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The George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES)- 10 Years of Testing Experience

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Abstract

The George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) functioned as a shared-use network of 14 advanced laboratories connected by state-of-the-art cyberinfrastructure fostering collaboration in research and education. In a decade since officially opening its doors, over 400 multi-year, multi-investigator projects were completed, yielding many advances in earthquake engineering and a wealth of valuable experimental data. In this paper, brief descriptions of some of the many research accomplishments of researchers using NEES are given as well as lessons learned from the years of operation with sponsorship from the National Science Foundation (NSF). This network of 14 laboratories enabled researchers to explore key aspects of the complex way that soils and structures behave in response to earthquakes and tsunamis. Many of the projects conducted have prompted, or laid the groundwork for, improvements in model building codes and in design and construction practices, enhancing societal resilience to earthquakes and tsunamis. In addition to projects funded by NSF, NEES laboratories were used for research funded by other federal, state, and local agencies, by private industry, and by international researchers under the partnerships that NEES cultivated with research facilities and agencies in Japan, Taiwan, Canada, and China.

Keywords: Experimental Testing; Earthquake Engineering; Research Infrastructures; Tsunamis.

1. Introduction

In November 1998, the National Science Board approved construction of the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) with funds totaling $82 million from the National Science Foundation (NSF) Major Research Equipment and Facilities Construction appropriation. As part of its contribution to the National Earthquake Hazards Reduction Program, the NSF funded NEES operations (NEESops) as well as many of the research projects that were conducted in NEES facilities.

Construction of the laboratories occurred during the period 2000-2004. In 2009, Purdue University became the headquarters of NEESops. At that time, the participating universities hosting NEES laboratories included: University of California, Berkeley (Large-Scale Structural Systems); University at Buffalo, State University of New York (Large-Scale Structural Systems); Cornell University (Lifelines); University of California, Davis (Large-Scale Centrifuge); University of Illinois, Urbana-Champaign (Large-Scale Structural Systems); Lehigh University (Large-Scale Structural Systems); University of California, Los Angeles (Field Testing); University of Minnesota (Large-Scale Structural Systems); University of Nevada, Reno (Shake-Table Array); Oregon State University (Tsunamis); Rensselaer Polytechnic Institute (Geotechnical Centrifuge); University of California, San Diego (Large-Scale Outdoor Shake Table); University of California, Santa Barbara (Instrumented Ground Site); University of Texas at Austin (Ground Field Testing). These university-based laboratories provided researchers with access to a tsunami basin; geotechnical centrifuges, large-scale testing equipment, real-time testing equipment and control systems, shake tables, field shakers, and instrumented test sites.

The laboratories were available not just to researchers at the universities where they were located, but to investigators throughout the United States who were awarded grants through NSF's annual NEES Research (NEESR) Program and other NSF programs. Researchers located at institutions remote from the NEES sites led 80% of NEESR projects. The laboratories were also 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.

Linking the NEES experimental facilities to each other and to off-site users, a unique cyberinrastructure enabled researchers participating on-site or remotely to collect, view, process, and store data from NEES experiments at the NEES-curated central repository. Using the NEES cyberinfrastructure, researchers were able to conduct numerical simulation studies and perform hybrid (combined experimental and numerical) testing involving one or more NEES equipment sites. 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 work in NEES was also felt on the development of future earthquake engineering researchers and practicing engineers. The network supported the efforts of educators to build the workforce necessary to discover and implement research findings. NEES students learned 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. At least 559 graduate students, including 191 PhD candidates, were trained through participation in NEES research. Many of those receiving PhDs now hold faculty positions at major research universities worldwide. In the next several sections, some of the outcomes and impacts of a decade of earthquake engineering research are discussed. A more extensive record of the testing capabilities in the network and the work conducted by the users of NEES over the last decade chosen by distinguished researchers and engineers representative of the NEES community is given elsewhere [1] as well as in the over 5000 citations of NEES related work.

