI: Development of a Seismic Design Methodology for Precast Floor Diaphragms, Robert Fleischman, University of Arizona	Advanced Testing Buttresses Braced-Frame Designs, Retrofits 34 NEESR-SG: International Hybrid Simulation of Tomorrow's Braced Frame Systems, Charles Roeder, University of Washington NEESR: Collaborative Developments for Seismic Rehabilitation of Vulnerable Braced Frames, Charles Roeder, University of Washington
Structural Design Creates Taller, Stronger Wood-Framed Buildings 26 NEESR SG: NEESWood: Development of a Performance-Based Seismic Design Philosophy For Mid-Rise Woodframe Construction (Capstone Test), John van de Lindt, Colorado State University NEESR-CR: NEES-Soft: Seismic Risk Reduction For Soft-Story, Wood Frame Buildings, John van de Lindt, Colorado State University	Full-Scale Testing Examines Nonstructural System Performance 36 NEESR-CR: Full-Scale Structural and Nonstructural Building System Performance During Earthquakes, Tara Hutchinson, University of California, San Diego
Strengthening Masonry Structures, Old and New 28 NEESR-SG: Seismic Performance Assessment and Retrofit of Non-Ductile RC Frames with Infill Walls, P. Benson Shing, University of California, San Diego NEESR: Seismic Performance and Design of Partially-Grouted Reinforced Masonry Buildings, P. Benson Shing, University of California, San Diego	NEES at UCLA Validates Seismic Retrofits for the LAX Theme Building 38 LAX Theme Building Retrofit, John Wallace, University of California, Los Angeles

Photo opposite: Testing bridge supports for the CABER project at the University of Nevada, Reno.

Smart Materials Boost Seismic Performance of Bridges

NEESR-SG: Seismic Performance of Bridge Systems with Conventional and Innovative Materials, Mehdi Saiidi, University of Nevada, Reno, NSF #0420347, NEEShub Project Warehouse #33, [2004]

Principal Investigator

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Co- Principal Investigators

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Ahmed Elgamal, University of California, San Diego
Gregory Fenves, University of Texas at Austin
Ian Buckle, University of Nevada, Reno
Filip Filippou, University of California, Berkeley

Educational Impact

Postdoctoral fellows: 4
Graduate students: 9
Undergraduate students: 5

IMPACTS

At the University of Nevada, Reno (UNR), engineering Professor M. Saiid Saiidi led a team that systematically examined seismic sustainability in bridges. The impact of the work is being felt today in Seattle. There, as part of the city's State Road 99 Alaskan Way Viaduct project, the Washington Department of Transportation is building a three-span bridge on-ramp using the "smart" materials evaluated and validated by this NEESR project, Seismic Performance of Bridge Systems with Conventional and Innovative Design, with subsequent, project-specific funding from the Federal Highway Administration's Innovative Bridge Research and Deployment program.

Specifically, the single-column piers of the SR-99 bridge incorporate the "superelastic" or "smart" materials confirmed seismically resistant by this study. Shape memory alloys are remarkable for their ability to "remember" and return to their original shape after deformation.

OUTCOMES

Using the shake tables at the NEES at UNR facilities, the research team proved the value of shape-memory alloys (SMAs) such as nickel titanium, of highly ductile engineered cementitious composites (ECCs), as well as of fiber reinforced polymer (FRP) tubes and fabrics in piers. The study's positive results have spurred the nation's first use of SMAs and ECCs in a highway bridge.

Although the initial cost of a bridge made of nickel titanium and ECC is about 3 percent higher than one built with conventional reinforced concrete, the increase in the initial cost of the "smart materials" bridge is negligible if one considers life-cycle cost. Not only does this new type of bridge require fewer repairs, in the event of a moderate-to-strong earthquake the bridge will remain open, a lifeline for emergency vehicles and other traffic. Upon success of the NEESR project, the National Academy of Sciences National Cooperative Highway Research Program is in the process of funding a project to develop design guidelines for resilient and earthquake-resistant highway bridge columns that utilize smart materials.

RESEARCH METHODOLOGY

The objective of the study was to develop and evaluate means for constructing bridges that would remain safe and serviceable after a quake. To do so, the research team investigated the seismic performance of three, large-scale, four-span bridge systems including the soil-structure effects at the footings and abutments. Soil-structure tests took place on the NEES at UC San Diego shake table facility. At NEES at University of Nevada, all three bridge models were subjected to modified 1994 Northridge earthquake ground motions, which were applied to each bridge model in ten runs with increasing amplitudes.

The team evaluated performance of components, bridge piers, and entire bridge systems in order to understand design implications. The tests with innovative materials in bridge piers set the stage for the next-generation of earthquake-resistant bridges by combining SMAs and ECCs in columns with built-in isolators and in post-tensioned columns. In order to comprehensively evaluate bridge models, researchers used the OpenSees software and calibrated analytical models in order to study important system parameters.

Testing prefabricated bridges in UNR's shake table lab provided a unique challenge. Although individual component tests had provided material and construction method performance data incorporated with structural elements at the microscopic level, in order to understand the effect of those components interacting within a system, entire bridges had to be tested.

The first model bridge was a conventional reinforced concrete bridge tested to failure. Conventional steel-reinforced concrete often used in bridge substructures is susceptible to damage even in moderate earthquakes.



Model of the project's four-span bridge with advanced details.

In addition, since they are typically cast-in place (CIP) they require a long construction or repair period. Road closures have far-reaching impacts, especially for repairs on CIP bridges. Using prefabricated bridge systems allows for accelerated bridge construction, vastly reducing the amount of time needed.

The second bridge model incorporated advanced materials and details in column plastic hinge zones; SMAs, such as nickel titanium alloys; polyvinyl fibers mixed with cement; and rubber materials in bridge columns.

The third model incorporated fiber-reinforced polymer (FRP) tubes and fabrics in piers, such as in glass FRP tubes and carbon FRP wrapping. In addition, the third bridge used segmental construction and precast columns, as well as steel pipe-pin connections and accelerated bridge construction (ABC) techniques. The incorporation of all of these details in a single bridge made it the first of its kind.

In testing the third bridge, researchers discovered that several of the methods used for ABC showed equivalent or better performance compared to the bridge constructed using CIP and standard construction. Pipe pin connections performed well, and the precast bent had similar performance to that of CIP in capacity and displacement. FRP jacketing and tubing was effective in reducing apparent damage even though the maximum resultant drift ratio of 9.3% was achieved under seismic loading. The use of FRP tube and post tensioning rods succeeded in reducing residual displacements. The columns showed no sign of damage in the FRP and no longitudinal reinforcements buckling. Despite high drift ratios, only minimal spalling of the concrete in the footing was observed. Minor cracking was initiated in the bent cap of the middle pier that turned into a wide crack by the end of testing. The research has helped researchers understand the self-centering characteristics of different column elements, which is in turn allowing for the incorporation of self-centering columns in order to reduce post-quake repairs.

To follow this pioneering study, Professor Saiidi and his team are investigating new ways to design sustainable,



View of the bridge after installation of superimposed mass.

earthquake-safe bridges. Through a research grant from the NSF Partnership for Innovation Program (PFI), Professor Saiidi has joined forces with four small businesses to develop smart bridge elements that are earthquake-resistant, resilient, and designed for deconstruction, a concept that is completely new in bridge engineering. As part of this project, Saiidi and researchers from Kyoto University in Japan are collaborating to develop smart bridge columns that utilize copper-based shape-memory alloys, which are substantially more cost-effective than nickel-titanium SMA, but which have yet to be explored. Also, through another research grant from the Federal Highway Administration Innovative Bridge Research and Deployment Program, Professor Saiidi has been developing new connection elements for SMA-reinforced bridge columns with optimized use of this material. And, in yet in another research project funded by the California Department of Transportation, Saiidi's investigations into the development of smart columns have been expanded to precast members for use in accelerated bridge construction in high seismic zones.

SELECTED RESEARCH PUBLICATIONS

Cruz, C., and M. Saiidi, "Performance of Advanced Materials during Shake Table Tests of a 4-Span Bridge Model," *Journal of Structural Engineering*, ASCE, Vol. 139, No. 1, January 2013, pp. 144-154.

Saiidi, M., A. Vosooghi, C. Cruz, S. Motaref, C. Ayoub, F. Kavianipour, and M. O'Brien, "Earthquake-Resistant Bridges of the Future with Advanced Materials," *Performance-Based Seismic Engineering- Vision for an Earthquake Resilient Society*, Bled 4, Lake Bled, Slovenia, Springer 2013.

Saiidi, M., Vosooghi, A., and Nelson, R. (2013). "Shake-Table Studies of a Four-Span Reinforced Concrete Bridge." *J. Struct. Eng.* 139, SPECIAL ISSUE: NEES 2: *Advances in Earthquake Engineering*, 1352-1361.

See the full list of publications resulting from this project at <http://nees.unr.edu/projects/4-span/publications>

Watershed Data Describes the Seismic Behavior of Concrete Walls

NEESR-SG: Seismic Behavior, Analysis and Design of Complex Wall Systems, Laura Lowes, University of Washington, NSF #0421577, NEES Warehouse Project #104 [2004]

Principal Investigator

Laura Lowes, University of Washington

Co-Principal Investigators

Dawn Lehman, University of Washington

Daniel Kuchma, University of Illinois, Urbana-Champaign

Jian Zhang, University of California, Los Angeles

Educational Impact

Graduate students: 12

Undergraduate students: 6

University of Washington Professor Laura Lowes led a landmark effort to discover vital, but heretofore missing data on the seismic performance of concrete walls. The research team, which included members from the University of Washington, the University of Illinois, Urbana-Champaign and UCLA, established the baseline seismic performance of modern, mid-rise, reinforced concrete structural walls. As an integral aspect of the project, the team developed the modeling tools and technologies necessary to advance performance-based design of these wall systems.

IMPACTS

Experiments conducted at the NEES at Illinois MAST-SIM laboratory provided extensive data characterizing the response, including damage characteristics, of modern slender concrete walls subjected to cyclic lateral loading. These data may be used by researchers and practitioners to advance numerical response models, damage-prediction models, design codes, and standards of practice.

The project's experimental data have led to recommended changes in design code. The team used the FEMA P695 method to evaluate current design procedures to desired seismic resiliency. One of the codes validated was the ACI 318, which mid-rise coupled walls must meet. In addition, the 10-story prototype was subjected to the ASCE 7-05 lateral load, and the 3-story test specimen was subjected to the loading protocol, which showed agreement between both global and local response. It was discovered that the maximum shear stress demands in the coupling

beams exceeded the nominal shear strength, but were less than the specified upper limit in ACI 318. The C-shaped walls were designed per ACI 318-08. The details of the planar wall were determined using ACI 318-05 21.7.2.3.

OUTCOMES

The completed and curated project, "Seismic Behavior, Analysis, and Design of Complex Wall Systems," provides design engineers a visual, repeatable method for quantifying the effects of seismic loading, resulting in improvements to building codes and safer, less damage-prone structures.

The work significantly improves existing models for discovering and understanding wall performance. Information now available includes high-resolution strain field data and digital crack maps. Numerical models are available for accurate simulations, including strength loss.

RESEARCH METHODOLOGY

The research employed laboratory testing and numerical modeling to advance understanding of the earthquake behavior and design of reinforced concrete (RC) walls and walled buildings.

To investigate behavior and develop data to advance simulation and design, eight RC wall specimens were tested using the NEES laboratory at the University of Illinois. Test specimens were one-third scale and represented the bottom three stories of a ten-story prototype planar, planar-coupled or C-shaped wall. All specimens were tested quasi-statically under axial loading and either unidirectional or bidirectional lateral loading. A large volume of experimental data was collected including load, displacement and deformation data, damage data, and video and still camera images.

Experimental data show the following:

- 1) Modern slender concrete walls have the potential to exhibit compression-controlled flexural failure, characterized by rapid strength loss, at relatively low drift demands.
- 2) The potential for compression-controlled flexural failure is exacerbated by increased compression demand resulting from high axial loads (rare), coupling of two walls (common in mid- to high-rise buildings with multiple elevators) or an asymmetric wall cross section (common in low- to mid-rise buildings).
- 3) Slender walls that exhibit significant loss of lateral load carrying capacity typically maintain moderate axial load carrying capacity.

Experimental data were used to develop fragility functions characterizing the likelihood of slender walls exhibiting a specific damage state given a specific level of earthquake demand. These fragility functions are included in the PACT software developed as part of the ATC-58 effort.

Numerical simulation was used also to investigate the earthquake response of RC walls and walled buildings. Experimental data were used to evaluate previously proposed wall models; results showed that existing models did not meet the objectives of accurate, reliable and computationally efficient simulation of response. Experimental data were used to develop a modeling procedure, employing beam-column line elements with fiber-type section models, that met the modeling objectives, including providing accurate simulation of wall response through failure. The model was validated using an extended data set.

The validated numerical model was used to investigate the earthquake response of walled buildings and advance seismic design procedures.

First, nonlinear analyses of code-compliant walled buildings indicated a likelihood of shear failure, which could be expected to result in rapid strength loss and possibly collapse, at relatively low seismic demand levels. To address this, a capacity-design procedure for shear was developed to ensure adequate shear capacity and minimize the likelihood of shear failure.

Second, nonlinear analyses of walls designed using the new shear-design procedure indicated the potential for nonlinear flexural response distributed over the height of the wall. Since a large volume of transverse reinforcement is required in regions where nonlinear action is expected, it is desirable to isolate nonlinear response to a relatively few known locations. It was found that methods proposed previously by others could be used to address this issue.

Third, the FEMA P-695 methodology was used to determine seismic performance factors for use in design of walled buildings; new factors are less than those used currently, indicating that current design methods are unconservative. Finally, numerical simulation was used also to show that foundation flexibility reduces the seismic demands on walled buildings due to the lengthening of the response period of the building and increased damping.

FUTURE

The results of this research effort motivated additional research to advance the design of concrete walled buildings, and the results of this research are being used by these new research teams.



C-Shaped Wall #3. This test was the final specimen in the project, which included seven prior tests at NEES at Illinois.

The results of experimental testing demonstrated the potential for modern ACI 318 Code-compliant walls to exhibit undesirable response modes. These results motivated additional experimental testing funded by NSF and NIST to investigate improved component design procedures. Results of numerical simulation demonstrated the potential for undesirable response modes and collapse risk in mid- to high-rise buildings subjected to typical earthquake ground motions. These results motivated NSF-funded research to investigate the earthquake response of tall concrete wall buildings subjected to severe earthquake demands resulting from subduction-zone earthquakes in the Pacific Northwest. The study of building response to subduction-zone earthquakes is employing the numerical models developed as part of this research effort.

SELECTED RESEARCH PUBLICATIONS

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Ji, J., Elnashai, A.S., and Kuchma, D.A., "An analytical framework for seismic fragility analysis of RC high-rise buildings" *Engineering Structures* 29(12): 3197-3209, 2007.

New, Seismically Sound Foundation for Precast Concrete Buildings

GOAL: Development of a Seismic Design Methodology for Precast Floor Diaphragms, Robert Fleischman, University of Arizona, NSF #0324522, NEEShub Project Warehouse #46, [2004]

Principal Investigator

Robert Fleischman, University of Arizona

Co-Principal Investigators

José Restropo, University of California, San Diego

Satyendra Ghosh, SK Ghosh Associates

Clay Naito, Lehigh University

Richard Sause, Lehigh University

Educational Impact

Graduate students: 8

Undergraduate students: 1

For earthquake engineers and builders alike, the 1994 Northridge, California, earthquake revealed foundational flaws in seismic design practices.

It's been estimated that the 6.7 magnitude quake caused \$25 billion in financial losses, including, surprisingly, severe structural damage to the floors of large, precast concrete buildings, such as the collapsed parking garage on the CSU Northridge campus.

This damage was unexpected, because in high seismic zones such as Los Angeles, precast concrete buildings were supposed to be protected by precast concrete slabs called floor diaphragms – which, when anchored to walls and other supports, enable buildings to resist the side-to-side, or lateral, movements induced by earthquakes. After Northridge, earthquake engineers began to question the safety of these diaphragms – which add to the time and cost of building construction.

Code changes were enacted, but research engineers and concrete industry experts alike understood that a new, comprehensive design procedure was needed to create more reliable – and affordable – precast diaphragms.

In 2003, a consortium of research engineers from the University of Arizona, the University of California, San Diego, Lehigh University, and industry experts from the Precast/Prestressed Concrete Institute (PCI) undertook the task. The study was led by University of Arizona Professor Robert Fleischman. Dubbed the DSDM (Diaphragm Seismic Design Methodology) project, the significance of the effort

is reflected by the sheer scope of the study and the number of public and private organizations involved.

In fact, a key aspect of the research was the close industry oversight. At the outset, the industry group worked with the researchers to establish the physical scope of the project. As the study progressed, the research and industry teams conferred regularly. The project's industry advisory team worked with code-writing bodies to move the results of the project into the design codes.

IMPACTS

Results of the study have radically affected seismic design practice and codes for precast concrete buildings in the United States and internationally.

Recommendations for diaphragm design were first published as part of the 2009 NEHRP recommended provisions for seismic design for new buildings, from the Building Seismic Safety Council (BSSC) TS-4, Federal Emergency Management Agency.

More recently, the Provisions Update Committee (PUC) of the Building Seismic Safety Committee (BSSC) convened an Issue Team, IT6, led by S.K. Ghosh, industry co-principal investigator. This team, whose membership included several of the researchers and industry task group, worked toward codification of the design methodology developed by the project. Among the accomplishments of this group, developed at the specific direction of the BSSC PUC, are:

- Proposal IT06-001 - 2014-01-27–Diaphragm Design Force Level, which was successfully balloted by the PUC for inclusion in the 2014 Provisions of ASCE7: Minimum Design Loads for Buildings and Other Structures, and includes aspects of the design methodology produced from this research project.
- Proposal IT06-002 - 2014-2-12 - Precast Concrete Diaphragm Design and was submitted for balloting to the National Earthquake Hazards Reduction Program (NEHRP) Provisions for the 2014 cycle.
- IT06 Resource Paper, Diaphragm Design: Current Practice, Past Performance and Future Improvements covering diaphragms of all major construction types, for inclusion in the Part 3 Appendix of the 2014 NEHRP Recommended Seismic Provisions.

The work has the potential to open up new markets for cost-effective and durable precast structures in regions of high seismic hazard. In fact, early adopter practitioners

in California have already implemented the new design procedures on several structures, including a new 400,000-square-foot dormitory complex.

OUTCOMES

With great success, the multi-university team employed the equipment, methods, and collaborative research tools provided by NEES to develop a new design methodology for precast concrete diaphragms.

The team used full-scale experiments, including hybrid testing at NEES at Lehigh and shake table testing at NEES at UCSD, to create and calibrate new research tools for investigating precast diaphragms, including 2D and 3D nonlinear static and dynamic computer analytical models. These calibrated models were used by the project to determine the design factors for the new seismic design procedures for precast diaphragms.

The project unearthed new knowledge about the seismic performance of precast concrete floor diaphragms, including the following:

- A new understanding of the stiffness, strength, and deformation capacity of existing and new precast diaphragm reinforcement.
- New data on the internal force paths occurring in precast diaphragms, and the relationship between global and local deformation demands in precast diaphragms.
- An understanding of the relationship between diaphragm design strength and inelastic deformation demand on the precast diaphragm reinforcement for a given level seismic hazard.
- New insight on the anticipated inertial forces occurring in precast diaphragms under the design basis earthquake, or DBE, the earthquake that the structure is required to safely withstand with repairable damage, in terms of maximum values and vertical profile.
- Knowledge of the anticipated inelastic force demands occurring in the maximum considered earthquake, or MCE, in terms of maximum values and profile in plan.
- A firm understanding of the magnitude of diaphragm-amplified gravity system drifts for a given level of diaphragm flexibility.
- These findings led to a new comprehensive seismic design methodology for precast concrete diaphragms, currently in the codification process. Project team members have made over three dozen presentations nationally at conferences, workshops and webinars, and seven international presentations.



Half-scale shake table test at the NEES at UC San Diego facility.

RESEARCH METHODOLOGY

With its goal of developing an industry-endorsed seismic design methodology for precast concrete diaphragms, the DSDM project team devised a plan to gather data and advance knowledge at three levels of resolution: (1) the local characteristics of the reinforcing (connector) details; (2) the behavior of the diaphragm itself, specifically its force-paths and deformation demands; and (3) the dynamic response of the structural system, which included diaphragm inertial forces and diaphragm deformation-induced interstory drifts.

Continued on page 162

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- Belleri, A., Schoettler, M. J., Restrepo, J. I., & Fleischman, R. B. (2014). Dynamic behavior of rocking and hybrid cantilever walls in a precast concrete building. *ACI Structural Journal*, 111(3), 661-672.
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- Schoettler, M. J., Belleri, A., Zhang, D., Restrepo, J. I., and Fleischman, R. B., "Preliminary Results of the Shake Table Testing of a Three-Story Precast Building in Support of the Development of a Diaphragm Seismic Design Methodology," *Precast/Prestressed Concrete Journal*, Vol. 53, n6, Nov./Dec. 2008.

Structural Design Creates Taller, Stronger Wood-Framed Buildings

NEESR SG: NEESWood: Development of a Performance-Based Seismic Design Philosophy For Mid-Rise Woodframe Construction (Capstone Test), John van de Lindt, Colorado State University, NSF #0529903, NEEShub Project Warehouse #138 and 895, [2005]

NEESR-CR: NEES-Soft: Seismic Risk Reduction For Soft-Story, Wood Frame Buildings, John van de Lindt, Colorado State University, NSF #1314957, NEEShub Project Warehouse #934, [2012]

Because wood-framed structures are less expensive than those made with steel and concrete, homes and low-rise structures, buildings up to four stories, are commonly framed in wood. In earthquake-prone regions, however, building codes have traditionally excluded wood-frames for mid-rise buildings, structures five to seven stories high. Another problem for older wood-frame buildings is the seismically dangerous “soft story” construction in which the bottom floor of a multi-story building lacks supports to transmit shear and lateral forces.



Andre Filiatrault of UB (right) and Michael Symans of Rensselaer Polytechnic Institute tested seismic dampers in a full-scale wood-frame house in UB's Structural Engineering and Earthquake Simulation Laboratory.

Armed with questions about the apparent vulnerability of soft-story and mid-rise wood-frame structures, as well as ideas for securing them, Colorado State University professor Dr. John van de Lindt has led two landmark studies that have pitched wood-frame design and retrofit practices into the 21st century.

With the “NEESWood” and “NEES-Soft” studies, Dr. van de Lindt and his teams have had a profound impact on the way engineers think about wood-frame engineering and retrofitting -- in the United States and around the world.

IMPACTS

Commencing in 2005, the NEESWood study resulted in the development of a performance-based seismic design (PBSD) philosophy for mid-rise wood-framed buildings.

For the first time, PBSD analysis techniques allowed engineers to design buildings and explicitly consider performance. The NEESWood shake tests conducted at the University at Buffalo benchmarked current construction early in the project and the E-Defense shake table NEESWood test program in Miki City, Japan, validated the team's PBSD philosophy and showed that mid-rise wood-frame buildings are viable alternatives in seismic zones.

Thanks to the NEESWood experimentation, the contribution of drywall to the strength and stiffness of wood-frame buildings is understood.

Continued on page 162

SELECTED RESEARCH PUBLICATIONS

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van de Lindt, J.W., S. Pei, S.E. Pryor, H. Shimizu, and H. Isoda. (2010). “Experimental Seismic Response of a Full-Scale Six-Story Light-frame Wood Building,” *ASCE Journal of Structural Engineering*, 136(10), 1262-1272; American Society of Civil Engineers Raymond C. Reese Research Prize.

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S. Pei and J.W. van de Lindt. (2009). “Coupled Shear-Bending Formulation for Seismic Analysis of Stacked Shear Wall Systems,” *Earthquake Engineering and Structural Dynamics*, 38 (2009), 1631-1647.



Andre Filiatrault, center, UB civil engineering professor, discusses construction progress on the NEESWood project while standing in the "dining room."

NEESWood

Principal Investigator

John W. van de Lindt, Colorado State University

Co-Principal Investigators

Rachel A. Davidson, University of Delaware
 Andre Filiatrault, State University of New York at Buffalo
 David V. Rosowsky, University of Vermont
 Michael D. Symans, Rensselaer Polytechnic Institute

Educational Impact

Post doctoral scholars: 2
 Graduate students: 5

Due to the paucity of data about the seismic performance of mid-rise wood-frame buildings and fire requirements, building codes typically limit such structures to four or five stories.

In the NEESWood project, Professor van de Lindt and a team of researchers from five U.S. universities set out to provide engineering data and analytical support for safely increasing the height of light-frame wood buildings to six stories.

In 2006, a full-scale shake test of a two-story townhouse at the NEES at Buffalo facility provided valuable data on seismic performance of existing wood-frame buildings, interior and exterior wall finish materials, and passive protective systems.

Next, the team spent several years in numerical model research, developing and refining their new performance-based design philosophy that now provides a logical, economical basis for the design of mid-rise wood-frame construction.

In 2009, the project culminated with the test of a full-scale, wood-frame condominium on the world's largest shake table at the E-Defense facility in Miki City, Japan. This was possible due to a memorandum of understanding signed between Japan's Ministry of Education, Culture, Sports, Science and Technology and NSF,

NEES-Soft

Principal Investigator

John W. van de Lindt, Colorado State University

Co-Principal Investigators

Wei Chiang Pang, Clemson University
 Xiaoyun Shao, Western Michigan University
 Michael D. Symans, Rensselaer Polytechnic
 Mikhail Gershfeld, Cal Poly – Pomona

Educational Impact

Graduate students: 6
 Undergraduate students: 6

Historically, low-rise wood-frame structures have fared well in earthquake-prone regions. However, soft-story wood-frame buildings are particularly vulnerable to earthquake damage and tend to be, in general, older buildings that do not satisfy current design code requirements. The building's "soft" story is a first floor, often functioning as an open garage or commercial space. The open space and its lack of lateral stiffness and strength render such structures prone to collapse.

At the NEES at UC San Diego facility, the team tested a full-scale, four-story soft-story building based on the typical design of homes built prior to 1920 in California. The work on UC San Diego's outdoor shake table provided fundamental data on the collapse mechanisms for soft-story buildings, and project experiments validated the FEMA P-807 retrofit procedure as well as the performance of seismic protection devices for retrofitting soft stories.

At the NEES at Buffalo site, through a combination of full-scale testing and computer modeling, the top two stories of a three-story building were pushed to the collapse limit, while software was used to simulate the soft story. The simulation allowed researchers to vary the amount of modification to the structure to determine the optimum amount of retrofitting needed in the first floor to protect the upper floors from collapse and control damage.

The experiment showed, among other findings, that structural walls with gypsum wallboard improve the seismic response of the building.

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Strengthening Masonry Structures, Old and New

NEESR-SG: Seismic Performance Assessment and Retrofit of Non-Ductile RC Frames with Infill Walls, P. Benson Shing, University of California, San Diego, NSF #0530709, NEEShub Project Warehouse #422, [2005]

Principal Investigator

P. Benson Shing, University of California, San Diego

Co-Principal Investigators

Jose Restrepo, University of California, San Diego

Sarah Billington, Stanford University

Kaspar Willam, University of Colorado at Boulder

Siva Mettupalayam, University at Buffalo, SUNY

Educational Impact

Graduate students: 4

Undergraduate students: 3

Masonry infill walls are often treated as non-structural elements in the design of older reinforced concrete frame buildings, and yet masonry often plays a major role in the amount of earthquake damage a building suffers and in the actual seismic performance of a building's frame. Many such older constructions exist on the West Coast, and they are still very common in new buildings in the rest of the country as well as in many earthquake-prone regions around the world. Outside the West Coast, most of the modern reinforced masonry structures are partially grouted. They normally do not perform as well as fully grouted masonry under seismic forces, and their seismic vulnerability has been a concern because some of these regions could have severe seismic events even though the likelihood is low.

Two studies led by P. Benson Shing, professor of Structural Engineering at the University of California, San Diego have resulted in techniques for retrofitting older reinforced concrete buildings with masonry infill walls and for securing the seismic safety of newer, partially grouted reinforced masonry buildings.

IMPACTS

These investigations have resulted in techniques to assess and improve the seismic performance of these structures and to facilitate the restoration and reinforcement of historic and modern buildings in the U.S. and around the world, and they are contributing to the continued use of masonry construction as a seismically safe, economically competitive, and sustainable building technique.

One of Professor Shing's former graduate students, Andreas Stavridis, is now assistant professor in the Department of Civil and Environmental Engineering at the State University of New York at Buffalo. His expertise is earthquake engineering. Another former graduate student, Ioannis Koutromanos, is now assistant professor in the Department of Civil and Environmental Engineering at Virginia Tech. His expertise is earthquake engineering and computational modeling of structures.

SECURING OLDER STRUCTURES

Many older reinforced concrete (RC) and steel frame buildings have unreinforced masonry infill walls that serve as interior and exterior partitions. Infill walls typically appear as a wall of brick between concrete columns. This construction technique was particularly prevalent in pre-1930's buildings on the West Coast of the United States, and currently is common practice in Central and South America, China, and parts of the Mediterranean world.

In an earthquake, these unreinforced masonry walls, if not properly constructed and installed, can cause severe damage to the building's frame, often resulting in catastrophic failures. Close examination of earthquake damage to RC framed buildings has revealed the cracking and crushing of infill walls and shear failures of the columns.

In an effort to facilitate the retrofit of these structures and prevent such failures, Professor Shing and his team assessed the seismic performance of non-ductile RC frames with unreinforced masonry walls and used the resulting data to develop the first-ever, reliable analytic methods for assessing the behavior of existing masonry-infilled RC frame structures. The research team included researchers from the University of California, San Diego, Stanford, and the University of Colorado at Boulder.

Further, the team developed an effective, inexpensive retrofit technique using an engineered cementitious composite (ECC) overlay on unreinforced masonry infill walls. The retrofit scheme and analytical tools were validated with experimental data obtained from small- and large-scale frame specimens representing 1920-era construction in California.

The simplified assessment techniques developed in this project for infilled frames have been adopted by ASCE 41-13, the American Society of Civil Engineers building code standards for improving seismic performance of existing buildings. The techniques address solid infill panels and

modification for openings. However, certain aspects, such as acceptable drifts, have not changed from previous editions, indicating that further research is required.

OUTCOMES AND METHODOLOGY

The project's experiments, which took place at Stanford University, the University of Colorado at Boulder, and UC San Diego, provided the data required to validate the team's analytical models and retrofit methods. Now researchers and design engineers can use the analytical methods to study the performance of similar types of masonry-infilled frame construction, including those with different structural configurations -- such as a different number of stories.

Quasi-static tests were conducted at Stanford University on four 1/5-scale, single-story, single-bay, masonry-infilled RC frames, and researchers evaluated the effectiveness of different retrofit details with an ECC overlay. Quasi-static tests were also conducted at the University of Colorado at Boulder on six 2/3-scale, single-story, single-bay, masonry-infilled RC frames to evaluate the influence of window and door openings on the performance of an infilled frame.

Some of the specimens were retrofitted with an ECC overlay. The third type of tests, shake table tests, were conducted at UC San Diego on two 2/3-scale, three-story, two-bay, masonry-infilled RC frames, one without retrofitting and the other with one infill wall at the bottom story strengthened with an ECC overlay and the walls on the second story strengthened by a Glass Fiber Reinforced Polymeric overlay.

The shake table specimen performed better than expected, showing that infills can actually improve the performance of non-ductile frames if the infill is of good quality and there are no irregularities, discontinuities, and asymmetries in placing infill walls.

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Evaluating Partially Grouted Masonry Construction

NEESR: Seismic Performance and Design of Partially-Grouted Reinforced Masonry Buildings, P. Benson Shing, University of California, San Diego, NSF #1208208, NEEShub Project Warehouse #1160, [2012]

Principal Investigator

P. Benson Shing, University of California, San Diego

Co-Principal Investigators

Ahmad Hamid, Drexel University

Franklin Moon, Drexel University

Arturo Schultz, University of Minnesota

Educational Impact

Graduate students: 3

Undergraduate students: 3

IMPACTS

In another current study, Professor Shing and a collaborative team from UC San Diego, Drexel University, and the University of Minnesota are investigating the seismic safety of partially grouted masonry walls.

In the United States, almost all masonry construction outside the West Coast uses partially grouted walls, which are structural walls in which only the reinforced hollow concrete masonry units are filled with grout to bond the reinforcing steel to the masonry. It's an inexpensive approach in that it requires less grout, but the seismic performance of partially grouted reinforced masonry wall systems is not well understood and is perceived to be not as good as fully grouted masonry normally used on the West Coast.

In fact, current code provisions for partially grouted masonry walls have not been satisfactorily validated by experimental data and could over-estimate the seismic resistance of this type of building. Furthermore, the lack of adequate data and design provisions, especially as compared to other construction materials, has led to a steady decline in the use of reinforced masonry in many parts of the country.

The goal of this project is to develop economically competitive design details and retrofit methods that will improve the seismic performance and safety of these structures – and revitalize masonry construction.

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Impacts of Combined Loading on Bridge-Column, System Response

NEESR-SG: Seismic Simulation and Design of Bridge Columns under Combined Actions, and Implications on System Response, David Sanders, University of Nevada, Reno, NSF #0530737, NEEShub Project Warehouse #71, [2005]

Principal Investigator

David H. Sanders, University of Nevada, Reno

Co- principal Investigators

Abdeldjelil DJ Belarbi, University of Houston

Shirley Dyke, Purdue University

Amr Elnashai, University of Illinois, Urbana-Champaign

Jian Zhang, University of California, Los Angeles

Pedro Silva, George Washington University

Educational Impact

Graduate students: 19

Undergraduate students: 15

In an earthquake, combined actions and loadings can have a significant effect on the force and deformation capacity of reinforced concrete columns, resulting in unexpected large deformations and extensive damage that weaken the performance of bridges – which are vital components of a nation's transportation infrastructure as well as lifelines during disasters.

These complex effects should be considered in earthquake analysis and in the design of bridges to mitigate significant earthquake damage and disruption of transportation systems.

IMPACTS

Professor David Sanders of the University of Nevada, Reno (UNR) led a multi-institutional study to discover and analyze the complexities of earthquake loading on bridge columns.

The ambitious project was called Seismic Simulation and Design of Bridge Columns under Combined Actions, and Implications on System Response, or "CABER." "CABER" stands for "Combined Actions on Bridge Earthquake Response." Over the course of the investigation, the team developed fundamental knowledge about the impact of combined actions on column performance and system response. The CABER project also established analysis procedures for determining the performance of columns under complex loading.

The team utilized a column-loading system that enabled torsion to be applied while laterally loading the columns. It also developed a bidirectional mass rig for the shake tables at NEES at UNR that could use concentric and eccentric mass as well as variable axial-load and compensation for large deformations (P-delta) and restoring forces. At NEES at the University of Illinois, Urbana-Champaign, a 4-span curved bridge hybrid experiment was conducted where three single-column bents were loaded physically (two large-scale columns and one small-scale column).

Purdue University led the educational, outreach and training (EOT) program for the CABER project. Modules were developed for K-12 teachers and professors for use in STEM-related courses. The modules were used by the research team in summer camps, visits to local elementary, middle and high schools, and in undergraduate and graduate courses. Specific programs were targeted towards underrepresented groups.

An inquiry-based "virtual experiment" was developed to teach students the implications of numerical modeling assumptions on structural behavior analysis. Numerical data calculated with OpenSees is directly compared to experimental data to observe hysteretic structural behavior of reinforced concrete columns and investigate the implications of modeling assumptions. This tool uses the cyber-infrastructure capabilities offered by NEES.

OUTCOMES

The CABER project was driven by both analytical and experimental research. The project developed a large number of physical tests that were used to calibrate the analytical models. The physical experimental data are available in the NEES data repository.

Analytical models were then used to study the impact of complex loads on individual columns as well as on system response. In addition to understanding system behavior, the project also developed a tool that is being implemented within OpenSees that can consider the interaction of moment, shear and torsion.

RESEARCH METHODOLOGY

The experimental program included quasi-static testing, shake table testing and hybrid testing. The NEES-funded experimental program included work at Missouri University of Science and Technology (MUST), the NEES facility at University of Illinois, Urbana-Champaign (UIUC), and the NEES facility at UNR. Analysis was conducted at NEES at UC Los Angeles, UIUC, University of Houston (UH), and UNR.



Project PI David Sanders (right) inspects a column specimen at the NEES at University of Nevada, Reno facility.

The education outreach program was the project focus at Purdue University.

Testing at the NEES at Illinois site consisted of large-scale experiments, small-scale experiments and the multiple-column curved bridge experiment. The large scale experiments consisted of two specimens which were hybrid analytical-experimental simulations used to verify the effects of vertical motion on pier loading and behavior, and two specimen tests which were conducted to directly compare pier responses under tension to pier responses under compression.

In the second phase, 37 small-scale tests were used to extend on the findings of the large-scale tests and to fortify the experimental database. The large number of tests enabled extensive investigation into axial loading patterns and their possible effects. Five of the small-scale tests investigated the influence of scale and verified the small-scale studies, while the other 32 investigated the influence of axial loading cycle amplitude. Researchers found that high levels of constant or coincident compression resulted in increases in demands that were unmatched by any increases in capacity, resulting in brittle shear-axial failures.

The third phase at Illinois was led by George Washington University and included researchers from UIUC and UH. The experiment was ground-breaking as it combined to two large-scale experimental columns and one small-scale experimental column in a 4-span curved bridge hybrid simulation. The experiment was very successful in showing the interaction between individual column performance and system behavior.

Analytical studies at NEES at Illinois investigated the effect of vertical ground motion on RC bridges, taking various geometric configurations into account. A bridge structure damaged in the Northridge Earthquake and a Federal Highway (FHWA) bridge design were analyzed in both vertical and horizontal tests and compared to horizontal-only tests.

Analytical modeling at the University of Houston included the development of a finite element that includes the simultaneous effect of moment, shear and torsion. The problem was solved through a system of equations that combine equilibrium and compatibility conditions, and constitutive laws of the materials at the section and structural level. The element is now being implemented in OpenSees, a state-of-the-art computational modeling tool.

At the MUST facility, the experimental investigation included 14 circular RC columns under various Torsion/Moment (T/M) ratios and bending moment-to-shear ratios. Degradation in the strength of columns under flexure with aspect ratios of six and three occurs by formation of a flexural plastic-hinge at the base of the column, followed by core degradation, and finally by the buckling of longitudinal bars on the compression side. The length of the plastic zone increases according to an increase in T/M ratio. A combination of bending and torsional moments reduces the torsional moment required to cause yielding of the transverse reinforcement and the peak torsional strength.

Continued on page 163

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Ayoub, A. and Mullapudi, R.S. (2013), Analysis of Reinforced Concrete Columns Subjected to Combined Axial, Flexure, Shear and Torsional Loads. *Journal of Structural Engineering*, 139(4), 548-560.

Kim, S.J., Holub, C., and Elnashai, A. (2011), "Analytical Assessment of the Effect of Vertical Earthquake Motion on RC Bridge Piers," *ASCE Journal of Structural Engineering*, Vol. 137 (2), pp. 252-260.

Frankie, T., Abdelnaby, A., Silva, P., Sanders, D., Elnashai, A., Spencer, B., Kuchma, D., and Chang, C. (2013) Hybrid Simulation of Curved Four-Span Bridge: Comparison of Numerical and Hybrid Experimental/Analytical Results and Methods of Numerical Model Calibration. *Structures Congress 2013*, pp. 721-732.

Arias-Acosta, J.G. and Sanders, D.H. (2010), "Performance of Bridge Reinforced Concrete Columns Under Combined Actions Throughout Shake Table Testing". *Proceedings of the 9th US National and 10th Canadian Conference on Earthquake Engineering: Research Beyond Borders*, Toronto, Canada, July 25-29, 2010.

Toward Seismically Safe Masonry: How the Data Stack Up

NEESR-SG: Performance-Based Design of New Masonry Structures, Richard Klingner, University of Texas at Austin, NSF #0619096, NEEShub Project Warehouse #634, [2006]

Principal Investigator

Richard Klingner, University of Texas at Austin

Co-Principal Investigators

W. Mark McGinley, University of Louisville

David McLean, Washington State University

P. Benson Shing, University of California, San Diego

Educational Impact

Graduate students: 2

Undergraduate students: 4

Masonry structures are constructed of bricks or blocks and mortar, or clad with a brick-and-mortar veneer. Such cladding, which is frequently used in low-rise residential and commercial buildings in North America, normally consists of a single wythe (width) of clay masonry attached to the structural backing wall with metal anchors.

Typically these structures are designed according to the Masonry Standards Joint Committee (MSJC) Building Code and Specifications for Masonry Structures. Surprisingly, however, until this study, little experimental data existed to validate the seismic performance of complete structures of masonry or of wood with masonry cladding. To discover the seismic safety of current, code-compliant buildings, a collaborative team of researchers, led by University of Texas professor Richard Klingner, worked to develop performance-based design methods for various types of new masonry structures.

In a coordinated experimental and analytical study, the team investigated the performance of wood-stud construction with clay masonry veneer, and of reinforced concrete masonry construction with clay masonry veneer.

IMPACTS

This research has resulted in multiple key design recommendations that will improve seismic safety and cost-effectiveness of low-rise masonry-veneer-clad residential and commercial buildings.

For example, code changes have been implemented to require the use of higher-capacity fasteners to attach masonry veneer to wood-stud walls.

Also, the researchers used their results to develop analytical models, with which they evaluated and improved current design requirements in the Masonry Standards Joint Committee (MSJC) code and International Residential Code for these types of masonry systems. This study's findings have been broadly disseminated within the design community, including the Masonry Standards Joint Committee, the Building Seismic Safety Council, and model-code groups such as the International Code Council.

In 2007 and 2008, engineering-education modules based on this study were incorporated into summer camps for Native American and Hispanic middle school and high school students in Washington State. The 5-day camps provided hands on engineering projects. Over 200 students participated in these educational camps, and the teaching modules were folded into broader Washington State University and UC San Diego outreach efforts to engage under-represented minorities in science and engineering.

OUTCOMES

The study gleaned information on the performance of masonry veneer and its backing, masonry veneer connectors, and the inelastic behavior of low-rise reinforced concrete masonry shear walls. The research culminated in the first-ever set of performance-based design guidelines.

The experiments suggested that the brick veneer acts out of plane as a rigid body before cracking. This causes it to rotate about its base and place larger loads on the ties at



In-plane testing of an 8 x 8 foot wall to determine the effects of corrugated ties and joint reinforcement.



Damage caused by the shake test.

the top of the wall. Despite this, both testing and analysis indicated that masonry veneer generally cracked near mid-height before tie failure occurred. Once cracked, the veneer rotated around the cracked mortar joint, spanning vertically and horizontally between the ties. Veneer cracking significantly changed the distribution of tie forces along the wall height.

In the full-scale test, excepting the west wall of the structure, the masonry veneer performed well under severe ground motions. Due to the high moisture content of the walls that likely caused the low extraction capacity of the nails, most of the veneer detached out of plane from the west wall.

In order to prevent such failure in the future, ring-shank nails or screws should be used to attach veneers. There was no evidence that joint reinforcement improved the seismic performance and safety of veneer walls with corrugated ties. However, for rigid ties it was noted that some form of mechanical anchor in mortar joints would be beneficial.

RESEARCH METHODOLOGY

The project included experimental and analytical research, education, and development of design recommendations for code implementation. The quasi-static experiments took place at the University of Texas at Austin and at North Carolina A & T State University. Shake table testing took place at the UC San Diego NEES facility. Educational outreach activities took place at Washington State University and UC San Diego.

The team conducted quasi-static tests of veneer over wood-stud and concrete-masonry wall segments, both in-plane and out-of-plane. There were shake-table tests of wall segments; and shake-table tests of prototype buildings comprising these wall constructions.

Assemblies representative of typical wall configurations were shake-tested quasi-statically in the form of smaller wall and window specimens. For the culmination of the project, two full-scale, one-story buildings were tested on the NEES Large High-Performance Outdoor Shake Table at the University of California, San Diego.

For both the wood-stud specimen and the reinforced-masonry specimen, behavior of the full-scale structure on the shake table was consistent with the results of quasi-static and shake-table testing of wall segments representing parts of the structure. Behavior of quasi-static and shaking-table specimens was reasonably well predicted by analytical models based on OpenSEES.

Masonry veneer cladding provides excellent durability, resistance to moisture penetration, thermal insulation and fire resistance, along with an attractive architectural appearance.

Thanks to this NSF-funded research, engineers as well as homeowners have additional assurance that reinforced masonry buildings and wood-stud buildings with masonry veneer can be safe in earthquake-prone regions.

FUTURE

Results from this NSF NEES project were used to design the multi-story shake-table specimens tested in NIST Project "Performance-Based Seismic Design Methods and Tools for Reinforced Masonry Structures" (ARRA Award No. 60NANB10D013). Results from that project corroborated the limit design provisions that have been approved for the 2013 MSJC Code and Specification.

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Advanced Testing Buttresses Braced-Frame Designs, Retrofits

NEESR-SG: International Hybrid Simulation of Tomorrow's Braced Frame Systems, Charles Roeder, University of Washington, NSF #0619161, NEEShub Project Warehouse #605, [2006]

Principal Investigator

Charles Roeder, University of Washington

Co-Principal Investigators

Dawn Lehman, University of Washington
 Stephen Mahin, University of California, Berkeley
 KC Tsai, National Taiwan University
 Carol Shield, University of Minnesota
 Taichiro Okazaki, Hokkaido University, Japan

Educational Impact

Graduate students: 9
 Undergraduate students: 6

NEESR: Collaborative Developments for Seismic Rehabilitation of Vulnerable Braced Frames, Charles Roeder, University of Washington, NSF #1208002, NEEShub Project Warehouse #1157, [2012]

Principal Investigator

Charles Roeder, University of Washington

Co-Principal Investigators

Jeffrey Berman, University of Washington
 Dawn Lehman, University of Washington
 Stephen Mahin, University of California, Berkeley

Educational Impact

Graduate students: 4
 Undergraduate students: 2

The braced frame is a commonly used building technique for counteracting horizontal loading forces such as wind and earthquakes. Essentially, braced frames are diagonal steel struts which, when added to select bays of a structure, stiffen the frame like a truss. In this way, engineers employ triangulation to transfer the load along the structure to the diagonal braces, then to the foundation.

University of Washington engineering professor Charles Roeder has spearheaded two research projects that are radically augmenting the field's understanding of braced frame (BF) systems. One study resulted in a new design method that increases overall structural resilience; a follow-up study, currently underway, looks at ways to protect buildings with older, poor-performing braced frame systems.

Professor Roeder's initial study, International Hybrid Simulation of Tomorrow's Braced Frame Systems, was a collaborative effort involving researchers from the University of Washington, UC Berkeley, University of Minnesota, and the National Earthquake Engineering Research Center (NCEE) in Taipei, Taiwan.

IMPACT

This project produced a novel, "balanced-design" method for braced frames that engineers may soon be able to use. Many yield mechanisms and failure modes must be considered in the seismic design of braced frames and their connections. The balanced design procedure balances the design so that multiple desired yielding mechanisms develop throughout the system in a desired sequence prior to initial brace fracture. Research has shown that this increases structural ductility and inelastic deformation capacity by an average of 46% and reduces and eliminates undesirable failure modes. Some of these balanced design recommendations were included in design examples from the 2010 AISC Seismic Design Provisions, but others require adoption into seismic design provisions before they can be commonly used.

In addition, the team's hybrid simulation experimentation produced improved analytical models that will further engineering design and research in braced frame systems.

OUTCOMES

Analytical results that were calibrated to test results show that the seismic response and safety of braced frames depends on the building size, and not simply the type of lateral resisting system as is currently implemented in the code. These analyses show that achieving a consistent economy and reliability of preventing collapse would require response modification factors that depend on building height and other parameters not currently considered in design.

Hybrid testing. For the first time, BF researchers used their experimental data to calibrate and validate computer models. Using the hybrid simulation testing technique, the team applied simulated structural responses to braced-frame specimens – a huge advancement in nonlinear modeling. Prior to this research, computer models seldom captured the full range of braced frame behavior. For a given specimen, the hybrid simulation technique provides a more direct correlation of its performance in a real earthquake.



Full-scale 3-D Braced Frame test specimen ready for testing in the MAST laboratory.

By capturing inelastic deformations of the brace, including large out-of-plane displacements, researchers were able to look at the secondary inelastic deformation demands on beams, columns, and connections. Analytical models, particularly the macro-element models, were verified and developed to improve the ability to predict the seismic performance of the system.

RESEARCH METHODOLOGY

Experiments for this study took place at the NEES at UC Berkeley lab, the NCEE lab in Taiwan, and at the NEES at Minnesota Multi-Axial Subassembly Testing (MAST) lab. Overall, the researchers sought to make system-level assessments of braced-frame performance. The team tested conventional buckling braces (CBF) and advanced buckling restrained braced frames (BRBF) in multi-story structures, in multiple configurations.

NEES at UC Berkeley. At UC Berkeley, four single-bay, two-story, conventional concentric braced frame specimens with second story inverted-V and first-story V-bracing configuration were tested to failure under quasi-static cyclic loadings. In particular, the team observed how beams and columns carry loads following the failure of the braces.



The cracked gusset-to-column weld after testing.

NCEE in Taiwan. Current BF design procedures often lead to soft stories, inadequate gusset plate connections, brittle welds, and unexpected and premature brace failure.

At the NCEE lab in Taiwan, three single-bay, two-story conventional braced-frame and three single-bay, three-story concentric braced-frame specimens were tested – in split-X and stacked split-X configurations.

Several experiments at NCEE successfully tested the team's new "balanced design" procedure, which relies on cyclic yielding of the brace while also permitting distributed yielding into the gusset plates and framing elements – all of which maximize the system's drift capacity.

Continued on page 163

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Full-Scale Testing Examines Nonstructural System Performance

NEESR-CR: Full-Scale Structural and Nonstructural Building System Performance During Earthquakes, Tara Hutchinson, University of California, San Diego, NSF #0936505, NEEShub Project Warehouse #722, [2009]

Principal Investigator

Tara Hutchinson, University of California, San Diego

Co-Principal Investigators

Joel Conte, University of California, San Diego

Jose Restrepo, University of California, San Diego

Educational Impact

Graduate students: 10

Undergraduate students: 6

Nonstructural components and systems are the elements that support the functionality of a building; however, they do not provide load-bearing support to the building itself. These components include the architectural, mechanical/electrical/plumbing, and furnishings of the building. For example, partitions, pipes, sprinklers, wiring, and HVAC ducts are all nonstructural components.

Since the 19th century, these nonstructural component and systems (NCS) have demonstrated their potential to endanger building occupants during an earthquake. Like the ornaments on a Christmas tree, nonstructural elements are at the mercy of the host structure. Further, because these elements comprise over 80% of a building's cost, even minor earthquake damage can lead to significant financial losses.

In a pioneering study, Professor Tara Hutchinson and colleagues from the University of California, San Diego, led the very first earthquake simulation focused on evaluating the response of a full-scale building, fully outfitted with functional nonstructural systems.

IMPACTS

Within the five-story test building a wide variety of typical nonstructural components and systems were installed. These represented a variety of occupancy and risk categories, and for the first time included a fully functioning passenger elevator. By subjecting the structure to simulated earthquake motions, researchers were able to gain an understanding of not only the structural component response, but importantly the nonstructural responses and their interactions with other components. Moreover, the research team subjected the test building to live fires following the earthquake simulations.

Many of the NCSs included in the test building had never been tested at full-scale in a dynamic building environment.

Not surprisingly, the dramatic shake tests at the NEES at UC San Diego outdoor shake table piqued the media's interest. As a result, the project raised awareness about earthquake engineering – and problems with nonstructural components – via national television networks NBC, ABC, CBS, CNN, and other major international and national media outlets, including the New York Times, USA Today, and BBC News.

Importantly, response measurements and associated physical damage observations from these tests are impacting design codes and construction practices. Researchers are contributing to design guidance on a variety of subjects using these test data, including, for example, egress systems such as stairs and elevators, and facades, including concrete cladding and lightweight metal stud systems.

OUTCOMES

The responses of the building-NCS system, both with and without base isolation, are being used to improve the accuracy of analytical models used to predict NCS performance under alternative building designs. The research has led to improvements in existing and new design methodologies for nonstructural components and systems that are superior to previous design methods. NCSs in need of further protective systems were identified and assessed for optimization.

As expected, the damage to fire protection measures, such as passive fire barriers, exacerbated the post-earthquake fire hazards that the building posed. Not only were fire protection systems damaged, but doors, stairs, the elevator, and other egresses were damaged, in some cases jammed open or shut, posing a major hazard to anyone attempting to escape the building or close a door to prevent the spread of fire – or worse, to rescue efforts. Compartment barrier components were compromised by large gaps at joint areas, which resulted in unlimited oxygen flow to the fires and an unconstrained spread of smoke and flame.

Structural connections damaged following the largest earthquake motions resulted in spalling and cracking of concrete, and subsequent exposure of reinforcing steel, as well as fracture of reinforcing steel in critical regions. The damage caused in the largest motions significantly degraded the fire resistance rating and load-bearing capacity of the structural system.



Structural skeleton during façade installation at UCSD shake table.

RESEARCH METHODOLOGY

The full-scale, 5-story reinforced concrete building was outfitted with a broad array of NCSs, including a fully functional elevator, prefabricated metal stairs, partition walls, ceilings, synthetic stucco and precast concrete cladding exterior facades, all in addition to mechanical, electrical, and plumbing systems and medical equipment. The test building's nonstructural system was subjected to simulated earthquake shaking, first while supported on rubber isolators and then while fixed to the NEES at UCSD shake table - the world's largest outdoor shake table.

Although NCSs make up approximately 80% of a building's investment and literally fill a building, most of these systems are not designed to resist seismic forces and relative displacements imposed during an earthquake are therefore not usually considered by seismic engineers. Nevertheless, damage to NCSs is often initiated at much lower deformations than damage to the structural system due to the use of brittle materials such as glass, plaster, and drywall that fail at low drift levels. Damage also occurs to ceilings, piping, or other systems due to high

floor accelerations associated with small drifts. Damaged NCSs often pose a major problem during rescue operations as the building loses vital systems or functions. This contributes not only to excessive economic losses, but also poses a threat to human lives.

In this project, testing consisted of three phases: one in which the building was shaken while mounted on large rubber bearings (commonly termed base isolators), a second phase in which the base isolators were removed and the test building was anchored directly to the shake table, and the final tests in which the researchers ignited controlled fires to study fire and smoke behavior in earthquake-damaged environments. This was the first time that the post-earthquake fire performance of a full-scale building and its systems was tested.

FUTURE

This unique test program revealed shortcomings in design and construction practices for a number of important nonstructural components and systems essential to supporting the buildings functionality. It further reinforced the need for collaboration amongst seismic and fire engineers to create buildings that are resilient against loss of egress and fire protection capacity. Finally, these tests highlighted the vulnerability of NCSs that interact amongst each other as well as with the building.

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NEES at UCLA Validates Seismic Retrofits for the LAX Theme Building

LAX Theme Building Retrofit, John Wallace University of California, Los Angeles, [2007]

Principal Investigators

John Wallace, University of California, Los Angeles
Jonathan Stewart, University of California, Los Angeles
Robert Nigbor, University of California, Los Angeles

Educational Impact

Graduate students: 2
Undergraduate interns: 3

Built in 1961, the futuristic-looking Theme Building at Los Angeles International Airport is an architectural icon in Southern California. In 2007, after a section of stucco fell from one of its arches and inspections revealed internal corrosion and other problems, airport officials decided to protect the building with a voluntary, \$12.3M seismic retrofit.

IMPACTS

Playing a key role in ensuring the seismic safety – and longevity – of this landmark structure, earthquake engineers from NEES at UCLA analyzed the building's dynamic properties and seismic performance before and after the retrofit.

NEES researchers Robert Nigbor, Jonathan Stewart, and John Wallace performed experimental modal analysis (EMA) on the structure to measure its response to ambient and forced vibration, including snapback testing of the innovative tuned mass damper (TMD) used as part of the seismic retrofit strategy.

METHODOLOGY

The retrofit included conventional strengthening of the building's core plus the use of a large 1.2 million pound TMD to increase damping and therefore reduce seismic design forces. This use of a TMD as part of the seismic retrofit strategy was unique.

UCLA researchers performed experimental modal analysis of the complex structure in 2007 to confirm finite element modeling of the structure during retrofit design. They then repeated the measurements in 2010 after construction.

The "Mighty Mouse" shaker was used to excite the structure well above ambient levels. Accelerometers were installed at 51 locations around the building to measure response to ambient, shaker, and small earthquake vibrations. The results were used to add confidence to the modeling of earthquake and wind response and to the final as-built system.

Of particular interest was the performance of the unique 1.2 million pound tuned-mass damper atop the central building core. UCLA engineers devised a way to push this large mass sideways and release it, allowing direct measurement of its as-built frequency and damping.

After these tests, UCLA engineers installed long-term earthquake monitoring instrumentation to capture response to future earthquakes and to act as a testbed for advanced structural monitoring research.

The innovative use of the tuned mass damper saved an estimated \$2-4 million in construction costs as compared to typical retrofits, and also allowed the Theme Building restaurant to remain operational during construction. Conventional seismic retrofits are expensive, interfere with structural integrity, interrupt business operations, and would affect the historic architecture. The unique retrofit of the Theme Building has opened the door to greater expectations for smart building solutions that support business objectives and keep people and their property safer.

FUTURE

The U.S. Geological Survey is considering taking over the earthquake monitoring of this building to make this a permanent part of their Advanced National Seismic System.

SELECTED RESEARCH PUBLICATIONS

Gilani, A. S., Miyamoto, H. K., Mahin, S., & Nigbor, R. Seismic Retrofit of the LAX Theme Building with Mass Damper: Analysis and Experimentation. Proc. 15th World Conference on Earthquake Engineering, Lisbon, September 2012.



NEES at UCLA used the "Mighty Mouse" shaker to validate the Los Angeles International Airport Theme building retrofit.



NEES expertise helped secure a landmark building in Los Angeles.



3. RECENTERING AND PROTECTIVE SYSTEMS

In conventional seismic design, structures typically are designed to absorb earthquake energy by sustaining controlled damage through ductile yielding of selected structural components. Ten years of NEES research has brought great advances in methods that eliminate or greatly minimize this controlled damage, thereby enabling structures to remain resilient and functional after an earthquake.

Two general research themes are recentering systems and response modification devices. Recentering systems allow structures to respond through rocking motions at critical sections. These systems employ easily replaceable elements for dissipating seismic damage, thereby allowing the structure itself to remain damage-free.

Response modification devices use isolation techniques to reduce the earthquake's effect on a structure by changing the structure's dynamic characteristics. In addition, devices such as dampers function like shock absorbers for the structure, dissipating seismic energy and thus reducing the structure's overall movement.

The following projects are profiled in this section.

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NEESR-SG: Self-Centering Damage-Free Seismic-Resistant Steel Frame Systems, Richard Sause, Lehigh University	
NEESR-CR: Performance-Based Design for Cost-Effective Seismic Hazard Mitigation in New Buildings Using Supplemental Passive Damper Systems, Richard Sause, Lehigh University	
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NEESR-SG: Controlled Rocking of Steel-Framed Buildings with Replaceable Energy Dissipating Fuses, Gregory Deierlein, Stanford University	
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NEESR-SG: TIPS — Tools to Facilitate Widespread Use of Isolation and Protective Systems, a NEES/E-Defense Collaboration, Keri Ryan, Utah State University	
A New Class of Protective System: Negative Stiffness Devices and Apparent Weakening	48
NEESR-SG: Development of Next Generation Adaptive Seismic Protection Systems, Satish Nagarajaiah, William Marsh Rice University	
A New Way to Create Seismically Resilient Buildings Using Unbonded Post-Tensioned Rocking Walls	50
NEESR-CR: Unbonded Post-Tensioned Rocking Walls for Seismic Resilient Structures, Sri Sritharan, Iowa State University	

Photo opposite: Self-centering steel concentrically-braced frame (orange) in laboratory test fixture.

Performance-Based Design: An Efficient Procedure for Designing Seismically Safe Structures

NEESR-SG: Self-Centering Damage-Free Seismic-Resistant Steel Frame Systems, Richard Sause, Lehigh University, NSF #0420974, NEEShub Project Warehouse #77, [2004]

Principal Investigator

Richard Sause, Lehigh University

Co-Principal Investigator

James M. Ricles, Lehigh University

Educational Impact

Graduate students: 7

Undergraduate students: 4

NEESR-CR: Performance-Based Design for Cost-Effective Seismic Hazard Mitigation in New Buildings Using Supplemental Passive Damper Systems, Richard Sause, Lehigh University, NSF #0936610, NEEShub Project Warehouse #18, [2009]

Principal Investigator

Richard Sause, Lehigh University

Co-Principal Investigator

James M. Ricles, Lehigh University

Educational Impact

Graduate students: 6

Undergraduate students: 13

Professor Richard Sause of Lehigh University and his colleagues developed and applied new performance-based design procedures in two major studies of protective systems. In one project, Self-Centering Damage-Free Seismic-Resistant Steel Frame Systems, Sause and a multi-disciplinary, multi-university team explored self-centering steel frames. In a later study called Performance-Based Design for Cost-Effective Seismic Hazard Mitigation in New Buildings Using Supplemental Passive Damper Systems, Professor Sause and his colleagues developed a validated design procedure for buildings with passive damping systems.

IMPACTS

The Self-Centering Damage-Free Steel Frames research project resulted in one new seismic lateral force resisting system, termed a self-centering, concentrically braced frame (SC-CBF) system, and produced an advanced version of a second, seismic lateral-force resisting system, termed a self-centering moment-resisting frame (SC-MRF) system. The probabilistic performance-based design (PBD) procedures and criteria produced by the project for the SC-CBF and the SC-MRF systems enable these systems to sustain essentially no structural damage under the design basis earthquake specified in modern building codes; in contrast, conventional seismic lateral-force resisting systems are expected to sustain notable structural damage under the design basis earthquake. Current research is extending the self-centering, damage-free system concept to timber and reinforced concrete structures.

For the Cost-Effective Buildings with Passive Damper Systems research project, Sause and his colleagues developed performance-based design (PBD) procedures as alternatives to current code provisions and experimentally evaluated those procedures. The procedures enable an engineer to specify the performance level (current code level or better) and also enable the engineer to select a balance of seismic resistance between the passive damping system and the steel moment resisting frame system. The project used real time hybrid earthquake simulations (RTHS) to validate the PBD procedures, and the project established RTHS as a significant and reliable laboratory technique for such validations through careful comparisons of the laboratory response data with data from purely numerical simulations.

OUTCOMES

In the Self-Centering Damage-Free Steel Frames project, it was discovered that SC-CBF systems could be designed and detailed to achieve reliable, damage-free performance under predetermined seismic conditions, making the SC-CBF system a viable seismic-resistant system. The project used hybrid earthquake simulations in the laboratory, as well as extensive numerical simulations, to validate these results. The extensive results (more than 30 laboratory simulations) demonstrated that the SC-CBF met or exceeded immediate occupancy performance under the design basis earthquake and met or exceeded collapse prevention performance under the maximum considered earthquake.

The nonlinear numerical simulations accurately predicted the response of the test structure, which sustained roof drift demands up to 4.33% radians without yielding or damaging the structural members.

The extensive data from the Cost-Effective Buildings with Passive Damper Systems project includes detailed data from characterization tests on two types of dampers studied by the research team as well as detailed data from real-time hybrid earthquake simulations (RTHS) of a steel moment resisting frame building with supplemental passive damping systems. Again, two types of dampers were studied in these RTHS. The team developed practical, performance-based seismic design and assessment procedures for steel moment-resisting frame (MRF) buildings with supplemental passive damping systems. Sause and his colleagues developed a number of seismic design cases for each building where the properties of the steel moment resisting frames and the damper systems were varied, yet the target performance was maintained.

RESEARCH METHODOLOGY

Conventional concentrically braced frame (CBF) systems are a commonly used lateral-force resisting system. Under expected design-basis seismic conditions, CBFs are expected to undergo drift demands that will yield or buckle the braces, which lead to residual lateral drift after the earthquake. Self-centering concentrically-braced frame (SC-CBF) systems were developed to maintain the advantages of common CBFs, such as economy and stiffness, while increasing the lateral drift capacity before damage occurs. In addition, they will have less residual lateral drift and remain elastic under expected design-basis seismic conditions. SC-CBF systems have post-tensioning (PT) bars that provide restoring forces and self-centering behavior, which in turn reduces residual drift.

The research team developed reliability-based seismic design procedures, system concepts and details, and energy dissipation elements for SC steel frame systems, in addition to developing sensor networks to monitor and assess SC steel frame systems. This led to the development of prototype buildings using SC steel frame systems. The researchers were able to perform nonlinear analyses and large-scale lab simulations on specimens derived from the prototype buildings. Large-scale hybrid earthquake simulations were completed at the NEES Real-Time Multidirectional (RTMD) testing facility at Lehigh University lab.

Cost-Effective Buildings with Passive Damper Systems.

This project studied seismic damage mitigation through the use of passive damper systems. The work was a

collaboration among researchers from Lehigh University, California State University, Northridge, and California State Polytechnic University, Pomona. In addition, the project team joined with Pennsylvania State University at Erie and the Corry Rubber Corp. to develop an innovative compressed elastomeric damper that was studied by the project. The project team also worked with Taylor Devices to develop nonlinear fluid viscous dampers designed for the large-scale multi-story steel frame studied by the project.

Conventional seismic design of steel frames often results in damage and residual drift under seismic conditions. Passive damping systems can improve the performance of buildings by reducing drift and inelastic deformation demands on the members of the primary lateral load resisting system in addition to reducing the velocity and acceleration demands on non-structural components.

The research team developed a set of steel moment resisting frame (MRF) buildings to serve as prototype structures. Then they selected the type of dampers to study and conducted characterization tests on these dampers to enable high-fidelity models for the force-deformation hysteretic response of the dampers to be developed. The team developed practical performance-based seismic design and assessment procedures. To complete their research, they conducted real-time hybrid earthquake simulations on prototype buildings with dampers in order to assess the performance of the building and evaluate the practical design and assessment procedure.

Continued on page 164

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Dong, B., Sause, R., and Ricles, J.M., "Real-Time Hybrid Simulation: Validation of PBD Procedure for Steel Frames with Nonlinear Viscous Dampers," Proceedings, 10th US National Conference on Earthquake Engineering, Anchorage, AK, July 21-25, 2014.

Lin, Y.-C., Sause, R., and Ricles, J.M., "Seismic Performance of a Steel Self-Centering Moment Resisting Frame: Hybrid Simulations under DBE," Journal of Structural Engineering, 139(11), 1823-1832, 2013 (DOI: 10.1061/(ASCE)ST.1943-541X.0000745).

Lin, Y.-C., Sause, R., and Ricles, J.M., "Seismic Performance of a Large-Scale Steel Self-Centering Moment Resisting Frame: MCE Hybrid Simulations and Quasi-Static Pushover Tests," Journal of Structural Engineering, 139(7), 1227-1236, 2013 (DOI: 10.1061/(ASCE)ST.1943-541X.0000661).

Sause, R., Ricles, J., Mahvashmohammadi, A., Michael, R., Sweeney, S., and Ferro, E., "Advanced Compressed Elastomer Dampers for Earthquake Hazard Reduction to Steel Frames," STESSA 2012, Proceedings of the 7th International Conference on Behavior of Steel Structures in Seismic Areas, Santiago, Chile, January 8-11, 2012, pp. 791-796.

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New Buildings Designed To Rock When Earthquakes Roll

NEESR-SG: Controlled Rocking of Steel-Framed Buildings with Replaceable Energy Dissipating Fuses, Gregory Deierlein, Stanford University, NSF #0530756, NEEShub Project Warehouse #75, [2005]

Principal Investigator

Gregory Deierlein, Stanford University

Co-Principal Investigators

Jerome Hajjar, Northeastern University

Sarah Billington, Stanford University

Educational Impact

Graduate students: 3

For today's earthquake engineers, it is not enough to design buildings that don't collapse. The challenge now is to design "build-for-repair" structures – structures that not only remain intact but that are easier and cheaper to repair after an earthquake strikes.

Such modern structures will help transform the nation's earthquake-prone cities to sustainable, economically resilient communities.

Stanford University civil and environmental engineer Gregory Deierlein and an international, multi-university team developed a new structural system that employs steel braced frames to resist seismic loading through controlled rocking. Under seismic loading, such buildings will rock, then stabilize themselves, much like a barstool might rock and right itself when tipped.

The group's experiments and analyses have shown that the "rocking frame" action, coupled with replaceable structural fuses, enables a building to absorb and sustain earthquake motions with minimal damage.

IMPACTS

The research has significantly advanced the state of earthquake-resistant construction. To assist practicing engineers, the team has developed design guidelines for rocking frames with fuses.

The investigative team, a mix of research engineers and practitioners, is working with building code managing bodies on performance-based, self-centering rocking system recommendations to facilitate the adoption of these systems.

- The proposed code provisions for ASCE 7 include a new system designation with a section incorporating special design requirements such as limit state checks and calculation of deflections.

- For ACI 318, the proposal recommends a new section in Chapter 21 on "self-centering rocking spines," with commentary references to the Innovation Task Group (ITG) and other resources.
- Similarly, for the ANSI/AISC 341, the recommendations are for a section on "self-centering rocking spines," with commentary references to other sources.

OUTCOMES

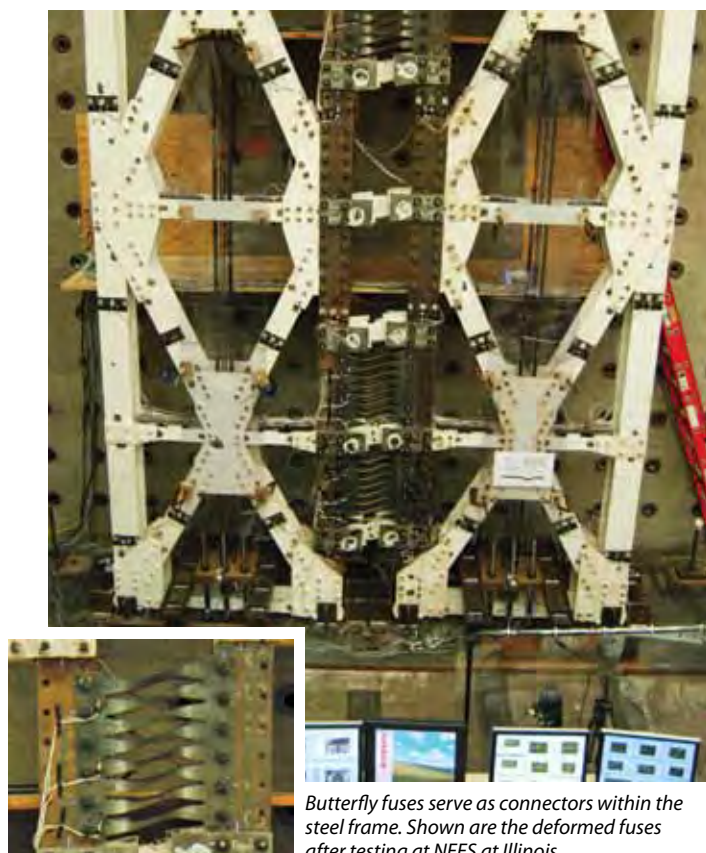
Several buildings have been constructed using rocking frame and fuse concepts, including the city offices in Orinda, California and the USC School of Cinematic Arts in Los Angeles. However, systematic studies of the seismic performance of rocking frame designs are lacking. Among other things, this particular study found the following.

- **Frame design.** The rocking frame system Deierlein and his team designed can sustain multiple earthquakes of moderate to high intensity without the need for repair or substantial compromise in performance. As long as the fuse is not excessively damaged and post-tensioned strands only experience limited yielding, repairing of the system is not urgent.
- **Repair.** With proper design, the braced frame and post-tensioned strands stay elastic and all damage is concentrated in the fuse. Following a large ground shaking, the system can be easily repaired by replacing the fuse only.
- **Self-centering behavior.** In a total of 29 shakings with two ground motion records scaled to various levels including the MCE hazard level, the system completely self-centered in all except two cases.
- **Fuses.** All four fuses survived testing without fracture. The tests of alternative fuse types suggest that the specific fuse type is not limited to steel shear plates or buckling restrained braces (BRB); rather, one can employ any fuse design that can reliably provide the strength and deformation capacity for the structure at hand.

RESEARCH METHODOLOGY

For seismic-force resisting systems, United States seismic building codes and engineers traditionally have relied on inelasticity, or stiffness, to dissipate seismic energy and protect against collapse. Unfortunately, this inelasticity also distributes structural damage throughout a building and causes permanent drifts, seen as a building tilt. These problems are difficult and quite expensive to repair.

In an innovative approach, Deierlein and his team devised a new type of lateral resisting system that concentrates the majority of structural damage in replaceable fuse elements. The controlled rocking system not only performs better



Butterfly fuses serve as connectors within the steel frame. Shown are the deformed fuses after testing at NEES at Illinois.

than conventional systems; it is also relatively simple and economical to repair after an earthquake.

The system combines conventional steel-braced framing with energy-dissipating shear fuses that are mobilized through the rocking action. To minimize residual drifts, vertical post-tensioning allows the building frame to self-center. Post-tensioning anchors the steel frame to the concrete foundation through high-strength steel strand reinforcement.

The research was comprised of six phases. After performing preliminary development and analysis of the rocking frame system, the team conducted structural fuse development and subassembly testing at Stanford University. Physical and simulation experiments took place at the NEES at University of Illinois, Urbana-Champaign (UIUC) facility and at the Hyogo Earthquake Engineering Research Center (E-Defense) in Japan.

NEES AT ILLINOIS

To develop and validate their rocking-frame system's concepts and details, the team performed large-scale quasi-static and hybrid simulation testing of dual and single rocking frame configurations at the NEES at Illinois laboratory, which is called the Multi-axial Full-scale Substructure Testing and Simulation or MUST-SIM lab. There, using equipment called Loading and Boundary Condition Boxes (LBCBs) the team subjected components

of their system to complex loading and deformation states.

Specifically, this quasi-static cycling exposed half-scale frames to slow loading and displacements, which allowed researchers to study the system's structural reaction and performance. The computerized hybrid simulation testing helped the team determine which type of fuse to employ. Three-dimensional numerical models of butterfly fuse specimens were created in order to simulate buckling and load-deformation response under cyclic loading with fairly good accuracy.

TESTING AT E-DEFENSE IN JAPAN

The final physical experiment – and proof-of-concept test for the new system – was conducted at the E-Defense shake table facility in Miki, Japan. The structure tested was a two-thirds scale, three-story rocking frame.

The shake table tests demonstrated that the system responded just as the researchers predicted it would. That is, when subjected to earthquake excitation, the response was column uplifting and frame rigid-body rotation.

The tests proved that the rocking frames can sustain Maximum Considered Earthquake (MCE) level ground motions with drifts on the order of 2% to 3% without any structural damage, other than yielding of the replaceable fuses. Under larger motions, the frames performed reliably up to 4% drifts.

Furthermore, researchers combined physical tests with an extended numerical study of other multi-story frames, ranging from three to nine stories tall.

Overall, data from the E-Defense shake table tests confirmed the reliability of the research team's rocking frame design concept and helped validate computational models that were used to develop models and criteria for the design.

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Deierlein, G. G., Ma, X., Eatherton, M., Krawinkler, H., Billington, S., & Hajjar, J. F. (2009). Collaborative research on development of innovative steel braced frame systems with controlled rocking and replaceable fuses. In *Proc. 6th International Conference on Urban Earthquake Engineering*, Tokyo (pp. 413-416).

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Research Fosters Widespread Adoption of Seismic Isolation Techniques

NEESR-SG: TIPS — Tools to Facilitate Widespread Use of Isolation and Protective Systems, a NEES/E-Defense Collaboration, Keri Ryan, Utah State University, NSF #0724208, NEEShub Project Warehouse #571, [2007] and NSF #1113275, NEEShub Project Warehouse #571, [2011]

Principal Investigator

Keri Ryan, University of Nevada, Reno

Co-Principal Investigators

Gilberto Mosqueda, University of California, San Diego
Stephen Mahin, University of California, Berkeley
Deborah Moore-Russo, SUNY at Buffalo
Lucy Arendt, University of Wisconsin, Green Bay

Educational Impact

Graduate students: 22

Undergraduate students: 11

A seismic isolation system is collection of structural elements that protect a building by separating (isolating) the structure from its foundation that rests on shaking ground. Isolation systems remain the most effective technology to control both structural and non-structural damage by simultaneously reducing accelerations and story drifts. They are a practical, realistic option for any building regardless of size, occupancy, and importance.

Understanding the promise of isolation techniques, Professor Keri Ryan of the University of Nevada, Reno founded an international, multi-institutional research project on the idea that widespread use of isolation technologies could significantly reduce losses and disruptive societal impacts associated with earthquakes. The project, with the apt acronym “TIPS,” aimed to provide practical ways for practitioners to employ base isolation in their work.

OUTCOMES AND IMPACTS

Through comparative case studies of isolated and conventional buildings, this project has modeled the use of the FEMA P-58 methodology and software to demonstrate the lifetime cost-versus-benefit considerations of isolated buildings. The studies suggest that a lifetime benefit from a seismic protective system is not automatic, but can be enhanced by the robustness of the design. Based on the project findings, future engineering practice is likely to involve less code

prescriptive design and more performance-based design using the advanced modeling techniques.

Several experiments were conducted over the course of the project, including hybrid simulation, shake table testing to assess performance limit states, and full-scale shaking experiments, to assess the performance of both the structure and nonstructural components. The modeling and simulation to understand these experiments has provided a variety of tools and techniques to validate and inform modeling and simulation for the design of seismically-isolated buildings.

New modeling tools include two bearing models and an impact model to represent pounding of the isolated building against a moat wall. The two triple pendulum bearing models, which take different approaches to the modeling problem, are accessible to engineers and researchers through the open-source earthquake engineering simulation platform OpenSees. In addition, modeling of the full-scale building was carried out in both OpenSees (used more frequently by researchers) and SAP 2000 (used more frequently by design engineers).

These studies led to guidelines for modeling assumptions and best practices to represent the response of an isolated building during the design process. A generalized modal analysis approach was developed for simplified design and analysis of base-isolated buildings.

At the E-Defense facility in Miki City, Japan, full-scale shake tests fully validated the effectiveness of seismic isolation systems to mitigate the effects of horizontal shaking on the structure and nonstructural components. However, the tests also showed that to prevent damage or provide continued occupancy (which is often the performance objective for a seismically-isolated buildings), the effects of vertical excitation also have to be considered and mitigated. The tests indicated the potential for vertical shaking to be significantly amplified as it propagates up through the columns and is transmitted to the floor slabs, as well as the potential for a horizontal-vertical coupling that amplifies the horizontal accelerations in the building.

The team produced a number of non-technical products, including enhanced understanding of the decision process leading to adoption of isolation systems, recommendations to simplify the peer-review process, and comparison of U.S. and Japanese design codes and practices. The team also developed an internet-based educational module for middle-school students.

The project has and will continue to influence future code development. Guidelines were developed for selecting impact model parameters based on the mechanical and material properties of the impacting surfaces and can be extended to other applications. Based on the impact modeling, FEMA P695 analyses can be performed to assess the acceptability of different lateral systems to be used in combination with seismic isolation.

In the current code development cycle (ASCE 7-16), commentary guidelines are being introduced for those opting to consider vertical ground motion in design and analysis, and it is likely that such analysis will eventually be required. Commentary guidelines are also being introduced for the consideration of residual displacements in the isolation system. The design peer review procedure is being simplified with consideration of the project recommendations.

Over the course of the project, the team held three practitioner workshops. In all workshops, participants discussed ideas for advancing the implementation of isolation systems in practice, while the final workshop placed greater emphasis on communicating project outcomes to participants. In addition, more than 250 participants from 23 countries tuned in for the Research to Practice Webinar in November 2013.

Continued on page 164

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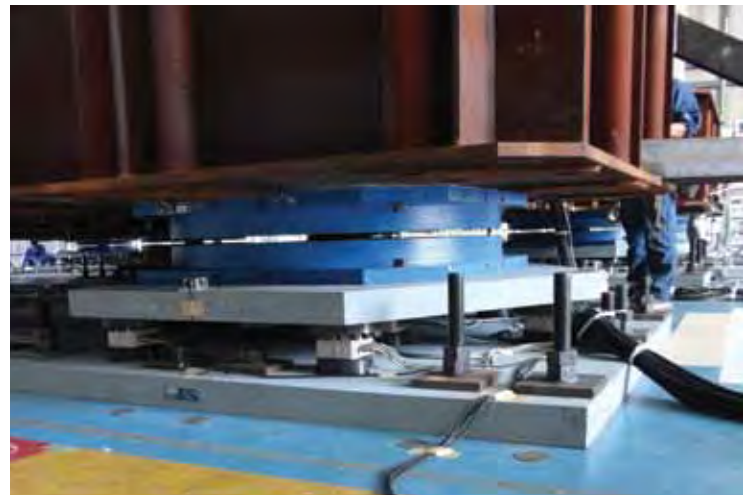
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Becker, T. C., and Mahin, S. A. "Approximating peak responses in seismically isolated buildings using generalized modal analysis." *Earthquake Engineering and Structural Dynamics*. 2013, 42(12): 1807-1825.

Dao, N.D. and Ryan, K.L., "Computational simulation of a full-scale fixed-base and isolated-base steel moment frame building tested at E-Defense," *ASCE Journal of Structural Engineering*, doi: 10.1061/(ASCE)ST.1943-541X.0000922.



At E-Defense, shake table tests were performed on a 5-story full scale steel moment frame building isolated with triple pendulum bearings. The isolation system consisted of 9 bearings, one beneath each column of the building.



Close up of the triple pendulum bearing on the E-Defense table.

A New Class of Protective System: Negative Stiffness Devices and Apparent Weakening

NEESR-SG: Development of Next Generation Adaptive Seismic Protection Systems, Satish Nagarajaiah, William Marsh Rice University, NSF #0830391, NEEShub Project Warehouse #653, [2008]

Principal Investigator

Satish Nagarajaiah, Rice University

Co-Principal Investigators

Andrei Reinhorn, SUNY at Buffalo

Michael Constantinou, SUNY at Buffalo

Michael Symans, Rensselaer Polytechnic Institute

Jian Zhang, University of California, Los Angeles

Douglas Taylor, President of Taylor Devices

Educational Impact

Graduate students: 7

Undergraduate students: 5

Design of conventional structures specified by building codes is based on the philosophy that the structure should withstand seismic loads while sustaining an acceptable level of damage. This is achieved by designing structures to be ductile and letting them yield significantly. Yielding, however, leads to stiffness and strength degradation, increased interstory drifts, and damage with permanent drifts.

To address these problems, Rice University Professor Satish Nagarajaiah and a multi-university team developed a new class of adaptive stiffness system and demonstrated the practicality of this new method.

Specifically, Professor Nagarajaiah and his colleagues discovered that yielding can be emulated in a structural system by adding an adaptive “negative stiffness device” (NSD) which shifts the yielding away from the main structural system, leading to the new idea of “apparent weakening” that occurs to ensure structural stability at all displacement amplitudes. This is achieved through an adaptive negative stiffness system, a combination of NSD and a fluid damper. By engaging the NSD at an appropriate displacement (apparent yield displacement that is well below the actual yield displacement of the primary structural system), the composite structure-device assembly behaves like a yielding structure while the primary structure remains mostly elastic.

IMPACTS

In this project, the transformative ideas of the negative stiffness device and “apparent weakening” were demonstrated by experimental and analytical study. The new approach results in significant damage and response reduction of nearly 30% to 40%. The system can be used in new buildings as well as for retrofit situations.

The research demonstrated that the novel adaptive negative stiffness system and apparent weakening is practical to implement in large structures. The NSD is adaptive but passive, and exhibits true negative stiffness behavior by possessing predesigned variations of stiffness as a function of structural displacement amplitude. The NSD properties can be easily adapted by changing the lever arm to accommodate any change in the properties of the structure observed over time.

Extensive analytical modeling also was developed and validated using the shake table test results. The nonlinear analytical models have been incorporated into 3D-BASIS, IDARC and OpenSees computer programs, thus enabling technology transfer and adoption of the new technology invented in this project. It is likely to impact the state of practice of supplemental devices in earthquake protection.

OUTCOMES

The feasibility of the new concept of negative stiffness and apparent yielding/weakening was experimentally verified at the NEES at Buffalo facility in a three-story base-isolated structure and single span base isolated bridge with the NSD at the isolation level and in a three-story inelastic fixed-base steel structure (moment frame) with the NSD in the first story. To accentuate the advantages of incorporating the NSD in structures, the responses of different systems including base structure; base structure with damper; base structure with NSD; and base structure with NSD and damper have been compared for a suite of ground motions. The behavior of all four systems was predicted analytically and the predicted results were found to be in agreement with the experiments.

Shake table tests confirmed that by adding the NSD and damper, the acceleration, base shear and deformations of the structure can be reduced by nearly 30 to 40%. In inelastic structures, the addition of the NSD and damper will prevent collapse as well as reduce its response during severe earthquakes.

Outcomes of the NEESR adaptive stiffness project include:

- The invention and patenting of the negative stiffness device and experimental validation and verification is expected to result in practical implementation in future.
- Results have been disseminated through nearly 17 journal papers, three MCEER reports, numerous conference papers and presentations, a NEES/EERI webinar, and other seminars widely available on the web.
- Real-time tele-observation during UB-NEES experiments and experimental videos are available through the NEEShub and the RiceSNDG YouTube channel. The test data generated from the project can be found in the NEEShub Project Warehouse #653.

RESEARCH METHODOLOGY

Structural weakening and the addition of damping is an approach previously proposed to reduce seismic forces and drifts in the retrofit of structures. It also may be used in the design of new buildings with damping systems.

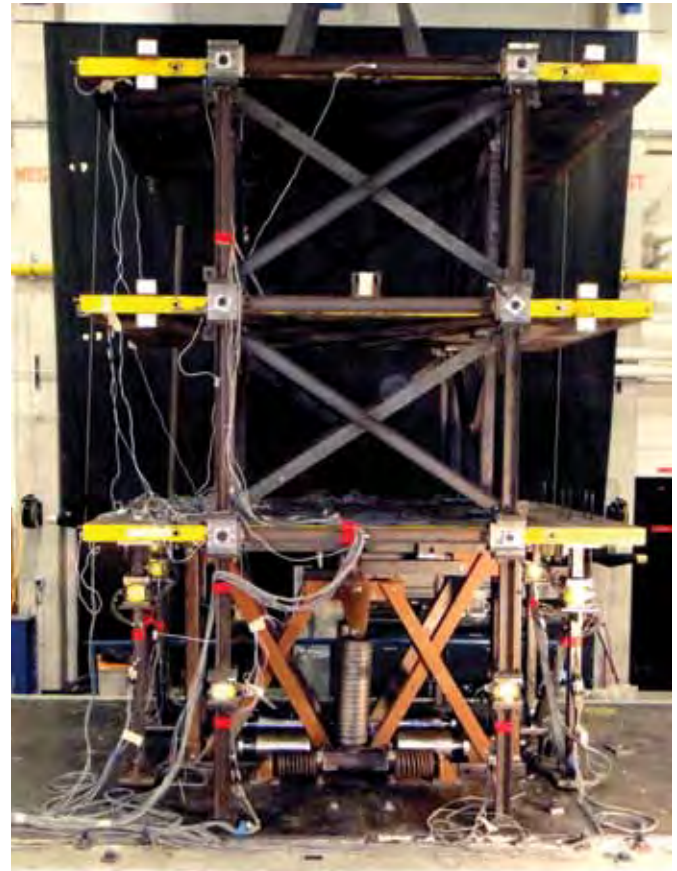
While the damping approach is efficient, it does not significantly reduce and may even amplify inelastic excursions and permanent deformations of the structural system during a seismic event. The novel negative stiffness device (NSD) developed in this project can emulate weakening of the structural system without inelastic excursions and permanent deformations.

The NSD produces yielding by engaging at a prescribed displacement and generating negative stiffness, thus reducing the stiffness of the combined primary structure and NSD system, which along with the damper, significantly reduces damage to the primary structure.

FUTURE

Future research involving adaptive stiffness shaping of structures would lead to further developments and innovations and code implementation.

The project PI's made an internationally broadcast NEES/EERI Webinar on the project with nearly 140 participants. Additionally, to disseminate the results widely, the PI's have made presentations at numerous conferences at the UC Berkeley, University of Illinois, Urbana-Champaign, University of Minnesota, UC Irvine and many other universities around the world.



Shake table testing of an inelastic three-story fixed-base structure with negative stiffness devices in the first story.

SELECTED RESEARCH PUBLICATIONS

Pasala, D.T.R., Sarlis, A.A., Nagarajaiah, S., Reinhorn, A.M., Constantinou, M.C. and Taylor, D. "Adaptive Negative Stiffness: A New Structural Modification Approach for Seismic Protection," *Journal of Structural Engineering, ASCE*, DOI10.1061/(ASCE)ST.1943-541X.0000615, 139 (7): 1112-1123 (2013).

Sarlis, A.A., Pasala, D.T.R., Constantinou, M.C., Reinhorn, A.M., Nagarajaiah, S., and Taylor, D. "Negative stiffness device for seismic protection of structures" *Journal of Structural Engineering, ASCE*, DOI10.1061/(ASCE)ST.1943-541X.0000616, 139 (7): 1124-1133 (2013).

Pasala, D. T. R., Sarlis, A. A. S., Nagarajaiah, S., Reinhorn, A. M., Constantinou, M. C., Taylor, D., "Seismic Response Control of Structures Using a Novel Adaptive Passive Negative Stiffness Device," Report No. MCEER-13-0004, Multidisciplinary Center for Earthquake Engineering Research, SUNY, Buffalo, New York (2013).

Sarlis, A.A., Pasala, D.T.R., Constantinou, M.C., Reinhorn, A.M., Nagarajaiah, S., and Taylor, D. "Negative stiffness device for seismic protection of structures," Report No. MCEER-13-0005, Multidisciplinary Center for Earthquake Engineering Research, SUNY, Buffalo, New York (2013).

Attary, N., Symans, M.D., Nagarajaiah, S., Reinhorn, A.M., Constantinou, M.C., Sarlis, A.A., Pasala, D.T.R. and Taylor, D.P. "Seismic Protection of Highway Bridges with Negative Stiffness Devices," Technical Report MCEER 13-0013, University at Buffalo, Buffalo, NY (2014).

The project website <http://www.ruf.rice.edu/~dsg/> has further details including journal publications, MCEER reports, and Ph.D. thesis resulting from the project.

A New Way to Create Seismically Resilient Buildings Using Unbonded Post-Tensioned Rocking Walls

NEESR-CR: Unbonded Post-Tensioned Rocking Walls for Seismic Resilient Structures, Sri Sritharan, Iowa State University, NSF #1041650, NEEShub Project Warehouse #946, [2010]

Principal Investigator

Sri Sritharan, Iowa State University

Co-Principal Investigators

Catherine Ellen French, University of Minnesota
Eric Musselman, Villanova University (formerly at University of Minnesota Duluth)

Educational Impact

Graduate students: 8

Undergraduate students: 10

Precast concrete is often used with prestressing through the use of bonded, internal active steel reinforcement called strands. For seismic applications, precast walls have been investigated with unbonded post-tensioning strands concentrated at one or more select locations so that they can recenter after experiencing a seismic load. Although these walls can resist lateral seismic forces, they lack the ability to dissipate seismic energy through a hysteretic mechanism. This drawback led to the development of Precast Walls with End Columns (PreWEC) at Iowa State University, which provides hysteretic energy dissipation through the use of easily replaceable O-connectors. In these investigations, the possible energy dissipation resulting from impact that takes place due to wall rocking was not captured.

To improve the understanding of self-centering walls under dynamic loads, Iowa State University engineer and researcher Sri Sritharan – who earlier developed PreWEC at ISU – led a project to develop seismically resilient buildings by studying the fundamental characteristics of Single Rocking Walls (SRW) and PreWEC systems as well as the interaction between rocking walls other structural elements including columns, beams and floor diaphragms.

IMPACTS

Researchers have determined that self-centering structural systems, including SRWs and PreWEC systems, could provide a significant reduction in the damage caused by a seismic event by resisting the lateral loads

caused by earthquakes. With the help of unbonded post-tensioning, these systems undergo rocking motions during earthquakes and thereby eliminate damage resulting from plastic hinge formation which typically occurs in conventional structural systems. As a result, the building designed with SRWs and PreWECs will be functional even after experiencing an earthquake, minimizing both downtime and associated financial losses. Findings include the following:

- A thorough understanding of energy dissipation due to impact of controlled rocking structures.
- Validation of the dynamic response of rocking structures and how their response can be captured using sophisticated analytical tools.
- Guidance on the use of SRWs and PreWEC systems.
- A thorough understanding of the seismic response of PreWEC systems connected rigidly with cast-in-place floors and gravity/seismic frames.
- Evaluation and improvement of a new type of connector to isolate the floor interaction with a PreWEC system in collaboration with an industry partner.
- The satisfactory use of pretopped precast floors in seismic regions.
- Evaluation of newly designed wedges to ensure development of sufficient strain in unbonded prestressing strands.

OUTCOMES

Previous research had shown that single rocking walls can provide excellent lateral force resistance with minimal structural damage, but information on the methods of energy loss caused by the rocking wall impacting the foundation was completely ignored and not well understood.

Professor Sritharan and his team conducted tests to quantify the amount of energy dissipation that can be reliably achieved through impact during rocking (i.e., radiation damping). The researchers also gathered unique data for PreWEC systems undergoing three-dimensional interaction with the floors and adjacent vertical elements to which they are attached, such as gravity columns.

RESEARCH METHODOLOGY

The team worked to develop new knowledge in the field through a five-prong approach. Studies were conducted on individual components, such as strand, anchorage, and coupling elements. At the NEES at University of Minnesota facility, large-scale, three-dimensional sub-assembly tests were used to investigate PreWEC-floor-gravity load system interaction, which could damage the floors and columns in addition to inhibiting the self-centering nature of the system.

At the NEES lab at the University of Nevada, Reno, the team did shake table studies on both SRWs and PreWEC systems in order to examine the impact of radiation damping and possible interaction between different damping components including damping expected due to hysteretic actions in PreWEC systems.

At the University of Auckland, New Zealand, the team did additional free vibration and shake table tests to investigate the influence of other variables including input motions and number of connectors. Finally, at the E-Defense shake table facility in Miki City, Japan, large-scale tests enabled researchers to compare the performance of two comparable buildings that incorporated conventional cast-in-place walls and rocking wall systems.

FUTURE

From the beginning, the project team involved a consulting engineer and several different precast companies who provided significant in-kind contributions for the large-scale tests. Between the tests, issues raised by the industry partners were addressed to ensure the outcomes of the project will be useful for SRWs and PreWEC to be easily implemented in design practice. Given the enthusiasm shown by the industry partners regarding the success of the project, field implementation of the new technology is expected in the near future.