2. Large-Scale Testing

In the 10 years of NEES Operations the National Science Foundation funded three NEESR Grand Challenge (GC) 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. One project addressed port systems, another one focused on vulnerable reinforced concrete buildings, and the third one dealt with nonstructural systems [1]. The NEESR-GC: Mitigation of Collapse Risk in Vulnerable Concrete Buildings (P.I. Jack Moehle, University of California, Berkeley, NSF #0618804, [2006]) aimed to improve seismic rehabilitation standards for concrete buildings constructed prior to 1976 and to create tools to support communities in developing mitigation strategies. In this project 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 using the NEES capabilities at the sites: UC Berkeley, University of Minnesota, UCLA, and UC Santa Barbara.

In the NSF Project #0618804, novel experimental studies of components and systems were carried out. Several tests of short columns were intended to elucidate the behavior of so-called 'captive columns' found in older buildings. Of the twelve specimens tested, seven were subjected to unidirectional displacement protocol and the remaining five specimens were subjected to bidirectional displacement protocol. Ten of the specimens were tested in Minnesota's Multi-Axial Subassemblage Testing (MAST) facility (Figure 1).

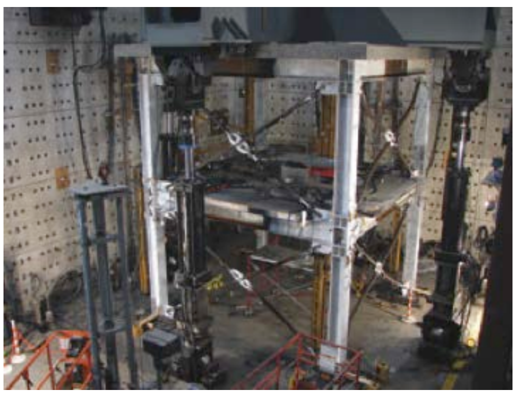

Fig. 1 - MAST Laboratory

In the University of Minnesota facility it was feasible to investigate the effects of earthquakes, high winds, and other extreme events on structures several stories tall. Structures up to 29 feet tall could be placed on a testing platform and subjected to heavy loads by hydraulic arms that mimic the conditions of extreme events. The arms are capable to simulate vertical forces of 1.32 million pounds and horizontal forces of 800,000 pounds. The work conducted at the NEES MAST facility by members of the research team through testing and numerical simulation of older concrete columns expanded the database of laboratory tests in key gap areas possible now thanks to the unique testing capabilities of the MAST Facility. The studies of the test results indicate that bidirectional loading can lead to a reduction of nearly 50% in the deformation capacity of a column. No data on the effects of bidirectional loading on the performance of non-ductile columns were available before this project. Those new data together with the re-use of other existing data contributed to at least two major impacts of the overall project:

- Project team members led the development of revisions to the concrete provisions of ASCE/SEI 41 [2], which were accepted as the ASCE/SEI 41 Supplement. The supplement to ASCE/SEI 41 Seismic Rehabilitation of Existing Buildings was developed for the purpose of updating provisions related to existing reinforced concrete buildings. Based on experimental evidence and empirical models, the proposed supplement includes revisions to modeling parameters and acceptance criteria for reinforced concrete beams, columns, structural walls, beam-column joints, and slab-column frames. The results of this work also have been incorporated into the ATC 72 report [3] in support of the PEER Tall Buildings Initiative.

- Findings from the project have been used in the development of ACI committee document 369R, Guide for Seismic Rehabilitation of Existing Concrete Frame Buildings and Commentary [4] published in 2011 by the American Concrete Institute. This guide, developed based on the format and content of ASCE/SEI 41-06 "Concrete", describes methods for estimating the seismic performance of both existing and new concrete components in an existing building.

After the column tests, eight full-scale beam-column joints were tested under three- directional loading at The University of California at Berkeley in the Reconfigurable Reaction Wall-Based Earthquake Simulation Facility. This facility was designed to support the development of a new generation of hybrid testing methods that smoothly integrate physical testing with simulations. The test specimens in the GC project explored the effects of joint aspect ratio, beam-to-joint strength ratio, and effect of lateral and vertical load history. Axial failures were achieved in four of the test specimens subjected to higher axial loads. An outcome from these tests is that beam-column joint failure is now considered a less-likely contributor to the collapse of older-type concrete buildings than was the case before this research were conducted.