The strand anchor tests led to the development and evaluation of a modified wedge geometry, which by increasing the ductility of post-tensioning systems, has the potential for rapid implementation in a broad range of industries including both building and bridge applications. The rocking wall tests on the shake-table confirm their reliable performance and help define the limits on when



Shake table test setup used at NEES at UNR for SRWs and PreWEC systems.

SRWs can be used and how much hysteretic damping is needed in a PreWEC system. The research on the three-dimensional interaction of the rocking wall system and surrounding structure is expected to produce design guidance on how to detail the floor and adjacent gravity columns to minimize damage to the surrounding structure and reduce the tendency of the damage to inhibit the self-righting nature of rocking wall systems.

SELECTED RESEARCH PUBLICATIONS

- Nazari, M., Aaleti, S., and Sritharan, S. 2014. Shake Table Testing of Unbonded Post-Tensioned Precast Concrete Walls. Proceedings of the 10th National Conference in Earthquake Engineering. July, Anchorage, Alaska.
- Watkins, J., Sritharan, S. and Henry, R. S. 2014. An Experimental Investigation of a Wall-To-Floor Connector for Self-Centering Walls. Proceedings of the 10th National Conference in Earthquake Engineering. July, Anchorage, Alaska.
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- Twigden, K. M., Watkins, J., Ma, Q., Henry, R. S., Sritharan, S., Cheng, Z. 2013. Experimental Testing of Self-Centering Concrete Walls and Wall-To-Floor Connection. In Proceedings of the Concrete Conference of the New Zealand Concrete Society. October, Queenstown, New Zealand.
- Abramson, D. A. 2013. Comprehensive Evaluation of Multi-strand Post Tensioning Anchorage Systems for Seismic Resilient Rocking Wall Structures. MS Thesis. University of Minnesota. May 2013.
- Qingzhi L., French E.C., Sritharan, S. 2014. Poster: Seismic Testing of PreWEC systems with Floor Interaction. Tenth U.S. National Conference on Earthquake Engineering Frontiers of Earthquake Engineering. July, Anchorage, Alaska.



4. LIFELINES

Lifelines provide the networks for delivering resources and services necessary for the economic well-being and security of modern communities. They are frequently grouped into six principal systems: electric power, gas and liquid fuels, telecommunications, transportation, waste disposal, and water supply. Taken individually, or in aggregate, lifeline systems are essential for emergency response and restoration after an earthquake, and are indispensable for community resilience.

The following projects are profiled in this section.

Ductile, Plastic Pipelines Secure Critical Services in Seismic Zones	54
NEESR-SG: Evaluation of Ground Rupture Effects on Critical Lifelines, Thomas O'Rourke, Cornell University	
Remotely Installed Liners Ensure Earthquake-Resistant Pipelines	56
NEESR-CR: Earthquake Response and Rehabilitation of Critical Lifelines, Thomas O'Rourke, Cornell University	

Ductile, Plastic Pipelines Secure Critical Services in Seismic Zones

NEESR-SG: Evaluation of Ground Rupture Effects on Critical Lifelines, Thomas O'Rourke, Cornell University, NSF #0421142, NEEShub Project Warehouse #13, [2004]

Principal Investigator

Thomas O'Rourke, Cornell University

Co-Principal Investigators

Harry Stewart, Cornell University

Kathleen Krafft, Sciencenter

Michael O'Rourke, Rensselaer Polytechnic Institute

Michael Symans, Rensselaer Polytechnic Institute

Educational Impact

Graduate students: 4

Undergraduate students: 10

Lifelines are parts of critical systems that deliver resources and services necessary for the economic well-being and security of our communities. Lifelines provide many essentials, such as power, fuels, telecommunications, transportation, waste disposal, and water.

NEES researchers, using a unique combination of large-scale soil-structure interaction at Cornell University and centrifuge-scale split box testing at Rensselaer Polytechnic Institute (RPI), performed a systematic and comprehensive assessment of ground rupture effects on critical underground lifelines. Deliverables from the project include:

- Quantification of serviceability and ultimate limit states for critical lifelines.
- Improved analytical procedures and guidelines for design.
- Experimental databases for benchmarking future numerical models and guiding the evolution of numerical simulations for soil-structure interaction.
- Validation and guidance for advanced sensor and robotics deployment in underground conduits.

The large-scale and centrifuge experiments demonstrated superior performance of high density polyethylene (HDPE) pipelines under abrupt ground rupture caused by earthquakes.

Polyethylene pipelines are made by thermo-welding lengths of pipe together to form a continuous pipeline. Conventional, segmental pipelines, by contrast, are not

continuous. They have couplings, or joints, which often are not restrained from pullout under tension caused by seismic loading. Segmental pipeline joints are generally weaker in bending and tension than a continuous pipeline.

IMPACTS

In Christchurch, NZ, the deployment of HDPE pipelines is being used to improve substantially the performance of water and wastewater systems following the Canterbury Earthquake sequence. In Los Angeles, HDPE pipelines are being used to reduce the seismic risk to the Los Angeles Aqueducts at the location where they cross the San Andreas Fault. In San Francisco, HDPE pipeline designs are being advanced for seismic retrofitting of critical facilities within the Auxiliary Water Supply System.

After the 2010 Darfield earthquake in New Zealand, NEES researchers with other members of a reconnaissance team advised the Christchurch City Council to replace damaged parts of its water distribution network with HDPE pipelines. The results were stunning. Even though two subsequent earthquakes induced soil liquefaction in the area of replacement, involving lateral spreading and settlements as large as two meters, there was not a single location of repair in the HDPE replacement pipelines.

Building on NEES test results and the favorable Christchurch pipeline performance, engineers are installing HDPE pipelines in the Elizabeth Tunnel, which carries all Los Angeles Aqueduct water across the San Andreas Fault. The tunnel is about three meters wide and conveys water by gravity flow. Pipelines of about 900 millimeter nominal diameter will be installed. The HDPE pipelines will be able to accommodate as much as 2.5 meters of lateral fault rupture, thereby conveying water even when the tunnel is virtually cut off. This installation is a cost-effective way to reduce the risk of fault rupture from more frequent, lower magnitude earthquakes.

In coordination with Cornell and Rensselaer Polytechnic Institute, the Sciencenter in Ithaca, New York, developed an interactive traveling exhibition for science museums called When the Earth Shakes. The exhibition shows how engineers at NEES sites study earthquake effects with networked experimental facilities.

It includes a simple hands-on shake table for K - 6 children to learn the basics of dynamic response and structural reinforcement and an interactive tsunami tank that allows users to experiment with wave-structure interaction. The

exhibition reaches over 100,000 people annually and allows offsite, web-based participation to broaden the range of outreach and demonstrate the capabilities of a collaboratory approach.

As part of the larger exhibition, five 90-second videos were produced that feature earthquake footage, engineering experiments, and interview with real engineers who describe how their work is making our built world safer through research.

The videos won several awards, including the Silver Davey Award. Cornell, RPI, and the Sciencenter won the Most Effective Education, Outreach, and Training Activity of the Year recognition from NEES Consortium, Inc. (NEESinc) in 2009 on behalf of the NSF-sponsored Network for Earthquake Engineering Simulation.

RESEARCH METHODOLOGY

This research on the safety and reliability of critical infrastructure was conducted at two NEES equipment sites: Cornell University and Rensselaer Polytechnic Institute (RPI). The equipment at these sites allows for large-scale soil-structure interaction and centrifuge-scale split box testing.

Cornell has large-displacement servo-hydraulic actuators and ancillary hydraulic systems, soil storage facilities and frame support systems for large-scale testing of lifeline-soil-structure interaction, and a variety of instrumentation and data acquisition systems. The facility allowed researchers to concentrate on detailed soil-structure-interaction for accurate representation of both the soil and buried lifelines in the vicinity of ground ruptures, where it is most important to duplicate pipe and soil material behaviors and reactions.

RPI has advanced split-box-centrifuge containers for simulating lifeline systems. These containers were used on the recently upgraded RPI 150 g-ton centrifuge. The research at Cornell involved the largest laboratory tests ever performed on pipeline response to ground rupture. Approximately 100 tons of soil were sheared and ruptured, generating fault displacements of 1.2 meters (4 feet) at the center of a 400-millimeter diameter pipeline composed of high density polyethylene. The RPI facility, through multi-g scaling, was able to simulate larger prototype dimensions and faster rates of loading. Both sites use telepresence (teleobservation, teleoperation, and teleparticipation) consistent with NEES requirements.

OUTCOMES

Large-scale testing at Cornell provided detailed, full-scale experimental data to compare with RPI centrifuge

data and advanced numerical modeling of soil-pipeline interaction. While emphasis was given to highly ductile pipeline materials, such as HDPE, significant attention was also given to steel pipelines used in numerous critical fuel, water, and electrical power facilities.

The experimental evidence provided by the full-scale tests confirmed the substantial ductility of HDPE pipe and the beneficial effects of its highly ductile performance in accommodating permanent ground deformation. The maximum measured strains for strike-slip displacement were far below strain levels associated with rupture of the pipe wall. The maximum reduction of pipe diameter due to ovaling, however, was greater than expected.

The experimental evidence therefore showed that loss of pipe cross-sectional area due to ovaling is likely to be the mode of deformation governing failure of larger HDPE pipes for earthquake-induced ground rupture effects.

FUTURE

Many water supplies and wastewater systems are beginning to deploy polyethylene piping for enhanced resilience to earthquakes, as well as other natural hazards. The use of highly ductile pipelines is expected to grow substantially.

The pipeline industry is now developing segmental pipelines that can accommodate large joint extension, compression, and rotation to accommodate earthquake-induced ground movements. Hence, the next generation hazard-resilient pipelines are being advanced by research and development at various companies, following the lead of NEES research.

SELECTED RESEARCH PUBLICATIONS

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Remotely Installed Liners Ensure Earthquake-Resistant Pipelines

NEESR-CR: Earthquake Response and Rehabilitation of Critical Lifelines, Thomas O'Rourke, Cornell University, NSF #1041498, NEEShub Project Warehouse #918, [2010]

Principal Investigator

Thomas O'Rourke, Cornell University

Co-Principal Investigators

Amjad J. Aref, State University of New York at Buffalo
Andre Filiatrault, State University of New York at Buffalo
Harry Stewart, Cornell University
Sofia Tangelos, State University of New York at Buffalo

Educational Impact

Graduate students: 5

Undergraduate students: 36

In the United States, there are more than 2.1 million kilometers of pipelines in water and wastewater systems. Nearly half of those consist of cast-iron pipelines ranging from 50 to 100 years old.

Thanks to the work of NEES researchers at Cornell University, SUNY at Buffalo, and CSU, Los Angeles, these aging underground lifelines, especially those in areas of high seismic hazard, may be rehabilitated through the remote installation of fiber-reinforced polymer liners in existing underground pipelines.

IMPACTS

The response and rehabilitation of critical lifelines can be enhanced substantially by in-situ pipe lining technologies that involve the remote installation of fiber-reinforced polymer (FRP) linings inside existing, underground pipelines through trenchless construction procedures.

In-situ linings are not used currently for earthquake protection, and the absence of experimental validation and analytical procedures for evaluating the seismic response of pipelines retrofitted with FRP technology is a barrier to the adoption of in-situ linings for improved performance.

Analytical models for seismic wave and permanent ground deformation effects on underground lifelines have been successfully harnessed to full-scale tests with the dual shake table facility at the University of Buffalo and the large-scale lifelines testing facility at Cornell to simulate the earthquake performance of pipelines retrofitted with FRP technology.

The results show that the retrofitted pipelines are able to accommodate very high levels of transient ground motion and moderate levels of permanent ground deformation. Thus, the in-situ lining technology is able to provide substantial benefits for strengthening in addition to rehabilitation of deteriorated underground infrastructure.

Education of the workforce was pursued in this project by conducting two annual short courses at the Los Angeles Department of Water and Power (LADWP), entitled "Water Supply Seismic System Performance, Planning, and Asset Management," with participation of LADWP managers and engineers, local consulting engineering companies, and Hispanic students from CSULA. Each short course was videotaped by LADWP and made available through the NEEShub. The course videos also were available at the Cornell and University at Buffalo NEES websites.

Research findings from this project were integrated into a freshman engineering course at CSULA, in which the students were required to design a new water conveyance system and support facilities. This course has been the foundation of a civil engineering design program that received two national awards for senior design projects.

OUTCOMES

The Cornell and University at Buffalo team developed a fundamental understanding – as well as analytical capabilities – for the in-situ reinforcement of lifelines. By combining full-scale experimental validation and computational simulation, the researchers are creating design and construction guidelines for such retrofits.

The research has dramatically increased the options for seismic mitigation of underground lifelines: in-situ lining technology has been qualified to retrofit existing underground infrastructure, averting the serious traffic and business disruptions and associated costs of excavating and replacing underground infrastructure in urban environments. The research work also has been disseminated to the water-industry through annual short courses and has been a catalyst in the United States to use rehabilitated pipes.

The research has explored the use of flexible electronics for combining micro-sensor systems with in-situ linings to create intelligent pipelines as a result of in-situ rehabilitation. The results of this work have the potential to transform underground utilities into real-time condition monitoring and data collection networks.

RESEARCH METHODOLOGY

The research has focused on cured-in-place pipelining (CIPP) technology, which involves the insertion of a flexible tubular membrane, which is saturated with a thermosetting resin, into an existing pipeline. The CIPP linings have been shown to be cost-effective and reliable for rehabilitation under both transient and permanent loading conditions.

Experiments in this collaborative project took place at the Cornell University Large-Scale Lifelines Testing Facility, at the University at Buffalo Dual Shake Table Facility, and at the California State University at Los Angeles (CSULA) Strength of Materials Instructional Laboratory. These laboratories were used for physical modeling in combination with advanced computational simulation to characterize the behavior of underground lined piping systems. The large-scale testing at Cornell was performed with large-stroke actuators linked together. The actuators were mounted on a reaction wall with movable pistons connected to a split test basin, which contained up to 100 tons of soil. These tests were able to simulate accurately soil-pipeline interaction under abrupt ground rupture conditions, which are representative of active faulting and the most severe types of ground deformation caused by liquefaction and landslides.

Full-scale dynamic testing of underground lifeline systems was conducted in the Structural Engineering and Earthquake Simulation Laboratory at the University at Buffalo, which hosts two high performance six-degrees-of-freedom shake tables that were positioned adjacent each other along a trench. Pipeline specimens were anchored to both shake tables to simulate the passage of a seismic wave through two adjacent push-on joints. The test results showed that pipelines reinforced with CIPP linings can accommodate very high intensity ground motions and can provide substantial seismic strengthening in addition to efficient rehabilitation of aging underground infrastructure.

Intelligent linings, or linings that include flexible electronics, are an exciting development for smart infrastructure technologies. Flexible electronics are devices on thin deformable metal or plastic foils mated to flexible polymeric substrates. In-situ linings embedded with micro sensor systems have the potential to transform local utility systems into real-time condition-monitoring and data-gathering networks.

Strain sensors capable of high strains of at least 60%, were fabricated from mixtures of multiwall carbon nanotubes (MWCNTs) mixed in polydimethylsiloxane (PDMS). The carbon nanotube and polymer mixture was optimized, and flexible gages, suitable for intelligent linings, were

fabricated and tested. A 2-4% by weight mixture of MWCNTs was found to produce a mechanically strong and conductive film that could be used as a strain gage.

The team partnered with Insituform Technologies, Inc., Progressive Pipeline Management, the Los Angeles Department of Water and Power, and the Center for Advanced Microelectronics Manufacturing at Binghamton University. These partnerships allowed for close interaction with industry.

FUTURE

The research has shown that FRP linings installed with trenchless construction methods can improve substantially the seismic response of existing pipelines in addition to enhancing performance and extending life under daily loading conditions. The additional seismic improvements from in-situ rehabilitation will provide more retrofit options in the future and open new markets for trenchless construction and in-situ rehabilitation companies. The knowledge gained from the comprehensive experimental program provides the basis for future improvements and optimization in the manufacturing and installation of FRP linings. Experiments with multiwall carbon nanotubes and polymer mixtures for flexible strain gages provides the catalyst for further development of flexible electronics suitable for intelligent linings in existing underground infrastructure.

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5. GEOTECHNICAL

Geotechnical engineering deals with the analysis, design, and construction of foundations, slopes, retaining structures, and other systems that are made of or are supported by soil or rock.

During a seismic event, soil may amplify ground shaking, interact with structural foundations, settle, liquefy, and spread laterally. Geotechnical engineers work to investigate and understand how the earth reacts in a seismic event, in order to reduce the damage caused to structures. Tests done with NEES mobile shakers and centrifuges have allowed researchers to gain a greater understanding of the reactions caused by an earthquake, in turn allowing them to protect and prevent the destruction of structures built on seismically vulnerable ground.

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Photo opposite: Preparation underway for testing the seismic fragility of the Sacramento-San Joaquin Delta levees.

Team Establishes Permanently Instrumented Field Sites

Permanently Instrumented Field Sites for Study of Soil-Foundation-Structure Interaction, T. Leslie Youd, Brigham Young University, NSF #0217421, [2002]

Principal Investigator

T. Leslie Youd, Brigham Young University

Co-Principal Investigators

Jamison Steidl, University of California, Santa Barbara
Robert Nigbor, University of California, Los Angeles

Educational Impact

Graduate students: 15

Undergraduate students: 46

In 2002, Brigham Young University Professor Leslie Youd, along with Jamison Steidl of UC Santa Barbara and Robert Nigbor of UCLA, initiated a program to establish the two permanently instrumented field sites used for NEES research into soil-foundation-structure interaction. This collaborative, multi-university project combined geotechnical, seismological, and structural engineering expertise, in a truly cross-disciplinary effort.

IMPACTS AND OUTCOMES

The project provided simple, well-characterized, densely instrumented field sites for the study of liquefaction, ground deformation, ground failure, and soil-foundation-structure interaction. New accelerometers, piezometers, inclinometer casings, and benchmarks were installed to monitor ground shaking, liquefaction, and induced ground deformation and displacement. A simple instrumented structure was constructed for use in active testing and passive earthquake monitoring to better understand soil-structure interaction. The project also provided teleobservation for remote monitoring and participation in experiments, and teleoperation capabilities for interaction with the site's equipment, permanently installed shaker, and downhole source.

The data collected over the last decade from active testing at the sites, as well as local and regional earthquake activity, not only has been the subject of multiple PhD theses, but continues to be analyzed by researchers worldwide, and remains available via the NEEShub for analysis by future researchers.

What makes these sites so unique and important is the unprecedented instrumented case histories provided during significant earthquakes. These case histories allow engineers to better understand how ground shaking and soil-type affect liquefaction susceptibility, by providing a detailed record of the generation of excess pore pressure, both in time and spatially within the soil layers. These unique observations help to improve our estimates of liquefaction hazard and our ability to simulate the effects of liquefaction in ground motion predictions.

RESEARCH METHODOLOGY

The Garner Valley Downhole Array (GVDA), located seven kilometers from the San Jacinto Fault and 40 kilometers from the San Andreas Fault, was originally instrumented in 1989 with funding from the Nuclear Regulatory Commission (NRC). The NEES project enhanced GVDA to include an instrumented structure intended to improve understanding of soil-foundation-structure interaction (SFSI). The structure's sensors provide observations from both rocking and torsional modes of the structure. This can be compared to fixed-base simulations to demonstrate the effect of soil on structural response. The NEES enhancement of the GVDA site included additional surface and borehole accelerometers to measure the response of the soil layers, and pore pressure transducers to monitor excess pore pressure generation and liquefaction. The NEES enhancement also included the addition of modern communications and data acquisition systems.

The Wildlife Liquefaction Array (WLA), located at the southern end of the San Andreas fault, was first instrumented by the US Geological Survey (USGS) in 1982. The USGS recorded 2 M6+ earthquakes in 1987, one of



The Wildlife Liquefaction Array (WLA) site operated by NEES at the University of California, Santa Barbara.



The Garner Valley Downhole Array (GVDA) site.

which generated liquefaction at the site, and the other which did not cause liquefaction. These well-known records provided the very first instrumented case histories of liquefaction. By 2002, much of the original instrumentation was no longer functioning. This NEES project rebuilt the WLA site with modern technology and three times as many sensors. The WLA site remains the most densely instrumented liquefaction monitoring site in the world.

The locations for the GVDA and WLA sites were chosen due to the high likelihood of a M6+ earthquake on the San Jacinto Fault and a M7+ earthquake on the southern San Andreas fault. While these events have yet to occur, the 2010 M7.1 El-Mayor Cucupah event in Baja, Mexico, about 90 kilometers from the WLA site, and multiple M5+ earthquakes in close proximity to both sites, have provided a trove of data in the first decade of NEES. These observations are producing extensive earthquake data sets that include observations from earthquakes in the magnitude range of 4 to 7, with maximum peak accelerations of about 30%g, well above the threshold where excess pore pressure generation and nonlinear effects start to become important.

With the large motions, pore pressure begins to build up in the liquefaction array at both sites. A nonlinear hysteretic finite difference model of the soil response was developed using the observed ground motions, making the pore pressure generation that occurs under moderate strain levels reproducible. An empirical model was developed

to predict pore pressure generation based on observed ground motions and shear strains within a saturated soil column using data from the GVDA and WLA field sites.

Teleoperation of the permanently attached shaker on the structure at GVDA has produced daily excitations that provide insight into the effect of seasonal and environmental conditions such as water table height, soil saturation, and temperature, on the structure's response.

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Tileylioglu, S, J.P. Stewart, and R.L. Nigbor (2011). "Dynamic stiffness and damping of a shallow foundation from forced vibration of a field test structure," *J. Geotech. & Geoenv. Engrg.*, 137 (4), 344-353.

Improving Seismic Performance of Structures by Quantifying Passive Earth Pressures

NEESR-II: Dynamic Passive Pressure on Full-Scale Pile Caps, Travis Gerber, Brigham Young University, NSF #0421312, NEEShub Project Warehouse #42, [2004]

Principal Investigator

Travis Gerber, Brigham Young University

Co-Principal Investigator

Kyle Rollins, Brigham Young University

Educational Impact

Graduate students: 9

Undergraduate students: 20

A pile cap is a reinforced concrete mass cast around the head of a group of piles, providing additional stability to building and bridge structures that the piles support. The interaction between the soil and the piles, as well as the passive earth pressure provided by the backfill material against the sides of the pile cap, provide the lateral resistance of a pile cap foundation.

Unfortunately, nearly all of the existing knowledge of load-displacement relationships for soils has been based on static or slowly applied loadings – not to the dynamic loadings that earthquakes apply. As a result, the engineering community can only apply static load-displacement relationships to seismic designs.

To address the problem and to quantify the effects of cyclic and dynamic loading that earthquakes cause on soils surrounding pile caps, Brigham Young University researchers Travis Gerber and Kyle Rollins undertook a study titled Dynamic Passive Pressure on Full-Scale Pile Caps.

The project defined specific load-displacement relationships for different types and densities of backfill soils. In addition to NSF grant funding, research funds were provided by the Utah Department of Transportation, with participation from the Departments of Transportation of California, Montana, New York, and Oregon.

IMPACTS

The research demonstrated immensely different behaviors depending on soil type and compactive effort (density). This behavior was correlated with different earth pressure theories to provide guidance for designers regarding how

much earth pressure can be expected based on soil shear strength parameters and levels of compaction.

It is important that these research findings are based on full-scale tests of real foundations, thus providing ground truth for design practices and also providing a benchmark against which theoretical and small-scale models can be compared. This information and other findings help engineers more reliably and efficiently design foundations to resist seismic loadings.

OUTCOMES

Passive earth pressure from the backfill acting on a pile cap (foundation) was found to significantly increase its load capacity. In the case of one pile cap with a sand backfill, loosely and densely compacted soils increased the total resistance of the pile cap otherwise without backfill by 50% and 245%, respectively.

As expected, ultimate resistance was found to occur at displacements of about 2 to 3% of the pile cap (foundation) height. The resistance provided by loosely compacted soils was found to be better described by Rankine earth pressure theory while the resistance of the densely compacted soils was better described by log-spiral earth pressure theory. Spatial displacement and cracking patterns in the backfill similarly reflect this conclusion.

Under both low and high frequency cyclic loadings, the apparent stiffness of the pile cap system increased with the presence of the backfill material and a dynamic damping ratio of at least 15% of observed, but the precise ratio will vary as inertial and total earth forces act in and out of phase.

The dynamic behavior highlighted the potential for changes in structural period due to changes in dynamic stiffness and damping ratio with forcing frequency and displacement amplitude. Other findings suggest that placement of a relatively narrow zone of densely compacted gravel immediately adjacent to a foundation where the surrounding soil is otherwise relatively loose can significantly increase the passive resistance provided by the soil backfill.

RESEARCH METHODOLOGY

Passive earth pressure contributes to overall stability of bridges and structures subject to the type of lateral loading that earthquakes generate. While the maximum

passive pressure acting on pile caps and abutment walls can readily be predicted, the issue of how passive pressure develops as a function of deflection is difficult. All of the load-displacement relationships previously used were derived from static or very slow loadings. Seismic loading conditions have both dynamic and cyclic effects present, which alter the load-deflection relationship. Cyclic loading effects typically reduce the strength and stiffness of the soil, but dynamic loading effects tend to produce an apparent increase in soil strength and stiffness due to material and radiation damping.

Using two 660-kip hydraulic actuators from BYU and the 100-kip/10-Hz eccentric mass shaker together with portable data acquisition equipment from the NEES at UCLA site, field testing was performed at two field sites in Salt Lake City, Utah – one near I-15 and South Temple Street and the other at the Salt Lake City International Airport.

At each site, a full-scale concrete pile cap foundation was constructed. The pile caps were then backfilled with soil and loaded using the actuators and shaker. Between the two sites, multiple backfill conditions were tested, including:

- 1) No backfill present (baseline response)
- 2) Loosely compacted clean sand
- 3) Densely compacted clean sand
- 4) Loosely compacted fine gravel
- 5) Densely compacted fine gravel
- 6) Loosely compacted coarse gravel
- 7) Densely compacted coarse gravel
- 8) A 3-foot (0.91-m) wide zone of densely compacted coarse gravel between the cap and loosely compacted clean sand
- 9) A 6-foot (1.83-m) wide zone of densely compacted coarse gravel between the cap and loosely compacted clean sand.

In the tests, the loading of the pile cap (foundation) was accomplished using the hydraulic load actuators and eccentric mass shaker in combination. The actuators were used to slowly push (statically load) the pile cap to incrementally larger displacement levels.

At each displacement level, the actuators were used to cyclically displace the pile cap a small distance and the shaker was then used to apply a dynamic loading on top of the static holding force from the actuators. In this manner, the pile cap was displaced under static loading and subjected to low frequency, small displacement loading cycles from load actuators and higher frequency, small displacement, dynamic loading cycles from the eccentric mass shaker.

The analysis and interpretation of the data collected during the full-scale field testing produced results associated with static, cyclic, and dynamic loading conditions. These results include horizontal load versus displacement relationships for the pile cap with differing backfill conditions and earth pressure distributions along the pile cap face. The results also include comparisons between measured and theoretically-based or calculated values.

Additional results include descriptions of vertical displacement, horizontal displacement and cracking of the backfill, as well as estimates of cyclic and dynamic stiffness and damping for the pile cap with different backfill conditions. The data provide insight into the performance of actual, full-scale foundations under earthquake-like loadings for a variety backfill conditions. The result of this research is the ability to make pile caps and abutment walls more efficient and reliable.

FUTURE

As part of this project, one additional backfill condition tested consisted of sand confined by mechanically stabilized earth (MSE) walls. The results of this test indicate that backfill bounded by MSE walls behaves differently than normal backfill. This backfill condition is becoming increasingly more common as MSE walls are used at bridge abutments, and this test serves as a baseline for future studies, studies since funded by several departments of transportation.

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Geotech Researchers Develop Models for Evaluating Liquefaction-induced Ground Displacements at Bridge Abutments

Pile Pinning Effects on a Bridge Abutment in Laterally Spreading Ground During Earthquakes, Ross Boulanger, University of California, Davis, PEER Lifelines, NEEShub Project Warehouse #205, [2005]

Principal Investigator

Ross Boulanger, University of California, Davis

Educational impact

Graduate students: 3

Undergraduate students: 1

Seismically generated ground liquefaction and lateral spreading under bridges presents a particular set of problems for bridge designers. In a landmark study, UC Davis Professor Ross Boulanger and his colleagues investigated the behavior in bridge piles at approach embankments and developed important recommendations for seismic design procedures that enable bridge piles to be designed to resist the damaging effects of liquefaction.

IMPACTS

Data from this research provided validation of a numerical simulation model and a design methodology that engineers have applied to bridges in liquefiable soil.

In addition, the team's analyses support the observation of a beneficial effect of the piles on embankment displacement and contribute to the broader validation of numerical simulation models. The improvement in the capabilities and limitations of numerical modeling is assisting in the development of practical and realistic design approaches for piled embankments in the field, where conditions are even more complex.

The National Cooperative Highway Research Program (NCHRP) 472 guidelines included a design methodology for the pinning effects that piles and bridge decks demonstrate in limiting abutment/embankment displacements and reducing demands on the piles. Until this study, that design methodology for "pile pinning" had never been validated by experimental data. Boulanger's study can be broken into three parts. First, the centrifuge tests confirmed the pile pinning effects and provided the first data set for validation of any analysis tools. Second, the team developed numerical models for simulating the dynamic response and deformations of these centrifuge

tests, and then used those calibrated numerical models to explore a broader range of conditions. Third, the team evaluated and revised the design methodology, which utilizes simplified methods, for estimating pile pinning effects in practice.

For impacts, the research results were incorporated in the design recommendations by Ashford et al. in the 2011/04 PEER report. In addition, these data and design procedures have been employed in a draft design guideline that is being applied on a trial basis at Caltrans.

OUTCOMES

Through the use of the FLAC software (a two-dimensional explicit finite difference software for mechanics computation) and the constitutive UBCSAND model, which estimates the response of the soil skeleton to general increments of loading, the researchers were generally capable of reproducing the primary features of the centrifuge tests, such as the patterns of deformation and differences between deformations between the piled and nonpiled embankments. Using the set of calibration protocols and numerical modeling details from this study, simulations tended to overpredict the magnitude of the embankment deformations. There are difficulties in using complex constitutive models and analysis tools to represent dynamic soil and structural responses, although the overpredictions may be the result of a conservative bias within the constitutive model or procedures.

Limitations of using 2D nonlinear deformation analysis (NDA) modeling to model 3D behavior was seen, as the 2D analysis missed many important out-of-plane factors, such as pore water flow, static shear stress bias, and lateral deformation. Despite the conservatism of the model, the importance of modeling the underlying dense sand layer became apparent as increasing stiffness of the sand provided support as well as increasing the intensity of the ground motions experienced by the loose sand layer.

RESEARCH METHODOLOGY

For this project, Professor Boulanger and his colleagues used the centrifuge at the NEES at UC Davis facility to examine two situations: pile groups in laterally spreading ground away from the abutments and pile groups at the abutments where the restraining or "pinning" effects of the piles and bridge superstructure can be advantageous.

Centrifuge model of two opposing approach embankments; the embankment in the foreground includes a pile group, whereas the embankment for the background does not.



Earthquake-induced deformation of piled bridge abutments in approach embankments with underlying liquefied soils may be reduced by restraining forces provided by the piles and bridge superstructure. Design methods have been applied in practice but lacked significant comparison with physical data, leading researchers to perform three dynamic centrifugal model tests to investigate pile-pinning effects.

The models consisted of identical embankments of dry sand separated by a channel, founded on a saturated loose sand layer overlying a dense sand layer. In each test, one of the embankments had a pile group at the crest with piles that extended into the saturated dense sand layer. All three centrifuge tests had the same soil properties and geometry, but different pile-group configurations or input motions. The model was placed under vacuum, clouded with carbon dioxide, and saturated from the bottom of the container upward until the channel between the two embankments was partially filled with fluid. To ensure that pore fluid could rise around the silt rather than through it, the silt layers didn't extend to the container walls. Prototype permeability was increased through the use of a methylcellulose solution as the pore fluid.

The researcher applied shaking motions perpendicular to the channel. For two models, motions were applied in a modified and scaled version of the ground motion recorded at a depth of 83 meters at Port Island during the 1995 Kobe earthquake. The third was subjected to two shaking events, the first consisting of 20 sine wave cycles and the second consisting of 42 sine wave cycles.

Based on the data gathered from the tests, nonlinear deformation analysis (NDA) was performed with the commercial program FLAC. The NDA captured the overall deformed shape of the tests, and the contours of the shear strain from the simulations give further insight into the failure surface at the end of shaking. The NDA also predicted

a strong reversal of bending moments in the embankment that was much greater than the measured bending moments.

FUTURE

The validation of different numerical simulation models for predicting pile pinning effects can now be systematically evaluated using the archived data; it is quite possible that such comparisons will identify limitations in different simulation tools and help guide improvements in them. These data are a great set for evaluating 3D effects as well.

Additional experiments are needed to cover different soil conditions, pile configurations, and the inclusion of bridge superstructures.

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Soil-Structure Interaction Research Supplies Key Data For Securing Cities During Earthquakes

NEESR-II: Towards Developing an Engineering Procedure for Evaluating Building Performance on Softened Ground, Jonathan Bray, University of California, Berkeley, NSF #0530714, NEEShub Project Warehouse #224, [2005]

Principal Investigator

Jonathan Bray, University of California, Berkeley

NEESR-SG: Seismic Performance Assessment in Dense Urban Environments, Jonathan Bray, University of California, Berkeley, NSF #0830331, NEEShub Project Warehouse #639, [2008]

Principal Investigator

Jonathan Bray, University of California, Berkeley

Co-Principal Investigators

Tara Hutchinson, University of California, San Diego
Bruce Kutter, University of California, San Diego
Robert Reitherman, Consortium of Universities for Research in Earthquake Engineering
Andrew Whittaker, State University of New York at Buffalo
Gregg Fiegel, Cal Poly, San Luis Obispo

Educational Impact

Post-doctoral scholar: 1
Graduate students: 10
Undergraduate students: 9

In the area of soil-structure-interaction, the relationships between ground and building responses to earthquake motions are not well understood. UC Berkeley Professor Jonathan Bray has led two research projects that have significantly advanced the field's understanding of the interacting responses of the ground and buildings to earthquakes.

IMPACTS

In Professor Bray's study, Towards Developing an Engineering Procedure for Evaluating Building Performance on Softened Ground, which he completed with graduate student Shideh Dashti, now a professor at the University of Colorado, Boulder, resulted in a procedure for evaluating building performance on liquefied ground. The goal was to find a way to predict structure movements by considering variables such as the timing, sequence and location of the cyclically-induced soil strength loss near buildings during earthquakes.

A related project, called Seismic Performance Assessment in Dense Urban Environments, explored soil-structure-interactions in dense urban environments and resulted in an improved understanding of the seismic performance of adjacent structures, a common occurrence in metropolitan areas. Data and insight from this study may lead to a more robust loss-estimation methodology for city blocks of buildings.

These research projects are notable for their educational impacts. Shideh Dashti earned her PhD (UC Berkeley) while working on Professor Bray's first SSI projects. Through the second SSI project, several graduate students earned their PhDs, including Ben Mason (UC Berkeley) who is now an assistant professor at Oregon State University. At UC San Diego, Nicholas Trombetta earned his PhD on the project; ZhiQiang Chen contributed as a post-doctoral scholar. Dr. Chen is now an assistant professor at University of Missouri, Kansas City.

At the University of Buffalo, graduate student Chandu Bolisetti will earn his PhD in 2014. Additionally, through Professor Fiegel's mentorship, nine undergraduate students enrolled at California Polytechnic State University, San Luis Obispo, actively participated in this project, and seven of these students have or will have earned graduate degrees in engineering.

RESEARCH METHODOLOGY

For both projects, Professor Bray and his team investigated soil-foundation-structure-interactions (SFSI) through a series of geotechnical-structural centrifuge experiments at the large, 9-meter-radius centrifuge at the NEES laboratory located at the University of California, Davis. Each test required approximately six weeks of setup and a week or so on the centrifuge arm, during which time the models were sequentially subjected to increasing intensity earthquake shaking. Data analysis was conducted at UC Berkeley for the first project. Data analysis for the second project, which was coined "Shaking of a City Block," took place at UC Berkeley, University at Buffalo, UC Davis, and UC San Diego. All data from the research is available for re-use on the NEEShub.

The Shaking of a City Block project examined foundation conditions and structural systems common to urban regions with high seismic hazard, such as downtown Los Angeles. The team had substantial guidance from a professional practice committee composed of design engineers familiar

with the issues and common building types in such cities. By using the Pacific Earthquake Engineering Research (PEER) Center OpenSEES simulation software in conjunction with centrifuge tests performed at the University of California Davis, it was possible to evaluate the capability of the team's numerical procedures to predict each building's seismic performance in each of the ground conditions and building configurations.

The large size of the UC Davis centrifuge enabled it to accommodate several model buildings during each experiment. In the first experiment, two nonlinear structural models with strategically placed inelastic fuses were separated so that each model responded independently, while in the second experiment, these two models were placed adjacent to each other so that structure-soil-structure-interaction aspects could be evaluated. In the next two experiments, grids of models were placed in the large centrifuge model container to replicate the arrangement found in a typical urban city block. The building models in these tests represented 3-to-9 story high structures founded on relatively dense sand. Some of the buildings had basements but most did not. Structures were founded on either individual spread footings or on a mat.

The final two centrifuge experiments of the Shaking of a City Block project involved various structures on ground that liquefied during the test. These two tests are among the first experiments wherein the seismic performance of adjacent structures on liquefied ground was captured. The experiments examined the sequence of liquefaction, ground failure, and the resulting impacts on the performance of adjacent structures, which are generally not available at key sites that are known to be affected by cyclic ground softening.

These two later centrifuge experiments built on the experience gained from the first project wherein Dashti and Bray tested the responses of different non-adjacent structures that had mat (thick slab) foundations overlying a soil deposit with a defined layer of liquefiable sand. Prior to these experiments, there was little understanding of the connections between ground response and building response. A thorough understanding of soil-structure-interactions was needed to develop advanced soil response models and building performance analytical procedures.

In small-scale centrifuge tests, the input motion, surface motion, ground conditions, ground response, and structural response can be carefully recorded and analyzed, which allowed the researchers to better understand ground failure and its impact on structures. Centrifuge tests investigated the importance of the thickness of the liquefiable soil layer

and its void ratio, as well as the effects of different buildings and foundation conditions on the response of liquefiable soils and building performance. This project allowed researchers to move beyond the practice of predicting free-field liquefaction to predicting structure movements by looking at the timing, sequence, and location of soil strength loss near constructed facilities.

FUTURE

The interdisciplinary composition of the Shaking of a City Block research team provided useful cross-training to the members of the project. This project advanced fundamental knowledge in engineering with substantial intellectual benefits to both geotechnical and structural engineering disciplines. The data and insights developed through the experiments and analyses serve as a sound basis in which to develop and evaluate new SSI design procedures. Moreover, the project has documented the experiences of the undergraduates involved in the research tasks, with recommendations for furthering such undergraduate research experiences. Lastly, the key findings, experiences and outcomes are shared broadly through a series of short videos available at the project website. The soil-structure-interaction knowledge unearthed by these projects will assist in urban planning for earthquake prone regions.

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NEES Research Provides New Tools for Predicting Soil Behavior

Using The NEES Field Shakers to Induce Liquefaction at Previous Liquefaction Sites, Kenneth H. Stokoe, University of Texas at Austin, USGS, NEEShub Project Warehouse #414, [2005]

Principal Investigator

Kenneth H. Stokoe, University of Texas at Austin

Co-Principal Investigator

Ellen Rathje, University of Texas at Austin

Field Measurement of the Linear and Nonlinear Constrained Moduli of Granular Soil, Kenneth H. Stokoe, University of Texas at Austin, NEEShub Project Warehouse #1174, [2011]

Principal Investigator

Kenneth H. Stokoe, University of Texas at Austin

Educational Impact

Graduate students: 5

In earthquake-prone regions, it is vital to predict how particular soils will behave under seismic conditions. Professor Kenneth Stokoe of the University of Texas at Austin, has led two studies that resulted in new tools for assessing soil behavior – significantly advancing our ability to create and evaluate, under controlled conditions, nonlinear soil behavior in the field.

IMPACTS

Specifically, Professor Stokoe and his research team developed a novel, direct-test method for dynamically assessing the liquefaction resistance of soils. With this new ability to make in-situ measurements, engineers have a powerful tool for evaluating the susceptibility of any given soil deposit to earthquake-induced liquefaction.

In this project, called Using the NEES Field Shakers to Induce Liquefaction at Previous Liquefaction Sites, the researchers demonstrated, for the first time, that pore pressure generation curves and nonlinear shear modulus reduction curves could be simultaneously developed from in-situ tests. These experiments were conducted at the NEES Wildlife Liquefaction Array (WLA) in Imperial Valley, California.

Operated by the NEES at Santa Barbara team, the WLA field site offered unique, well-documented conditions that contributed to verification of the test method.

The study demonstrated the potential this new field method has for advancing geotechnical research and developing new knowledge, especially in hard-to-sample soils like liquefiable or strain-softening soils. The results will also contribute significantly to research in the area of deformation-based liquefaction analyses.

In another project, Field Measurement of the Linear and Nonlinear Constrained Moduli of Granular Soil, Professor Stokoe and his team used the large, NEES at Texas mobile shakers, Thumper and T-Rex, to evaluate in-situ the constrained modulus over a range in axial strains. The constrained modulus represents the stiffness of geotechnical materials in one-dimensional compression that is created during earthquake shaking. The large shakers imparted vertical sinusoidal excitations directly above an embedded sensor array to create, for the first time, this type of loading under controlled conditions in the field.

This new methodology essentially performs parametric studies on the constrained moduli of geotechnical materials in-situ over axial strains ranging from linear to nonlinear. The research made important inroads for future investigations of the constrained modulus.

RESEARCH METHODOLOGY

In the first project, the researchers used the NEES at Texas T-Rex shaker to generate vertically-propagating shear waves in the ground, where embedded sensors were used to measure the response of soil particle motion and pore water pressure generation.

T-Rex was used to load the soil with a series of increasing dynamic horizontal loads. The embedded sensors allowed the coupled response of shear strains and pore water pressure generation to be evaluated. Testing was performed at three locations at the Wildlife Liquefaction Array.

Researchers found that different pore pressure generation responses between the test locations could be attributed to local site conditions, such as soil layering and fines content. Shear wave velocity profiles at each test location were similar. Odd pore pressure behavior at one site was attributed to partially saturated soil in the upper portion of the liquefiable silty-sand layer. These measurements



T-Rex in position to apply horizontal dynamic loads to an embedded array of sensors at the NEES Wildlife Liquefaction Array.

also emphasized the importance of making P-wave velocity measurements in potentially liquefiable soil deposits to determine their level of saturation.

For Stokoe's investigations into the linear and nonlinear responses of constrained moduli, the team used the NEES large shakers at the Hornsby Bend field site near the University of Texas. The field site has been created by the NEES at Texas team and has been used for various seismic investigations.

The NEES at Texas large shakers were used to impart vertical sinusoidal loads to the soil over a series of increasing amplitudes. The loading series was repeated at different vertical static loads. The resulting staged testing permitted parametric studies of constrained moduli to be conducted at different confining pressures over a large range in axial strains at each pressure. The constrained moduli were determined from constrained compression wave (P) velocities measured between an array of embedded vertical receivers. Average axial strains generated between sensors were estimated using a displacement-based method.

The resulting measurements of the variation in constrained modulus (M) with axial strain (ϵ) is rather complex. First, the constrained state is difficult to create. This state is only created directly beneath the central portion of the loading plate in the field. In this zone, measurements in a sandy silt showed that a constant value of M versus axial strain existed up to a threshold of $\epsilon \sim 0.0008\%$. As axial strain increased above the threshold, M increased – approximately doubling at the highest strain of 0.02% . The results of the study indicate that, for the first time, a field method can be used to investigate the constrained modulus.

FUTURE

The two field measurement methods have significant potential to create new knowledge that will continue to advance geotechnical earthquake engineering. Field-based research in liquefaction triggering of granular soils that are not readily tested in the laboratory is needed. No testing of soils under constrained compression exists in the civilian sector and field research is needed to replace or validate assumptions now made.

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Probing Peat–Based Levees in Sacramento–San Joaquin River Delta

NEESR-II: Evaluation of Seismic Levee Deformation Potential by Destructive Cyclic Field Testing, Scott Brandenburg, University of California, Los Angeles, NSF #0830081, NEEShub Project Warehouse #644, [2008]

Principal Investigator

Scott Brandenburg, University of California, Los Angeles

Co-Principal Investigators

Jonathan Stewart, University of California, Los Angeles
Robb Moss, California Polytechnic State University, San Luis Obispo

Educational Impact

Graduate students: 5

Undergraduate students: 1

In the wake of the significant agricultural damage caused by the 2004 breach of the Jones Tract in the Sacramento–San Joaquin River Delta and the devastating levee failures in New Orleans following Hurricane Katrina in 2005, earthquake engineer Scott Brandenburg and his research teams have worked to improve the existing understanding of peat-based levee reaction to seismic conditions. A professor of civil and environmental engineering at the University of California, Los Angeles (UCLA), Brandenburg has led two related studies investigating the behavior of the soils underlying the Sacramento–San Joaquin River Delta levees.

IMPACTS

Overall, the goal of the research was to measure the seismic deformation potential of peaty organic soil beneath a model levee using mobile field shakers. Liquefaction of saturated sandy materials within and beneath some levees is recognized as a significant, relatively well-understood, hazard. By contrast, much less is currently known about the seismic deformation potential of peat. Benefits of the study include a clearer understanding of the seismic response of levees resting atop peat, thereby improving seismic hazard analysis of the Delta levees.

The Delta levees are critical components of California's water distribution system. The Delta supplies fresh water to over 22 million people in southern and central California as well as eastern portions of the San Francisco Bay Area and directly supports California's \$400 billion per year economy.

The levees circumscribe "islands" that are commonly 3 to 5 meters below sea level. These levees continuously retain fresh water within the river channels with only about 1 to 1.5 meters of freeboard at high tide. A levee breach would flood the islands, inundating farmland and wildlife habitat with salt water. The risk posed by a strong earthquake is particularly perilous. Levee failures that allowed many islands to flood simultaneously, drawing saline water from the San Francisco Bay into the Delta, would severely damage the region's rich farmland and potentially halt the crucial flow of fresh water.



The NEES at UCLA eccentric mass shaker sits atop a model levee.

OUTCOMES

In the initial study, Brandenburg and his team worked to determine whether peat soils might contribute to levee settlement.

A model levee was constructed on the interior of Sherman Island near the western edge of the Sacramento-San Joaquin Delta. The NEES at UCLA MK-15 eccentric mass shaker, a portable earthquake simulation machine, was attached to a sturdy timber frame embedded in the model levee, and a suite of shaking intensities were imposed on the model levee at cyclic forces of up 40,000 pounds of dynamic force at a frequency of 3 Hz.

The embankment was heavily instrumented to measure acceleration of the levee and the surrounding soil, as well as pore water pressure under the levee. After shaking, long-term monitoring was performed to measure settlement induced by the weight of the fill after construction as well as any shaking-induced settlement of the levee.

Cyclic laboratory testing of the peat soils indicate that post-cyclic volumetric strain becomes significant in the peat when cyclic strain amplitude exceeds about 1%. This is a potentially significant finding that was previously unidentified, and has not been included in seismic hazard assessments for the Delta.

However, shaking of the model levee produced negligible settlement of the levee because levels of shear strain imposed on the peat were below the levels needed to trigger such deformations.

Continued on page 165

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Reinert, E.T., Brandenburg, S.J., and Stewart, J.P. (2013). "Measurements of translational and rotational dynamic stiffness for a model levee on peat," Proceedings 10th International Conference on Urban Earthquake Engineering, Tokyo Institute of Technology, Tokyo, Japan.

NEESR: Levees and Earthquakes: Averting an Impending Disaster, Scott Brandenburg, University of California, Los Angeles, NSF #1208170, NEEShub Project Warehouse #1161, [2012]

Principal Investigator
Scott Brandenburg, UCLA

Co-Principal Investigators
Jonathan Stewart, UCLA
Anne Lemnitzer, UCLA

In the second project, Levees and Earthquakes: Averting an Impending Disaster, Brandenburg and his team continued their investigations into the liquefaction and deformation risks of levees in the Sacramento-San Joaquin Delta.

The researchers constructed levee models on a geotechnical centrifuge at the NEES at UC Davis laboratory. This simulation technique enables a small-scale model to behave like a much larger prototype. Water is introduced on one side of the model to better produce reactions similar to those found in a full-sized levee. Sensors embedded in the models record acceleration, porewater pressure, and deformation in order to enable accurate characterization of levee response and the transmission of seismic energy through the various soil layers of a levee.

Two different model levees were tested on the centrifuge: (1) a nonliquefiable clay levee intended to mimic the cyclic field test, and (2) a liquefiable sandy levee intended to mimic realistic conditions in the Delta. Testing on the clay levee indicated that shaking produced post-cyclic volume changes in the peat soils, although settlements were relatively small. Work is ongoing to interpret the test data and develop constitutive models for peat for advanced numerical simulations.

Testing on the liquefiable levee resulted in significant settlement, and the levee was overtopped by the impounded water and an erosion channel formed as the water rushed over the levee. Furthermore, recent numerical simulations indicate that saturated sandy levees resting atop peat may be more susceptible to liquefaction than if they rested on stiffer soil conditions. Vertical accelerations in the fills near the levee toe generate an increment of shear stress that is not considered in many simplified liquefaction triggering evaluation procedures. It is anticipated that this research will therefore alter the manner in which liquefaction triggering procedures are applied to levees.

FUTURE

Future work on this project will involve first archiving and curating the experimental dataset in the NEEShub data repository. A thorough analysis of the data will be undertaken, including calculation of shear strains in the peat soils induced during shaking and comparison with laboratory test data that relates cyclic shear strain to volumetric strain. Finally, a constitutive model will be developed for peat soil that will be implemented in computational tools commonly used by geotechnical earthquake engineers.

New Process Uses Bacteria to Stabilize Soil, Sustainably

NEESR-II: Biological Improvement of Sands for Liquefaction Prevention and Damage Mitigation, Jason DeJong, University of California, Davis, NSF #0830182, NEEShub Project Warehouse #953, [2008]

Principal Investigator

Jason DeJong, University of California, Davis

Co-Principal Investigators

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Educational Impact

Post-doctoral scholars: 1
Graduate students: 2
Undergraduate students: 3

Liquefaction occurs when water-saturated soil temporarily loses strength and behaves like a fluid. Earthquakes can induce liquefaction by causing an increase in water pressure between the particles of soil.

Each year, to support new or existing infrastructure, over \$7 billion is spent on ground improvements to address the problem of liquefaction-prone soil. Most existing improvement technologies, however, are energy and cement intensive. So, although current methods are effective, they have relatively large carbon footprints.

The University of California, Davis has been at the forefront of an alternative ground improvement method called bio-mediated soil improvement. New, biologically driven soil improvement processes employ bacteria to control and regulate natural soil-solidifying processes, such as the precipitation of calcium, to improve soil properties.

Specifically, Professor Jason DeJong in the UC Davis College of Engineering investigates ground improvement methods harnessing biological processes that are less energy and carbon intensive than conventional methods.

IMPACTS

In a project called "Biological Improvement of Sands for Liquefaction Prevention and Damage Mitigation," DeJong and his team at UC Davis focused on microbial induced calcite precipitation (MICP). This method employs naturally occurring bacteria and only requires the addition of calcium and nutrients. The precipitated calcium effectively cements sand particles together, resulting in a sandstone-like material.

The team has developed a unified, bio-geotechnical approach for improved understanding of MICP, for advancing the field of biomediation, and for scaling the use of MICP for field applications.

OUTCOMES

Results from dynamic testing demonstrate a clear increase in resistance to liquefaction of MICP-treated sands compared to untreated loose sand. The observed behavior of bio-cemented sands in the direct simple shear tests confirmed observations made in previous tri-axial tests.

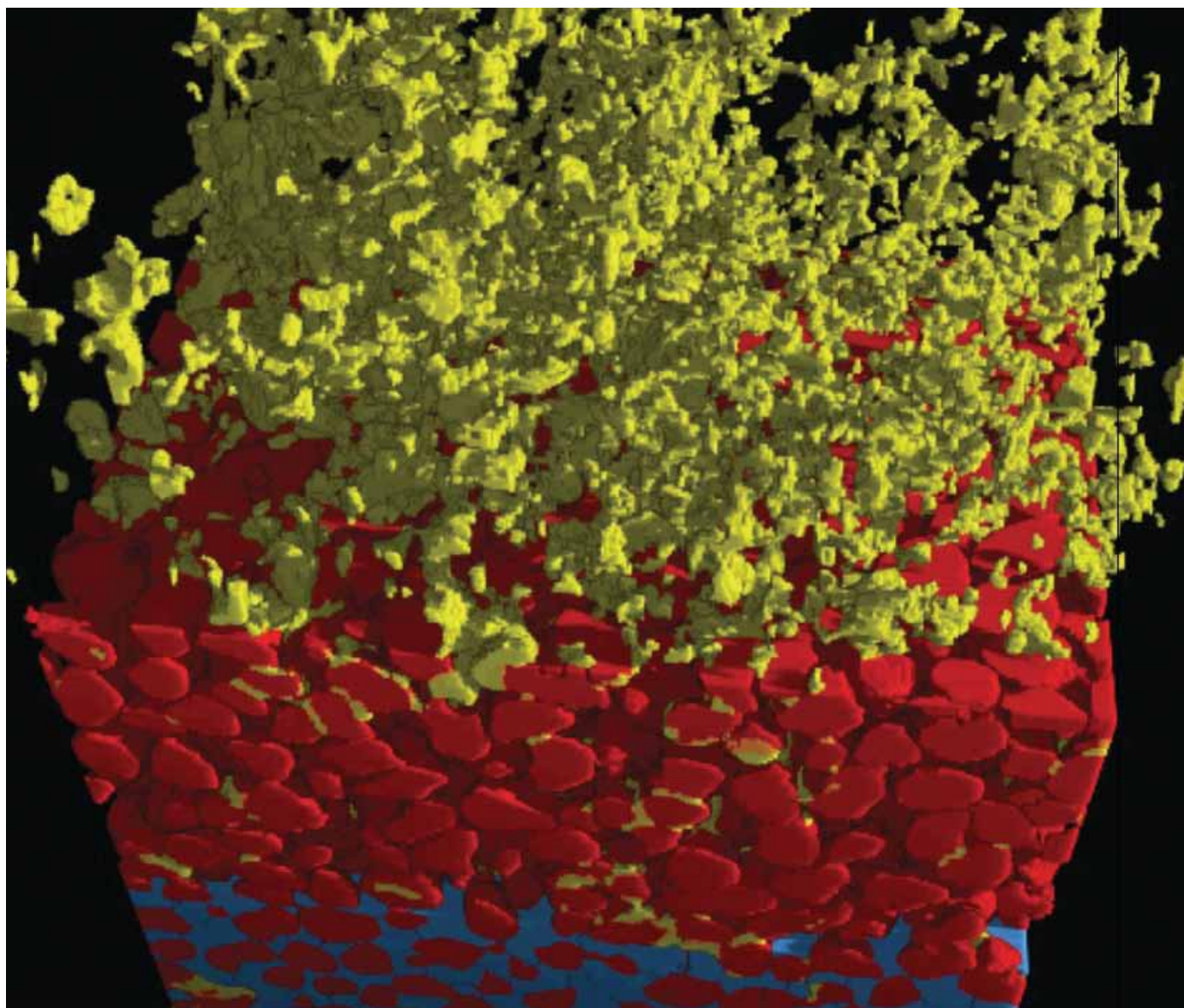
Increased resistance to liquefaction was demonstrated with a decrease in excess pore pressure ratios in the MICP-treated models as well as in post-shake settlements, although surface accelerations were amplified at heavy levels of cementation. The team recognized that when designing the soil improvement level, the natural tradeoff between improving liquefaction resistance and minimizing undesirable higher surface acceleration should be considered.

RESEARCH METHODOLOGY

Through the use of geotechnical centrifuge tests, Professor DeJong and his team evaluated and established the potential of MICP treatments to increase soil resistance to liquefaction triggering and to reduce the consequences if liquefaction does occur. For example, one set of centrifuge tests was designed to investigate the destabilizing effects of sensitivity, shear strength, and peak ground acceleration for sensitive clay slopes.

The small, 1-meter radius centrifuge at the Center for Geotechnical Modeling at NEES at UC Davis was used to test a simple model in order to evaluate the soil response. Tests were constructed identically but for the variation of cementation, or density, of the sand. The simple design was used to compare the behavior of the model at different treatment levels. A small, rigid structure was placed in the center of the model, with a small enough footprint so that less than 20% of the bearing pressure was felt by the soil at the base of the model.

MICP sands were treated to varying levels of cementation (light, moderate, and heavy cementation levels) and then assessed using non-destructive shear wave velocity measurements. The centrifuge models were subjected to sine waves of increasing amplitude. Acceleration, pore pressure, and settlement were measured in the soil.



3-D rendering of X-Ray CT scan of bio-cemented sand. Yellow is calcite, red is particles, blue is void space.

Change in soil behavior and post-shake shear wave velocity were investigated and dynamic tests were conducted at a centrifugal acceleration of 50g. The response of the MICP treated soil was compared to the untreated soil, loose and dense, as a baseline of poor and adequate behavior, respectively. In addition, the response of the soil in the free field and beneath the structure was evaluated and compared, and the response of the structure founded on the MICP treated soil was compared to the baseline behavior of the structure.

FUTURE

Research on MICP continues for Prof. Jason DeJong. He is now working with industry partners to identify opportunities for field scale testing.

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Generating New Knowledge About Seismic Behavior of Pile Foundations

NEESR-SG: Understanding and Improving the Seismic Behavior of Pile Foundations in Soft Clays, Kanthasamy Muraleetharan, University of Oklahoma, Norman Campus, NSF #0830328, NEEShub Project Warehouse #952, [2008]

Principal Investigator

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Key Senior Personnel

Arul Arulmoli, Earth Mechanics, Inc.

Juan Baez, Advanced GeoSolutions, Inc.

Educational Impact

Post-doctoral student: 1

Graduate students: 7

Undergraduate students: 7

High school students: 1

Pile foundations, which form an integral part of many civil engineering structures, have incredibly complex seismic behavior with interactions between soils, piles, and the superstructure. Weak soils like soft clays or liquefiable loose sands further exacerbate the complexities. Pile foundation behavior in liquefiable sands has been studied extensively but there has been a distinct lack of investigation into piles in soft clays or improved soils.

To address this lack of data, a research team led by University of Oklahoma Professor Kanthasamy Muraleetharan undertook a project entitled Understanding and Improving the Seismic Behavior of Pile Foundations in Soft Clays. The project is also known as “NEES pILes,” for piles in low E soils. E is a measure of soil stiffness and represents the Young’s modulus.

Professor Muraleetharan and his team investigated techniques for improving soft clays around pile foundations for seismic design and retrofit, as well as to determine how individual piles and pile groups behave during seismic events in improved and unimproved soft clays.

IMPACTS

The project for the first time systematically quantified the impact of soil improvement on seismic response of piles and pile groups. Uncertainty in the design and analyses of pile foundations in improved soft clays for seismic loading has been reduced through centrifuge and large-scale field tests. The industrial partners involved in this project are implementing the project findings in their practice as well as promoting the findings among other practicing engineers.

Readily implementable recommendations for practicing engineers were developed. Over 200 people, mostly practicing engineers, participated in the NEES/EERI research to practice webinar conducted by the project participants to discuss the key project findings and recommendations.

A successful education module, entirely based on edible materials, was developed for middle school students to expose them to concepts such as seismic behavior of pile foundations in soft soils, soil-structure interaction, and ground improvement in a fun and engaging manner.

OUTCOMES

The team designed, analyzed, and tested pile foundations in soft clays with and without ground improvement for earthquake loads. In addition, by examining pile and pile-group behavior during seismic events, they created a practical design methodology that benefits the broader earthquake engineering community. Findings include:

- Depending on ground improvement, lateral stiffness and resistance of a pile foundation can be increased 2 to 8 times and 4 to 5 times, respectively, from that of a pile in unimproved soil.
- Full benefit of ground improvement may be realized around 6.5 to 8.5D horizontal distance from the centerline of the pile, where D is the diameter of the pile. That is, further ground improvement beyond this lateral extent will only produce negligible improvement in the lateral loading behavior for the soil-pile system.
- Piles in improved soils can resist larger bending moments and shear forces, reducing the number of piles.
- The soil around a pile should be improved to a sufficiently large extent to realize the improvement in seismic behavior of that pile. If not, pile top acceleration for a pile in improved soil can be more than that of a pile in the unimproved soil.

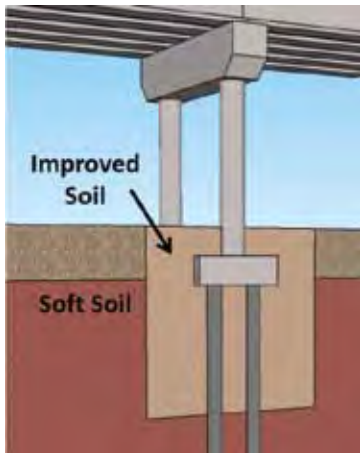


Diagram of piles and improved soil in place under a bridge.



Full-scale field testing in Miami, Oklahoma, using NEES at UCLA equipment.

- In pile groups, shadow-effect is minimal at 7D pile spacing. However, at 3D pile spacing, shadow-effect increases as the lateral extent of improvement increases.
- Simplified analyses can accurately capture the lateral load response of a pile in improved soils. Dynamic analyses are, however, essential for understanding the seismic behavior of single piles and pile groups in improved soil.

RESEARCH METHODOLOGY

Due to the difficulty of detecting foundation damage after a seismic event, current design practice avoids inelastic behavior of pile foundations by restricting their lateral displacements, a relatively easy process in competent soils. With weak soils, current practice calls for the use of a larger number of more ductile, larger diameter piles. These piles, however, are difficult to design and expensive to construct.

The team took an innovative look at an alternative solution, the improvement of soil surrounding the pile foundation – an infrequently used strategy since little is known about the behavior of improved versus unimproved soils. The project focused specifically on soft clays, which are quite prevalent in earthquake prone areas of the United States.

Through ground improvement such as Cement Deep Soil Mixing (CDSM), it is possible to restrict lateral displacements of piles during seismic activity. Static and dynamic loading tests on single piles and pile groups with different CDSM configurations confirmed that CDSM is an effective way to increase the lateral stiffness of the pile foundation and the lateral displacement can be significantly reduced. The larger the CDSM block, the smaller the dynamic displacements, and the peak acceleration of the top of the pile during an earthquake would also be significantly reduced.

Small-scale (1/30) model tests of single piles and pile groups in improved and unimproved soils were conducted at the

NEES at UC Davis centrifuge facility. The piles were subjected to quasi-static loading on top of the piles as well as simulated earthquake loadings in the centrifuge.

Full-scale testing took place in Miami, Oklahoma, with portable equipment from NEES at UCLA with a pair of identical steel pipe piles (1' diameter and 27' long) embedded in improved and unimproved soft clay. CDSM was used as the method of soil improvement. Piles were subjected to dynamic and quasi-static loading.

FUTURE

It is expected that the findings from this project will increase the use of ground improvement as a viable and economical solution for improving the behavior of pile foundations during earthquakes. The knowledge gained through this project will be extended through future research to behavior of pile foundations in other improved soft soils such as liquefiable sands.

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- Taghavi, A., and Muraleetharan, K.K. (2014). "Simulating Centrifuge Model Tests of Laterally Loaded Pile Groups in CDSM Improved Soft Clay Using a Nonlinear Winkler Model." Proceedings (CDROM), GeoCongress 2014, Geo-Institute, ASCE, Atlanta, Georgia, February.
- Cerato, A.B., Taghavi, A., Muraleetharan, K.K., and Miller, G.A. (2013). Educational Module to Demonstrate the Seismic Behavior of Piles in Improved and Unimproved Soft Soils. Journal of Professional Issues in Engineering Education & Practice, ASCE. 138 (4), 274.
- Fleming, B., Huang, J., and Sritharan, S. (2012). Seismic Behavior of Full-Scale Piles in Improved Soft Clay, Conference on Deep Foundations, Houston, Texas.
- Liu, C., Soltani, H., Pinilla, J. D., Muraleetharan, K.K., Cerato, A.B., and Miller, G.A. (2011). "Centrifuge investigation of seismic behavior of pile foundations in soft clays." GSP No. 211, Proceedings (CDROM), Geo-Frontiers 2011: Advances in Geotechnical Engineering, Geo-Institute, ASCE, Dallas, Texas, March, 585-594.

Retaining Wall Studies Revise Current Practices

NEESR-CR: Seismic Earth Pressures on Retaining Structures, Nicholas Sitar, University of California, Berkeley, NSF #0936376, NEEShub Project Warehouse #943, [2009]

Principal Investigator

Nicholas Sitar, University of California, Berkeley

Educational Impact

Graduate students: 3

Undergraduate students: 1

Modern advances in the understanding of the potential magnitude of seismic ground motions resulted in a significant increase in the magnitude of ground motions for which structures such as retaining walls must be designed.

As a result, traditional seismic design of retaining structures, based on experimental work dating to 1920's era experimental methods, are exceedingly conservative. This has led to overdesign and excessive costs for new retaining and basement walls.

In contrast, however, experience from recent major earthquakes suggests that retaining structures perform well even if they are under-designed for earthquake loading.

In a significant advance for earth-retaining structure modeling, UC Berkeley Civil Engineering Professor Nicholas Sitar embarked on an experimental and analytical study of the mechanics of soil-structure interaction between different types of retaining walls and the retained soil. The project was called "Seismic Earth Pressures on Retaining Structures."

IMPACTS

The results of the experiments, confirmed using advanced numerical simulations, showed that some of the basic assumptions currently accepted as given do not match observed behavior.

Most importantly, the observed loads were significantly lower than would have been predicted with traditionally used design methods. This study was complemented by a parallel study funded by the California Department of Transportation (Caltrans) and Caltrans immediately adopted the results of the study in their latest design recommendations. Caltrans also worked with the American

Association of State Highway Transportation Officials to similarly change its recommendations throughout the United States.

OUTCOMES

The objective was to characterize the seismic interaction of backfill retaining wall systems, such as basements and retaining walls, and to determine the actual magnitude of the resulting forces acting on the retaining structures during major seismic events. The experimental component of the work consisted of dynamic centrifuge tests on scaled models with sand and clay fill.

The investigations showed that stiff, embedded structures do not experience substantial increase in seismic earth pressure over that experienced by cantilever structures with a fixed base. The centrifuge experiment data similarly showed that one of the previously accepted solutions for a rigid structure on a rigid foundation is not representative of the most common conditions and unnecessarily overestimates the actual earth pressure by a very large factor.

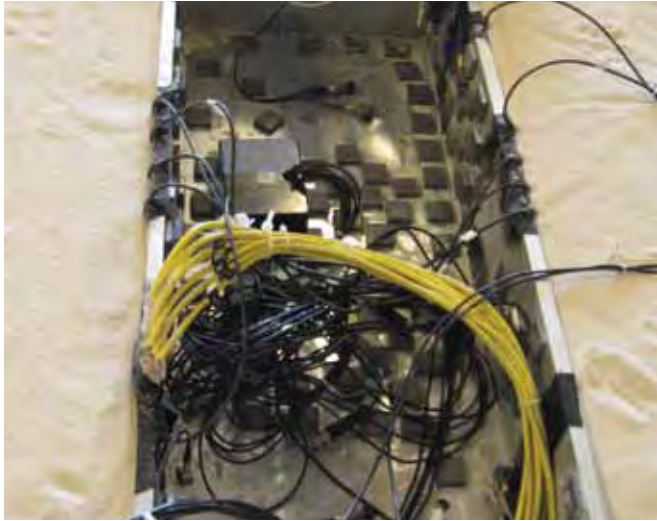
In addition, the experimental and numerical analysis results consistently show that the maximum dynamic earth pressures increase with depth and can be reasonably approximated by a triangular distribution analogous to that used to represent static earth pressures.

Consequently, this finding allows the point of application of the dynamic load at $1/3 H$ (height) of the wall, as originally suggested by Mononobe and Matsuo (1932), effectively halving the design moment at the base of the structure.

Finally, the results showed that typical retaining walls designed with a static factor of safety of 1.5 have enough strength capacity to resist ground accelerations up to almost 0.4g. Consequently, the recommendations stemming from this research provide an upper limit of expected seismically induced earth pressures for retaining structures that are in general lower than would have been obtained with traditional design.

RESEARCH METHODOLOGY

Observations of the performance of many different types of retaining structures in recent earthquakes showed failures were rare in basement or deep excavation walls and in other retaining structures such as braced excavation supports, even if the structures were not designed for the actual intensity of earthquake loading.



Experiments consisted of dynamic centrifuge tests on scaled models with sand (shown above) and clay fill.

Though some failures were observed, there was no evidence of a systematic problem with traditional static retaining wall design, even under severe loading conditions. No significant damage or failures of retaining structures occurred in the recent earthquakes such as Wenchuan earthquake in China in 2008 or the large subduction zone earthquakes in Chile and Japan, in 2010 and 2011 respectively.

This experimental study was undertaken to better understand the distribution and magnitude of seismic earth pressures on various types of retaining structures, such as cantilever retaining structures.

The purpose of the project was to produce a comprehensive study of the problem by performing a series of high quality geotechnical centrifuge tests to measure dynamic lateral earth pressures on embedded walls. In addition, the data from this research was used in the latest generation of non-linear code to produce better modeling and predictive capabilities as well as to develop probabilistic procedures suitable for the development of performance based design methodology.

The research took advantage of the advanced experimental research facilities at NEES at UC Davis to develop a better understanding of how soil and retaining structures interact during earthquakes. Centrifuge models, which are relatively inexpensive and reproducible, are ideal for the modeling needed, due to favorable scaling and boundary conditions, which allow for correct modeling of the soil behavior. The NEES at UC Davis centrifuge enabled Sitar to produce highly reproducible, high quality data in a relatively short time frame.



Trial 1 examined seismic earth pressures on a non-displacing and displacing retaining wall in sand.

FUTURE

Although this study forms an excellent basis for improving the design of typical retaining structures, the understanding of deeply embedded retaining structures, such as multi-story basements under tall buildings and shallow urban transportation tunnels, is still imperfect and needs to be examined further. At the same time, the results of this work will be gradually implemented in design of retaining structures and lead to significant design and cost efficiencies.

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Candia, G., Geraili Mikola, R. and Sitar, N. "Seismic earth pressures on displacing retaining wall in clay soil with slope ground (GC02)," *Network for Earthquake Engineering Simulation (database)*, Dataset, 2013, DOI:10.4231/D34746R4K.

New Testing Methodologies for Designing Seismically Safe Landfills

NEESR-CR: Seismic Response of Landfills: In-Situ Evaluation of Dynamic Properties of Municipal Solid Waste, Comparison to Laboratory Testing, and Impact on Numerical Analyses, Dimitrios Zekkos, University of Michigan, Ann Arbor, NSF #1041566, NEEShub Project Warehouse #920, [2010]

Principal Investigator

Dimitrios Zekkos, University of Michigan

Co-Principal Investigators

Mark Tufenkjian, California State University, Los Angeles
Neven Matasovic, Geosyntec Consultants

Educational Impact

Graduate students: 3

Undergraduate students: 20

In the United States, the majority of the municipal solid waste (MSW) generated each year ends up in landfills. Modern landfills are environmentally sensitive, sophisticated facilities similar in size to large dams.

IMPACTS

The potential seismic vulnerability of modern municipal solid waste landfills was highlighted by recent earthquakes in the United States. The impact of failures in these structures could be devastating to the environment and public health. Failure may be caused by excessive shaking and movement that damages the landfill's cover or subsurface containment system, as well as affecting the stability of the structure. Understanding the dynamic properties of landfills is a requirement to their reliable seismic analysis and design.

This research is providing new methodologies for field testing of solid waste, validating the applicability of large-scale laboratory testing of municipal solid waste, generating unique and unprecedented experimental field data, and developing recommended methodologies for the performance of seismic analyses of landfills.

OUTCOMES

Principal investigator Dimitrios Zekkos and his team from the University of Michigan worked closely with researchers from California State University in Los Angeles, the University of Texas at Austin, and with landfill designers from Geosyntec Consultants to gain a fundamental understanding of how landfills are expected to perform under seismic loading.

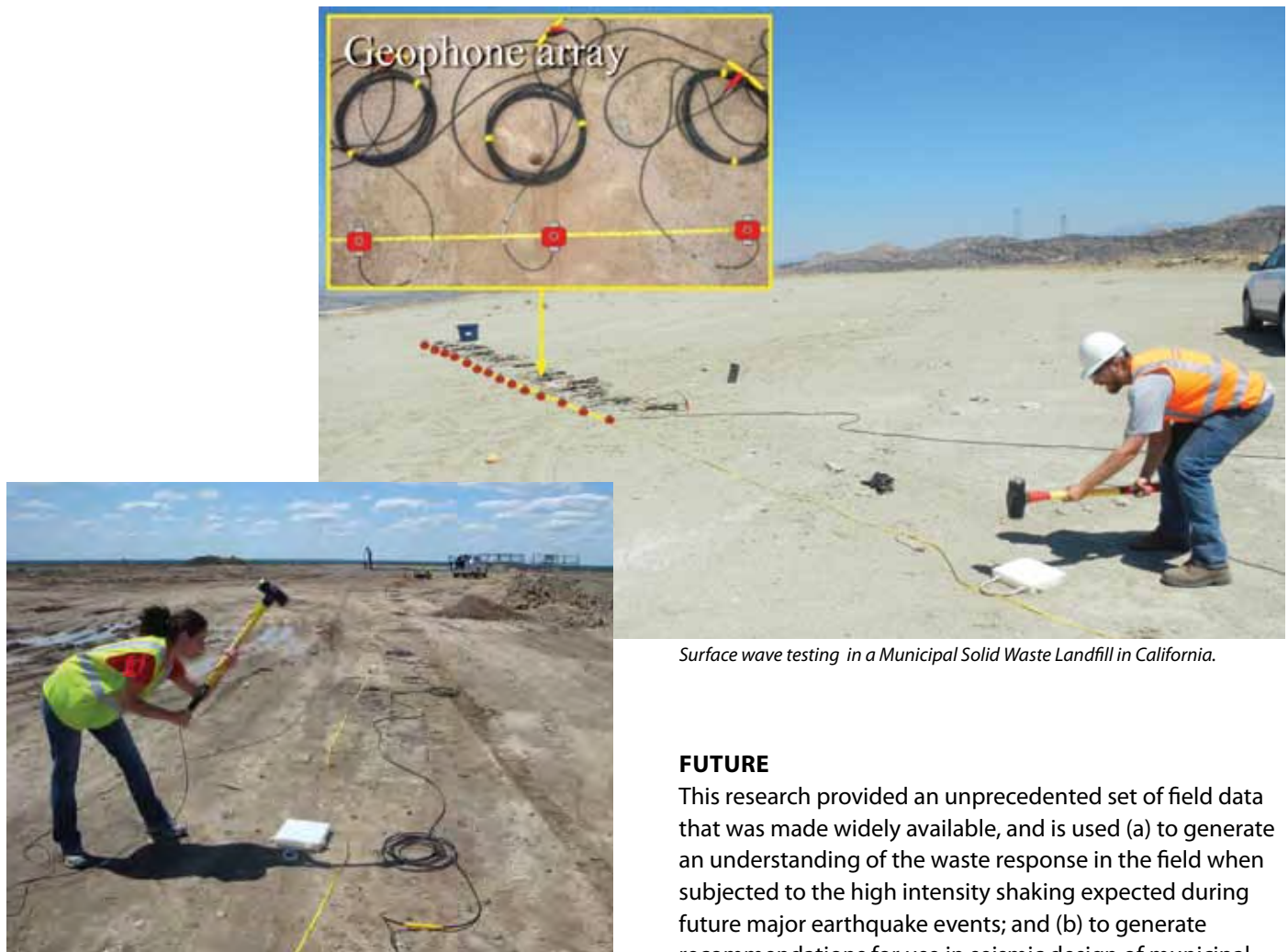
This study used two mobile shakers from the University of Texas at Austin, T-Rex and Thumper, to evaluate for the first time in-situ the dynamic properties of municipal solid waste not only in the small strain, but also in the intermediate-to-large strain range, where material response becomes nonlinear.

T-Rex is a truck-mounted, high capacity shaker that was coupled to geophone sensors to record the motion of the waste mass at various depths. Testing was performed at four landfills quantifying the variability of waste material and characterizing the influence of a variety of factors such as age, degradation, and moisture content on the dynamic properties of the material.

During field testing, test pits were excavated and waste material was collected. The material was used in the laboratory to reconstitute specimens and study the various



A mobile field shaker simulating earthquake shaking in an Arizona landfill.



Surface wave testing in a Municipal Solid Waste Landfill in California.

factors that affect the dynamic properties of waste, such as confining stress, density, and composition.

Additionally, the dynamic properties of reconstituted municipal solid waste were evaluated in the laboratory and were compared to results from the field. The comparison verified that the dynamic properties of reconstituted MSW evaluated in large-scale lab testing were generally representative of field conditions, a finding that affects research not only in earthquake engineering, but also in geoenvironmental engineering.

Large-scale laboratory tests took place at the University of Michigan and small-scale tests took place at California State University in Los Angeles.

Numerical analyses are currently performed using the new dynamic properties allowing the researchers to generate recommendations on the seismic response of landfills that can be used in designing these facilities.

FUTURE

This research provided an unprecedented set of field data that was made widely available, and is used (a) to generate an understanding of the waste response in the field when subjected to the high intensity shaking expected during future major earthquake events; and (b) to generate recommendations for use in seismic design of municipal solid waste landfills in seismic regions.

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Zekkos, D. (2013). "Experimental Evidence of Anisotropy in Municipal Solid Waste," *Proc., Coupled Phenomena in Environmental Geotechnics*, Politecnico di Torino, Italy, 1 – 3 July 2013, 69-79.



6. TSUNAMI

Researchers in tsunami hazard mitigation investigate new methods for modeling the generation, propagation and coastal inundation of tsunamis, and designing and constructing buildings, bridges, and other coastal structures to withstand the resulting loads and associated effects..

Tsunami hazard mitigation is focused on reducing the loss of life and property due to tsunami inundation so as to improve the resilience of coastal infrastructure and communities. Improved modeling of tsunami generation and open ocean propagation has been used to develop more effective evacuation procedures in tsunami-prone communities. Enhancements to tsunami inundation modeling have improved the understanding of flow velocities, resulting loads, and scour effects produced by a tsunami, and have allowed engineers to develop design standards for new structures to resist these loads and effects.

Much of the research on tsunami hazard mitigation has taken place at the Oregon State University's O. H. Hinsdale Wave Research Laboratory, which houses a large wave flume and one of largest tsunami wave basins in the world.

The following projects are profiled in this section.

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NEESR-CR: Impact Forces from Tsunami-Driven Debris, H. Ronald Riggs, University of Hawaii	

Photo opposite: The NEES at OSU Large Wave Flume, the largest in North America, is 104 meters long, nearly 4 meters wide and 4.6 meters deep.

Tsunami Projects Illustrate Impact of Landslide Modeling to Mitigate Real-World Tsunami Damage

NEESR-SG: Physical Modeling of 3D Tsunami Evolution Using a Landslide Tsunami Generator, Hermann Fritz, Georgia Institute of Technology, NSF #0421090, NEEShub Project Warehouse #343, [2004]

Principal Investigator

Hermann Fritz, Georgia Institute of Technology

Co-Principal Investigators

Leonid Germanovich, Georgia Institute of Technology
Alexander Puzrin, Institute for Geotechnical Engineering of ETH Zurich

NEESR-CR: Tsunami Generation by Landslides: Integrating Laboratory Scale Experiments, Numerical Models and Natural Scale Applications, Hermann Fritz, Georgia Institute of Technology, NSF #0936603, NEEShub Project Warehouse #968, [2009]

Principal Investigator

Hermann Fritz, Georgia Institute of Technology

Co-Principal Investigators

Zygmunt Kowalik, University of Alaska at Fairbanks
James Beget, University of Alaska at Fairbanks

Educational impact

Graduate students: 4
Undergraduate students: 8
High school students: 1

Tsunamis generated by landslides and volcano-flank collapse account for some of the most catastrophic natural disasters, and they can be particularly devastating in the near field region due to locally high wave amplitudes and runup. The events of 1958 in Lituya Bay, 1963 in Vajont reservoir, 1980 at Spirit Lake, 2002 in Stromboli, and 2010 in Haiti demonstrate the danger of tsunamis generated by landslides or volcano flank collapses.

IMPACTS

Critical field data from these events is limited. To address this lack of information, Georgia Institute of Technology researcher Hermann Fritz and his team investigated wave responses to landslide-generated tsunamis using 3D-modeling techniques developed at Oregon State University's tsunami wave basin.

The goal of these two projects was to mitigate damage and loss of life caused by tsunamis through hybrid modeling of landslide tsunami evolution in real-world scenarios, in which generation, propagation, and run-up stages overlap. The understanding gained from this research helped to compensate for the gaps in knowledge of landslide-generated tsunamis and the wave responses caused by them.

OUTCOMES

Tsunamis generated by three-dimensional deformable granular landslides are physically modeled based on the generalized Froude similarity. The team developed a novel pneumatic landslide tsunami generator (LTG) to control the individual landslide parameters at impact, thus enabling the study of wave generation and propagation across a wide range of landslide parameters in various water depth regimes.

The wave generation is influenced by the non-dimensional landslide parameters at impact. Three-dimensional landslide generated tsunami waves travel as radial wave fronts away from the impact region.

Recorded wave profiles were either non-linear oscillatory or non-linear transition type of waves. The leading wave crest amplitudes are mainly dependent on the landslide Froude number F and thickness S at impact, while the length of the slide additionally affects the leading wave trough and trailing waves. Wave periods and wavelengths are widely independent of the angular direction and increase with propagation distance.

The propagation velocity of the leading wave crest corresponds closely to the theoretical approximation of the solitary wave speed while the trailing waves are slower owing to dispersion effects.

Three-dimensional landslides are less efficient wave generators compared with two-dimensional cases, due to the increased landslide deformation in 3D compared with 2D and the spread of the unidirectional landslide energy across the radial wave front.

Between 1 to 23% of the landslide kinetic energy is converted into the wave train. The recorded 3D landslide generated tsunami waves are mostly weakly non-linear in nature and may span from shallow to deep water depth

regimes within a generated wave train. This unique experimental data on tsunamis generated by three dimensional deformable granular landslides serves as validation of numerical models.

RESEARCH METHODOLOGY

The bathymetric and topographic scenarios tested with the LTG were the basin-wide propagation and runup, fjord, curved headland fjord, and a conical island setting representing a landslide off an island or a volcano flank collapse. The LTG consists of a sliding box filled with 1,350 kilograms of landslide material which is accelerated by means of four pneumatic pistons down a 2H:1V slope up to velocities of 5 m/s. Two different materials are used to simulate landslides to study the granulometry effects: naturally rounded river gravel and cobble mixtures.

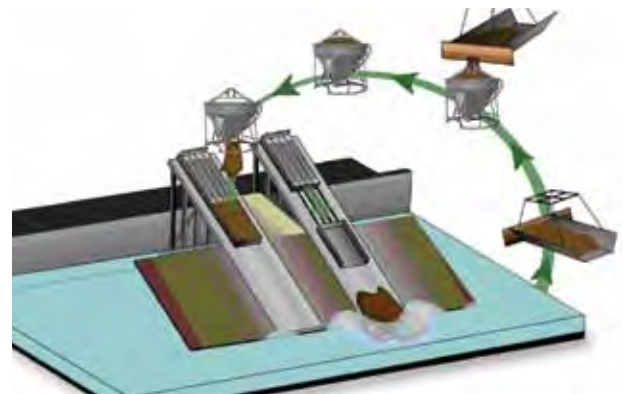
Water surface elevations were measured by an array of 40 resistance wave gauges. The landslide surface was reconstructed in 3D and surface velocities were computed with a stereo particle image velocimetry (PIV) setup. Wave runup was measured with resistance wave gauges along the slope and verified with video image processing.

FUTURE

Field data from landslide-generated tsunami are scarce. These experiments fill the gap for subaerial landslide impacts, while experimental data for 3D deformable fully submarine landslides is still missing. Numerical models validated based on the physical model scenarios and field data may be used for landslide tsunami hazard mapping and mitigation.



The team's novel pneumatic landslide simulator allows for controlled acceleration and shape of the granular landslide material. It consists of a sled which is driven by four pneumatic pistons.



Landslide tsunami generation cycle.



Landslide impact creates the first wave crest.

SELECTED RESEARCH PUBLICATIONS

Mohammed, F., and Fritz, H.M. (2012). Physical modeling of tsunamis generated by three-dimensional deformable granular landslides, *J. Geophys. Res. Oceans*, 117, C11015, doi:10.1029/2011JC007850.

Fritz, H.M., Mohammed, F., Yoo, J. (2009). Lituya Bay Landslide Impact Generated Mega-Tsunami 50th Anniversary. *Pure Appl. Geophys.* 166(1-2):153-175, doi:10.1007/s00024-008-0435-4.

Fritz, H.M., J.V. Hillaire, E. Molière, Y. Wei, and F. Mohammed (2013). Twin tsunamis triggered by the 12 January 2010 Haiti earthquake. *Pure Appl. Geophys.*, 170(9-10):1463-1474, doi:10.1007/s00024-012-0479-3.

Weiss, R., Fritz, H.M., Wuennemann, K. (2009). Hybrid modeling of the mega-tsunami runup in Lituya Bay after half a century, *Geophys. Res. Lett.*, 36, L09602, doi:10.1029/2009GL037814.

Mohammed, F., H.M. Fritz (2010). Experiments on tsunamis generated by 3D granular landslides, D.C. Mosher et al. (eds.), *Submarine Mass Movements and Their Consequences*, 4th Intl. Symposium, Series: Advances in Natural and Technological Hazards Research, 28:705-718, Springer, New York. ISBN 978-90-481-3070-2.

First-Ever Methodology for Tsunami-Resistant Structural Design

NEESR-SG: Development of Performance Based Tsunami Engineering, H. Ronald Riggs, University of Hawaii, NSF #0530759, NEEShub Project Warehouse #664, [2005]

Principal Investigator

H. Ronald Riggs, University of Hawaii, Manoa

Co-Principal Investigators

Ian N. Robertson, University of Hawaii, Manoa
Kwok Fai Cheung, University of Hawaii, Manoa
Solomon C.S. Yim, Oregon State University
Yin Lu Young, Princeton University

Educational Impact

Graduate students: 21

Undergraduate students 6

Tsunamis threaten coastal communities and infrastructure around the world. Tsunami-resilient buildings will lead to more resilient communities that are able to recover more quickly from a tsunami. In addition, horizontal evacuation is often impossible due to factors such as topography, population density, and short warning time. Hence, vertical evacuation is required for life-safety, and new and existing tall building and emergency centers should often be designed for vertical evacuation.

IMPACTS

In a first-of-its-kind effort, researchers H. Ronald Riggs, Ian N. Robertson, and Kwok Fai Cheung from the University of Hawaii, together with teams from Oregon State University and Princeton University, developed a methodology and tools for the implementation of site-specific Performance Based Tsunami Engineering (PBTE), which will allow for the analysis and design of coastal structures to withstand tsunamis.

Prior to this project there was little research on the effect of tsunami waves on coastal infrastructure such as buildings, bridges, and harbor facilities. The PBTE is having significant impact on building codes in tsunami-prone regions of the United States.

The structural design load standard in the United States is ASCE 7, Minimum Design Loads for Buildings and Other Structures. The current version of ASCE 7 does not include loads from tsunamis. A multi-year effort to develop a new chapter for the next edition of ASCE 7 is nearing completion. Many of the loading provisions in

this new chapter are based principally on the results from this study (and another NEESR project). With these provisions, structural engineers will have the guidance (and confidence) to design survivable buildings in tsunami inundation zones.

Through NEES and the Earthquake Engineering Research Institute (EERI), a nationwide webinar on tsunami design was given in 2013. This webinar was well-attended and introduced the design community to the fundamental issues and provisions of tsunami-resistant design.

Two REU students from Princeton University helped review design guidelines for erosion and scour protection of existing structures and assisted in development of the sediment transport experiments. At Oregon State University, all wave experiments in the tsunami wave basin were webcast, and a compilation of selected experiments was developed for webcasting to K-12 audiences.

Also, at the University of Hawaii, two high school interns worked with a graduate student and the PI on computational fluid dynamic (CFD) modeling of tsunamis. This work was then continued over three summers via a separate NSF REU site grant, during which undergraduate students from around the country spent the summer at the University of Hawaii working on CFD modeling of on-shore tsunami flow.

RESEARCH METHODOLOGY

The project employed the 3D Tsunami Wave Basin wave generator at the NEES at Oregon State University facility. The study focused on the experimental simulation of tsunami hazards to buildings and bridges. The complete experimental set-ups and the sequence of experiments, as well as all experimental data, are documented on the NEEShub.

A multi-faceted series of experimental tests were carried out for this project. In tests investigating tsunami bore formation over a fringing reef, the experimental data gathered during the numerous wave tests provided a valuable database for use in validation of numerical models.

Specifically, the numerically predicted wave plunging, hydraulic jump formation, and tsunami bore characteristics were all confirmed by the experimental data. This proved a positive step toward more accurate modeling of tsunami wave behavior as it comes onshore.



Wave propagating down the wave flume at the NEES at Oregon State facility.

Another set of tests focused on the fluid loads during tsunami inundation and run-up to which coastal infrastructure may be subjected. Tests quantified these loads, and then substantial effort was extended to quantify these loads by provisions useful for design.

Researchers determined that multi-story reinforced concrete residential and office buildings can be designed to survive tsunami fluid loads with less than 8% increase in reinforcing steel weight and less than 3% increase in concrete volume, and can therefore provide refuge through vertical evacuation. Out-of-plane shear of structural walls may require the addition of shear reinforcement in the form of headed studs.

A third set of tests focused on sediment transport and scour from tsunami inundation and run-up, which can also pose a significant risk to coastal infrastructure. The scour on the outflow, because of potentially high velocities depending on the onshore topography, can exceed the scour on inundation. The potential for liquefaction was also investigated as part of this series of experiments.

Both a residence and an office building were designed in accordance with IBC 2006. Each building was designed for three different seismic conditions common to Hawaii. Each was subjected to tsunami loads using guidelines provided by FEMA P646, which was based on preliminary project results.

FEMA P646 recommends one of two strategies: tie force strategy or missing column strategy. Tie force strategy consists of putting continuous reinforcement throughout beams and slabs so that if one fails, the reinforcement will redistribute the load.

Missing column strategy relies on plastic capacity of adjacent members to redistribute the load when one of the columns fails. These beginning ideas were designed to prevent the full collapse of a building in the event of a severe impact.

FUTURE

As mentioned previously, a multi-year effort is underway to develop a chapter on tsunami design load for ASCE 7. Initiated by Gary Chock, a practicing structural engineer and member of the PBTE team, the effort is pending acceptance by ASCE for the 2016 edition.

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Modeling Tool Provides Comprehensive Assessment of Tsunami Risk

NEESR-SG: TSUNAMIS: A Validated, Multi-Scale Tsunami Model for Hybrid Numerical-Experimental Simulation, Patrick Lynett, University of Southern California, NSF #0619083, [2006], NEEShub Project Warehouse #577, and NSF #1215454, [2011]

Principal Investigator

Patrick Lynett, University of Southern California

Co-Principal Investigator

Philip Liu, Cornell University

Educational Impact

Graduate students : 8

Undergraduate students: 12

High school students: 5

In a study aimed at bolstering the comprehensive engineering data and tools needed to mitigate structural damage from tsunamis, coastal engineer and researcher Patrick Lynett led a project to create a tsunami simulation software application called TSUNAMOS. The name stands for Tsunami Open Source Community Model; the project was called TSUNAMOS: A Validated, Multi-Scale Tsunami Model for Hybrid Numerical-Experimental Simulation.

IMPACTS

Before this study, there were few methods for accurately modeling and understanding complex near- and on-shore tsunami processes. TSUNAMOS, a comprehensive tsunami simulator, is based on results gathered from this project's experiments at the NEES at Oregon State University Tsunami Wave Basin facility.

TSUNAMOS allows research engineers to model experimental and geophysical-scale processes much more accurately.

To validate and calibrate the developed simulation tools as well as improve the field's understanding of nearshore, three-dimensional tsunami evolution, an extensive set of physical experiments were performed at the Tsunami Wave Basin. The team also created an extensible framework that provides a systematic structure for validating computational models with experimental and field data.

The team developed an outreach program targeting middle and high school students in coastal states. Students formulated a harbor tsunami-response plan

that was implemented and tested in the Tsunami Wave Basin. In addition, the research team provided significant knowledge transfer to engineering practitioners with NEES webinars that discussed harbor design, sediment scour, and sediment liquefaction. The webinars are available on the NEEShub.

OUTCOME

Using the 3D Tsunami Wave Generator at NEES facilities at Oregon State University lab, the researchers improved the existing understanding of nearshore three-dimensional tsunami evolution and refined modeling capabilities by coupling various components together in order to create a multi-scale simulation tool. Preexisting knowledge of three-dimensional nearshore evolution of tsunami waves was lacking, and the team worked to investigate breaking through focusing and bathymetry as well as overland flow across irregular and rough topographies. All of the data from the experiments is available online to all researchers, and the simulation tool is likewise open source and available for public use.

RESEARCH METHODOLOGY

Professor Lynett and his team performed experiments to investigate the three-dimensional turbulence and kinematic properties based on bathymetry.

Phase I of the project included dense measurements of free surface and velocity measurements for 3-D wave breaking under five different wave conditions, including solitary and N-waves. For each wave, acoustic velocity measurements provided 3D velocity data at 120 different x, y, z combinations clustered near the onset of breaking. Wave height was measured with wave gauges and the breaking envelope was tracked using overhead video through the course of 225 trials.

Phase II used a long shore-variable sloping beach to create a 3D bathymetry-forced breaking pattern. A single solitary wave and its depth condition was investigated, with the use of a pattern like a triangular reef, where the largest shelf existed along the centerline of the tank, tapering to zero at the basin side wall. The purpose was to force a 3D bathymetry-forced breaking pattern, while the free surface elevation was mapped with approximately 170 resistance wave gauges. Runup was recorded with video cameras, and dye studies provided information on the mixing and transport by the solitary wave.

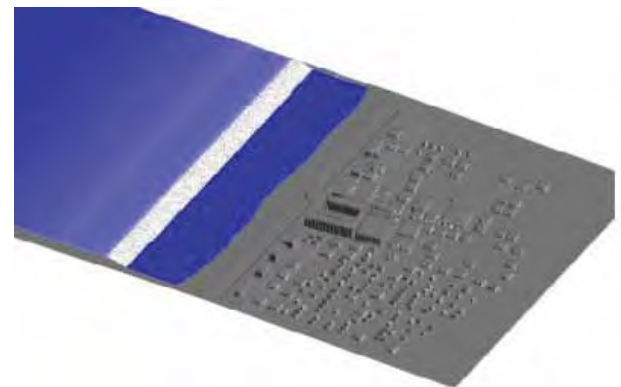


The Tsunami Wave Generator at NEES at Oregon State University.

Phase III of the TSUNAMOS project focused on the dynamics of a solitary wave passing by a conical obstacle, placed at the apex of an alongshore-variable shelf. The study included free surface elevation data recorded by wave gauges, as well as velocity and turbulence information from acoustic Doppler velocimeters, and a large-scale particle image velocimetry study in the lee of the obstacle.

FUTURE

The data from these experiments has been used in tsunami modeling workshops, and has become a standard benchmark case for researchers developing the next generation of hydrodynamic models.



Snapshots from a numerical model of a tsunami flooding a coastal town. The top plot shows the approaching tsunami, where the white face of the wave indicates breaking. The lower plot shows the wave inundating the town, and interacting with the infrastructure.

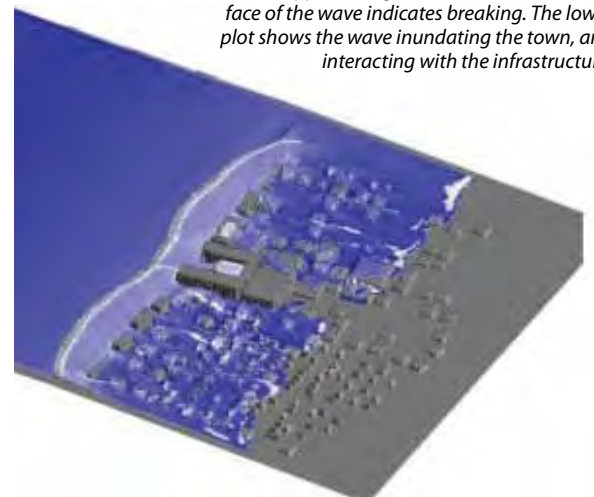
SELECTED RESEARCH PUBLICATIONS

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Discovering the Structural Impact of Tsunami-Driven Debris

NEESR-CR: Impact Forces from Tsunami-Driven Debris, H. Ronald Riggs, University of Hawaii, NSF #1041666, NEEShub Project Warehouse #942, [2010]

Principal Investigator

H. Ronald Riggs, University of Hawaii

Co-principal Investigators

Clay Naito, Lehigh University

Daniel Cox, Oregon State University

Marcelo Kobayashi, University of Hawaii

Educational Impact

Graduate students: 6

Undergraduate students: 5

Visually, the tsunami wave is frightening. But NEES researchers have discovered that tsunami-driven debris are a hidden source of very large loads on coastal structures.

University of Hawaii Professor H. Ronald Riggs led a project to clarify our understanding of tsunami-driven debris impact-forces on buildings and bridges. The multi-university research team focused on impacts of utility poles and shipping containers. Shipping containers, which are virtually everywhere in coastal zones, will float even when fully loaded.

The project, Impact Forces from Tsunami-Driven Debris, investigated the low-speed impact of heavy debris on structures, and it resulted in fully validated numerical models and load provisions that can be used for design.

IMPACTS

The structural design load standard in the United States is ASCE 7, Minimum Design Loads for Buildings and Other Structures. The current version of ASCE 7 does not include loads from tsunamis. A multi-year effort to develop a new chapter for the next edition of ASCE 7 is nearing completion. The loading provisions for fluid-driven debris impact in this new chapter are based on the results from this study. It is anticipated that the flood loading chapter will be updated to reflect the new research results and the improved understanding of debris impact.

Through NEES and Earthquake Engineering Research Institute (EERI), a nationwide webinar on tsunami design was held in 2013. Professor Riggs presented the debris-impact loading section of the webinar, which introduced

the design community to the new load formulation for this important design condition.

The study's experimental results have led to design load equations for structural designers to use to ensure their designs will withstand fluid driven debris. Researchers discovered that the impact forces are primarily caused by the structural impact, with a secondary effect provided by the fluid forces.

Project results will contribute to the improvement of community resilience in tsunami-prone regions, and are impacting future design specifications for forces of debris impact. These design specifications are particularly important for the design of tsunami shelters, fuel and chemical storage tanks, and for port and industrial facilities.

OUTCOMES

The study significantly improved upon the current understanding and predictive capabilities for tsunami-driven debris impact forces on structures. The team examined high mass, low velocity debris. Results were used to demonstrate the important physics leading to the impact forces and to validate simplified numerical models that can be used for design.

Water-borne debris can impose unanticipated loads when striking structures. This project validated a relatively simple theory to obtain design impact loads for wood poles and shipping containers. Results showed that longitudinal impact usually results in higher impact forces, and that equations based on simple wave propagation provides adequate estimates for the peak impact force.

RESEARCH METHODOLOGY

The team worked at the Large Indoor Structural Laboratory at Lehigh University, the Tsunami Wave Flume Lab at Oregon State University, and the Hawaii Supercomputing Center at the University of Hawaii. Water-driven debris generated during tsunamis and hurricanes can impose substantial impact forces on structures that are not designed for such loads, and researchers worked to determine how structural impacts really work.

Work at Lehigh determined the debris impact forces from tsunami-generated debris on structures. Full scale impact tests were carried out in-air with a wooden utility pole and a shipping container. However, it was discovered that the different codes (ASCE7, FEMA55 & FEMA P646, and AASHTO) predict very different loads. Testing showed that

the proposed equations for peak impact force and impact duration matched the experimental data sufficiently well as to provide an adequate approximation for design.

To assess if water-borne debris had an added mass effect, in-water tests were done in the Oregon State University large wave flume. A 1:5 scale shipping container model was used for tests that allowed researchers to quantify the effect of the fluid on the impact forces. The effect under investigation is essentially geometric, so the actual structural properties of a shipping container were not modeled. In both cases, the impact was centered on the bottom plate, which had a protruding lip to provide a contact between the bottom plate and load cell. The effect of the water was secondary compared to the “pure” structural impact, and can likely be neglected in the design.

It was determined that water-borne debris striking structures can impose unanticipated loads, and the current design specifications for such loads require updating with the models developed in this project.

FUTURE

The present study focused on moderate size debris. Large debris, such as ships and barges, was not considered. Future work on their impact on facilities near ports is an interesting extension of this work.



A 1:5 scale model shipping container in the Oregon State Wave Flume, waiting for the tsunami.



Shipping container in pendulum test setup at Lehigh University being inspected by Prof. Clay Naito.

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7. HYBRID SIMULATION

Hybrid Simulation is recognized as a powerful emerging technique that offers the opportunity for global system evaluation of civil infrastructure systems subjected to extreme dynamic loading.

In this approach a physical portion of the structural system (e.g., a bridge column) is tested, while components of the structure that are well understood may be replaced with a computational model. This approach offers an alternative or enhancement to traditional shake table testing to evaluate global responses for earthquake inputs. Thus, it facilitates testing of larger and more complex structures by integrating physical and computational portions in a single simulation.

Hybrid simulation offers great promise in accelerating the understanding of structural systems by enabling a broader range of testing at lower cost, through the integration of physical and computational simulations.

The following projects are profiled in this section.

Hybrid Models Shown to Simulate Complex Conditions Accurately..... 92

Behavior of Braced Steel Frames With Innovative Bracing Schemes
A NEES Collaboratory Project, Andrei Reinhorn, SUNY at Buffalo,
P. Benson Shing, University of California, San Diego,
Roberto Leon, Georgia Institute of Technology,
Božidar Stojadinović, University of California, Berkeley

Pioneering Studies Demonstrate Power of Real-time Hybrid Simulation 94

NEES Experimental Project for Verifying Full-Scale Semiactive Control of
Nonlinear Structures, Richard Christenson, University of Connecticut

NEESR-SG: Performance-Based Design and Real-time Large-scale Testing
to Enable Implementation of Advanced Damping Systems,
Shirley Dyke, Purdue University

An Open-Source, Integrated Earthquake Impact Assessment Tool 96

NEESR-SD: Framework for Development of Hybrid Simulation in an Earthquake
Impact Assessment Context, Billie Spencer, University of Illinois, Urbana-Champaign

Hybrid Models Shown to Simulate Complex Conditions Accurately

Behavior of Braced Steel Frames With Innovative Bracing Schemes — A NEES Collaboratory Project, NSF #0324277, Andrei Reinhorn, SUNY at Buffalo, NSF #0324468, P. Benson Shing, University of Colorado, (currently University of California, San Diego), NSF #0324542, Roberto Leon, Georgia Institute of Technology, NSF #0324629, Božidar Stojadinović, University of California, Berkeley, NEEShub Project Warehouse #24, [2003]

Principal Investigators

Roberto Leon, Georgia Institute of Technology (Currently Virginia Tech)
Božidar Stojadinović, University of California, Berkeley (Currently Swiss Federal Institute of Technology)
Andrei Reinhorn, State University of New York at Buffalo
P. Benson Shing, University of Colorado, Boulder (Currently University of California, San Diego)

Educational Impact

Post-doctoral scholars: 1
Graduate students: 4
Undergraduate students: 2

In an innovative study, an international, multi-university team used hybrid simulation testing techniques to develop and then evaluate the performance of suspended zipper frames through a combination of physical and hybrid simulation tests.

In the context of the 1994 Northridge and 1995 Kobe earthquakes, it was clear to earthquake engineers that modern steel frame buildings needed additional stiffness, which led to renewed interest in chevron braced frame configurations. Chevron braced frames, however, are not very ductile; once the traditional steel braces buckle, the reduction of brace stiffness causes severe deterioration and concentrations of deformations in particular floors.

To solve traditional problems associated with conventional braced frames, a team of researchers led by principal investigators from four universities developed and tested a new class of bracing system, known as a zipper frame. Principal investigators were Roberto Leon of the Georgia Institute of Technology (GT); Božidar Stojadinovic of UC Berkeley (UCB); Andrei Reinhorn of the University at Buffalo (UB); and P. Benson Shing from the University of Colorado, Boulder (UC).

IMPACT

This project was a groundbreaking demonstration of the benefits of hybrid simulation testing, verifying that hybrid models are capable of simulating complex conditions accurately.

Not only did hybrid models prove practical, the researchers developed an innovative bracing scheme for the suspended zipper frame. They developed and calibrated very accurate computer models of a Chevron braced configuration and zipper-braced configuration. The proposed design procedure for zipper-braced frames and related publications have been cited by AISC Seismic Provisions for Structural Steel Buildings.

To complement the collaborative research program, which included a large exchange of graduate students, a NEES undergraduate research (REU) program was developed. The program consisted of an undergraduate research experience at the sites and a summer undergraduate research exchange program.

OUTCOMES

The team's proposed design strategies resulted in suspended zipper frames having more ductile behavior and higher strength than ordinary zipper frames.

The first group of findings pertains to conducting a hybrid simulation test using NEESgrid. The team improved the testing algorithm and gained crucial experience in setting the algorithm parameters to enable distributed hybrid simulation tests. This was a crucial step toward making this testing technique robust, and demonstrated its capabilities in multi-laboratory tests between the NEES Berkeley and Colorado facilities.

The second group of findings pertains to the behavior of zipper-braced frames under quasi-static loading (performed at Georgia Institute of Technology) and dynamic loading (shaking table tests at the University at Buffalo). The teams implemented a zipper braced frame model in OpenSees and calibrated the model using the experimental results from both individual brace and one-third-scale three-story zipper-braced frame tests.

The results of the tests were very similar to the simulations produced in OpenSEES, with the first- and second-floor braces buckling and yielding. The structure showed a spread of yielding and buckling, fairly different from damage that appears in typical concentrically braced frames.

The effect of the vertical zipper element was dramatic, as it tied all braced floors together and channeled the force to the top story which was designed as a “top hat” truss. Hybrid simulation was proven to be an excellent tool to evaluate the seismic performance of structural systems with complex substructures, such as the suspended zipper frame’s chevron brace system. The results had been arranged and published and the design procedure has been noticed by AISC Seismic Provisions.

RESEARCH METHODOLOGY

The research consisted of two major phases.

In the experimental portion of the first phase, four laboratories – including Georgia Tech, the University at Buffalo, UC Berkeley, and the University of Colorado at Boulder – conducted experiments on the behavior of whole systems, subassemblages, and individual elements. The elements were tested under a variety of load regimes, ranging from shake table tests to quasi-static ones, in order to provide comprehensive data on which to base design recommendations.

The second phase of testing took place at the NEES at Buffalo site, in the new, NEES expansion of the Structural Engineering and Earthquake Simulation Laboratory (SEESL) of the Department of Civil, Structural and Environmental Engineering (CSEE) at the University at Buffalo (State University of New York). At UB, the team conducted shake table testing of a 3-story, 62 kips (~30 mtons), steel frame model equipped with advanced braces (“Zipper Frames”) on one of the two new seismic simulators.

RESEARCH METHODOLOGY

Conventional concentrically braced steel frames are incapable of redistributing large unbalanced vertical forces caused by brace buckling through the system. In order to retain the advantages of providing efficient stiffness and strength to limit inter-story drifts, new concentrically braced steel frame configurations were developed. The basic design objective for a zipper-braced frame is to mitigate the typical soft-story mechanism associated with braced frames by distributing more uniformly both story drift and energy dissipation over the height of a building.

A suspended zipper frame is designed to distribute the unbalanced forces along its height using the zipper column, a vertical structural element connecting the gusset plates at beam mid-span points from the second to the top story of the frame, unlike the conventional chevron braced frame.

Theories and analytical simulations demonstrate that the intended force redistribution worked as envisioned. However, the inelastic behavior of the entire frame depends strongly on the brace hysteresis and the interaction of the zipper columns. In a zipper frame, the unbalanced forces set up as a result of buckling of the inverted V braces in compression are taken by an additional vertical element, leading to nearly simultaneous buckling of all stories. Traditional inverted V braced frames exhibit poor performance arising from early buckling of the lower story braces. A different effect is seen in a zipper frame, which provides better performance by forcing simultaneous buckling of all braces.

Due to the geometry, most of the lateral stiffness is provided by the braces until they buckle. Once the braces buckle, the reduction in brace stiffness causes drastic force redistributions in the frame, which is caused in a highly nonlinear process. Tracing the force redistribution is very complex, prompting the need for a hybrid simulation test.

The results of the hybrid simulation tests were verified with an analytical simulation model using OpenSees. The analytical simulation models used the calibrated analytical brace to simulate the physical element at the first story. Comparing brace hysteresis showed that the analytical simulation test was an effective way to investigate a complex structural framing system like the suspended zipper frame.

SELECTED RESEARCH PUBLICATIONS

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Studies Demonstrate Power of Real-time Hybrid Simulation

NEES Experimental Project for Verifying Full-Scale Semiactive Control of Nonlinear Structures, Richard Christenson, University of Connecticut, NSF #0324558 and NSF #0612661, NEES Project Warehouse #648 [2006]

Principal Investigator

Richard Christenson, University of Connecticut

Educational Impact

Graduate students: 3

Undergraduate students: 1

NEESR-SG: Performance-Based Design and Real-time Large-scale Testing to Enable Implementation of Advanced Damping Systems, Shirley Dyke, Purdue University, NSF #0830173, [2008] and NSF #1011534, NEES Project Warehouse #648 [2009]

Principal Investigator

Shirley Dyke, Purdue University

Co-Principal Investigators

Anil Agrawal, City University of New York

Richard Christenson, University of Connecticut

James Ricles, Lehigh University

Billie Spencer, University of Illinois, Urbana-Champaign

Educational Impact

Post-doctoral scholars: 2

Graduate students: 9

Undergraduate students: 1

Damping systems are an effective and economical way to reduce structural damage from earthquakes. Dampers come in many forms, but they all work by reducing vibration, much like shock absorbers on a car. Advanced dampers are available that allow the damping to be controlled based on the vibrations in the structure, and these appear to offer the best performance. The low power requirements of semiactive devices make them highly appealing in a severe seismic event when external power may not be available.

Validating damper performance presents challenges. Small-scale simulations of damping systems in structures may not be convincing to structural designers, and large-scale structural tests are significantly more expensive.

To address this difficulty, two NEES research projects pioneered the use of real-time hybrid simulation (RTHS) to complete and validate physical tests of magneto-rheological

(MR) fluid dampers. In hybrid simulation, a physical portion of the structural system is tested in the lab while components of the structure that are well-understood are replaced with a computational model. RTHS enables such a test to take place in the actual time that the earthquake would occur, thus preserving rate effects.

One study led by University of Connecticut Professor Richard Christenson examined semiactive control for damping in nonlinear structures using RTHS, with the physical portion being three MR fluid dampers. With RTHS the dynamic behavior of the dampers is fully captured.

Another study, led by Purdue University Professor Shirley Dyke, developed and validated large-scale RTHS techniques where the physical portion was a 3-story steel frame with MR dampers placed between the stories. Studies such as these provide earthquake engineers a more thorough idea of how damping systems validated by hybrid simulation may improve the seismic performance of a variety of structures.

IMPACTS

The development of methods for hybrid simulation (HS) and real-time hybrid simulation (RTHS) of advanced structural damping systems has proven to be quite valuable to successfully validate damping systems. Magneto-rheological (MR) damping systems exhibit excellent protective potential; both projects examined and validated MR dampers. Furthermore, RTHS methods were applied in these projects in entirely new ways.

Christenson project. The project led by Professor Christenson produced (i) the first experimental demonstration of semiactive control in the presence of nonlinear structural behavior, and (ii) the first experimental implementation of MR dampers within NEES. With the structure included in the computational model and no physical damage occurring during a test, there was no limitation on the number of tests that could be performed. Furthermore, the research team opened up the testing to allow nine other United States and international research teams to join in the experiments, thus increasing awareness about RTHS for a number of new users.

Dyke project. The project led by Professor Dyke demonstrated (i) the use of advanced damping devices for designing high performing structures, and (ii) the viability of employing RTHS with large-scale frames. Prior hybrid testing involving large frame structures had not been performed in real time, and thus was not useful for evaluation of many

damping systems. Newly established algorithms to achieve real-time hybrid simulation will enable efficient evaluation of new structural systems. Experimental validation of the performance of advanced dampers in large-scale structures will increase awareness of the potential of advanced damping systems.

OUTCOMES

In the first project, Professor Christenson and his team investigated the mitigation of structural damage through innovative full-scale experimental verification of semiactive devices applied to structures exhibiting nonlinear behavior. New developments included: simulation models for large-scale MR dampers, verification that advanced dampers can reduce uncertainty in the building's response, and validation of the stability of these dampers in the presence of structural damage.

The project run by Shirley Dyke and her team performed the first large-scale RTHS on a complex frame system. New developments included: simulation models for large-scale MR dampers, algorithms that control coupled actuators and achieve real-time displacement tracking, performance-based design methodologies for structures with controllable dampers, and validation of RTHS methods using a large-scale frame.

In each of the projects, the models, methods and algorithms developed throughout the project were combined to demonstrate the validation of advanced damping technologies for civil engineering applications. The advanced dampers tested in these projects showed great promise for improving the seismic performance of steel frame buildings. Furthermore, the three large-scale MR dampers have been tested rigorously for the past 10 years demonstrating their durability.

RESEARCH METHODOLOGY

The earlier of the two projects used the NEES shared-use Fast Hybrid Test system at the University of Colorado at Boulder. Semiactive control of the advanced dampers more efficiently dissipated the energy of dynamic loads, while increasing the safety and performance of the structure. First, the team used simulation to develop control strategies for buildings exhibiting nonlinear behavior during large seismic events using a new high fidelity model developed from extensive MR damper characterization tests. The team then performed full-scale experimental verification. The hybrid simulation physically tested three semiactive 200 kN magneto-rheological fluid dampers while the nonlinear response of the structure was simulated computationally. Experiments allowed the team to verify control strategies they had developed in the initial stages of the project.

The project yielded the first experimental demonstration of semiactive control in the presence of nonlinear structural behavior and the first large-scale RTHS of MR dampers. Pioneering Studies Demonstrate Power of Real-time Hybrid Simulation.

In the second project, the team designed a 3-story prototype structure, and used this as the basis for many of the simulations and experiments. MR dampers were characterized and new high fidelity models capturing the dynamic control of these advanced dampers were developed. New control algorithms that overdrive the MR damper and speed up the response time were designed. Performance-based design methodologies were established for advanced damping systems.

All of these products were brought together to develop and validated real-time large-scale testing techniques. A large-scale structural frame was tested at the NEES at Lehigh Real Time Multi-Directional (RTMD) laboratory using RTHS techniques. The experimental setup comprised a 30-foot tall, large-scale damper-braced frame and MR dampers, while the gravity system and moment resisting frame were modeled as analytical substructures. Additional testing using the same setup considered a 9-story building. This project was the first successful experimental demonstration of RTHS applied to a large-scale frame with multiple actuators.

FUTURE

Innovation in the methods used to design, test and build our infrastructure will enhance resilience and reduce losses,

Continued on page 165

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An Open-Source, Integrated Earthquake Impact Assessment Tool

NEESR-SD: Framework for Development of Hybrid Simulation in an Earthquake Impact Assessment Context, Billie Spencer, University of Illinois, Urbana-Champaign, NSF #0724172, NEEShub Project Warehouse #685, [2007]

Principal Investigator

Billie Spencer, University of Illinois, Urbana-Champaign

Co-Principal Investigator

Amr Elnashai, University of Illinois, Urbana-Champaign

Educational Impact

Graduate students: 2

Undergraduate students: 1

In recent decades, researchers have improved their understanding of earthquake impact on structures. In particular, component-specific studies have allowed researchers to focus on particular problems at a fundamental level, and the recent development of hybrid simulation has increased the potential for growth and understanding.

However, as researchers gain the capability to gather larger quantities of data, the manner in which that data can be used has fallen behind.

To create a more reliable method for earthquake damage assessment, Professor Billie Spencer of the University of Illinois, Urbana-Champaign led a project to build a software tool called the NEES Integrated Seismic Risk Assessment Framework, or NISRAF. The NSF-funded study, called Framework for Development of Hybrid Simulation in Earthquake Impact Assessment Context, also leveraged significant resources through the Missouri Department of Transportation, the Federal Emergency Management Agency, the Federal Highway Administration, and the Mid-America Earthquake Center headquartered at the University of Illinois, Urbana-Champaign.

IMPACTS

The framework developed with this project is extending the state-of-the-art hybrid simulation approach to hybrid analysis and offers a novel method for hazard characterization and model calibration.

The NISRAF tool combines the necessary components for obtaining the most reliable earthquake impact assessment results possible. It allows researchers to obtain the most reliable earthquake assessment results from the integration of free-field and structure sensor measurements, hazard characterization, system identification-based model updating technology, hybrid fragility analysis, and impact assessment. It has been downloaded a significant number of times from the NEEShub and the project teams has fielded inquiries from many countries.

The combination of hybrid simulation with free-field and structure sensor measurements allows researchers a more complex system of analysis that provides more detailed and more reliable earthquake assessment results.

For seismologists, geotechnical and structural earthquake engineers, and for structural control and impact assessment experts, this project provides a stimulus to improve current algorithms to produce more reliable assessment of losses that underpin seismic mitigation, response, and recovery planning.

OUTCOMES

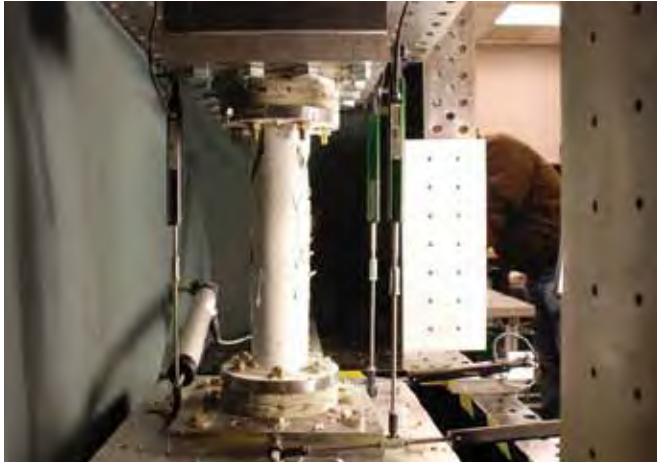
NISRAF is a user friendly software platform that allows engineers to efficiently and reliably perform impact assessment at a regional scale through a combination of exposure and sensitivity, namely, earthquake hazard and structural fragility. NISRAF provides accurate hazard and structural models and generates excellent fragility curves.

Hybrid simulation techniques enable NISRAF to integrate testing capabilities at multiple NEES sites, thereby employing the strength of existing computational models and the expertise of individual research groups to explore previously impractical problems.

The NISRAF source code is available on the NEEShub along with a user manual and sample data for the Burbank Building and the Meloland Road Overcrossing Bridge. The NEES team at Illinois is responsible for maintaining and providing technical support for the software.

RESEARCH METHODOLOGY

Researchers worked to develop an earthquake impact assessment framework that integrated hybrid simulation with free-field and structure sensor measurements, in addition to system identification-based model updating technology, probabilistic fragility analysis, and existing earthquake loss assessment software.



Physical testing at the NEES at Illinois MUST SIM lab.

The project utilized the one-fifth scale Loading and Boundary Condition Boxes (LBCB) at the NEES equipment site at the University of Illinois, Urbana-Champaign.

NISRAF was built and demonstrated via applications to an actual test bed in the Los Angeles area. A six-story steel building in Burbank, CA, and the Meloland Road Overcrossing Bridge in El Centro, CA, were used to conduct a pilot implementation of the earthquake impact assessment framework. Free field measurements were used to characterize the hazard at the site and define strong motion records while the structural sensors were used to tune the building and bridge-foundation-soil model.

From there, algorithms were developed and communication protocols were created to link sensor measurements directly to the hybrid system. Hybrid simulations were then undertaken with the use of the model and the input motion. The most critical component of the structural system was physically tested in the laboratory while the remainder of the structure was simulated analytically. Simulated results closely matched their measured counterparts. The building and bridge responses were used to derive fragility relationships which were used to estimate earthquake impact based on variation of the ground motion and pier/column response.

The integrated framework contains several advanced features. It has a user-friendly graphical interface, and the software and source code are open to the public, allowing NISRAF to be used efficiently. NISRAF is extensible and accessible, meaning that each component is developed separately, which facilitates understanding and maintenance. It is extensible to the most recent



Hybrid simulation setup using NEES facilities at the University of Illinois, Urbana-Champaign.

research findings and program techniques, due to its modular nature. NISRAF also allows for efficient and reliable impact assessment, since this is the first time that all the components for impact assessment were integrated and work seamlessly in a single software platform. The integrated feature provides highly advanced tools in order to obtain very reliable earthquake impact assessment results.

FUTURE

Two proof-of-concept pilot studies have been implemented to validate the software and the integrated approach based on small-scale tests. Large-scale implementations in the future will be able to show a greater benefit to society.

SELECTED RESEARCH PUBLICATIONS

- Li, J., Ruiz-Sandoval, M., Spencer Jr., B.F., and Elnashai, A.S. (2014). "Parametric Time-domain Identification of Multiple-Input Systems Using Decoupled Output Signals." *Earthquake Engineering and Structural Dynamics*, Vol. 34, No. 9, pp.1307-1324.
- Li, J., Spencer Jr., B.F., and Elnashai, A.S. (2013). "Bayesian Updating of Fragility Functions using Hybrid Simulation." *ASCE Journal of Structural Engineering*, Vol. 139, No. 7, pp. 1160-1171.
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- Lin, S., Li, J., Elnashai, A.S., and Spencer Jr., B.F. (2012). "NEES Integrated Seismic Risk Assessment Framework (NISRAF)," *Proc. The 2012 NZSEE Annual Conference, the University of Canterbury, Christchurch, New Zealand.*



8. CYBERINFRASTRUCTURE

The NEES cyberinfrastructure, with the NEEShub as its focal point, provides a state-of-the-art shared research and education environment. The cyberinfrastructure connects and empowers the network's 14 distributed earthquake engineering facilities, serves as a curated data repository for engineering researchers and professionals, and provides powerful computing tools for the research and education community dedicated to the mitigation of losses from earthquakes.

Computing systems. *The NEEShub is powered by Purdue University's HUBzero, a powerful, open-source software platform for supporting scientific research in educational activity. The NEEShub provides seamless access to tools, data, and high-performance computing venues. The NEES cyberinfrastructure provides abundant storage space and computing infrastructure for simulation.*

Data. *NEES provides access to earthquake engineering data through its Project Warehouse, which contains traditional NEES experimental research data, test-results, and databases, as well as searchable, community-contributed repositories of earthquake engineering research data, vetted by professional communities.*

Information resources. *NEEShub contains a wealth of learning and outreach information oriented to all levels of students, teachers, and engineering practitioners. The following projects are profiled in this section.*

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NEEShub: Co-location of Research Data and Software Tools Advance Research

NEEShub: Co-location of Research Data and Software Tools Advance Engineering Research, developed under NEES Operations, Julio Ramirez, Purdue University, NSF #0927178, [2009]

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Ellen Rathje, University of Texas at Austin

Thomas Hacker, Purdue University

Barbara Fossum, Purdue University

Project Team

Brian Rohler, Director for Information Technology, Purdue University

Stanislav Pejša, Data Curator, Purdue University

Educational Impact

Graduate students: 33

Undergraduate students: 24

Today, much of the world is fully connected through the Internet. People can keep in touch with friends and family anytime, anywhere in the world. Similarly, distributed research communities are emerging that empower academics and practitioners to undertake research, share expertise, software, and knowledge — anytime and anywhere. One of the challenges facing these communities is the need for an “always on, always available, accessible anywhere” information resource that can provide easy access to software, data, and communications facilities.

Over the past decade, the National Science Foundation created a network of earthquake engineering facilities, the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES), to allow the civil engineering community to undertake new forms of discovery and experimentation that would not have otherwise been possible. To address the research needs of this community and provide access to software, project data, and collaboration tools, Purdue University created the NEEShub, a robust computing platform based on Purdue University’s HUBzero software, at nees.org. The NEEShub provides easy access to tools and the nation’s most powerful computing resources, a curated and authoritative

repository for earthquake engineering data (the NEES Project Warehouse), and a suite of collaboration and communication facilities.

A model for NSF-funded academic cyberinfrastructure, the NEEShub exemplifies a collaborative platform that empowers researchers and engineers to harness software tools, the high-performance computing (HPC) resources required to run them, and an authoritative and curated data repository. The NEES cyberinfrastructure enables research engineers to tackle the most challenging problems in earthquake engineering to aid their efforts to make our communities more secure against earthquakes and tsunamis.

SOFTWARE TOOLS AND COMPUTING POWER

The NEEShub provides “software as a service,” which allows users to run tools, share data, communicate, and collaborate through the Internet without the need to install software or download data to their computer. The NEEShub allows users to run software tools with direct access to NEES experimental data in the Project Warehouse. Leveraging virtual machine technology, the NEEShub provides a secure and configurable computing environment for tools running in Linux or Windows.

Running detailed computational simulations at a high resolution is a highly complex, processor-intensive operation. On a personal computer, it can take days or weeks to complete a set of simulations, and the size and complexity of physical systems that can be modeled is constrained by the limited capabilities of a desktop computer. In 2010 the NEEShub began to provide access to supercomputing resources at

Purdue University, the NSF Teragrid and XSEDE, and the Open Science Grid directly through the NEEShub to provide more powerful computing resources for the most challenging computational problems,

PROJECT WAREHOUSE: A CURATED, AUTHORITATIVE DATA REPOSITORY FOR CIVIL ENGINEERING

The co-location of raw computing power and software tools with authoritative experimental data is an essential core capability of the NEES cyberinfrastructure that is unique. Through the NEEShub, researchers can apply robust computing power and tools to a growing repository

of experimental data generated by NSF-funded earthquake engineering research.

The NEES Project Warehouse is an authoritative and curated repository for valuable earthquake engineering data generated by decades of experiments conducted at civil engineering facilities across the U.S. The Project Warehouse today contains 1428 fully curated experiments, many of which are comprised of thousands of data files, images, and reports that can be reused and cited by research projects well into the future.

One important aspect of experiments in the Warehouse is the use of permanent Digital Object Identifiers (DOIs), rendering them discoverable, citable, and reusable for the foreseeable future. The NEES PW represents a critical and valuable knowledge asset for the global earthquake engineering community, which is evidenced daily by worldwide use of the NEEShub.

After a decade of NEES earthquake engineering research, the NEES Project Warehouse contains over 2 million project files and directories. By the completion of the NEES award in September 2014, the NEEShub was providing access to approximately 25 Terabytes of data with more than 70 applications being shared by 112,862 users from 208 countries.

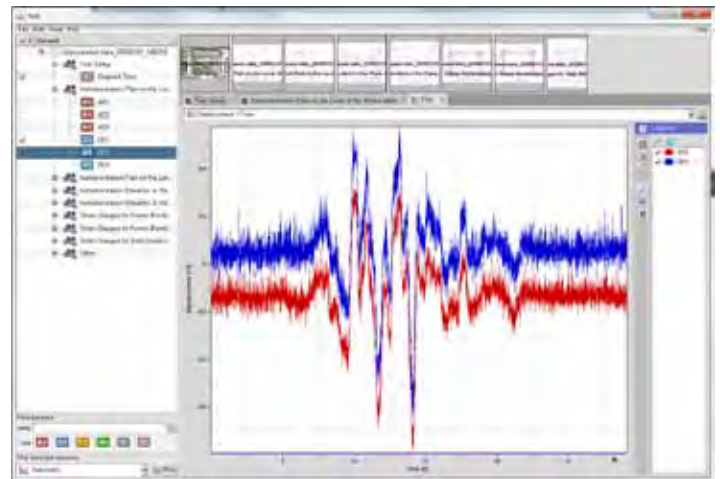
SELECTED RESEARCH PUBLICATIONS

Hacker, T., Eigenmann, R., & Rathje, E. (2013). Advancing Earthquake Engineering Research through Cyberinfrastructure. *Journal of Structural Engineering*, 139(7), 1099-1111.

Hacker, T. J., Eigenmann, R., Bagchi, S., Irfanoglu, A., Pujol, S., Catlin, A., & Rathje, E. (2011). The neeshub cyberinfrastructure for earthquake engineering. *Computing in Science & Engineering*, 13(4), 67-78.

Pejša, S., & Hacker, T. (2013, January). Curation of Earthquake Engineering Research Data. In *Archiving Conference* (Vol. 2013, No. 1, pp. 245-250). Society for Imaging Science and Technology.

Eigenmann, R., Hacker, T., & Rathje, E. (2010, July). Nees cyberinfrastructure: A foundation for innovative research and education. In *Proceedings of the 9th US/10th Canadian Conference on Earthquake Engineering* (pp. 25-29).



Data visualization tool executing directly on the NEEShub.



Global NEEShub users.

Open-source Tools Developed at NEES

The NEEShub: Open-source Tools Developed at NEES, developed under NEES Operations, Julio Ramirez, Purdue University, NSF #0927178, [2009]

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Project Team

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Educational Impact

Graduate students: 33

Undergraduate students: 24

The NEES cyberinfrastructure is the ideal platform for the earthquake engineering community to develop and contribute software applications for collecting, uploading, visualizing and analyzing research data.

The NEES cyberinfrastructure of today is the product of a broad collaborative effort, developed over a ten-year period to meet the evolving needs of the researchers and students conducting tests and performing the research.

The suite of applications that supports the NEES community has been developed and supported by the various institutions in NEES network. For example, 3D Data Viewer (3DDV) was developed at NEES at Rensselaer Polytechnic Institute (RPI) in collaboration with Oregon State University. The Real-time Data Viewer (RDV) is accredited to both the University of Buffalo and the University of Minnesota.

Through the integrated tools on the NEEShub, users are able to interact with data. The Real-time Data Viewer (RDV), the 3D Data Viewer (3DDV), the NEES 3D Viewer (N3DV), are available for visualization. High performance simulation capabilities using supercomputing centers also are supported. Enabled by the OpenSees simulation software framework, users are able to access these supercomputers for parameterized or parallel simulations.

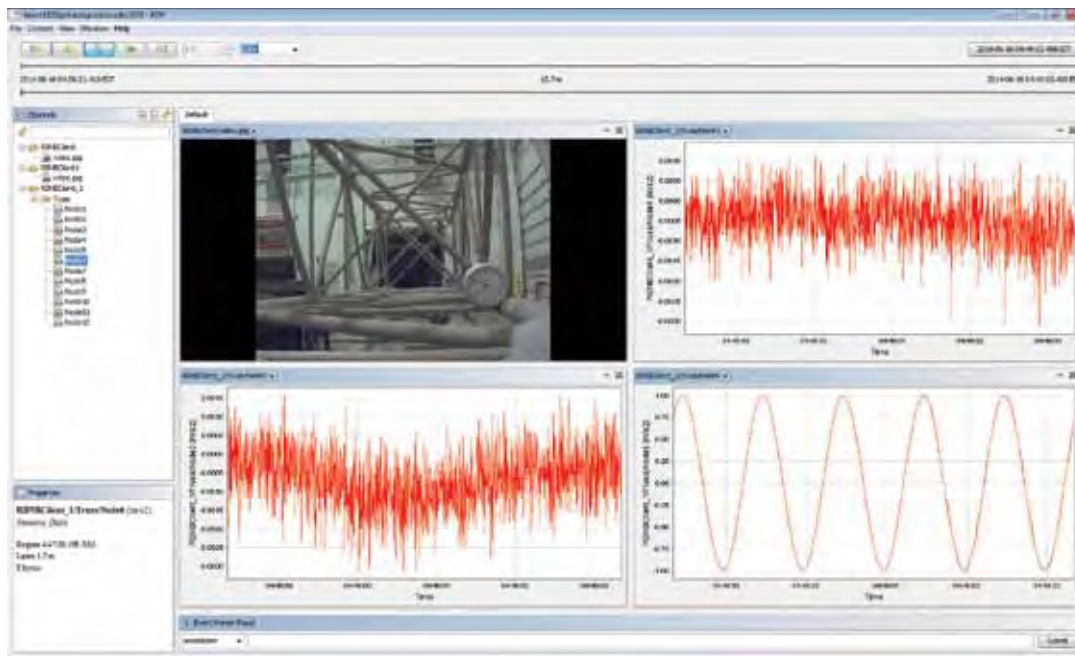
The open-source, user-contributed tools on the NEEShub are too numerous to list in full. Below is a sampling of applications available.

REAL-TIME DATA VIEWER

The Real-time Data Viewer (RDV) provides an interface for viewing and analysing live or archived time-synchronized data, either locally or streamed across a network from a Data Turbine (RBNB) server. RDV is capable of displaying graphical and numerical data, animations, still images, and video. The tool was originally developed at the NEES site at the University of Buffalo site and quickly was adopted throughout the NEES community to enable tele-participation and collaboration between geographically dispersed researchers during experiments and to facilitate time synchronization of disparate types of data upon playback, such as sensor data, videos, and still images. The University of Minnesota has more recently supported it. Researchers are able to send graduate students to testing sites to prepare and conduct tests and participate via RDV as though actually located onsite. As an example, using RDV, researchers located in New Zealand and Iowa have been able to view the experiment data in real time and use that data to make real-time decisions on the next course of action for the experiment. Researchers at nearly all NEES equipment sites regularly use RDV for testing and webcasts of experiments. Furthermore, some other federally funded research communities have adopted RDV, including the U.S. National Science Foundation's Long Term Ecological Research (LTER) program.

3D DATA VIEWER

The 3D Data Viewer (3DDV) was developed by the Center for Earthquake Engineering Simulation (CEES) at RPI in collaboration with Oregon State University. This tool is specially designed to display both 3D models as well as 2D plots side by side and is especially useful when used to organize data from various sources, which can be represented in 3D space. Tests on geotechnical models frequently use dozens of sensors embedded within the model capturing thousands of data points. To organize all that data 3DDV will display a virtual representation of the physical model and make the sensors interactive elements so the user can select them and plot their data. This aids tremendously in organizing the data and getting a good high-level understanding of the test results. 3D Data Viewer is also a great collaboration tool.



Real time data viewer (RDV) screen shot.

NEES 3D VIEWER

The NEES 3D Viewer (N3DV) was a tool designed by the team at NEES at UC Davis for visualizing and understanding experimental earthquake data. It provides a 3D view with 3D objects representing the various structures and instruments within the experiment. It also allows users to access VCR-like controls to play back the experiment events and to see how the structures or instruments react to various forces acted upon them. The tool also allows users to view the experiment in a semi-immersive virtual reality environment such as a GeoWall. Users can configure the 3D view of the experiment, and how individual sensors or instruments visually respond to their recorded values. Users can select areas of interest to view, show and hide sensors, and draw curves between sensors to help show shockwave propagation.

OPENSEES

The Open System for Earthquake Engineering Simulation (OpenSees) is perhaps the best-known open-source software framework for simulating the seismic response of structural and geotechnical systems. It is an open-source

"I could run hundreds of OpenSees simulations using HPC resources on NEEShub in the time it took me to run one simulation on my own computer. I was able to make broader conclusion about the seismic performance of the structural system that would not have been possible without the HPC resources."

– Researcher Patricia Clayton, University of Texas at Austin

tool developed by UC Berkeley as the computational platform for research in performance-based earthquake engineering at the Pacific Earthquake Engineering Research Center (PEER). OpenSees allows users to create finite element applications for simulating the response of structural and geotechnical systems subjected to earthquakes. OpenSees has advanced capabilities for modeling and analyzing the nonlinear response of systems using a wide range of material models, elements, and solution algorithms.

OpenSees is the most frequently used simulation tool on the NEEShub. Through the use of OpenSees on the NEEShub, researchers can rapidly simulate the effects of earthquakes on structural systems, develop advanced components using the latest research results, and share them for others to use within this community-based software. When used in combination with high performance computing resources available through the NEEShub, OpenSees can be run in parallel to allow scalable simulations on high-end computers or for parameter studies.

"I found RDV helpful, not only during the test, but also afterwards. During the test, RDV helps me monitor all sensor outputs. After the tests, RDV enables me to go over sensor data at a desired rate, which helps me understand the behavior of specimens at different stages of testing. Sensor data at each stage of testing can be considered along with still images and video, which adds to RDV's value."

– Alireza Nojavan, graduate student, Minnesota

NEES Project Warehouse Provides a Secure Home for Research Data

NEEShub: NEES Project Warehouse Provides a Secure Home for Research Data, developed under NEES Operations, Julio Ramirez, Purdue University, NSF #0927178, NEEShub Project Warehouse #353, [2009]

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Educational Impact

Graduate students: 5

The NEEShub Project Warehouse provides the nation's first-ever public curated and archived collection of earthquake engineering research data operating in the cloud.

Traditionally, research engineers have worked in isolation, generating and storing experimental data on a local network, or even on desktop computers. In the past, it was as if researchers were burying their treasured data – without providing a map to it.

Beginning with the NSF-funded NEES Operations award, however, engineering research data is systematically collected, curated, stored, and shared. Earthquake engineers now have access to their own authoritative repository of valuable knowledge: the NEEShub Project Warehouse.

Those data are organized, clearly described and understandable, re-usable, and preserved for the long-term. With this, the NEES community in the United States and abroad has engaged in collaboration in ways that were impossible before NEES.

IMPACTS

International Collaboration. The availability of a secure data repository has been a central feature for international earthquake engineering collaborations. Indeed, the availability of the NEEShub's Project Warehouse has enabled key agreements between the National Science Foundation in the United States and peer research organizations in Japan, Canada, China, and Taiwan.

Collaboration is integral to the NEES network. For example, the NEES project called "Tools to Facilitate Widespread Use of Isolation and Protective Systems" combined datasets generated at Japan's E-Defense site with data generated at the NEES at Buffalo site and the NEES at Berkeley facility. In total, NEES and E-Defense researchers have collaborated on 10 projects.

Similarly, two NEES projects have collected data generated at the National Center for Research on Earthquake Engineering (NCREE) in Taiwan. Data from all the projects that reside in the NEEShub are publicly accessible now, or will be soon.

The data repository is available to host all research data, be it generated by NEES researchers and laboratories, by United States institutions outside the NEES network, or by international research groups. NEEScomm today is engaged with partners in the European Union in an attempt to take the first steps in the direction of future collaborations.

DOIs for Data. The huge volumes of research data generated today require novel ways to manage it. To convey and enhance the value of data in the Project Warehouse, in December 2012 the NEEScomm began issuing digital object identifiers (DOI) for all newly curated research datasets. Similar to a DOI for research publications, the DOI for data serves as a persistent identification number. Providing DOIs for datasets facilitates information discoverability, accessibility, and re-use.

With assigned DOIs, earthquake engineering (EE) data becomes a citable source, not simply a supplement to published articles. DOIs may be used in publications, workflows, further scientific efforts, as well as in long-term curation and archive activities. For example, by tracking DOI citations it is possible to discover the impacts of NEES research. The Project Warehouse provides a standardized format for data citations and for crediting research teams. As of March 2014, over 500 DOIs have been issued out of almost 1,500 public and curated projects.

Data Curation. All data stored in the NEES data repository go through a curation process. Curation is a formal method of analyzing and sorting information and presenting it in a meaningful and organized way.

From the outset, the curation process involves interaction between the researcher and curator, who monitors the data throughout the duration of the project and through the life cycle of the data. The NEES curator mediates between the documentary efforts of current researchers and the needs of the broader community of engineers who may wish to re-use the data – now or in the future.

Without proper care and judicious thinking about future research needs, data files would become obsolete and impossible to locate, and due to format changes, even impossible to open.

OUTCOMES

Although the Project Warehouse is at the core of the NEES mission, NEEScomm recognized that the needs of the EE community are diverse. The powerful NEES cyberinfrastructure also supports innovative data-oriented activities such as topic-specific databases, computational simulation, and enforced re-use of archived data.

Datastore Databases. In response to user-requests to store databases online, in 2013 the DataStore tool was created for the NEEShub. DataStore enables any NEEShub user to upload a data-spreadsheet and transform it into a searchable, editable database accessible to researchers around the world. Examples are the American Concrete Institute's ACI 445B punching shear collected databank, and the Database for Structural Control and Monitoring Benchmark Problems, from the ASCE Committee on Structural Control. As with research datasets in the Project Warehouse, databases on the NEEShub also can be assigned DOIs.

Computational Models. Computational models have been used in earthquake engineering since the 1950s. However, earthquake engineering numerical models are not always publically available, and only the main results of numerical simulations can be found in the literature. NEEShub provides consistency into what's considered a computational model and determines how it should be documented and lends specific functionality for models to be shared with the earthquake engineering community at large. The computational models are reviewed, and they too can be assigned a DOI. As with datasets, the DOI for computational models foster the reuse of models, enhance research, and translate research results into practice faster. DOIs also will provide the appropriate recognition and credit to the original authors of the model and help demonstrate the impact of their work.

Data Re-use. Since 2011, the NEES data repository was robust enough for NSF to solicit proposals for awards that "require significant reuse of data that is curated and archived" in the NEES data repository. This leveraging of previous experimental data multiplies the scientific utility of NSF sponsored research.

FUTURE

The NEEShub and NEES Project Warehouse serve as a model for capturing and preserving treasured academic data. As the ultimate curators of the Project Warehouse, NEEScomm leadership has developed plans to ensure a baseline level of service to enable future engineers and researchers to contribute to and access this valuable storehouse of earthquake engineering information.

NEESHUB DATA BY THE NUMBERS

The number of files and the sheer volume of the data repository had increased steadily as well. The first chunk of data was stored in the NEES data repository in 2006; that year the NEES data repository contained 0.3 terabytes (TB) of data. In 2013 it was over 20 TB. For the same period, the number of files has grown from about 9,000 files to nearly 2 million. By the end of September 2014, the repository will contain about 25 TB of data and 2 million files.

CURATION CRITERIA

On the NEEShub, curation organizes and validates all relevant data to provide a complete and accurate description of an experiment. A fully curated experiment is fit for archiving and future re-use by research engineers around the world. A curated project includes:

Data

- Unprocessed data and corrected data.

Metadata

- Names of researchers.
- Project or experiment title.
- Testing facility.
- Equipment.
- Specimen material properties.

Documentation

- A list of sensors and their locations.
- Technical drawings in JPEG or PNG format.
- Experiment report in PDF format.

Reports

- Final report on the project in PDF format.
- Executive summary for the project or project in PDF format.

User-centric Cyberinfrastructure Development

User-centric Cyberinfrastructure Development, developed under NEES Operations, Julio Ramirez, Purdue University, NSF #0927178, [2009]

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Julio Ramirez, Purdue University

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Thomas Hacker, Purdue University

Barbara Fossum, Purdue University

Educational Impact

Graduate students: 33

Undergraduate students: 24

Software development for scientific communities is a challenging task requiring much iteration between the development team and the research community before a useful tool is produced.

In most cases the development pipeline begins with a “middle man,” usually someone unfamiliar with the scientific discipline or software development, who collects the user requirements, interprets them and communicates them to the technical development team.

Often, the end product is heavily influenced by the viewpoint of the development team, and inaccurate interpretations of the scientific requirements result in cyberinfrastructure that is not responsive to the needs of the community and remains unused.

The NEEScomm team took a novel approach to developing the NEES cyberinfrastructure and the NEEShub. The group focused on meeting the immediate needs of the civil engineering community as well as providing new features to meet the community’s near-term-future needs.

As well as technical matters, the software development process took into account the sociological aspects of interdisciplinary work among computer scientists, civil engineers, and digital librarians. The process culminated in the development of a successful cyberinfrastructure that meets the needs of the community and has been widely adopted. Not only that, the NEES cyberinfrastructure stands as a unique model for future scientific software development.

The first area of effort was sociological. One problem the team faced was how to effectively involve civil engineering researchers in the software development and deployment process.

To address this issue, engineering professionals, both paid and volunteer, were directly partnered with members of the software development team to reduce any confusion about the scientific user requirements. Small groups involving developers and engineers were created to address important components of the development cycle including requirements-gathering, prioritization, review, and feedback.

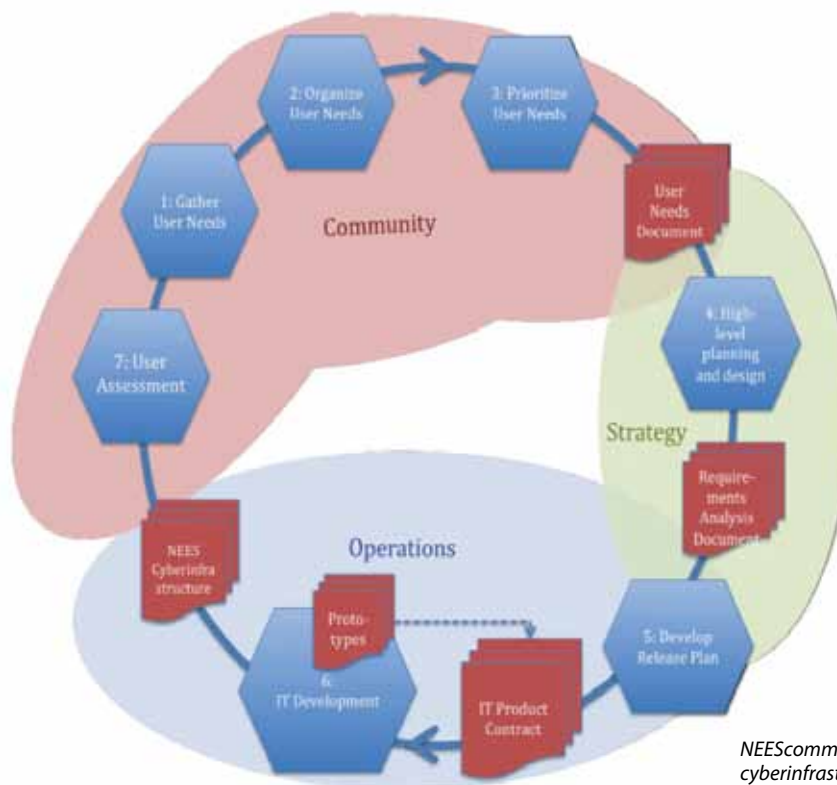
These embedded community professionals worked side-by-side with the development team, reducing the number of iterations required to interpret user requirements and providing immediate access for both the engineering professionals and the technical team to learn first hand about the limitations and opportunities presented by implementing the user requirements.

Another problem was structuring the software requirements-gathering and prioritization tasks to ensure that development efforts remained focused on the most pressing needs identified by the community. To address these needs, the team implemented its own iterative software development process, which is shown on the next page.

In this development process, there are three areas of activity: Community, which is primarily comprised of civil engineering researchers and users; Strategy, which is a partnership of software engineers, computer scientists, and civil engineers working within a formal framework of communication and assessment; and Operations, primarily composed of software engineers and computer scientists with some involvement from project leadership and civil engineers.

This cyclical, 7-phase process begins with requirements-gathering and analysis from sources such as user “wishes” submitted to the NEEShub. Needs also are identified by the Requirements Analysis and Assessment Subcommittee (RAAS), which is a group comprised of civil engineering researchers.

The RAAS collects needs and requirements through user focus groups conducted annually and ranks them in priority order to produce a user-needs document that is then handed off to the Cyberinfrastructure Requirements Committee (CRC). The CRC is comprised of civil engineers,



NEEScomm's user-centric approach for cyberinfrastructure development.

software developers, and computer scientists. The CRC carefully assesses each requirement, and based on the strategic needs of the project and software development resources, produces a release plan and IT Product Contract (ITPC) that specifically describes the software and features to be developed, along with a project timeline. Next, NEEScomm project leadership and the NEES Strategic Council review the ITPC.

The ITPC is a key document because it clearly communicates to all stakeholders the requirements that are to be addressed, the new features and software to be provided, and a definitive timeline with deadlines by which these features will be put into production in the NEES cyberinfrastructure.

Once the actual software development begins, a critical aspect of the effort is the close involvement of embedded civil engineers, called the Core Feedback Group, who review the software as it is being created. This group gives immediate feedback and ideas to the NEEScomm software developers who can quickly make changes to the software in response to feedback.

Finally, once all of the new features have been completed, the new software release is announced to the community with a date for switching to the new cyberinfrastructure.

Employing this user-centric methodology, from 2009 to 2014 NEEScomm delivered six successful releases to the NEES cyberinfrastructure with minimal downtime. In fact, over the past five years the NEES cyberinfrastructure has delivered 99.63% uptime, a remarkable accomplishment.

Building a cyberinfrastructure for a large and distributed science and engineering community is a complex task. In terms of "lessons learned" from this development process, the NEEScomm team discovered that social factors are as important as the technical aspects of the work. It is essential to understand disciplinary differences in how communities collaborate and conduct their work to provide cyberinfrastructure responsive to their needs.

Thus, it is crucial to embed engaged and interested domain scientists into every aspect of the cyberinfrastructure software design, development, and operation. Moreover, needs, requirements, and priorities should come primarily from the domain scientist community. And clearly, it is important to set expectations about the software and features that will be delivered, and to deliver these features on schedule.

Ultimately, the approach NEEScomm developed and followed has resulted in a robust, usable cyberinfrastructure that meets the needs of researchers and has fostered collaboration in the global earthquake engineering community.

EARTHQUAKE SHAKE TABLE

NEES & HOWARD UNIVERSITY

DEFD
DISCOVER
ENGINEERING
FAMILY DAY

**NATIONAL
BUILDING
MUSEUM**



9. EDUCATION

In addition to its mission of accelerating improvements in seismic design and performance, NEES has a strong commitment to training the existing workforce in the field of earthquake and tsunami risk mitigation as well as attracting and developing a diverse future workforce.

The NEEScomm Education, Outreach, and Training team, including equipment site staff, researchers, university faculty and students, have worked together as a community dedicated to developing programs, activities, lesson plans, products, and museum displays to educate a diverse set of constituents about NEES research and earthquake engineering in general.

Undergraduates have participated in the Research Experience for Undergraduates (REU), practitioners have attended Research-to-Practice webinars, educators have accessed the learning materials in NEESacademy, and children and their families have learned from NEES-based museum exhibits.

The following projects are profiled in this section.

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NEES Ambassador Program Engages Students, Grows Leadership Skills,
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REU Site: Network for Earthquake Engineering Simulation — Reducing
Seismic Vulnerability, Sean Brophy, Purdue University

Ambassador Program Engages Students, Grows Leadership Skills

NEES Ambassador Program Engages Students, Grows Leadership Skills, developed under NEES Operations, Julio Ramirez, Purdue University, NSF #0927178, [2009]

Principal Investigator

Julio Ramirez, Purdue University

Co-Principal Investigators

Thalia Anagnos, San José State University

Ellen Rathje, University of Texas at Austin

Thomas Hacker, Purdue University

Barbara Fossum, Purdue University

Project Team

Alicia Lyman-Holt, Oregon State University

Claudia Marin, Howard University

Educational Impact

Graduate students: 3

Undergraduate students: 113

Ambassador programs are used at universities across the country to highlight high-performing undergraduates to the larger university community, to recruit students to specific programs, to provide leadership and labor for in-house publicity and outreach events, and to encourage pre-college students to consider STEM careers. Two lively Ambassador Programs are affiliated with NEES at Oregon State University and Howard University.

IMPACTS

While the NEES Ambassador Programs were developed to help deliver education and outreach to the K-12 community, an internal study of the programs revealed that they are serving an equally important function in developing the skills and attitudes of the ambassadors themselves. The study found that participating in the NEES Ambassador Program benefits the students through significant gains in self confidence; interest in pursuing undergraduate research and graduate school; and skills that promote leadership such as communication, delegation, teamwork, flexibility, time-management, decision making, and problem solving.

Both programs engage undergraduate students in outreach to K-12 and the general public and promote careers in engineering. The NEES Ambassador Program at the two schools work in different ways: one focuses on performing traditional campus-based ambassadorial duties and the other on taking equipment into the field to provide hands-on experiences for kids.

OREGON STATE

Students in the Ambassador Program at Oregon State University (OSU) train with NEES personnel to serve as tour leaders for the tsunami research laboratory and facilitators for hands-on engineering challenges at large-scale public outreach events. The ambassadors lead tours, make presentations and run activities at K-12 schools throughout the state, meet with engineering professionals when they visit campus, manage the programs, and train incoming ambassadors.

Ambassadors working at the NEES at OSU wave lab are members of the OSU College of Engineering (CoE) Ambassador program. Created in 2004 as a diversity recruiting program, the CoE program has grown from 12 to 23 ambassadors annually and its duties expanded to include activities such as leading more than 85 tours per year of the NEES at OSU wave facility, giving approximately 80 presentations in classrooms at high schools throughout the state, and managing media tools such as Facebook and YouTube, to name a few. More importantly, the program is managed almost entirely by the students themselves.

The students complete a training program that includes leadership and communication skills as well as some technical content that they typically would not get in their undergraduate curriculum. The topic-specific training covers protocols and best practices for university tours, laboratory tours, and school visits. Each training module consists of a training manual and observation of an experienced tour guide, followed by co-leading tours before advancing to individually leading tours. Each program has program-specific feedback and mentoring for the ambassadors to encourage development and self-confidence.





In addition to organizing and operating the flume activity at large events, ambassadors support the training of volunteers from other organizations, and run several educational activities at elementary and middle schools.

HOWARD UNIVERSITY

The original objective of the NEES Ambassadors Program based at Howard University was to lead an outreach activity using the NEES mini-wave flume at National Engineering Week Family Day in Washington, D.C. which usually hosts more than 9,000 children and their families. In response to the ambassadors' enthusiasm for the one-day hands-on activity in the first year (2011), the objectives of the program were expanded.

Howard now maintains the 16-foot long mini-wave flume, and the ambassadors are in charge of the logistics for transporting and setting up the flume, organizing materials, interacting with the activity's participants, and introducing concepts related to tsunami hazard mitigation and the role of engineers in society. The 16 to 20 ambassadors now participate annually in several very large scale outreach events in D.C. and have developed a program for outreach to local K-12 schools.

Further, in 2014 the NEES Ambassador program at Howard grew to include students from Morgan State University in Baltimore and has added a new activity using the NEES instructional shake table developed through the EPICS program at Purdue University.

Howard's training focuses on teaching ambassadors to effectively deliver the two outreach activities, so students attend several sessions where they work on specifics about the activities and their roles as ambassadors. They read specified materials about tsunamis and earthquakes prior to training sessions, and they also practice the introductory talk and how to answer potential questions. The more experienced ambassadors take leadership roles in the training sessions.

NETWORKING WITH FACULTY

Ambassador programs provide an avenue for networking with faculty, students, and other professionals. For faculty, the Ambassador programs provide the opportunity to:

- Interact with the students outside of the classroom and in different environments.
- Use out-of-classroom activities to develop students' communication and teamwork skills.
- Provide experience in public relations (meeting people, public speaking, representing the university, etc.), which enables ambassadors to feel more "connected" to their role in society as engineers.
- Identify potential students for research activities.

IMPACTS ON PARTICIPANTS

The study found that most students joined the Ambassador programs for three primary goals: to make a difference in their community, to have fun, and to build their resumes. A significant percentage of the students indicate they made gains in professional skills and attitudes, such as teamwork, communication, conflict resolution, time management, flexibility, and motivation of others.

- 91% of participants experienced gains in confidence in ability to make positive change through leadership.
- 84% of students feel they are better leaders.
- Large majority reported gains in confidence in public speaking (75% to 100%).

One of the most important impacts of the NEES ambassador programs is this statistic: 69% of the participants say the program boosted their confidence in their ability to succeed as engineers.

Make Your Own Earthquake Transforms How Kids Learn Engineering

Make Your Own Earthquake Transforms How Kids Learn Engineering, developed under NEES Operations, Julio Ramirez, Purdue University, NSF #0927178, [2009]

Principal Investigator

Julio Ramirez, Purdue University

Co-Principal Investigators

Thalia Anagnos, San José State University

Ellen Rathje, University of Texas at Austin

Thomas Hacker, Purdue University

Barbara Fossum, Purdue University

Project Team

Jamie Steidl, University of California, Santa Barbara

Sandy Seale, University of California, Santa Barbara

Educational Impact

Graduate students: 2

Undergraduate students: 5

High school students: 3

It's much easier to understand how earthquakes work when you can experience first-hand how your own movement affects the ground beneath your feet. That was the idea behind "Make Your Own Earthquake," an interactive learning activity developed 20 years ago by Aaron Martin, the project manager for the Southern California Earthquake Center Portable Broadband Instrument Center (PBIC) at UC Santa Barbara.

Recently, Make Your Own Earthquake (MYOE) was enhanced by NEES at UCSB as an activity for teaching elementary through high school students the fundamentals of earthquake engineering using principles of physics, earth science, mathematics, and problem solving. The MYOE lessons align to many state science curricula.

When earthquake engineers design structures for a seismic region, they rely on acceleration data to help them understand how buildings and bridges of various designs and sizes will respond to ground shaking. Only then can they engineer designs that can minimize structural damage due to moderate and large magnitude earthquakes.

With the MYOE module, kids are instructed to jump for ten seconds near a portable accelerometer, a movement-sensing device. The sensor's data is sent to a nearby computer where a scaled graph of the jump appears as a waveform, which is the same process that is used to record earthquake ground motions.

Students see their earthquake trace live on the screen, and the instructor can print a copy of the earthquake with the student's name on it. Students can compare their waveforms and take them home.

The module originally employed the PBIC field equipment used for earthquake monitoring research, and later the NEES at UC Santa Barbara (UCSB) field equipment. Lab staff and engineering students transported the lab's research-grade accelerometers and data acquisition instruments to the schools to measure the "earthquakes" generated by the students. The equipment was expensive, delicate, bulky, and time-consuming to set up.

Sandy Seale joined the NEES at UCSB team in 2009 as Outreach Coordinator and took on the responsibility for scheduling MYOE demonstrations at local schools and science fairs. At the annual Southern California Earthquake Center meeting in 2010, Dr. Seale saw a demonstration of new, consumer-type accelerometers that plug into a laptop computer and saw the possibility of making the MYOE activity more portable and easier to use – for her and for other engineering educators.

The new micro electro mechanical systems (MEMS) accelerometers on the market were equipped with a USB cable and could be connected to a standard laptop computer. The small, lightweight accelerometers used for MYOE were developed by the Quake-Catcher Network (QCN). At \$50, it was affordable. NEES at UCSB adapted their MYOE software to use the new MEMS accelerometer. Under direction from NEES at UCSB, the QCN group also developed software for MYOE that downloads from their website and is free and easy to use.

NEEScomm became involved in developing MYOE, with the QCN sensor, into an activity that more educators could adopt. NEES organized meetings of the site Outreach Coordinators to develop content for MYOE. NEES REU students working at UCSB over the summer wrote and tested curriculum modules to supplement MYOE. Over time, additional activities and assessments have been created for older students, including an exploration of magnitude and intensity of an earthquake.

As well as the interactive activity, NEES earthquake engineering educators Sandra Seale, Kelly Doyle, Cathy French, Heidi Tremayne, Lelli Van Den Einde, and Thalia Anagnos have developed an expanded curriculum called "Make Your Own Earthquake." It includes several dozen units that introduce concepts related to ground motion, instrumentation, liquefaction and building response and is



Student with Make Your Own Earthquake results.

freely available on the NEEShub, in NEESacademy, a section of the NEES website devoted to education and outreach.

IMPACTS

Currently, MYOE is used as an outreach activity by five NEES equipment sites, including UC Santa Barbara; University of Nevada, Reno; UC Berkeley; University of Illinois, Urbana-Champaign; and UC San Diego.

In addition, with technical support from NEES at Cornell University and NEES at Reno, MYOE currently serves as the basis for a museum exhibit at the Nevada Discovery Museum in Reno, as well as a traveling exhibit called When the Earth Shakes developed by the Sciencenter in Ithaca, New York.

MYOE is one of the most popular exhibits at the Nevada Discovery Museum and attracted more than 50,000 jumpers during its first year. The When the Earth Shakes exhibit has visited museums in California, New Hampshire, Minnesota, and Texas exposing tens of thousands of children and their families to earthquake engineering concepts.

In addition, MYOE and its associated outreach programs have been shown to improve students' understanding of ground acceleration. To measure this, NEES outreach coordinators developed a short quiz. Fourth through seventh grade students who participate in the MYOE module show a significant improvement in the percentage of quiz questions answered correctly.

OUTCOMES

NEES at Santa Barbara. The NEES facility at UC Santa Barbara uses MYOE in two different ways. Local elementary school science fairs are a prime place for students of all ages and their families to participate in MYOE. NEES at UCSB also do

formal presentations to sixth grade classes, accompanied by a slide show and videos on plate tectonics and seismology, which introduce important science concepts. The demonstration concludes with an earthquake generated by the whole class jumping at the same time, teaching students about "Band-Limited-White-Noise."

NEES at Nevada. The University of Nevada, Reno, NEES site has designed portable carts for storing the large monitor, computer, printer, and jumping platform, which makes it convenient to transport and set up the MYOE activities for visitors to the lab. Students also build and test structures made of age-appropriate materials, toothpicks and marshmallows for the young ones and balsa wood for older students.

NEES at UC Berkeley. At the NEES lab at UC Berkeley, local elementary students tour the facility to learn about experimental specimens and large-scale lab test equipment. Through the MYOE activity and building small structures out of K-NEX, the students learn earthquake engineering concepts. The structures are placed on a table-top shake table and tested. In addition, NEES at Berkeley takes the MYOE program to the local school district science fair.

NEES at Illinois. At the University of Illinois, Urbana-Champaign, MYOE is coupled with a presentation on earthquakes and inquiry-based activities. Students shake model structures of different heights to understand concepts of resonance.

NEES at UC San Diego. NEES at UC San Diego holds a K'NEX building competition that draws over 500 students each year. The students involved participate in MYOE. The outreach program has undergraduate students from the university visit various sixth grade classrooms to teach about earthquakes and basic concepts of structural design.

Continued on page 165

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Shaking Up the Classroom: The Development of Affordable Instructional Shake Tables

Shaking Up the Classroom: The Development of Affordable Instructional Shake Tables, developed under NEES Operations, Julio Ramirez, Purdue University, NSF #0927178, [2009]

Principal Investigator

Julio Ramirez, Purdue University

Co-Principal Investigators

Thalia Anagnos, San José State University
Ellen Rathje, University of Texas at Austin
Sean Brophy, Purdue University
Thomas Hacker, Purdue University
Barbara Fossum, Purdue University

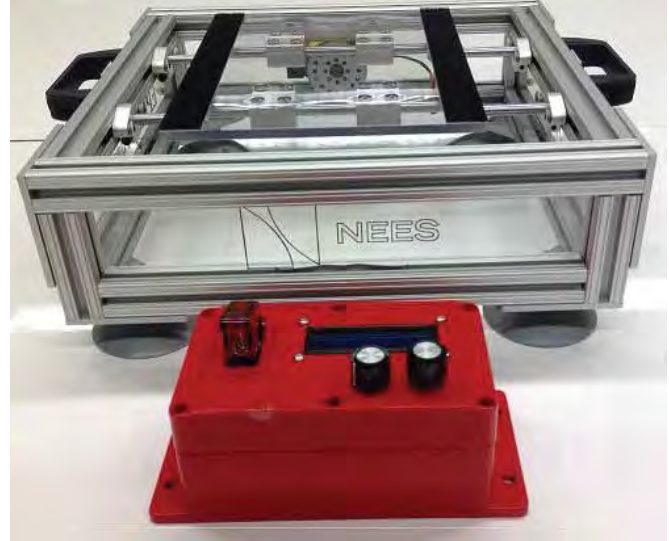
Educational Impact

Graduate students: 6
Undergraduate students: 31
High school teachers: 3

Shake tables are routinely used to test the impact of simulated earthquakes on physical models of structures. These models could be small balsa wood towers made by students, or full-scale multi-story concrete buildings. Whether the models are large or small, performance is evaluated with the goal of creating innovative structures that can resist the impact of seismic forces.

Many NEES sites use instructional shake tables to give students a first-hand look at the impact of an earthquake on a structure. For example, students design an earthquake-resistant structure that they build with common materials, and then test their structure on the table. To support the learning experience they are taught about innovative methods earthquake engineers use to improve building performance such as dampers and bracing. Learners often adopt these ideas into their designs and can explain why they work.

NEES sites use small, commercial grade, shake tables build by Quanser or MTS systems. These high-quality systems provide reliable and accurate simulation of historical earthquake and harmonic motion. However, the units are expensive, heavy to transport, and require some training to operate, limiting their potential for outreach to the K-12 community.



IMPACTS

A low-cost, light-weight and easy-to-operate instructional shake table was designed and built by a team of undergraduate engineering students under the guidance of Professor Sean Brophy, NEES co-leader for Education, Outreach and Training. The team of Purdue undergraduates was part of the Engineering Projects In Community Service (EPICS) program. They designed and built a prototype of a motion controlled shake table that was inexpensive enough to support the outreach needs of the NEES sites.

The innovative design, which only weighs 11 pounds, reduced the cost from \$28,000 for a small commercial shake table to a much more reasonable \$800, making the tables more viable for use in the classroom, at NEES sites and at informal learning venues (museums and public outreach events).

RESEARCH METHODOLOGY

The initial shake table design was conceived by a team of 14 energetic undergraduates on the NEES-EPICS team in Fall 2012.

The EPICS experience gives students the opportunity to engage in an authentic design process to produce a device or service for a client. The NEES EOT community was a client needing a low-cost shake table solution to complement their education programs. The EPICS team won the Purdue EPICS Corcoran Award for outstanding productivity and teamwork.

The team continued the work to produce a robust design and software package which provides the shake table with multiple modes of functionality. The initial prototype demonstrated the potential of the system, and finished units were delivered to NEES test sites at the University of California, Berkeley; University of California, San Diego; University of Nevada, Reno; University of Minnesota; Lehigh University; and Oregon State University; as well as to NEES affiliates at San José State University; Howard University; Morgan State University; and the University of Texas, El Paso.

The instructional shake table includes a control box that offers several modes of operation. With the control box a user can regulate the harmonic motion by varying the amplitude and frequency. If the user connects the control box to a computer, the control box and special interface software can provide several additional modes of operation.

For example, one mode replicates pre-recorded historical earthquakes, and another controls the shake table motions based on the signal from an accelerometer sensor connected to a jumping platform. This second mode, called Make Your Own Earthquake (MYOE), allows children to simulate their own earthquake by jumping on the platform and then watching the table move based on their jumping pattern. The control box is also capable of receiving additional accelerometer traces that can be graphed with special software.

OUTCOMES

NEES representatives can visit K-16 classrooms and use the newly developed instructional shake table to introduce students to earthquake engineering concepts through an introductory lesson, and then loan the shake table to the teacher. This allows the teacher to guide the students through additional lessons and activities before the class visits the NEES site to observe first-hand what engineers and researchers do.

The NEES Instructional Shake Table debuted at the 2014 Family Discovery Day in Washington DC as seen in the images to the right. Student Ambassadors from Howard University joined NEES at OSU in hosting thousands of children in demonstrations of seismic response of K'Nex towers fitted with cross-bracing. Children also built structures with marshmallows and straws and then tested them on a manually controlled shake table (another project from the NEES/EPICS team).



Building and testing a manual shake table designed by the NEES/EPICS team.

In the NEES assessments at these public outreach events, the majority of the participants say they are now more interested in learning more about science and engineering. In addition, they are often able to repeat some of the important engineering concepts described in the demonstrations.

Interest in using and obtaining a NEES instructional shake table continues to grow. The project is exploring ways to expand the user base for these materials and the curriculum associated with it. The future of earthquake engineering, and other STEM careers, depends on engaging young children in engineering and science practices through learning experiences like the design-build-test activities supported by the instructional shake tables.



Demonstrations with motion controlled instructional shake table designed by the NEES/EPICS team.

NEES Undergraduate Research Program: Not Your Typical REU

REU Site: Network for Earthquake Engineering Simulation — Reducing Seismic Vulnerability, Sean Brophy, Purdue University, NSF #1005054, [2010], and NSF #1263155, [2012]

Principal Investigator

Sean P. Brophy, Purdue University

Co-Principal Investigator

Thalia Anagnos, San José State University

Project Team

Alicia L. Lyman-Holt, Oregon State University

Additional support provided by NEES Operations, Julio Ramirez, NSF #0927178 [2009]

Educational Impact

Graduate students: 220

Undergraduate students: 239

The Research Experiences for Undergraduates (REU) program is a ten-week summer experience where undergraduate students work side-by-side with NEES researchers to hone their skills conducting independent research and participating as research team members.

What makes this REU program unusual is that the 30 selected students are distributed throughout the United States at multiple NEES sites and interconnected through a variety of online collaboration tools to create a cohesive and interdependent cohort. To maximize student learning and personal growth, the program uses a combination of face-to-face and technology-mediated interactions.

IMPACTS

Since 2006 the REU program has hosted more than 235 students on projects ranging from software development to the design, construction, and testing of specimens. One year the program sent two students to New Zealand to help with reconnaissance after the Christchurch earthquakes. Students develop strong bonds with people from universities around the country initiating a professional network that they can tap into later in their careers.

REU students often present their outstanding work on NEES research projects at the Young Researchers Symposiums. About 10% present their research at additional research conferences. Additionally, 65% of NEES REU students have gone on to earn MS or PhD degrees in STEM fields. Others have been awarded prestigious scholarships and internships, and 85% feel that the REU program influenced their career path.



The 2013 NEES REU cohort visits the Folsom Dam Auxiliary Spillway construction project near Sacramento, California. Photo by Thalia Anagnos.



REU student Winston Boyce presents his work on the Watts Tower structural monitoring project at NEES at UCLA.

DEVELOPING THE COHORT

In-Person Interaction

Over the course of the summer, the REU cohorts have two face-to-face meetings to establish and reinforce the development of a cohesive group. The first is the two-day orientation, and the second is the Young Researchers Symposium (YRS) at which they present their research results.

The orientation event often is scheduled to coincide with the NEES annual meeting to give students a firsthand look at the expectations of performance at a professional conference. Targeted sessions are used to

prepare students for the various activities they will engage in including performing a literature search, designing experiments, collaborating with peers, and writing and presenting results.

After orientation, students spend eight weeks at the research site working with graduate students and mentors on a research project. Each participating NEES laboratory hosts between 2 and 8 students and engages those students in site-specific professional development activities such as seminars, workshops and field trips.

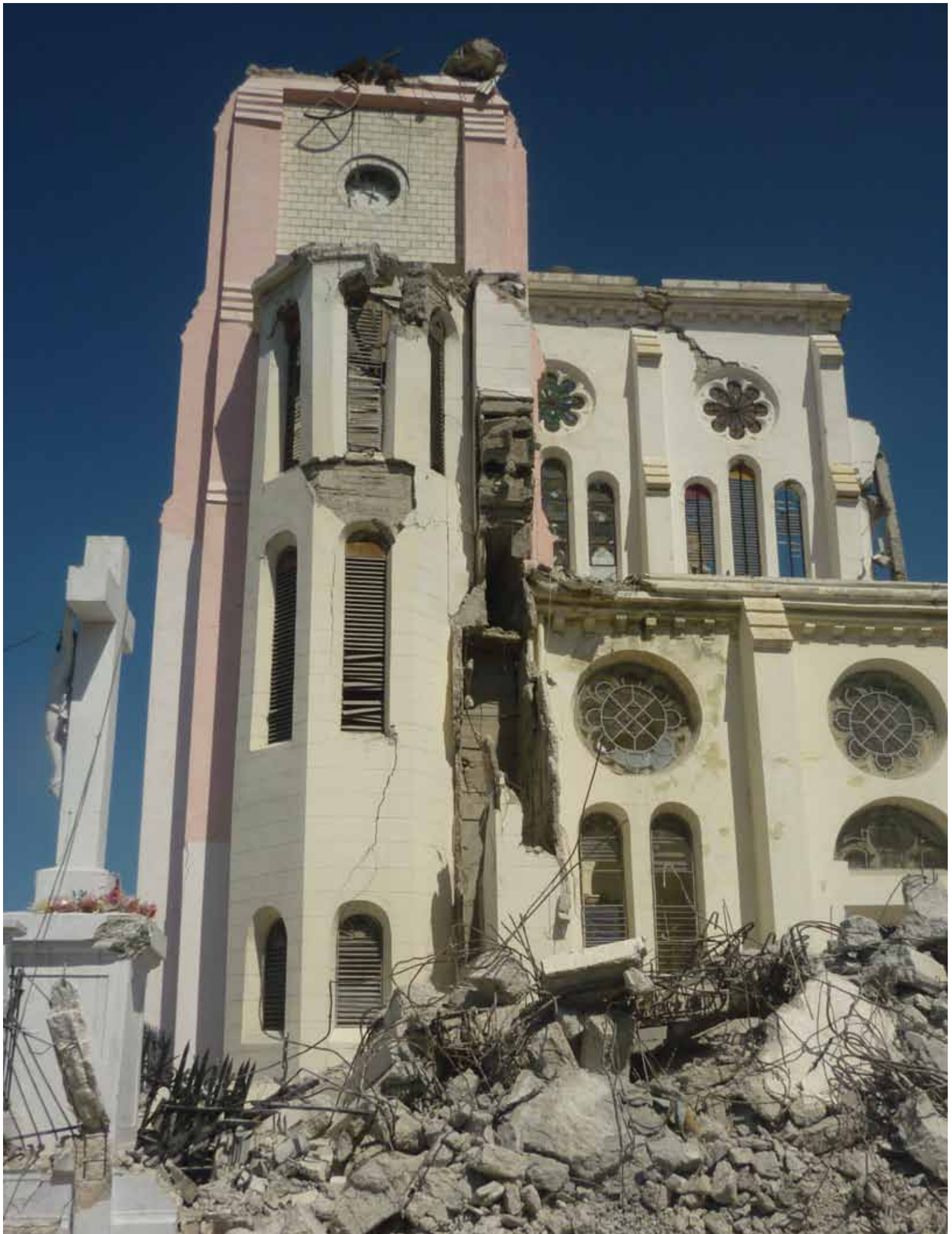
ONLINE INTERACTION

The program also includes a strong online component, hosted on the NEEShub cyberinfrastructure that links the network's 14 experimental research sites. Students can use tools including a course management system embedded in NEEShub (labeled the REU Network), WebEx video conferencing, and free online collaboration tools such as Google Hangouts.

"The REU program was one of the first times I was able to work on a project to solve a real world problem. This very valuable experience strengthened my passion to continue on my path towards becoming an engineer."

—REU Participant





10. RAPIDS

The best lessons for earthquake resiliency can be obtained by the study of what worked and did not work in regions that are struck by earthquakes and tsunamis. The NSF RAPID funding mechanism is used for projects having a severe urgency with regard to availability of, or access to data, facilities, or specialized equipment, including quick-response research on natural disasters.

In the field of earthquake engineering, RAPID teams focus on collecting perishable data from earthquake and tsunami ravaged regions in order to distill lessons to improve the performance of our built environment and to chart new areas of inquiry based on the final arbiter of such performance—the earthquake and tsunami impact on society.

In the space of 14 months in 2010-11, four devastating earthquakes occurred in Haiti, Chile, Japan, and New Zealand—each providing unique lessons and opportunities for research. The following stories summarize RAPID grants which allowed study of the impacts of these earthquakes and resulting tsunamis.

New Method for Rapid, Image-Based, Post-Disaster Damage Detection	120
NSF RAPID: Collection Of Damage Data Following Haiti Earthquake, Laura Lowes, University of Washington	
RAPID: Post-Earthquake Monitoring and Mentoring in Chile.....	122
NSF RAPID: Post-Earthquake Monitoring Of Buildings In Chile Using NEES at UCLA Resources, John Wallace, University of California, Los Angeles	
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High-Resolution Data Collection After Tōhoku Earthquake and Tsunami.....	126
Collaborative Research: RAPID: Post-Disaster Structural Data Collection Following the 11 March 2011 Tōhoku, Japan Tsunami, Ian Robertson, University of Hawaii	
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Recurring Liquefaction and its Effects on Buildings and Lifelines following the 2010-2011 New Zealand Earthquakes	128
RAPID: Liquefaction and its Effects on Buildings and Lifelines in the 2010-2011 Canterbury, New Zealand Earthquake Sequence, Russell Green, Virginia Polytechnic Institute and State University	
NEES Researchers Validate Ground Improvements in Liquefaction-Prone Christchurch, New Zealand	130
RAPID: Field Investigation of Shallow Ground Improvement Methods For Inhibiting Liquefaction Triggering; Christchurch, New Zealand, Kenneth H. Stokoe, University of Texas at Austin	

New Method for Rapid, Image-Based, Disaster Damage Detection

NSF RAPID: Collection Of Damage Data Following Haiti Earthquake, Laura Lowes, University of Washington, NSF #1034845, NEEShub Project Warehouse #872, [2010]

Principal Investigator

Laura Lowes, University of Washington

Co-Principal Investigators

Ioannis Brilakis, University of Cambridge (formerly Georgia Institute of Technology)

Gustavo Parra-Montesinos, University of Michigan

Marc Eberhard, University of Washington

Reginald DesRoches, Georgia Institute of Technology

Educational Impact

Graduate students: 3

The National Science Foundation RAPID funding mechanism is used for proposals having a severe urgency with regard to availability of, or access to data, facilities or specialized equipment, including quick-response research on unanticipated events.

One such event was the devastating magnitude 7.0 Haiti earthquake that took place in 2010.

Post-earthquake inspection of damaged structures typically requires a large number of trained professionals to spend many hours in the field. With many individuals involved, results can be inconsistent.

Professor Lowes and her team sought to reduce the time and improve the reliability of post-event damage inspection. They devised a rapid, image-based, semi-automated method for assessing damage and collapse-risk for reinforced concrete structures.

The method entailed first responders wearing hardhat-mounted video cameras collecting images of the damaged structures, near real-time processing of the data to identify and characterize structural damage, use of fragility functions for idealized buildings to predict aftershock collapse risk, and, ultimately, assimilation of the data by engineers to establish appropriate post-earthquake access to the building. Research to develop this method was funded by NSF awards #1000440 and #1000700 (PIs Lowes and DesRoches and Brilakis); data collected following the Haiti earthquake were ultimately used to demonstrate the method.

IMPACT

This assessment process, with its novel data collection method, may be used by future first responders and engineers to determine, faster and more reliably, the risk posed by earthquake damaged buildings.

METHODOLOGY

Recent earthquakes in the United States and elsewhere in the world suggest that for even a moderate intensity earthquake affecting a metropolitan area, it could take weeks or months to inspect and grant access to damaged buildings. Families are forced from their homes, businesses are without facilities, and recovery is delayed by the slow assessment of damaged buildings.

Following the 7.0 Haiti earthquake, University of Washington Professor Laura Lowes assembled a team to travel to Haiti and collect detailed damage data and design information for a series of concrete buildings damaged in the earthquake.

The data were used to validate image processing algorithms and damage assessment techniques, and thereby further development of the proposed rapid inspection method. Not only did the data allow researchers to analyze the condition of the structures, but data collection activities were a significant educational experience for the members of the team.

The comprehensive, image-based data sets collected by the team were made available for use by earthquake engineering educators and researchers around the globe, with over a thousand pictures available for public access on the NEEShub.

The team collected detailed damage and design-data from five reinforced concrete buildings that were damaged in the earthquake, including the two buildings of Union School, CDTI Hospital, a parking structure, and the Digicel Building.

In order to assess the building response to earthquake loading, the team applied automated post-processing algorithms to extract damage data, for example, the length and width of concrete cracks, from the video data. They evaluated the algorithms using collected damage data in order to identify future research needs for better semi-automated post-earthquake inspection and assessment.

The team's initial findings determined that the algorithms for extraction of concrete crack properties from video



Earthquake damage in Haiti following the January 2010 earthquake.

provided acceptable accuracy. Similar algorithms could be used to enable extraction of data characterizing the extent and severity of other damage, such as spalling, bar buckling and bar fracture. The initial review of the damage data and construction drawings indicated that for several of the structures investigated, earthquake loading resulted in the development of column shear mechanisms.

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University of Washington researcher Marc Eberhard inspects damage to a bridge near Port-au-Prince, Haiti.

RAPID: Post-Earthquake Monitoring and Mentoring in Chile

NSF RAPID: Post-Earthquake Monitoring Of Buildings In Chile Using NEES at UCLA Resources, John Wallace, University of California, Los Angeles, NSF #040574, NEEShub Project Warehouse #941, [2010]

Principal Investigator

John Wallace, University of California, Los Angeles

Co-principal Investigator

Robert Nigbor, University of California, Los Angeles

Educational Impact

Graduate students: 3

Undergraduate students: 2

Following the February 27th 2010, 8.8 magnitude earthquake in Chile, a team of U.S. researchers and professionals traveled to Santiago, Chile, and joined with local collaborators on a mission to gather post-event damage data. Participating in the team were NEES researchers from the University of California, Los Angeles.

Between March 13th and 28th, UCLA Professors John Wallace and Robert Nigbor led the NEES at UCLA field team in instrumenting four reinforced concrete buildings in Santiago to gather aftershock response data and inspecting the buildings to assess and model earthquake damage.

The selected buildings represented typical structural designs in the United States and Chile, such as high-rise office buildings with large office space and mid-rise residential shear wall buildings. Monitoring was continued for two months after the team left, supported by local researchers. High-quality ambient data and many aftershocks were captured during this monitoring effort.

IMPACTS

The unique data collected from these buildings, especially the damaged buildings, will support ongoing research on the strength of earth-damaged structural components and the real impact of damaged shear walls to building response and performance.

Similar projects were undertaken in New Zealand following the devastating earthquake in Christchurch in February 2011, based on the results of this work.

OUTCOMES

Building drawings, documentation of earthquake damage, and measured response data were archived in the NEES Data Repository for future use.

In addition, the project provided an opportunity to assess shipping, logistical, and legal issues associated with deploying NEES at UCLA equipment to foreign countries following large earthquakes.

Furthermore, similar projects in Istanbul, Turkey, and Christchurch, New Zealand provided the NEES at UCLA Equipment Site with valuable experience, increasing the potential that unique and valuable structural data will be collected by NEES in future earthquakes.

RESEARCH METHODOLOGY

Following the Chilean earthquake, the UCLA team and the NEES post-earthquake monitoring equipment were rapidly deployed to Santiago. The team coordinated with other post-earthquake engineering teams, including one from EERI. There was also close coordination with local Chilean researchers.

The NEES at UCLA team installed monitoring equipment in four buildings to collect data during aftershocks and ambient vibrations. Two of the instrumented buildings were undamaged, one building suffered only minor non-structural damage, and the fourth exhibited significant structural damage such as column buckling and shear wall cracking.

Most buildings over five stories in Chile are constructed using reinforced concrete (RC) shear walls, a method also common in the United States. The Chilean and U.S. seismic design requirements are very similar, and design of RC buildings in Chile is based on US ACI 318-95, with minor modifications.

The project was the first aftershock monitoring project conducted by the NEES at UCLA equipment site; the experience provided the team an opportunity to identify critical issues and challenges associated with remote deployments, such as shipping large equipment overseas in a challenging, post-disaster environment.

The team worked with local collaborator Juan Carlos de la Lleria and Professor Patricio Bonelli from Federico Santa Maria Technical University in order to select the appropriate buildings to monitor. The 24-channel monitoring systems

NEES at UCLA engineer Alberto Salamanca operating the temporary monitoring system in the Mistral Building.



arrived in Chile 14 days after the earthquake; owing to the helpful partnership with Pontificia Universidad Católica de Chile, the systems were deployed in the buildings within four days. One of the systems remained in Chile for two months, continuing the monitoring of aftershocks.



UCLA researcher Anne Lemnitzer and PI John Wallace next to an earthquake-damaged column in Chile.

The collaborative efforts with universities in Chile enabled the team from UCLA to train three graduate students from Pontificia Universidad Católica de Chile and a professor from the University of Chile on the use of the monitoring equipment.

Information collected from the four buildings came from schematic drawings as well as sensor data from the monitoring equipment. Instrumentation consisted mainly of uniaxial and triaxial accelerometers as well as some displacement transducers; data were recorded with 24-bit, GPS-synchronized digital data systems. Both data and drawings are available on the NEEShub.

The team hopes to use the data gathered for 3D model calibration, such as accelerations, displacements, strains, and damping effects. Contact and collaboration with researchers in Chile were expanded with this project, and longer-term studies involving future collaboration with researchers in Chile have great potential.

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Pioneering Data Collection on Tsunami Debris Impacts

RAPID: Impact of Debris Generated from the 11 March 2011 Tōhoku, Japan Tsunami, Clay Naito, Lehigh University, NSF #1138668, [2011]

Principal Investigator

Clay Naito, Lehigh University

RAPID Team

Dan Cox, Oregon State University
 Ronald Riggs, University of Hawaii
 Marcelo Kobayashi, University of Hawaii
 Hillary Brooker, Lehigh University ME student
 Kent Yu, Degenkolb Engineers

Educational Impact

Graduate students: 5

Undergraduate students: 1

On March 11, 2011, a magnitude 9.0 earthquake occurred off the northeast coast of Honshu, Japan. The Tōhoku Earthquake, as it is now known, was focused in the subduction zone plate boundary resulting in the formation of a tsunami that radiated across the Pacific toward Japan. The tsunami inundation across the northeast coast of Japan was severe, resulting in run-up heights in excess of 23 meters above sea level in some areas. The earthquake and tsunami produced devastating and widespread damage to coastal ports and communities, which resulted in thousands of deaths and tens of billions of dollars in damage. Following the events, NSF RAPID projects were quickly coordinated and launched.

Lehigh University engineer Clay Naito headed up the RAPID project called Impact of Debris Generated from the 11 March 2011 Tōhoku Japan Tsunami. Professor Naito, along with practitioners and researchers from American and Japanese universities, traveled to tsunami damage sites in northeast Japan to assess the type of debris generated by the inundation and to quantify the resulting impact damage to structures.

The team observed damage to structures caused by hydrostatic, hydrodynamic, and impact demands. While likely that hydrostatic and hydrodynamic forces resulted in a majority of the damage, impact from tsunami debris significantly contributed to the losses observed.

Current knowledge on how to quantify the effects of impact demands from tsunami generated debris was limited; in fact, this team was among the first ever to

collect and categorize tsunami impact data. They collected information on impact-related damage, debris type, and debris flow characteristics. From the field investigations preliminary observations on debris type, likelihood of damage, and debris region were developed and summarized.

IMPACTS

The team's recommendations, which resulted in order of magnitude differences in expected demands, were used to help develop code language for ASCE 7 Standard: Minimum Design Loads for Buildings and Other Structures. The observations from the RAPID were also used to develop an approach for quantifying the spread of debris from a particular site, thus allowing the determination of which structures will have a higher likelihood of debris impact.

Not only were code changes recommended, but international partnerships were fostered as post-disaster reconnaissance teams learned how to negotiate and collaborate with international groups such as the UNESCO-led International Tsunami Survey Team. Professor Naito's team also coordinated with many Japanese research centers including Nagoya University, the Building Research Institute, and the National Institute for Land and Infrastructure Management.

OUTCOMES

Tsunami-generated debris can be divided into three categories: small disbursed debris which alters water density, low-to-moderate size/mass debris which can result in localized impact and damming on structures, and large-size debris which can result in significant damage to evacuation shelters.

Type of debris present in a region is dependent on the coastal region, as ports and residential communities are subject to different debris demands. Structural damage from debris impact is dependent on the structural configuration of the facility below inundation depth and the debris category of the region and the structural component strength.

RESEARCH METHODOLOGY

The team examined the debris demands generated on coastal communities in the tsunami and collected quantifiable data on impact related damage, debris type, and debris flow characteristics. This allowed them to develop and summarize preliminary observations on debris



Professor Clay Naito and Dr. Kent Yu examine fuel storage container damage.

type, likelihood of damage, and debris region. Debris was characterized by size, mass, buoyancy, and resultant demands.

Residential regions were shown to be at greatest risk from small to large woody debris, destruction of houses and trees, small vehicles and buoyant buildings. Commercial areas were shown to be at greatest risk for impact from boats, vehicles, fuel storage, and small-building debris. Industrial areas were shown to be at greatest risk from containers, boats, vehicles, fuel storage, and large vessels.

Part of the team's effort was devoted to the study of fuel storage containers and the damage they could cause. Fuel storage containers located in the inundation zones are often subject to tie-down failure and lateral movement resulting in fuel contamination in the tsunami-damaged region.

The team recommended underground storage, elevating low-drag fuel tank supports, or using tethers to prevent containers from becoming debris.

FUTURE

The research has led to a better understanding of the likelihood of debris-spread due to a tsunami event and how to estimate the demands that are generated under a head-on impact event. With the findings being codified as part of standard building loads, it is expected that new facilities will be more resilient to tsunamis and their effects. The team plans to pursue further efforts to quantify the effects of impact from other types of debris and impact scenarios including transverse impact of floating vehicles and objects typical of flood and tsunami events.

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High-Resolution Data Collection After Tōhoku Earthquake, Tsunami

Collaborative Research: RAPID: Post-Disaster Structural Data Collection Following the 11 March 2011 Tōhoku, Japan Tsunami, Ian Robertson, University of Hawaii, NSF #1138710, [2011]

Collaborative Research: RAPID: Post-Disaster Structural Data Collection Following the 11 March 2011 Tōhoku, Japan Tsunami, Michael Olsen, Oregon State University, NSF #1138699, [2011]

Principal Investigators

Ian Robertson, University of Hawaii, Manoa
Michael Olsen, Oregon State University

Co-Principal Investigators

Kwok Fai Cheung, University of Hawaii, Manoa
Solomon Yim, Oregon State University

Educational Impact

Graduate students: 3

IMPACTS

The massive 9.0 earthquake off the coast of Honshu, Japan, in March of 2011, and subsequent tsunami, caused enormous damage to Japan's northeastern coastal communities. Soon after the earthquake and tsunami, a small expeditionary RAPID team led by Professors Ian Robertson of the University of Hawaii and Michael Olsen of Oregon State University traveled to the region. Their immediate goal was to perform a high-resolution survey of the damaged area in order to gather time-sensitive topographic data. Their ultimate goal was to use these data in conjunction with prior NEES-funded experimental research to develop tsunami design provisions for building codes and coastal region planning.

This field reconnaissance helped resolve several key questions in the tsunami design provisions regarding flow velocities and momentum of tsunami bores and wave surges over land and scouring. The data also address overarching questions on risk-based design criteria and the ultimate capabilities of structures to resist a maximum credible tsunami.

OUTCOMES

The team focused their efforts on the most severely damaged coastlines, in the Miyagi and Iwate Prefectures.

The group collected high resolution, ground-based LIDAR data. LIDAR is a remote sensing technology that illuminates a target with laser light and then analyzes the reflected light.

The LIDAR data was used to generate virtual models that can be queried for measurements such as flow depths, observed maximum run-up, and scour depths at key sites. These were complemented with manual measurements and analysis of videos and photographs. The LIDAR data also provided detailed dimensional data for the structures to be studied, including deformations resulting from damage due to tsunami loading.

The data gathered provides a virtual time capsule, allowing researchers in multiple disciplines to return to the post-disaster environment and gather data at a future date, since the LIDAR survey provided a complete model of the damage, information impossible to attain with manual measurement techniques. This means that the data produced by the Tōhoku tsunami can be preserved indefinitely and will continue to be available to researchers as the area recovers.

Graduate students Evon Silvia and Shawn Butcher from OSU participated in the reconnaissance team and a portion of the data analysis.

Yoshiki Yamasaki from UH utilized the LIDAR topographical data from Onagawa, Japan, to model inundation during the tsunami. This inundation was then compared with field observations based on eyewitness videos and the LIDAR capture of building dimensions.

Results from this project were incorporated into a Research-to-Practice webinar presenting results of this and prior NEES laboratory research. The webinar was attended by 200 members of the general research community, professionals, and the public. The team also presented their results at a number of conferences and in a number of journal publications.

RESEARCH METHODOLOGY

LIDAR scans are created through a remote sensing method that allows researchers to use a pulsed laser to measure variable distances to the earth, creating a 3D virtual world. The team's portable laser scanner provided high accuracy and high resolution, in combination with GPS geo-referencing in order to create simultaneously registered imagery.



Combined LIDAR scans of buildings damaged by the tsunami in Onagawa with photographic color overlain on the point cloud.

The combination of mobile laser scanning, done by Asia Air Co., and the static scans done by the team, allowed for a detailed and complete analysis of the damage. The team scanned several locations in the Tōhoku region of Japan, resulting in approximately 2 billion data points.

FUTURE

Analyses of the data collected from this effort have been useful for the committee working on the new Chapter 6 - Tsunami Loads and Effects for the ASCE 7-16 Standard. Once adopted by ASCE 7, this new chapter will provide probabilistic tsunami design provisions for use in new construction in tsunami inundation zones in Alaska, Washington, Oregon, California and Hawaii. They may also be referenced internationally by other countries exposed to tsunamis.



Deformation analysis for the Gamou Wastewater treatment plant after impact by the the 2011 Tohoku Tsunami. The histogram on the right shows the distribution of various levels of change across the wall.

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Robertson, I.N., Carden, L.P., and Chock, G.Y.K., Case Study of Tsunami Bore Impact on RC Wall, Proceedings of the 32nd International Conference on Ocean, Offshore and Arctic Engineering, OMAE 2013, Nantes, France, June 9-14, 2013.

Recurring Liquefaction and its Effects on Buildings and Lifelines following the 2010-2011 New Zealand Earthquakes

RAPID: Liquefaction and its Effects on Buildings and Lifelines in the 2010-2011 Canterbury, New Zealand Earthquake Sequence, Russell Green, Virginia Polytechnic Institute and State University, NSF #1306261, [2013]

Principal Investigator

Russell Green, Virginia Polytechnic Institute

Co-Principal Investigators

Thomas O'Rourke, Cornell University

Jonathan Bray, University of California, Berkeley

Educational Impact

Graduate students: 4

The 2010-2011 Canterbury, New Zealand, earthquake sequence started with the Darfield earthquake in September 2010, which had a magnitude of 7.0 and occurred west of Christchurch. The Canterbury earthquake sequence included 3 events having a magnitude greater than 6.0 and 45 events having a magnitude greater than 5.0. Due to the close proximity to Christchurch and shallow depth of fault rupture, the magnitude 6.2 Christchurch earthquake in February 2011 was the most devastating event in the sequence, resulting in nearly 200 deaths and thousands of injuries, with widespread soil liquefaction and damage to the built environment.

Liquefaction is a phenomenon that occurs in saturated sandy soils and involves the transfer of overburden stress from the soil skeleton to the fluid between soil grains. This results in an increase in pore water pressure and causes the soil to behave like a liquid. In Christchurch, liquefaction was initiated by earthquake shaking.

Following the massive earthquakes in New Zealand in September 2010 ($M_w = 7.0$) and February 2011 ($M_w = 6.1$), Professor Russell Green led a multi-disciplinary team to the region to investigate the terrain and capture perishable data pertaining to liquefaction and other geologic/geotechnical phenomena.

The damage caused by liquefaction in New Zealand, though devastating, provided a unique opportunity to evaluate the effects of seismic shaking of different intensities on the response of various soil profiles, as well as the effects of liquefaction on building foundations and critical lifeline systems.

Significant accomplishments were made in each of these areas in a previous RAPID effort. However, as is often the case in research, the previous investigations identified additional significant, time-critical opportunities to advance the knowledge of geotechnical and lifeline earthquake engineering. There is still much to learn from comparing the different levels of soil liquefaction caused by the earthquakes in this sequence and from evaluating the differing seismic performance of buildings, lifelines, and engineered systems during these events.

IMPACTS

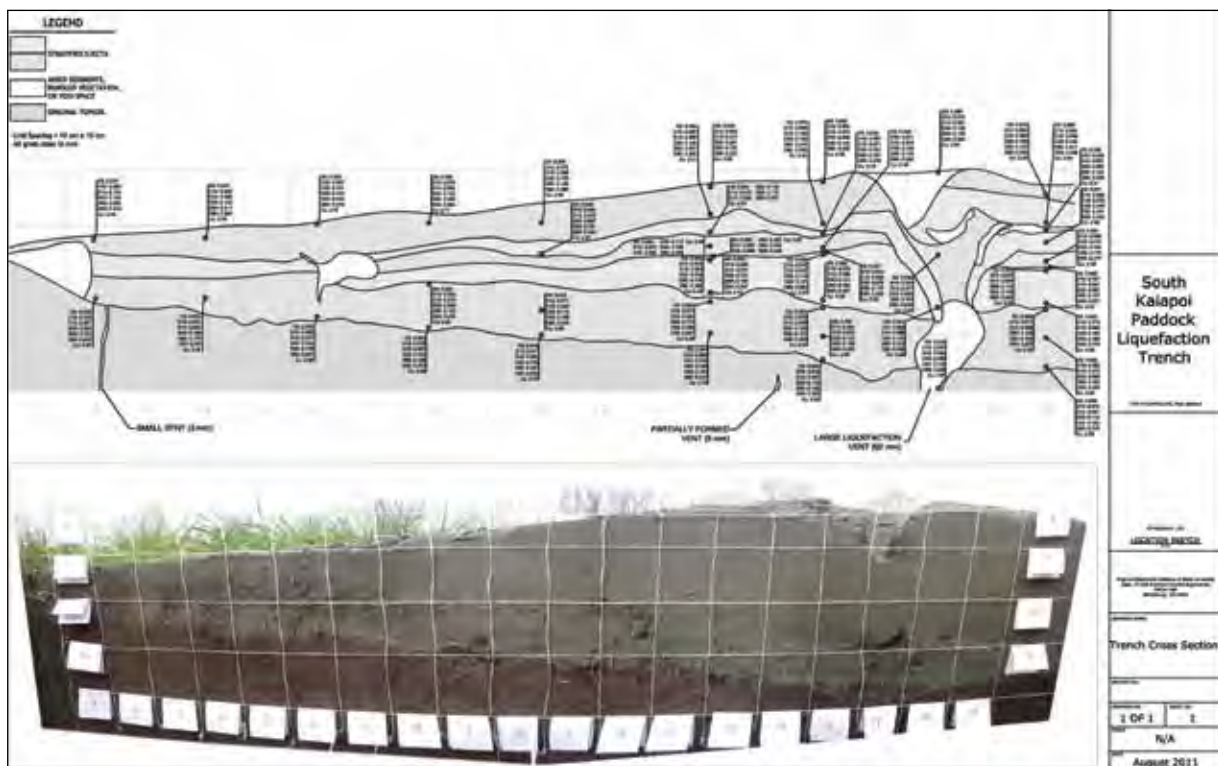
The team is working to understand the re-occurrence of liquefaction, as well as building and lifeline performance in affected areas. Due to the rarity of the data, it is providing new insights about how the same ground and infrastructure responded to multiple seismic events having different levels of shaking intensities.

The Darfield and Christchurch earthquakes, in particular, represent important earthquake scenarios for the United States. Thus, there is a real need to document their geotechnical effects. Moreover, these earthquakes involve multi-hazard effects. The combined settlement caused by liquefaction during both earthquakes has exposed many Christchurch neighborhoods to increased threats from river and ocean flooding, including tsunami. Conclusions and observations drawn from the collected data will form the basis for flood risk assessment as well as earthquake vulnerability.

OUTCOMES

The team focused its efforts on building foundation response, liquefaction and other ground failures, performance of bridges and other lifelines, the performance of port facilities, and slope failures.

The Canterbury earthquakes yielded the most comprehensive data of the integrated effects of multiple earthquakes and liquefaction episodes, including the locations and types of damage for all underground lifelines in Christchurch, thousands of residential structures, and scores of commercial buildings. High-resolution airborne Light Detection and Ranging (LIDAR) measurements of lateral and vertical surface movements for multiple earthquakes and hundreds of liquefaction surveys and geodetic measurements have also provided excellent data for the team to analyze.



Trench through sand boil at a site of recurrent liquefaction. The number and the severity of the liquefaction episodes can be identified in the structure of the sand boil.

The research team discovered that soil liquefaction damaged many multi-story buildings in a substantial part of Christchurch. Multiple episodes of liquefaction could be identified in trenches cut through undisturbed sand boils. They also integrated geographic information systems for water supply, wastewater, storm water, electric power, and gas distribution systems to show spatial damage distribution relative to ground motions and liquefaction induced ground movement.

Thousands of repairs were needed in water lines made of asbestos cement, cast iron, or PVC. High density polyethylene water mains sustained no damage when

RESEARCH METHODOLOGY

The project was coordinated through the Geotechnical Extreme Events Reconnaissance (GEER) Association in collaboration with the University of Canterbury and the New Zealand government. The team's eventual goal is to document the effects of soil liquefaction on the performance of buildings with different types of foundations, and to document the effects of liquefaction and ground deformation patterns on the performance of lifelines.

The team looked at buildings in order to document the subsurface conditions and building performance at several key sites in Christchurch. Field reconnaissance was focused

on capturing perishable data and characterizing the soil profiles at select sites. Shallow, silty sand or poorly graded sand deposits were found to be largely responsible for poor foundation performance.

Continued on page 165

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- O'Rourke, T.D., Jeon, S.-S., Toprak, S., Cubrinovski, M., Hughes, M., van Ballegooy, S., and Bouziou, D. (2014). "Earthquake Response of Underground Pipeline Networks in Christchurch, NZ," *Earthquake Spectra J.*, 30(1), 183-204.
- Wotherspoon, L., Orense, R., Jacka, M., Green, R.A., Cox, B., and Wood, C., (2014). "Seismic Performance of Improved Ground Sites during the Canterbury Earthquakes," *Earthquake Spectra J.*, 30(1), 111-129.

NEES Researchers Validate Ground Improvements in Liquefaction-Prone Christchurch, New Zealand

RAPID: Field Investigation of Shallow Ground Improvement Methods for Inhibiting Liquefaction Triggering; Christchurch, New Zealand, Kenneth H. Stokoe, University of Texas at Austin, NSF #1343524, NEEShub Project Warehouse #1204, [2013]

Principal Investigator

Kenneth Stokoe, University of Texas at Austin

Co-Principal Investigator

Brady Cox, University of Texas at Austin

Educational Impact

Graduate students: 5

Christchurch and the Canterbury region of New Zealand were devastated in 2010 and 2011 by a series of earthquakes that caused widespread liquefaction and extensive damage to homes and buildings. One critical problem local governments face as they attempt to rebuild a resilient infrastructure is that the land remains at risk to liquefaction in future earthquakes.

For the RAPID grant called Field Investigation of Shallow Ground Improvement Methods for Inhibiting Liquefaction Triggering, researchers from the University of Texas at Austin collaborated with researchers and engineers in New Zealand to develop ground-improvement methods to strengthen the ground and decrease liquefaction vulnerability. The treatments are designed for homes and low-rise structures built on soils previously prone to liquefaction.

Field trials involved testing ten different ground improvement methods at three locations of differing ground conditions in Christchurch. Professor Kenneth Stokoe and his team employed the NEES at Texas T-Rex shaker to investigate the ground improvement methods under consideration. The NEES team also developed field verification procedures based on small-strain seismic testing to evaluate the improvement or lack of improvement created by each method.

IMPACTS

As a result of the study with T-Rex combined with a blast-loading study at the third testing location, Christchurch has begun a full-scale program in which NEES-validated ground improvement methods and other

similar improvement methods are being used at sites for new homes as well as larger structures. The ground improvements are also being verified in the field using procedures developed on the project. This approach will be employed by local governments to remediate land in the most cost-effective manner and will be applied at thousands of sites.

The improved ground will reduce land subsidence and render subsidence more uniform; hence, it will create more resilient infrastructure.

The new knowledge gained regarding the design of ground improvements to lessen liquefaction damage on level-ground or nearly level-ground sites will transfer directly to U.S. cities such as Seattle, WA, Los Angeles, CA, Memphis, TN, and Charleston, SC.

OUTCOMES

Findings from the research are detailed in a paper presented at the New Zealand – Japan Workshop on Soil Liquefaction during Recent Large-Scale Earthquakes. Professor Stokoe and his team from the University of Texas at Austin worked with Sjoerd Van Ballegooy from Tonkin & Taylor Ltd, an international environmental and engineering consulting firm in Auckland, New Zealand.

RESEARCH METHODOLOGY

In early 2013, NEES at Texas researcher Professor Brady Cox evaluated seven potential test locations along the Avon River in the Christchurch area, an area highly prone to seismic liquefaction. Three of the seven test locations were selected to represent the differing sandy soil conditions in Christchurch. A previously developed direct test method for dynamically assessing the liquefaction resistance of granular soils in-situ using T-Rex (Cox et al., 2009) was deployed to characterize local soils in order to determine the most effective and cost-efficient methods of ground remediation.

The field tests were conducted at the three locations along the Avon River and involved from six to 10 test panels of different shallow ground improvements. The ground improvement test panels were dynamically loaded with T-Rex, a large mobile shaker shipped to New Zealand from the University of Texas at Austin. T-Rex was also used to install sensors in the ground before shaking so that the ground response could be directly measured.



Preparing for T-Rex shaking: (1) Burying sensor cables in native soil; (2) placing gravel pad; (3) load with T-Rex overnight, and (4) T-Rex shaking and recording.

T-Rex was used to load each test panel with an increasingly forceful sequence of dynamic horizontal loads. Researchers collected data from test panels of improved and unimproved natural soils. Embedded sensors monitored key factors: ground motion and pore water pressure during shaking. The sensors provided data that allowed researchers to determine the most effective ground improvement methods. Further, the Texas team developed field seismic verification methods to evaluate the change in ground stiffness created by each improvement method before T-Rex shaking. The verification methods are critical in evaluating the effectiveness of the improvements installed by contractors during the Christchurch rebuilding effort.

Eight of the ground-improvement methods tested were: rapid impact compaction (RIC), rammed aggregate piers (RAP), low-mobility grouting (LMG), construction of a single row of horizontal beams (SRB) or a double row of horizontal beams (DRB), driven timber piles (DTP), gravel mats (GM) and soil-cement mats (SCM). The RIC, RAP, DRB, and DTP inhibited liquefaction triggering the most, although researchers are still analyzing the results.

FUTURE

The Christchurch testing program, initial results, and new knowledge demonstrate the importance of the work.

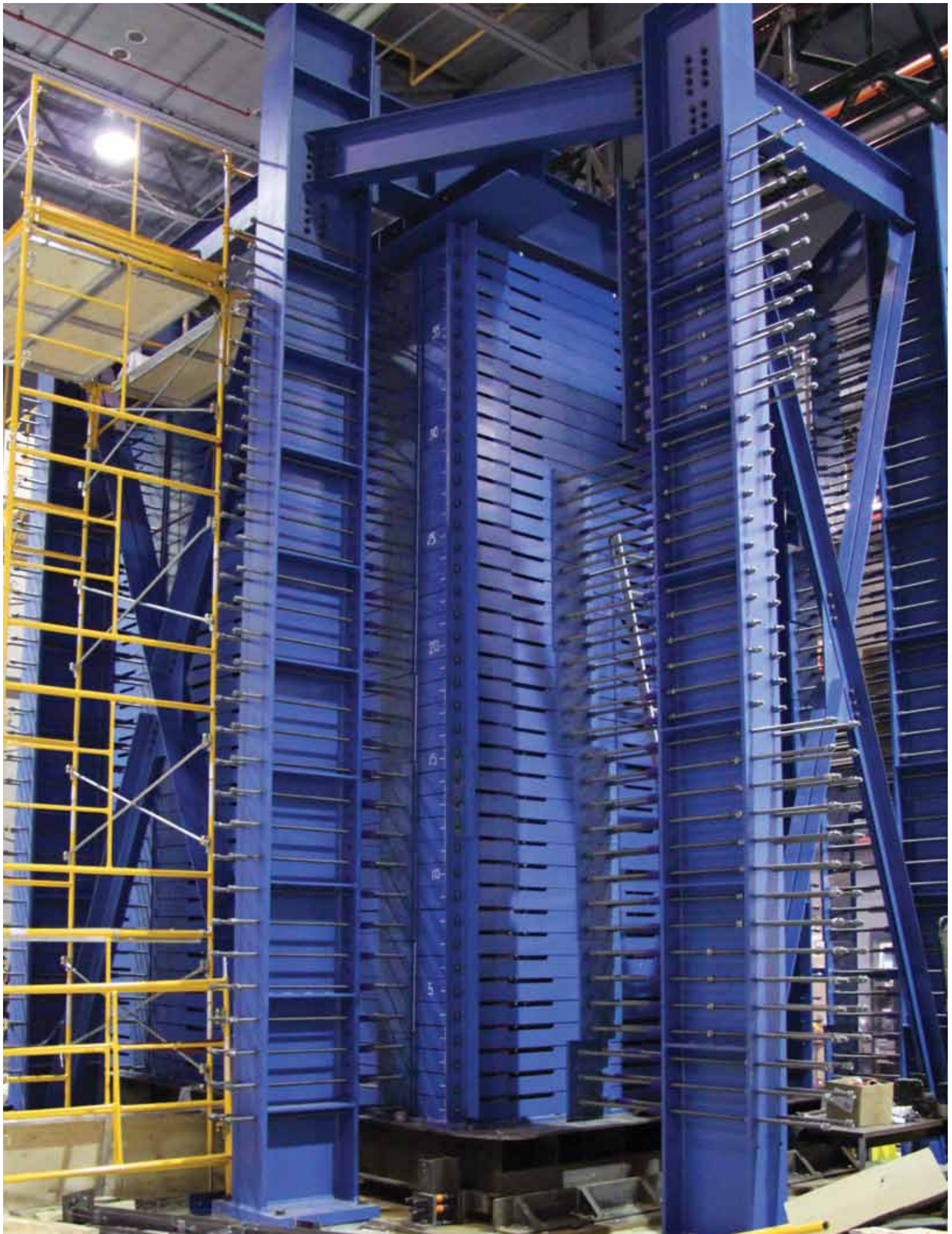
A wealth of data on the basic phenomenon of pore water pressure generation in partially saturated and saturated sandy soils remain to be analyzed. These data will contribute to improved deformation-based models of pore water pressure generation using nonlinear soil behavior for new research projects. The overall approach demonstrated in this project will generate new field research in difficult soils such as gravels and silty materials.

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11. EQUIPMENT SITE PROFILES

The NEES network features 14 geographically distributed, shared-use laboratories that support several types of experimental work: geotechnical centrifuge research, shake table tests, large-scale structural testing, tsunami wave basin experiments, and field site research. Participating universities include:*

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** From 2004 to 2009, the Fast Hybrid Testing laboratory, located at the University of Colorado, Boulder, operated as a node of the NEES network. Further information on this site may be found at <http://fht.colorado.edu/index.php>*



The Berkeley team (from left to right) Shakhzod Takhirov, Site Operations Manager; Khalid Mosalam, Principal Investigator; Selim Gunay, Hybrid Systems and Test Operations; Jose Robles, Maintenance and Test Preparation; Zulema Lara, Administration; Donald Patterson, IT Administration; Robert Cerney, Maintenance and Test Preparation; Darlene Wright, Administration; Heidi Tremayne, Educational Outreach.

The NEES at University of California, Berkeley, laboratory specializes in modeling and evaluating the response of large-scale structural systems to earthquakes. Researchers use the facility to perform conventional as well as hybrid tests using the OpenFresco and OpenSees frameworks for interaction between a physical test specimen and analytical sub-structured models.

SITE TEAM

Principal Investigator

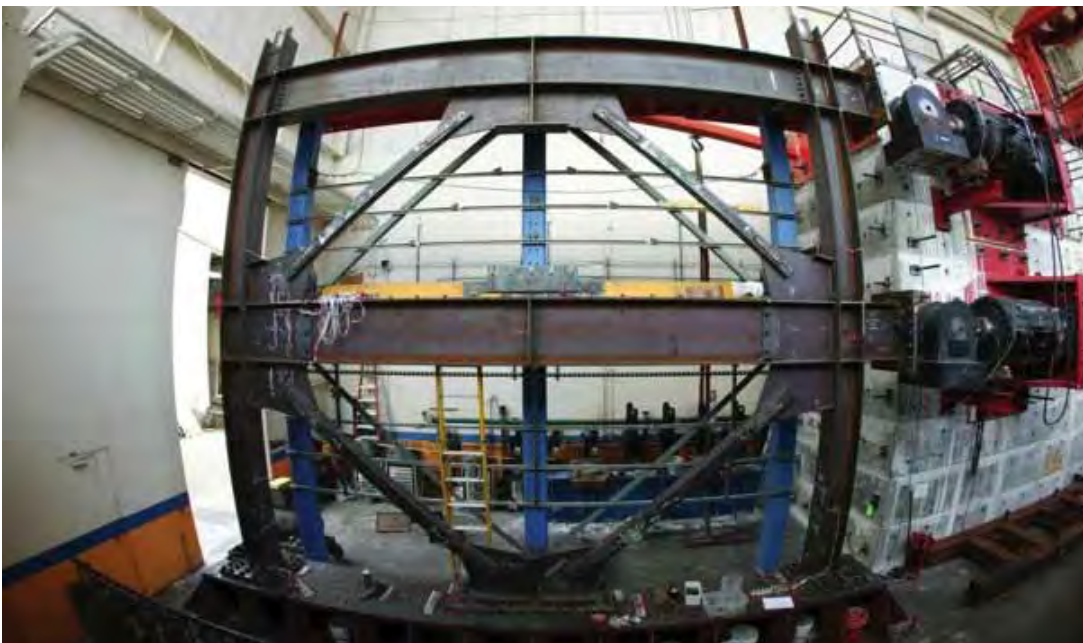
Khalid M. Mosalam

Senior Development Engineer, Shakhzod Takhirov

Hybrid Systems and Test Operations, Selim Gunay

EOT Director, Heidi Tremayne

IT Administrator, Donald Patterson



Testing a steel concentrically braced frame.

NEES at the University of California, Berkeley, has a unique reconfigurable reaction wall, with accompanying servo-hydraulic actuators, which provides a versatility for testing full-scale or near full-scale structural assemblies in a variety of geometrical configurations. In addition, the Southwark-Emery Universal Testing Machine, a 65-foot tall hydraulic press, is capable of applying up to 4 million pounds in compression and up to 3 million pounds in tension.

The Berkeley team also has developed new hybrid simulation methods including high-performance real-time techniques that combine physical and analytical sub-structures into a hybrid model of an entire structure using state-of-the-art digital controllers, the OpenFresco interface framework, and the finite element models developed using the OpenSees analysis framework.

Groundbreaking research aimed at advancing seismic protective systems leveraged multiple strengths of the Berkeley lab. The Tools to Facilitate the Widespread Use of Isolation and Protective Systems, also known as the TIPS project, showed how isolation techniques could be practical solutions for controlling seismic accelerations and building deformations caused by earthquakes (p. 46). Led by Keri Ryan (currently with UNR), Stephen Mahin (UC Berkeley) and Gilberto Mosqueda (currently with UCSD), the project assessed the economic, technical, and procedural barriers that stand in the way of widespread use of seismic isolation in the United States.

The TIPS experiments employed the NEES Reconfigurable Platform for Earthquake Testing (REPEAT) frame to test multiple superstructure configurations in order to determine the best design approach to achieve acceptable post-yield performance in the event of a superstructure yielding. The REPEAT frame can simulate the behavior of fracturing and ductile moment connections.

The tests were conducted on a newly developed high-performance long-stroke Hybrid Simulation Platform (HSP) that reproduced long-stroke, near-fault motions required for studying ultimate behavior of the seismically isolated building specimen. The capabilities of the HSP were used to assess the effect of soil-structure interaction on the response of seismically isolated structures on a variety of soil conditions, and the feasibility of locating the isolation plane along the height of a building away from the base. A controlled failure of the isolation systems studied was achieved to demonstrate acceptable performance of the isolation system even after the failure caused by a catastrophic earthquake.



A hydraulic actuator installed on a station on NEES at Berkeley's reconfigurable reaction wall. Site Manager Shakhzod Takhirov is pictured.

The TIPS project has provided essential proof-of-concept evidence about the importance of isolation technology, paving the way for it to become a more common tool in the reduction of seismic damage in the US and worldwide.

The high-impact TIPS project, which included experiments at the University at Buffalo and the E-Defense facility in Miki City, Japan, represents the successful multi-site and multi-university research collaboration that is the strength of the NEES network.



Reconfigurable reaction wall being used to test a suspended zipper frame.

The Structural Engineering and Earthquake Simulation Laboratory at the NEES at Buffalo site is capable of conducting testing full- and large-scale structures using dynamic or static loading.

SITE TEAM

Principal Investigator

Amjad Aref

Co-Principal Investigator

Michael Constantinou

Operations Manager, Tom Albrechcinski

IT Services Manager, Goran Josipovic

For earthquake simulation, NEES at Buffalo's two large shake tables can be relocated in a 38-meter long trench. The site's three large-scale dynamic (100 metric ton) and 2-static (200 metric ton) servo-controlled actuators have a cumulative capacity to apply forces of up to 7800 tons. A modular, two-level Nonstructural Component Simulator (NCS) is used for the evaluating nonstructural components and equipment under realistic seismic floor motions. A large scale geotechnical laminar box is available for soil-foundation-structure interaction studies, at full-scale or near full-scale. The lab has a 320-square-meter strong floor and a 9m x 19.5m reaction wall. The site uses its 40- and 20-ton overhead gantry cranes for placing large specimens.

The UB NEES site is capable of hybrid testing techniques, such as Real-Time Dynamic Hybrid Testing (RTDHT), enabled by dual SCRAMNET rings and multiple high-performance equipment systems and infrastructure.



The Buffalo team (left to right) includes Goran Josipovic, IT service manager; Amjad Aref, site director and principal investigator; Scot Weinreber, electronic/instrumentation engineer; Michael Constantinou, deputy director, Co-PI; Mark Pitman, technical services manager; Jeff Cizdziel, mechanical technician; Lou Moretta, mechanical technician; Tom Albrechcinski, site operations manager; Myrto Anagnostopoulou, structural and test engineer; Chris Zweirlein, electronic/instrumentation specialist; Chris Budden, electronic/instrumentation specialist; Jerry Meyers, business and contracts manager.



A large scale bridge model was designed according to the Accelerated Bridge Construction techniques.

To achieve the high loading rates required for seismic simulation, the test equipment is supported by a high-capacity, high-performance hydraulic supply and distribution system (capable of supplying up to 6000 lpm), operated by numerous high-performance digital control systems.

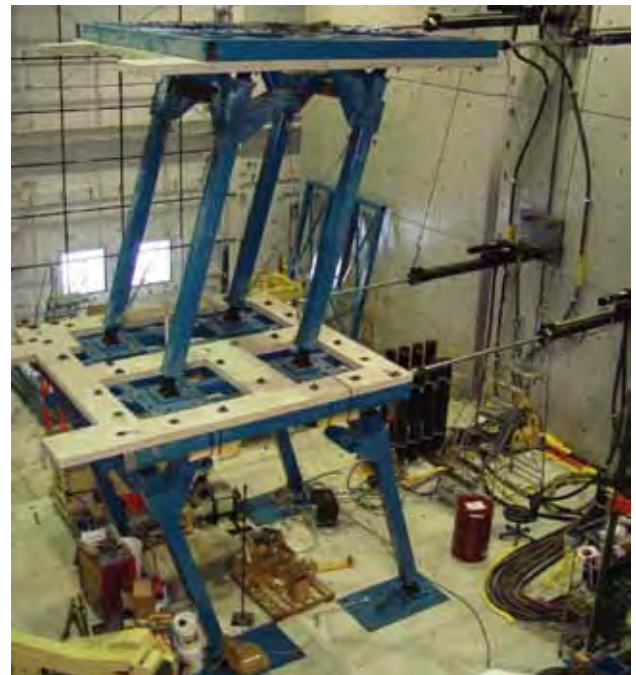
The versatile testing capabilities of UB NEES has enabled earthquake engineering research that is revolutionizing the understanding of how large structures react to seismic activity.

For example, the NEESwood project employed the UB NEES twin shake tables to advanced the earthquake engineering community's understanding of how wood-frame structures behave during an earthquake (p.26).

Testing of a two-story, 1,800 square-foot town-house over a 6-month period, at various stages of construction, enabled University of Colorado researcher John W. van de Lindt and his project team to develop computer models for predicting how wood-frame structures respond in an earthquake.

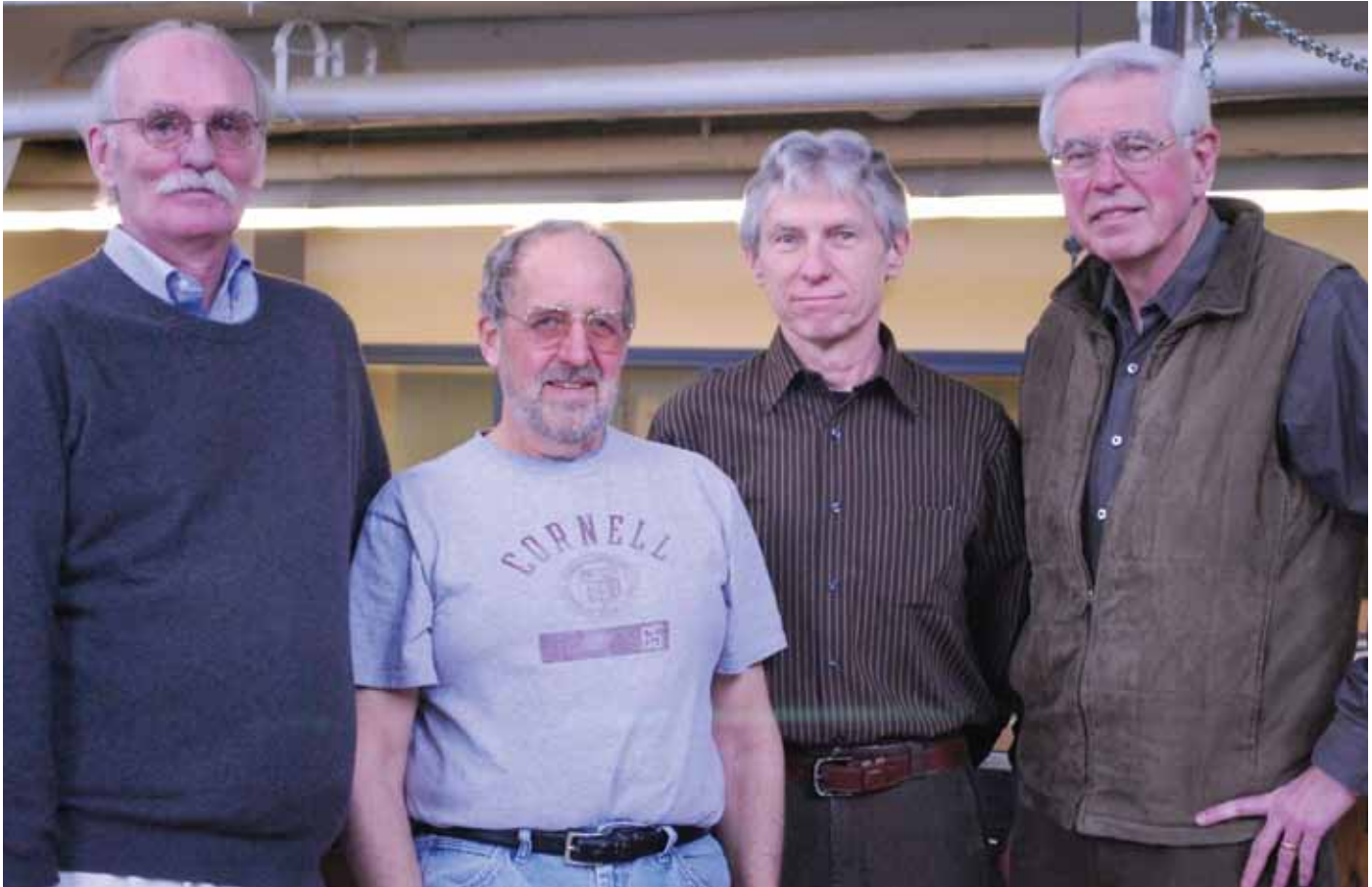
The final NEESwood experiment at UB NEES involved the completely constructed and furnished structure subjected to a simulated magnitude 6.7 1994 Northridge earthquake.

In Professor van de Lindt's follow-on project, NEES-Soft, the UB NEES site facilities also were instrumental (p.26).



The nonstructural component simulator is a modular and versatile two-level platform for experimental performance evaluation.

Research conducted at UB NEES will improve modeling mechanisms for wood-frame buildings as well as experimentally validate and enhance the ATC 71.1 retrofit options for wood-frame buildings, all of which will better protect occupants during earthquakes. These tests also employed the UB NEES site hybrid testing capabilities.



The Cornell team includes (from left) Harry E. Stewart, site PI; Tim Bond, Manager of Technical Services and Safety; Joe Chipalowsky, Site Operations Manager, and Thomas D. O'Rourke, site Co-PI.

The NEES at Cornell University equipment site is a unique laboratory for testing underground lifeline responses to large ground deformations and the seismic performance of above-ground structures.

SITE TEAM

Principal Investigator

Harry Stewart

Co-Principal Investigator

Thomas O'Rourke

Operations Manager, Joseph Chipalowsky
Manager of Technical Services, Timothy K. Bond
IT Specialist, Michael Wickham



The Soil Storage System is capable of holding 22 square yards of soil for full-scale interaction experiments.

The NEES at Cornell site focuses on large-displacement lifelines research, such as soil-structure interaction for underground gas, petroleum, and water transmission, as well as trunk and distribution pipelines. The testing facilities have no counterpart elsewhere.

Housed at the Harry E. Bovay Jr., Civil Infrastructure Laboratory Complex, key equipment includes a large, split soil-box that allows up to 48 inches of displacement. Its soil storage and conveying system is capable of holding and moving large quantities of soil for full-scale and near full-scale soil-structure interaction experiments. The soil storage bins hold 100 tons of soil in a controlled environment.

In addition, Cornell's large, configurable reaction wall enables testing of large-scale structural elements, and the facility's four large-stroke actuators provide large displacements under heavy loads. A high resolution, expandable, configurable, multi-channel measurement system is used to capture research data.

Research at Cornell has addressed both the safety and reliability of critical infrastructure, most importantly water pipelines. The largest tests ever performed in an

experimental facility, involving more than 90 metric tons of partially saturated sand per test in Cornell's soil storage system, led to promising results in Thomas O'Rourke's project, Evaluation of Ground Rupture Effects on Critical Lifelines (p. 54).

In particular, the tests on high-density polyethylene (HDPE) pipeline led to a proven leap in pipeline performance in Christchurch, New Zealand, where this new type of pipe proved more resilient than conventional ones. In Christchurch, after the series of devastating earthquakes in 2010-2011, 2.5 kilometers of polyethylene pipelines were used to complete repairs. When two additional earthquakes subsequently hit, the conventional segmental pipelines were destroyed, yet all of the polyethylene conduits held.

Based on the favorable NEES at Cornell research and the Christchurch results, engineers in the City of Los Angeles are preparing to install HDPE pipelines in the Elizabeth Tunnel, which provides half of the city's water supply. The installation of HDPE pipelines over the course of the next four-to-eight years will increase the likelihood that water will be accessible to the four million residents of Los Angeles after an earthquake.



A large scale pipeline test at Cornell University.

NEES at the University of California, Davis, is a facility capable of performing complex, detailed, large-scale centrifuge model tests for which gravity is a primary driving force.

SITE TEAM

Principal Investigator

Ross Boulanger

Co-Principal Investigators

Dan Wilson

Bruce Kutter

IT Manager, Peter Rojas

EOT Coordinator, Jenny Chen

Researchers come to NEES at the University of California, Davis, also known as the Center for Geotechnical Modeling, to conduct physical model simulations of soil and soil-structure systems subjected to in-flight earthquake shaking.

The site is notable for having one of the largest geotechnical centrifuges in the world. The 9-meter radius centrifuge is capable of producing 75 g's of centrifugal acceleration at its effective radius of 8.5 meters.

The site's smaller, 1-meter centrifuge is ideal for conducting preliminary studies. The onboard shaker enables researchers to simulate realistic seismic events using reduced scale models so that they may understand the complexity of soil behavior and soil structure interaction.

The UC Davis site has facilitated key research aimed at improving the nation's seismic resiliency.

For example, UC Davis Professor Bruce Kutter has led a series of research projects using NEES at UC Davis to study rocking foundations. Conventional practice has led engineers to design foundation components to remain essentially elastic during earthquakes.

By looking at the response of more than 20 centrifuge experiments on over 100 structures combined with parametric studies using finite element modeling, Professor Kutter has shown that rocking can be controlled and engineered to be beneficial.

This work has influenced changes to design codes to now allow rocking in foundation elements. These changes affect the evaluation of seismic risk to existing buildings and reduce the requirements, and costs, for foundation elements in new construction.



The UC Davis centrifuge has the largest radius and platform area of any geotechnical centrifuge in the United States and is among the largest in the world.



The UC Davis team includes (clockwise from bottom left: Peter Rojas, IT Manager; Chad Justice, Technician; Dan Wilson, Associate Director; Anatoliy Ganchenko, Technician; Lars Pedersen, Engineer; Ray Gerhard, Engineer; Jenny Chen, Administration, and Ross Boulanger, Director.

Another project conducted at NEES at UC Davis has provided vital data about behavior of the peat soil underlying the levees protecting the Sacramento/San Joaquin Delta, the state's water hub (p. 71). The 1100-mile levee system is at risk for severe flooding, even after a moderate earthquake. Levee failure could disrupt the state's water supply for years, crippling the state, as well as national, economy.

A team led by UCLA Professor Scott Brandenburg examined the peat-soil-based levees' vulnerability to post-cyclic deformation in the event of an earthquake. Model levees were constructed in the facility's large centrifuge, where the small-scale models behaved like full-scale models as they were saturated and tested. Sensors measuring acceleration, porewater pressure, and deformation were embedded in the levee models to characterize the response to seismic energy.

The resulting data, including video, has led to improvements in existing seismic hazard analyses of the Delta levees, giving engineers and California policy-makers a better understanding of peat-based levees – and their vulnerability.

Also at UC Davis, researchers investigating seismic risk mitigation for ports conducted centrifuge tests to evaluate liquefaction remediation techniques for pile-supported marginal wharves (p. 12).

The team, lead by Georgia Institute of Technology Professor Glenn Rix, examined the dynamic behavior of soils treated with colloidal silica to reduce liquefaction susceptibility. The team concluded that, for pile-supported marginal wharves, this particular soil improvement effectively reduced pore pressure response and the shear strains induced when subjected to large dynamic loads. These findings are key to securing the safety of our nation's susceptible wharves.

The combination of the physical test capabilities and the hybrid simulation framework and expertise at Illinois has facilitated cutting edge earthquake engineering research that is expanding understanding of structural behavior and improving the design methods and evaluation tools that are making structures safer and more resistant to damage from earthquakes.

SITE TEAM

Principal Investigator

Billie F. Spencer, Jr.

Co-Principal Investigator

Daniel A. Kuchma

Operations Manager, Michael A. Johnson

IT Administrator, Michael Bletzing

Project Coordinator, Weslee Walton

Technical Services Tim Prunkard, Supervisor

The NEES at Illinois MUST-SIM (Multi-Axial Full Scale Sub-Structured Testing and Simulation) laboratory provides a total testing-analysis-visualization-display environment that combines the ability to test full-scale subassemblies under complex loading and boundary conditions.

In this facility, full-scale structures or structural subassemblies may be subjected to complex loading and deformation states at multiple connection points on the structural specimen. The MUST-SIM large laboratory space includes the reaction frame (strong floor and strong wall) and three (3) loading and boundary condition boxes (LBCBs), along with the control systems, featuring mixed-mode control software. There is also a 1/5th-scale facility that provides a realistic pre-test environment, as well as an education and outreach facility.

The NEES at Illinois team has developed considerable expertise in hybrid simulation (HS) and real time hybrid simulation (RTHS) testing. Utilizing the UI-SimCor simulation coordinator software developed at Illinois—the most versatile HS and testing framework available—has enabled the modeling of computational components using a wide array of numerical modeling software.



One of three Loading and Boundary Condition Boxes mounted on the strongwall for the CABER connect.

In one example of research conducted at Illinois, Stanford University engineer Gregory Deierlein and his team sought to design a controlled rocking system for steel-framed buildings that would minimize building downtime after an earthquake (p. 44). At Illinois, the researchers performed quasi-static testing of a half-scale rocking frame specimen using the unique LBCBs to apply two-dimensional loading. The study verified that a controlled rocking system could eliminate residual drift and significantly minimize structural damage from earthquakes.

In another project, University of Washington engineer Laura Lowes and her team employed the LBCBs to study the behavior of complex wall systems (p. 22). The researchers used sophisticated, multi-directional seismic-loading protocols on a series of large-scale wall configurations detailed in current building codes. The models generated by Lowes' research will provide design engineers with a visual, repeatable method for quantifying the effects of seismic loading on walls, resulting in improvements to building codes for safer, less damage-prone structures.



NEES at University of Illinois, Urbana-Champaign include (left to right) Dan Kuchma, Co-PI; Tim Prunkard, Technical Services Director; Weslee Walton, Project Coordinator; Bill Spencer, PI; Michael Johnson, Operations Manager, and Michael Bletzinger, IT Administrator.

NEES at Lehigh University focuses on real-time multi-directional testing for earthquake simulation of large-scale structural systems.

SITE TEAM

Principal Investigator

James M. Ricles

Co-Principal Investigator

Richard Sause

Operations Manager, Gary Novak

IT Manager and Systems Administrator, Thomas Marullo

NEES at Lehigh University focuses on real-time multi-directional (RTMD) testing for earthquake simulation of large-scale structural systems. The facility is located in the ATLSS Research Center on Lehigh's Mountaintop Campus. Site equipment includes a large, L-shaped reaction wall and 5 high-capacity actuators, plus a complement of data acquisition and real-time execution platforms to implement a suite of coordinated communications and actions.

RTMD testing at Lehigh can be linked with other laboratories through the NEES cyberinfrastructure to

support multi-site distributed hybrid testing. In this approach, multiple substructures are tested at different geographic locations, and coordination of the control and communication tasks is needed to implement the test.

The site specializes in advanced hybrid simulation (HS) testing, and especially in the use of large-scale real-time hybrid simulation (RTHS). Real-time execution is achieved using a xPC target and a Speedgoat real-time computer. Numerical models and actuator controllers are coded using the Matlab environment. Scramnet hardware enables shared memory and synchronizes data channels from the control and data acquisition systems with simulation data, which in turn triggers camera snapshots aligned with simulation data.

Research at the NEES Lehigh facility is advancing seismic resilience in buildings.

One example is the study of advanced damping systems led by Purdue University researcher Shirley Dyke (p. 94). Similar to the way shock absorbers reduce road vibrations, damping systems protect buildings from seismic loading by attenuating vibrations in a structure. Engineers have been slow to adapt such systems, however, due to a lack of design procedures for incorporating them, and, until this project, inadequate testing methods for validating damping-system performance on a convincing scale.



A self-centering concentric braced frame is maneuvered into place for testing.



The Lehigh team includes (from left) Tim Alvin, mechanical technician; Roger Moyer, mechanical technician; Adam Kline, mechanical technician; Gilbert Perez, instrumentation technician; Chad Kusko, administrative director; Jeff Sampson, mechanical technician; Darrick Fritchman, lab manager; Tommy Marullo, IT manager; Carl Bowman, instrumentation manager; Mike Kurtz, mechanical technician; Jim Ricles, site PI, and Gary Novak, operations manager.

Due to the complex, rate-dependent behavior of advanced dampers, they must be tested in real-time. Lehigh's high-speed actuators, real-time hybrid simulation capabilities and technical expertise allowed Dyke's research team to explore and validate the best methods for using high performance dampers using different classes of structures. Research results are leading to a performance-based design methodology for equipping and securing at-risk structures with advanced damping systems.

Another innovative and high-impact study at Lehigh was led by University of Notre Dame investigator Yahya Kurama, who examined the feasibility of a reinforced concrete (RC) coupled shear wall system where the widely used, unbonded post-tensioned (PT) RC floor slab construction method is adapted for coupling (i.e., link) beams to develop coupling forces between the wall piers.

The objective is to develop a coupled wall system that provides significant performance, construction, and economic benefits, and that sustains little damage during a severe earthquake.

This system not only represents a significant innovation and transformation, but one that can be realistically achieved with existing and widely used technology. Implementation barriers include the lack of experimentally validated design methods, construction procedures, and numerical simulation models. To fill this knowledge gap, large-scale physical laboratory experiments of multi-story coupled wall structures were conducted at Lehigh University.

Deformations of the laboratory structures were monitored using multiple, three-dimensional, digital image correlation sensors, and the resulting near-full-field data will inform the other project areas.

The outcome of Dr. Kurama's study was a coupled wall system that sustains little damage during an earthquake, providing significant performance, construction, and economic benefits. Ultimately, this research performed at Lehigh will lead to the development of validated design procedures and modeling/prediction tools for the RC coupled shear wall system.



The UCLA team includes (back row, left to right) Alberto Salamanca, instrumentation engineer; Ann Lemnitzer, faculty UC Irvine; John Wallace, PI; Steve Kang, IT engineer. (Front row, left to right) Steve Keowen, mechanical engineer; Eric Ahlberg, student; Bob Nigbor, co-PI and manager. Not pictured: Erica Eskes, EOT coordinator and assistant manager.

NEES at University of California, Los Angeles, provides state-of-the-art field equipment for carrying out detailed seismic performance analyses of full-scale structural and foundation systems to develop inventories of field test results, examine nonlinear responses of full-scale structural systems, and measure soil-structure interactions.

SITE TEAM

Principal Investigator

John Wallace

Co-Principal Investigators

Jonathan P. Stewart

Robert Nigbor, Co-PI and Operations Manager

Education, Outreach, and Training Coordinator:

Erica Eskes

NEES at University of California, Los Angeles, also known as the Earthquake Engineering Mobile Laboratory, provides state-of-the-art field equipment for carrying out detailed seismic performance analyses of full-scale structural and foundation systems.

Field-based researchers utilize the NEES at UCLA equipment to develop inventories of field test results, examine nonlinear responses of full-scale structural systems, and measure soil-structure interactions.

The UCLA equipment inventory includes four large mobile shakers, including an omni-directional eccentric mass shaker nicknamed “Mighty Mouse” and two uni-directional shakers, which can be used singly or together, and a smaller portable eccentric shaker.

The shakers enable large-amplitude excitation of structures, field-testing, temporary monitoring of structures, as well as site characterization.

For structural monitoring, UCLA provides sensors and a sophisticated data acquisition system that collects data wirelessly. The site’s mobile network enables remote and shared access to data collected.

NEES at UCLA has tested buildings, bridges, foundations, and even geological structures in its 10 years of operation. The site’s unique equipment enables earthquake engineers to ensure the safety of such structures as the iconic Theme Building at the Los Angeles International Airport (p. 38).



Testing a model levee.



The NEES at UCLA eccentric mass shaker.



Testing with the MK-15 eccentric mass shaker at Elliot Field.

In 2007, this building, which was suffering from corrosion, underwent a seismic retrofit. The design team and airport officials turned to NEES at UCLA to validate the retrofitting.

The UCLA team, led by Robert Nigbor and John Wallace, conducted an experimental modal analysis on this unusually designed historic structure to understand its dynamic behavior in response to vibration, wind and earthquake loading.

Using the UCLA instrumentation and shaking equipment, the researchers measured the mode shapes, frequencies and damping ratios under ambient and forced vibration.

After these tests, the NEES at UCLA team helped install permanent earthquake monitoring instrumentation to capture the building’s response to future earthquakes. The LAX Theme Building now serves as a testbed for advanced structural monitoring research.

Equipment in Minnesota's Multi-Axial Subassembly Testing Lab allows researchers to twist, bend, compress and stretch components to determine how buildings, bridges, and other structures withstand earthquakes, hurricanes, floods, or even deliberate attacks by humans.

SITE TEAM

Principal Investigator

Carol Shield

Co-Principal Investigators

Doug Ernie

Catherine French

Operations Manager, Paul Bergson

IT Manager, Michael Boldischar

Minnesota's Multi-Axial Subassembly Testing (MAST) Laboratory is comprised of a strong floor and a 94,000 pound steel cross head (between which specimens are mounted). It is located at the university's Minneapolis campus.

A 6 degree-of-freedom (DOF) servo hydraulic control system is capable of applying 1.3 million pounds of vertical force and 880,000 pounds of horizontal force in each of two perpendicular directions to structures up to 28.75 feet tall. The system's multi-directional capabilities allow earthquake engineers to test a variety of specimens, such as beam-column joints, multi-story frames, and walls.

In addition, NEES at Minnesota's reaction wall and actuator system allow researchers to evaluate of new structural systems and materials as well as validate existing structures and the effects of retrofitting.

Tests performed at NEES at Minnesota are paving the way for modern braced-frame systems, steel systems which, working under tension and compression, can be used in structures to resist seismic loading. A collaborative international effort led by University of Washington researcher Charles Roeder explored design methods used to improve the seismic capacity of braced frames (p. 34).

During the final tests for the braced-frame project at the MAST lab, both conventional buckling braces and



Team Minnesota includes (left to right) Doug Ernie, co-PI for CI; Rachel Gaulke, Research Engineer; Cathy French, Co-PI for EOT; Paul Bergson, Site Operations Manager; Samantha Thomas, System Administrator; Chris Bruhn, Research Engineer; Mike Boldischar, IT Manager; and Carol Shield, PI.

advanced buckling-restrained systems were tested in order to understand the latest advances in braced-frame design and detailing, as well as appreciate the effects of out-of-plane deformation on the behavior of braced frames.

Before this project, computer models could not accurately capture the full range of braced behavior. The NEES at Minnesota experiments sought to understand demands on beams, columns, and connections when braces fail, and the results indicate that the seismic reduction factor depends on the size of the building, not just the type of lateral resisting system.



Minnesota's Multi-Axial Subassembly Testing (MAST) Laboratory is comprised of a strong floor and a 94,000 pound steel cross head which allows earthquake engineers to test a variety of specimens, such as beam-column joints, multi-story frames, and walls.

NEES at the University of Nevada, Reno, is a multiple shake table array facility especially suited for experiments involving long, spatially distributed structural and geotechnical systems.

SITE TEAM

Principal Investigator

Ian Buckle

Co-Principal Investigator

David Sanders

Operations Manager, Sherif Elfass

Laboratory Manager, Patrick Laplace

IT Systems Admin and Data Manager, Rebecca Hayhurst

EOT Coordinator, Kelly Doyle

The team at NEES at the University of Nevada, Reno (UNR) operates four configurable shake tables; three are biaxial while one has 6 degrees of freedom.

The site is capable of testing conventional structural and non-structural systems by using the biaxial shake tables individually in large-table mode, and by configuring

them as a single unit. This unique capacity allows for experiments on bridges and other long structures.

In addition, UNR's equipment inventory includes ten servo hydraulic actuators with a wide range of capacities, an eccentric mass shaker, and uniaxial and biaxial mass rigs.

In 2013, UNR completed the expansion of its shake table lab. The combined area of the new and existing facility exceeds 30,000 square feet. The new building can accommodate a fifth shake table and allow for more versatile use of the equipment while freeing up space for additional experiments.

The unique equipment at UNR has led to many advances in earthquake engineering, including modifications to AASHTO specifications with respect to design of curved bridges, updated construction details and improved risk assessment tools of non-structural components, as well as deployment of smart materials in bridge construction.

UNR's test portfolio includes experiments that could not be conducted before NEES, such as testing a one-of-a-kind 2/5 scale three-span curved-bridge, a 1/4 scale four-span straight bridge with abutments, a full-scale straw bale house, and ceiling-piping-partition system connected to a two-story, two-bay test bed.



Checking longitudinal post-tension duct path prior to placement of reinforcement cages.



The NEES team at University of Nevada, Reno includes (front row from left) Kelly Doyle, Education, Outreach and Training Coordinator; Sherif Elfass, NEES Operations Manager; Rebecca Hayhurst, IT Systems Administrator and Data Manager. Back row from left: Chad Lyttle, Development Technician; Patrick Laplace, Lab Manager and Safety Officer; Ian Buckle, Professor, Center Director and PI; David Sanders, Professor and Co-PI; Todd Lyttle, Development Technician.

A NEES study led by UNR professor M. Saiid Saiidi examined the shake table response of columns that incorporate smart materials. The experiments demonstrated that shape memory alloys (SMAs) have the ability to re-center bridge columns, minimizing the permanent tilt columns can experience after an earthquake (p. 20).

Thus, not only would the bridge require less repair, it would also be serviceable in the event of moderate and strong earthquakes. Following a strong earthquake, the bridge would remain open to emergency vehicles and other

traffic. As a result of Dr. Saiidi's research at UNR, columns incorporating SMAs and engineered cementitious composites (ECC) are being used in the construction of SR-99 on-ramp structure in Seattle, Washington.

The data and results provided by all these studies will assist in the evaluation of bridge seismic codes in addition to providing data for performance-based seismic design.

The NEES at Oregon State University Tsunami Research Facility is one of the world's largest and most advanced laboratories for testing scenarios in coastal and ocean-related areas.

SITE TEAM

Principal Investigator

Solomon Yim

Co-Principal Investigators

Cherri Pancake

Harry Yeh

Operations Manager, David Trejo

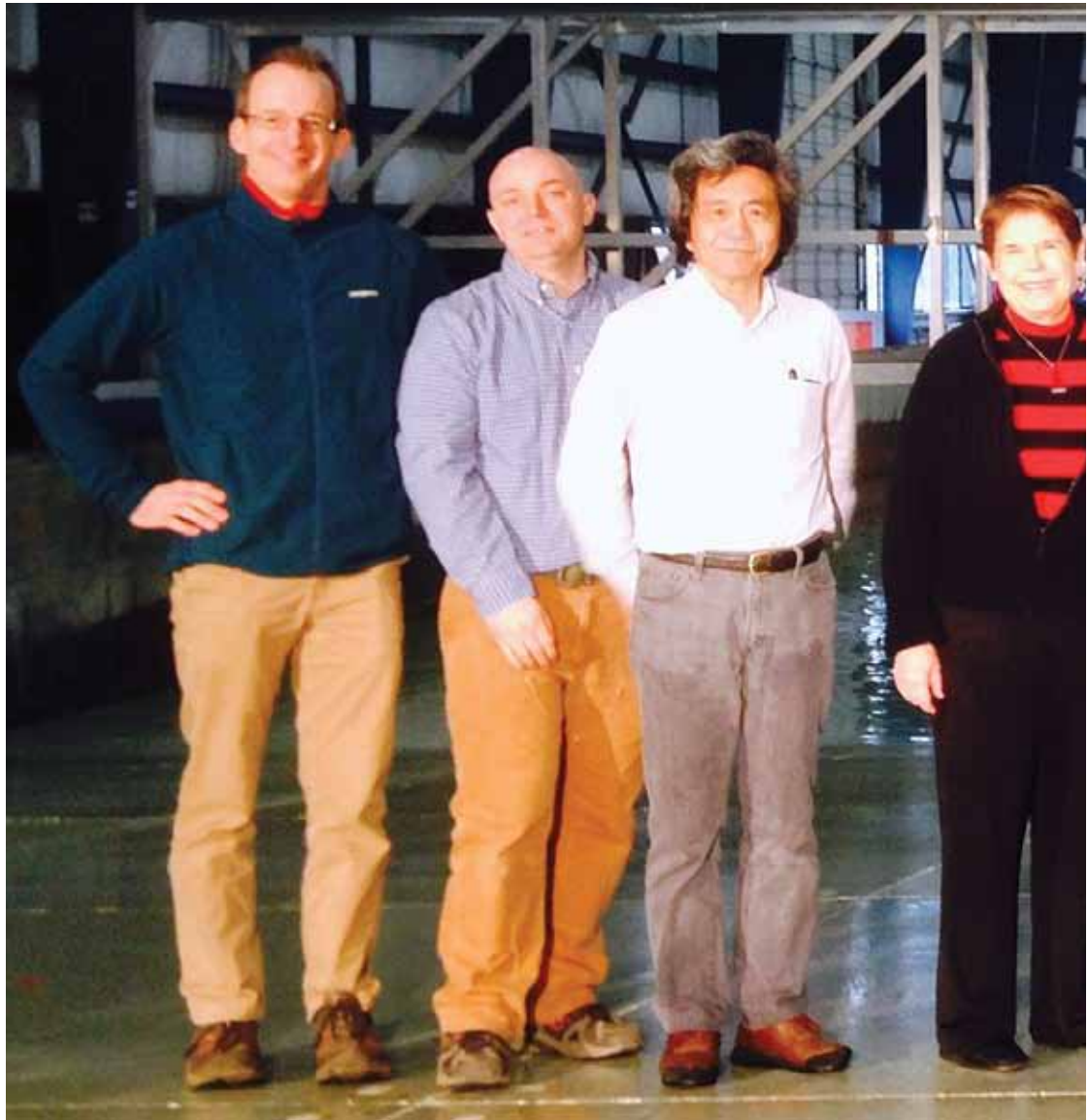
IT Manager, Leanne Lai

EOT Coordinator, Alicia Lyman-Holt

The unique NEES at Oregon State University Tsunami Research Facility, part of the O.H. Hinsdale Wave Research Laboratory, allows researchers to model earthquake and landslide-generated tsunami waves and their impact on nearshore and coastal environments.

Processes studied here include tsunami-structure interaction, tsunami inundation and overland flow, tsunami debris flow and scour, landslide-generated tsunamis, and harbor resonance – the phenomenon in which a harbor's edge can amplify tsunami waves.

The site's massive Tsunami Wave Basin is a pool nearly 50 meters long and over 25 meters wide. In the 1.37-meter deep water, the basin's wavemaker is capable of generating multiple wave-types for studying tsunami behavior and impact.



The Oregon team includes (from left)
Tim Maddux, Research Associate;
Eric Emerson, Research Assistant;
Harry Yeh, co-PI;
Cherri Pancake, co-PI;
Solomon Yim, PI;
Liam Neely-Brown, Research Assistant;
Adam Ryan, Software Engineer;
David Trejo, NEES operation manager;
James Batti, Electronics Technician.
Not pictured: Leanna Lai, IT;
Alicia Lyman-Holt, EOT;
Ben Steinberg, Data and Video Tech.

The NEES at OSU Large Wave Flume, the largest in North America, is 104 meters long, nearly 4 meters wide and 4.6 meters deep. The flume's size makes it suitable for studying hurricane and storm waves, wave generation, and various wave behaviors.

With the wave basin and wave flume facility at Oregon State University and the NEES research program, a flood of research data is becoming available on which to base design provisions.

For example, one study titled Development of Performance-Based Tsunami Engineering led by University of Hawaii engineer H. Ronald Riggs may lead to a prescriptive load chapter for tsunami effects in the ASCE/SEI 7 standards that govern minimum design loads for buildings and other structures (p. 84).

Employing data gathered in multiple tests using OSU's Tsunami Wave Basin and Large Wave Flume, Dr. Riggs' research team developed methodology and simulation tools for site-specific Performance Based Tsunami Engineering (PBTE). These PBTE tools allow engineers to analyze, evaluate, design, and retrofit coastal structures in a manner more consistent with tsunami-resistant structural design.

Many other projects that focus on minimizing impacts of tsunamis and other hurricane and storm events have been performed in the facilities

The information and modeling tools developed through projects at NEES at OSU provide vital information for designing and retrofitting coastal structures for a higher degree of safety in the face of severe tsunamis and resulting events.





The NEES equipment site at Rensselaer Polytechnic is part of the Institute's Center for Earthquake Engineering Simulation, a multi-disciplinary research center with a core mission of conducting geotechnical and soil-structure centrifuge modeling, mainly towards investigating, quantifying and mitigating the effects of earthquakes and other hazards.

SITE TEAM

Principal Investigator
Tarek Abdoun

Co-Principal Investigators
Ricardo Dobry
Thomas Zimme
Michael O'Rourke

Operations Manager, Inthuorn Sasanakul

IT Manager, Jason Thomas

Mechanical Engineer, John Lawler

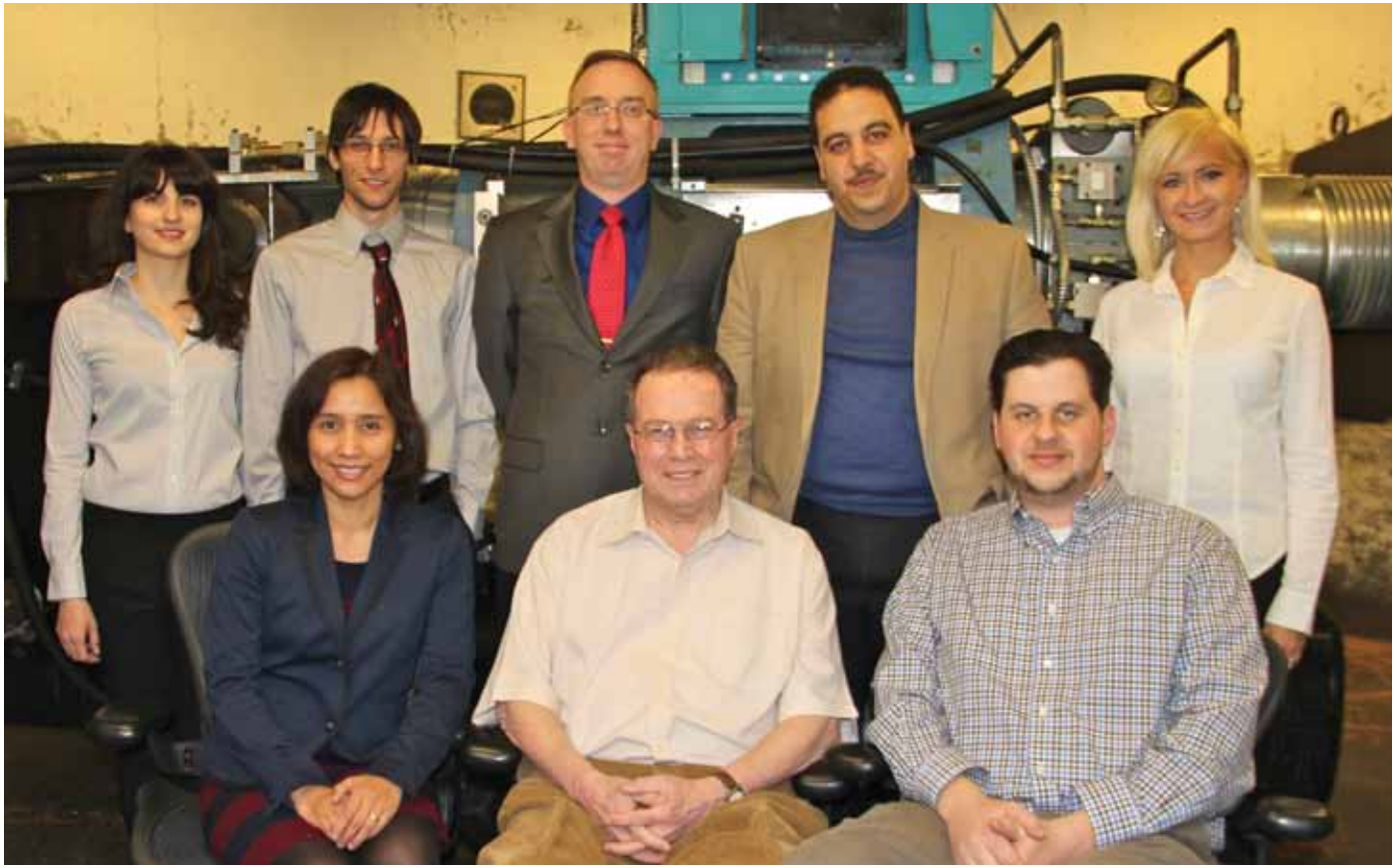
Electrical Engineer, Michael Bretti

Geotechnical Engineer, Panagiota Kokkali

Program Administrator / EOT Specialist, Tanya Volchek



The team working in the Centrifuge Control and Teleparticipation room.



The Rensselaer Polytechnic Institute team includes (back row from the left) Panagiota Kokkali, Geotechnical Engineer; Michael Bretti, Electrical Engineer; Jason Thomas, IT Manager; Tarek Abdoun, Principal Investigator; Tanya Volchek, Program Administrator / EOT Specialist. (Front row from left) Inthuorn Sasanakul, Operations Manager; Ricardo Dobry, Co-PI, and John Lawler, Mechanical Engineer. Not pictured are Thomas Zimme, Co-PI and Michael O'Rourke, Co-PI.

Located in the Jonsson Engineering Center, NEES at Rensselaer Polytechnic Institute (RPI) focuses on conducting physical model simulations of soil and soil-structure systems subjected to in-flight earthquake shaking.

Over the last 10 years, the published results of over 360 earthquake-related model simulations have served as the basis for 18 PhD dissertations and 20 master's theses at RPI. Curated in the NEEShub, RPI's data and research results also are accessed by scholars and earthquake engineers around the globe.

Researchers employ RPI's large-scale, 150g-ton geotechnical centrifuge to conduct physical model simulations of soil and soil-structure systems subjected to specific seismic-modeling conditions.

The centrifuge has an in-flight radius of 3 meters and can carry a one-ton payload at 150 g's. Tasks may be performed while the centrifuge is operating through in-flight 2D base shaker and in-flight robots. High-

speed and high-resolution cameras provide real-time visual monitoring. The "medium-size" centrifuge at RPI is purposed for smaller models that allow for speedy model preparation time. RPI has also developed the advanced NEES 3D data analyses and visualization software tools to aid near real-time processing and data mining. This new mode of research holds great promise in solving some of the critical outstanding geotechnical earthquake engineering questions.

In addition, the RPI facility is a multi-hazard mitigation site with the capability to support research for mitigating other natural hazards. The RPI facility has developed an outstanding track record in supporting the national interest in reduction of other hazards, such as hurricanes and floods.

The NEES at RPI facility is in high demand. Since 2004, it has been used in a total of 26 projects by both NEES and industrial researchers.

The NEES site at the University of California, San Diego, is a unique shake table facility that allows researchers to conduct one-of-a-kind, large-scale, experiments on sub-systems and systems for validating analytical simulation tools, which cannot be readily achieved from testing at smaller scale, or under quasi-static or pseudo-dynamic test conditions. Earthquake engineers use the NEES at UCSD facility to investigate structural, geotechnical and soil-foundation-structure interaction performance issues.

SITE TEAM

Principal Investigator

Joel P. Conte

Co-Principal Investigators

Enrique Luco

Jose Restrepo

P. Benson Shing

Operations Manager: Dan Radulescu

Education, Outreach, and Training Director:

Lelli Van Den Einde

The shake table at NEES at the University of California, San Diego (UCSD) is the world's largest outdoor shake table. Part of the UCSD Englekirk Structural Engineering Research Center, its outdoor location removes the physical constraints of an enclosed, indoor laboratory.



The UCSD team includes (left to right) Hector Vicencio, Dan Radulescu, Raymond Hughey, Lawton Rodrigues, P. Benson Shing, Jose Restrepo, Joel Conte, Robert Beckley, Alex Sherman, Linda Johnson, Enrique Luco.



The Large High Performance Outdoor Shake Table is one of the largest shake tables in the world.

The shake table has a moving steel platen 7.6 meters wide and 12.2 meters long, although the size of the platen is not a limitation for the physical footprint of a test specimen. In its current configuration, the table has a single axis of motion with a stroke of $\pm 0.75\text{m}$, a peak horizontal velocity of 1.8m/s , a horizontal force capacity of 6.8MN , an overturning moment capacity of $50\text{MN}\cdot\text{m}$, a vertical payload capacity of 20MN , and a testing frequency range of $0\text{--}33\text{Hz}$. The NEES-UCSD table was designed to be readily upgradable to a 6-DOF shake table.

The shake table can reproduce strong, near-source earthquake ground motions for testing structural and soil-foundation-structure interaction (SFSI) systems at large- or full-scale.

In addition to the shake table, the UCSD NEES site houses a soil-foundation-structure interaction (SFSI) facility consisting of a large laminar soil shear box, a large soil confinement box, and two refillable soil pits separated by a strong reaction wall. This SFSI facility can be used to test deep foundations and bridge abutments when subjected to simulated earthquake lateral loading.

One high-impact project that leveraged the UCSD facility is the Full-Scale Structural and Nonstructural Building System Performance During Earthquakes project led by UCSD Professor Tara Hutchinson (p. 36). In this \$5 million project, a multi-disciplinary and multi-university team combining researchers, code writing officials and industry advisors made breakthrough advances in the understanding of total building system (structural and nonstructural systems) performance under moderate and extreme seismic loading conditions and during a post-earthquake fire.

The capstone test was a full-scale, fully furnished five-story building, incorporating an operational intensive care unit, a surgery room, a complete egress system with a functional elevator, among various nonstructural components and systems. The building was first tested under base-isolated and then fixed-base condition. The landmark datasets collected from this project will serve to improve seismic design codes and analytical tools developed by researchers in the United States and around the world.



Engineers and members of the media watch a specially constructed five-story building during an earthquake test in San Diego.

NEES at University of California, Santa Barbara is comprised of two Southern California test facilities where the ground is permanently instrumented to collect data that will improve our understanding of the effects of surface geology on ground shaking and liquefaction during earthquakes.

SITE TEAM

Principal Investigator

Jamison Steidl

Development Engineer, Paul Hegarty

Network Technician, Aaron Martin

EOT Coordinator, Sandra Seale

The Garner Valley Downhole Array (GVDA) site is Located in a seismically active area southwest of Palm Springs, California, ~7 kilometers from the San Jacinto fault and ~35 kilometers from the San Andreas Fault.

The Wildlife Liquefaction Array (WLA) is located 160 kilometers east of San Diego in the Imperial Valley within the Brawley Seismic Zone, at the southern-most terminus of the San Andreas Fault system. This NEES at UCSB field site records numerous earthquakes on a daily basis.

While a primary goal of the UCSB field sites is to capture data from the next "Big One" in southern California, the UCSB team is not just waiting for earthquakes. The sites at UC Santa Barbara have played a key role in active testing through the NEES research program including liquefaction mitigation research, advanced site characterization research, and the NEES Grand Challenge, Mitigation of Collapse Risk in Vulnerable Concrete Buildings (p. 14). This high-impact project explored the seismic performance of older concrete buildings.

Many older concrete buildings include stiff, lateral-force resisting systems, such as shear walls. During an earthquake, such buildings are strongly influenced by soil-



The Santa Barbara team includes (left to right) Paul Hegarty, Senior Development Engineer; Adrian Cortina, Associate Development Engineer; Sandra Seale, EOT Coordinator; Jamie Steidl, PI/Site Manager; Andy Granatelli, Undergraduate Assistant; Zachary Babtkis, Computer Network Technician I. Not shown: Aaron Martin, Computer Network Technician III; Kris Duckett, Administrative Assistant; Jeri O'Mahoney, Administrative Assistant; Nathaniel Vassar, Undergraduate Assistant, and Alex Semplinski, Undergraduate Assistant.

structure interaction (SSI), which contributes significantly to deformation and energy dissipation in the structural system. Researchers sought to better understand the complex interaction between shallow foundation elements and the underlying soil for a range of loading conditions. A team lead by UCLA engineer and project co-PI Jonathan Stewart installed a configurable 1/5-scale test structure at both UCSB sites for SSI field-testing using mobile shakers operated by NEES at UCLA.

The data from these experiments revealed critically important information about ways a shallow foundation interacts with soil, revealing the limits of existing models and motivating the research team to develop improved models.

The enhanced procedures increase the reliability with which soil-structure interaction effects can be simulated, which in turn improves the reliability of seismic risk assessments for concrete (and other buildings) in seismically active areas.

The research study, which included a variety of tests at multiple NEES facilities, concluded that as many as 1,500 reinforced concrete structures in Los Angeles may be at risk of collapsing during an earthquake.



Pressure transducer being saturated in a bucket of water in preparation for installation of the assembly in the casting below the bucket.



The Wildlife Liquefaction Array records numerous earthquakes daily.

NEES at Texas provides state-of-the-art, large-scale mobile shakers that perform many types of dynamic field tests, including deep shear-wave velocity profiling, in-situ nonlinear modulus measurements, in-situ soil liquefaction tests, seismic reflection and refraction testing, dynamic testing of soil structures like dams and levees, and dynamic testing of structures.

SITE TEAM

Principal Investigator

Kenneth H. Stokoe, II

Co Principal Investigators

Ellen M. Rathje

Clark R. Wilson

Operations Manager, Farnyuh Menq

IT Manager, Robert L. Kent

NEES at the University of Texas at Austin has five mobile shakers with various force and frequency capabilities applicable to a wide range of experiments.

The shakers include T-Rex, a tri-axial vibrator, Liquidator, a low-frequency vibrator, and Rattler, a shear wave vibrator. These big shakers are transported to test sites on a 26-wheel tractor-trailer rig. Raptor, a P-wave vibrator, and Thumper, a high-frequency vibrator, are both street legal.

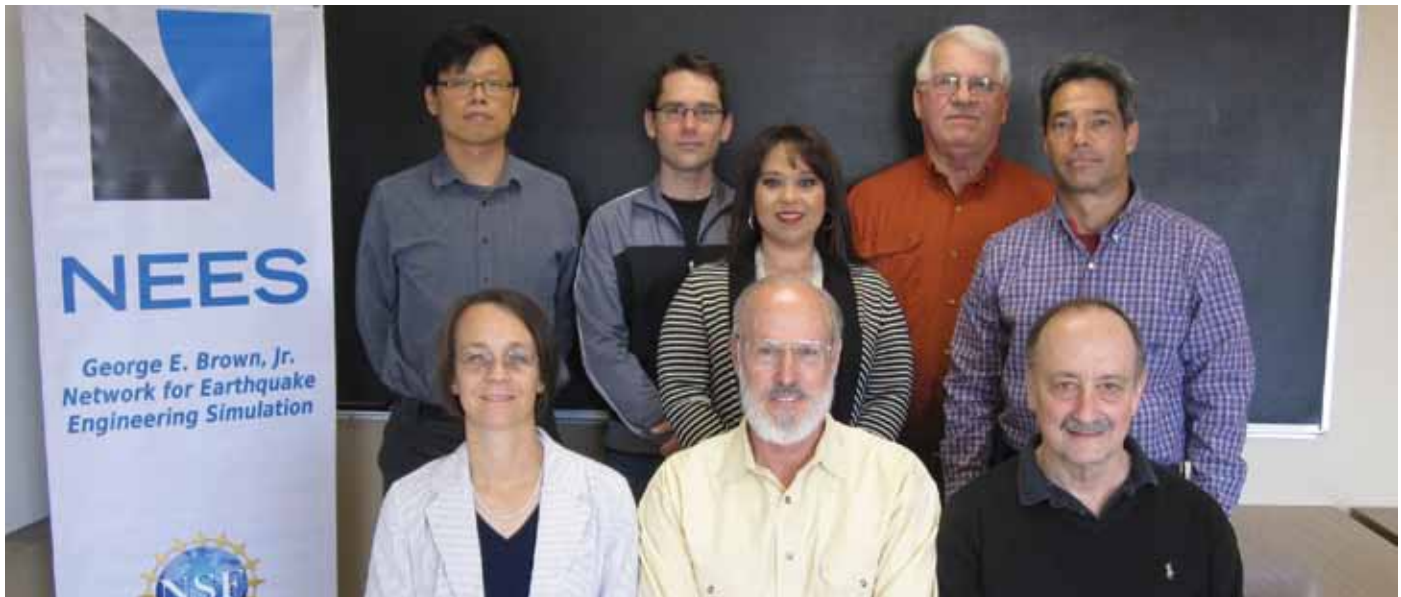
Research using the NEES at Texas shakers is ensuring human and environmental safety in surprising ways.

A team led by University of Michigan researcher Prof. Dimitrios Zekkos used T-Rex to evaluate the in-situ nonlinear dynamic properties of municipal solid waste landfills in California, Arizona, and Texas, providing valuable data on the effects of age, degradation, and moisture content (p. 78). This information is providing the basic data required for designing a landfill that is safe during earthquakes.

Recently, researchers at University of Texas at Austin led by Professor Kenneth H. Stokoe teamed up with practitioners in New Zealand for a series of in-situ liquefaction tests at Christchurch, NZ (p. 130). T-Rex was shipped to New Zealand by a cargo ship for the study. Improved and unimproved soil sites were tested over a wide range of loads simulating earthquake shaking using T-Rex.



The T-Rex being used to evaluate the dynamic properties of municipal solid waste.



The NEES at Texas team includes (front row from left) Ellen M. Rathje, Co-PI; Kenneth H. Stokoe, II, PI; Clark R. Wilson, Co-PI. Back row from left: Farnyuh Meng, Operations Manager; Robert Kent, Computer Systems Analyst; Alicia Zapata, Senior Administrative Associate; Cecil G. Hoffpauir, Vibroseis Specialist, and Andrew Valentine, Mechanical Technician.

This study provides the basis for evaluating the effectiveness of various ground improvement methods that are needed to re-construct Christchurch. Besides being used in rebuilding Christchurch after the 2010-2011 earthquakes, this new knowledge will be applicable in the United States.

SHEAR WAVE DATABASE AVAILABLE

Shear wave velocity profiles have been measured at sites across the United States using surface wave methods with the NEES at Texas equipment. A database of these profiles can be found at the NEEShub Project Warehouse, a vital element of the NEES cyberinfrastructure.

The availability of the database shows the outcome of using the NEEShub to further leverage research results from testing and the value of the NEES cyberinfrastructure to enhance testing outcomes.

Shear wave velocity profiles are key input parameters for site response analyses and liquefaction susceptibility assessments. The availability of these profiles allows engineers, geologists, and researchers to better understand regional differences in shear wave velocity.



Field instrumentation measures excess pore pressure.

Research Identifies Killer Concrete Structures in Los Angeles

Continued from page 15

The data provided by this NEES grand challenge study provides an excellent basis for the City of Los Angeles to renew its efforts to ensure the safety of its older, vulnerable concrete buildings. Using the HAZUS methodology, losses were estimated based on both a retrofitted inventory and a non-retrofitted inventory, which was used to open a dialog with the City of Los Angeles. This led to a cooperative agreement between the city and USGS to develop a mitigation program for older concrete buildings in Los Angeles.

Although each building must be individually examined for individual risk factor, Professor Moehle and his team have set events in motion for securing the physical safety and economic viability of our nation's second most populous urban area. Follow-up research and development activities, in collaboration with NIST and FEMA, are developing practical assessment tools so that the collapse risk of individual buildings can be efficiently determined.

New, Seismically Sound Foundation for Precast Concrete Buildings

Continued from page 25

The team created three-dimensional (3D) analytical models of precast concrete structures for use in nonlinear dynamic time history analysis (NTHA), models which were used to perform simulation-driven physical testing at the NEES at Lehigh facility, including hybrid simulation of earthquake response.

At the NEES at UC San Diego facility, the team examined the performance of diaphragms under earthquake excitation through a half-scale shake table test, the results of which were used to calibrate the 3D NTHA model. The calibrated analytical model was used to determine trial design factors for the diaphragm based on NLTA of a simple evaluation structure.

Structural Design Creates Taller, Stronger Wood-Framed Buildings

Continued from page 26

The project team worked with the Building Seismic Safety Council (BSSC) TS-7 to provide information related to design of low-rise and mid-rise wood-frame buildings. And in 2009, the NEESWood team helped validate the Canadian government's decision to allow six-story mid-rise wood-frame buildings into the Canadian National Building Code.

Starting in 2010, the NEES-Soft project developed a performance-based seismic retrofit approach for soft-story wood-frame buildings. The team also experimentally validated the FEMA P-807 retrofit guidelines for soft-story wood-frame buildings through a full-scale shake table test at NEES at UCSD and hybrid testing at NEES at UB. For the City of San Francisco, where soft-story apartment buildings are prevalent, the NEES-Soft data has provided valuable information for earthquake engineering decision-making.

As of 2013, San Francisco's new Mandatory Soft Story Retrofit Program ordinance requires evaluation and retrofit for multi-unit soft-story buildings. The ordinance includes the option to retrofit using the FEMA P-807 guidelines, which were tested and experimentally validated by the NEES-Soft team at full-scale in San Diego. Other seismically vulnerable cities such as Los Angeles are considering similar laws.

NEESWood

Continued from page 27

and Japan's NSF and NEES. In phase I, the test shook a seven-story, 40-foot by 60-foot tower. In phase II, the specimen's first-floor steel moment frame was locked down to be an extension of the shake table, and the structure was subjected to three levels of earthquake tests simulating the 1994 Northridge earthquake. To date, it is still the largest full-scale shake test ever conducted.

This capstone test, which was watched by 500 practicing engineers and made national news in the United States, confirmed that a structure designed using the NEESWood PBSD philosophy satisfied pre-defined performance objectives.

Evaluating Partially Grouted Masonry Construction

Continued from page 29

RESEARCH METHODOLOGY

At the component and system levels, the team is investigating the seismic behavior of partially grouted reinforced masonry wall buildings, whose complex behavior can be attributed to the combination of masonry block units, the block cavities, mortar joints, reinforcing bars, and grout. Walls are the main seismic load-resisting elements in a masonry structure. To evaluate their structural performance, quasi-static cyclic loading will be conducted to test 17 partially grouted reinforced masonry wall components and subassemblies, and two full-scale one-story buildings will be tested on a shake table.

Continued on next page

With the data derived from these comprehensive tests, the team will assess the shear capacities of these walls as compared to that expected in current codes, which could be inadequate and perhaps unsafe. In addition, advanced computational models will be developed and calibrated with test data to provide a simulation tool that can be used to understand the performance of partially grouted structures in order to develop a performance-based seismic design. This tool will be available on the NEEShub.

Impacts of Combined Loading on Bridge-Column, System Response

Continued from page 31

Similarly, a combination of bending and torsional moment reduces the bending moment required to cause yielding of the longitudinal reinforcement and the peak flexural strength.

At NEES at UNR, four large-scale cantilever RC columns were designed and tested under a unique bidirectional mass in order to enable changes in mass eccentricity for a single column under biaxial ground motions. Pairs of circular and interlocking RC specimens were subjected to different levels of bidirectional real-time earthquake motions. It was also observed that the asymmetric mass configuration used for specimens C2 and I2 only induced low values of torsion on the columns with measured values of the torque-to-bending ratio below 20%. An analytical investigation using OpenSees software was conducted to develop and validate analytical models that can reasonably predict the seismic behavior of RC columns subjected to bidirectional earthquake loading.

At NEES at UCLA, a proposed shear flexure interaction (SFI) model was applied to evaluate the system level seismic responses of three prototype bridges where the soil-structural interaction effects were also considered. The model was verified against a fiber section model and has been used to successfully simulate the behavior of columns when integrated within a prototype bridge model.

FUTURE

The project team is working towards ensuring its conclusions are incorporated into design methodologies used by bridge engineers. Team members are also working towards the OpenSees implementation of the finite element that was developed as part of the project.

Advanced Testing Buttresses Braced-Frame Designs, Retrofits

Continued from page 35

NEES at Minnesota. The culmination of this project was a pair of first-of-their-kind 3D experiments at the MAST lab at the University of Minnesota. The tests were conducted on a large-scale, two-story, one-bay by one-bay, steel, concentrically braced frame system -- representing the latest advances in braced frame design and detailing. The team tested both conventional buckling braces (CBF) and advanced, buckling-restrained systems (BRBF).

The near full-scale specimens included unique features such as: some braces framing into the column web; orthogonal brace bents sharing a corner column; and braced bents loaded in the out-of-plane as well as in-plane direction. The 3D specimens were tested under a bidirectional loading program based on a series of nonlinear time history analyses.

One of the primary contributing factors proved to be the gusset plate model, which in most braced-frame models is not accounted for. The test results showed that the gusset provides significant rotational restraint but is not rigid, meaning that the behavior must be simulated to accurately predict the frame's response.

REHABILITATING BUILDINGS WITH VULNERABLE BRACED FRAMES

In a second study of braced frames, called Collaborative Developments for Seismic Rehabilitation of Vulnerable Braced Frames, Professor Roeder and another, multi-university team are investigating the seismic performance of braced frames with common deficiencies of this era and rehabilitation methods for these older, poor performing braced frame systems.

IMPACT

This multi-phase study, currently underway, will produce practical retrofit procedures for the large inventory of non-seismic concentrically braced frames (NCBF) still in service. It will also determine which deficiencies are less critical and more critical than others so that priorities for economical retrofit can be established.

RESEARCH METHODOLOGY

Since the 1960s and 70s, steel concentrically braced frames (CBFs) have been known as efficient seismic resisting systems. Their seismic performance, however, depends not only on the specific brace properties but

Continued on next page

also on the structure's column and connection details. These aspects of design were not recognized in older construction, and in high seismic areas, these older buildings are highly vulnerable to fracture damage and collapse in earthquakes.

In high seismic regions such as California, thousands of NCBFs remain in service. The team's preliminary analyses of NCBFs indicate that 100% are susceptible to fracture damage, and that as many as 10% are prone to collapse in a large earthquake. These results confirm what engineers have long recognized: older braced frames are a critical seismic hazard, and without comprehensive, innovative, and cost-effective retrofit strategies, they will remain so.

Again using the advanced testing capabilities of the NEES at Berkeley lab and the NCREC lab in Taiwan, this research project aims to investigate, evaluate, and rehabilitate the large and critical infrastructure of NCBF buildings. To date, single-story and multi-story braced frames have been tested, and some rehabilitation strategies have been evaluated. The research is showing that some design flaws are clearly more serious than others, since the more serious flaws result in more dramatic loss of resistance and inelastic deformation capacity while less critical flaws may have more minor effects. Some very quick and economical retrofits may result in significant improvements in performance even though the performance is less than targeted in new construction. The combined information will allow engineers to prioritize their retrofit work to focus on more critical design flaws and in some cases economically improve the seismic performance of older structures that would not be retrofitted because of high costs.

Performance-Based Design: An Efficient Procedure for Designing Seismically Safe Structures

Continued from page 43

FUTURE

Current research is assessing the self-centering concentrically-braced frame (SC-CBF) system for a wide range of building heights. Also, a rigorous assessment of the resistance of SC-CBF systems against collapse under extreme earthquake ground motions is underway. Current research is extending the self-centering, damage-free system concept to timber and reinforced concrete structures. Further research, using numerical simulations, is studying the response of various steel frame buildings with passive damper systems designed to meet a range of performance criteria.

Research Fosters Widespread Adoption of Seismic Isolation Techniques

Continued from page 47

RESEARCH METHODOLOGY

The project consisted of three main sets of experiments as well as numerical simulation.

In test series one, led by Professor Gilberto Mosqueda, experiments were conducted at the NEES at Buffalo facility to evaluate performance limit states in isolated buildings. Critical load capacity was evaluated for four different bearing configurations through the use of two methods on a single bearing test machine. Shake table tests were conducted on a 3-story steel moment structure in fixed-base and isolated configurations. In these tests, the influence of impact was evaluated using various moat wall configurations.

Test series two was led by Professor Stephen Mahin at the NEES at UC Berkeley lab, and incorporated both hybrid and shake table testing. The Reconfigurable Platform for Earthquake Testing (REPEAT) frame was used with replaceable plastic hinges to repeat many tests at yield levels and beyond. In the hybrid tests, the frame represented the top two stories of a larger structure. The tests used friction pendulum bearings and significantly aged lead-rubber bearings, in order to make the results as accurate as possible. The strength and configuration of the REPEAT frame was varied to represent both special and intermediate moment resisting frames. Based on the data gathered in bi-directional testing of triple friction pendulum isolators, a kinematically consistent model was developed and is available in OpenSees.

The third test series was led by Professors Keri Ryan of UNR and Eiji Sato of the National Research Institute for Earth Science and Disaster Prevention, Miki City, Hyogo, Japan. The specimen was a full-scale, 5-story, 2 bay x 2 bay steel moment frame building on the E-Defense shake table in Japan. It was tested with two innovative isolation systems and in the fixed-base configuration. The building incorporated a realistic floor system and nonstructural components. Triple pendulum bearings and a combination of lead-rubber bearings (LRB) and cross linear bearings (CLB) were tested as isolation systems and led to a series of considerations for design.

As well as for the testing of structures, NEES resources were used for experimental and numerical simulation, data mining, networking, and collaboration to understand the complex interrelationship among the factors controlling the overall performance of isolation systems. Workshops were held through the project, allowing collaborators to expand communication amongst themselves and the community and facilitating the effective application of isolation technology.

Continued on next page

FUTURE

Project participants in collaboration with practitioners will produce a summary of research products from this project, and project participants will stay active in code development. Continuing research to better understand and mitigate the effects of vertical ground shaking on isolated buildings is expected, followed by gradual implementation into practice.

Probing Peat-Based Levees in Sacramento-San Joaquin Delta

Continued from page 71

Numerical simulations show that, for a given level of levee crest acceleration, the top-down shaking imposed on the model levee produce much smaller shear strains in the peat than would be anticipated for bottom-up earthquake shaking conditions.

Strains higher than 1% may occur during earthquake shaking, even though strains were lower during the cyclic field test. For this reason, it is currently unclear whether an earthquake would be anticipated to cause post-cyclic settlement of peaty soils. More work is needed to develop the concepts so that they may be included in future seismic levee evaluation procedures.

The model levee was deliberately constructed to be stiff and strong so that it could transfer energy from the shaker into the underlying soft peat. The model was composed of unsaturated compacted clay reinforced with geogrids, and was therefore not susceptible to liquefaction and was much stronger than most Delta levees. The research team anticipates that liquefaction will result in significant damage to Delta levees in the event of a moderate magnitude earthquake in the region.

Unfortunately, this point was lost in some of the media coverage of the event in which several local engineers claimed that the test proved that Delta levees are seismically stable. These claims do not represent the opinions of the research team, and it is unfortunate that these engineers misrepresented the outcome of the study in a public forum.

Studies Demonstrate Power of Real-time Hybrid Simulation

Continued from page 95

both human and financial, during significant earthquakes and other natural hazards. The RTHS methods developed here will enable an infinite number of tests to be performed with a single setup, empowering the community to perform more efficient and cost-effective global evaluation

of structural systems. Structural systems that are too tall or long, or cannot be tested in a typical laboratory, may be examined using hybrid simulation and real-time hybrid simulation methods. Thus, these projects are leading to the possibility of sophisticated testing of more complex structures than have ever been tested before.

Make Your Own Earthquake Transforms How Kids Learn Engineering

Continued from page 113

Students are required to build K-NEX structures that meet structural and cost parameters, accompanied by structural drawings and architectural renderings. On a subsequent campus visit, they tour the facilities, participate in MYOE, and culminate in a K-NEX competition.

FUTURE

The team at UC Santa Barbara has been busy attending science fairs and elementary schools. After visiting the Make Your Own Earthquake exhibit at the Nevada Discovery Museum, the group decided to build a similar exhibit for the Santa Barbara Museum of Natural History. All local elementary students visit the Santa Barbara Museum of Natural History, so the number of students served by MYOE will greatly increase.

Recurring Liquefaction and its Effects on Buildings and Lifelines, New Zealand

Continued from page 129

As the team documented the re-occurrence of soil liquefaction, they determined that proper interpretation in areas of recurrent liquefaction is critical for assessing the magnitudes of paleoearthquakes (pre-instrumental and prehistoric earthquakes). Field research was focused on capturing data and characterizing the subsurface conditions through the trenching of liquefaction features, performing cone penetration tests, and measuring shear wave velocities.

FUTURE

The PI and Co-PI are continuing their collaborative research with researchers from the University of Canterbury and the University of Auckland. These follow-on efforts have focused on characterizing the geologic profiles at strong ground motion stations throughout Christchurch, performing detailed numerical analyses of select building-foundation systems during the Darfield and Christchurch earthquakes, correlating performance of lifelines with ground conditions, documenting liquefaction case histories, evaluating the efficacy of liquefaction potential damage indices, and assessing paleoliquefaction analysis procedures.

Purdue's NEEScomm Center (NEES Community and Communications Center) serves as operational headquarters for the NEES network. The NEEScomm Team is responsible for the collaborative development of the NEEShub, oversight of the 14 research facilities, and programs aimed at developing the next generation of earthquake engineers. Without these extraordinary individuals the achievements of this award would not have been possible.

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Marti LaChance, Communications Specialist

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Jason Lambert, Software Engineer – Web Systems
Barbara Cooper, Education, Outreach, and Training Coordinator



"An experiment, like every other event which takes place, is a natural phenomenon; but in a scientific experiment the circumstances are so arranged that the relations between a particular set of phenomena may be studied to the best advantage."

--James Clerk Maxwell — Scottish Physicist, 19th Century



NEES