Two more NEES facilities were used to study soil-structure interaction in this project. The test specimen consisted of a steel frame with reconfigurable cross braces that were used to change the stiffness. The frame was tested in 2009 in the UCLA Structural Engineering lab and then relocated to a foundation installed at the NEES@UCSB Wildlife field test site with appropriate on-structure and in-ground instrumentation. An additional foundation was constructed at the NEES@UCSB Gamer Valley test site and the frame was relocated and tested in June and August of 2011. The tests utilized NEES@UCLA shakers, data acquisition, and instrumentation on and near the structure and NEES@UCSB instrumentation and data acquisition in the 'free field.' The test data were evaluated to identify mode shapes, modal frequencies and damping. The NEES@UCSB facility consisted of two permanently-instrumented geotechnical test sites designed to improve the understanding of the effects of surface geology on strong ground motion. The instrumentation at these sites included surface and borehole arrays of accelerometers and pore pressure transducers designed to record strong ground motions, excess pore pressure generation and liquefaction that occurs during large earthquakes.

A significant example of the multi-site large-scale testing capabilities in NEES was provided by the testing conducted under the direction of Prof. John van de Lindt in two projects, the NEESWood (NSF # 0529903) and the NEES-Soft (NSF # 1314957). 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. 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 (Fig. 2) provided valuable data on seismic performance of existing wood-frame buildings, interior and exterior wall finish materials, and passive protective systems. The Structural Engineering and Earthquake Simulation Laboratory at the NEES at Buffalo site was capable of conducting testing of full- and large-scale structures using dynamic or static loading. 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 was also available for soil-foundation-structure interaction studies, at full-scale or near full-scale. The laboratory has a 320-square- meter strong floor and a 9m x 19.5m reaction wall.

Fig. 2 - Testing of a two-story townhouse at the NEES at Buffalo

Next, Prof. van de Lindt's 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 (Figure 3). This was possible due to a memorandum of understanding signed between Japan's Ministry of Education, Culture, Sports, Science and Technology and NSF, Japan's NIED 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. In 2014, it was 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.

Fig. 3 - Testing at E-Defense of 6-story building in NEESWood

As part of the NEES-Soft project the team tested at the NEES@UCSD facility 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 (Fig. 4) provided fundamental data on the collapse mechanisms for soft-story buildings, and project experiments validated the FEMA P-807 [5] retrofit procedure as well as the performance of seismic protection devices for retrofitting soft stories. 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 removed the physical constraints of an enclosed, indoor laboratory.

Fig. 4 - NEES@UCSD Outdoor Shake-Table

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. During testing in NEES the table had a single axis of motion with a stroke of ±0.75m, a peak horizontal velocity of 1.8m/s, a horizontal force capacity of 6.8MN, an overturning moment capacity of 50MN-m, a vertical payload capacity of 20MN, and a testing frequency range of 0-33Hz.

3. Tsunami Testing

Researchers in tsunami hazard mitigation in NEES focused on new methods for modeling the generation, propagation and coastal inundation of tsunamis, and on the design and construction of buildings, bridges, and other coastal structures to withstand the resulting loads and associated effects. Improved modeling of tsunami generation and open ocean propagation has been used to develop more effective evacuation procedures in communities at risk of tsunamis. 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 in NEES took 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.

Fig. 5 - Testing at the OSU O.H. Hinsdale Laboratory

In the NEESR-SG: Physical Modeling of 3D Tsunami Evolution Using a Landslide Tsunami Generator (NSF #0421090) a team of researchers led by Principal Investigator Prof. Hermann Fritz of the Georgia Institute of Technology studied new ways 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 (Fig. 5).

In the OSU facility, researchers can study processes such as 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 (Fig. 5) 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 OSU facility also has a 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 became available on which to base design provisions. For example, one study titled Development of Performance-Based Tsunami Engineering (NSF #0530759) led by University of Hawaii Principal 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 [6].

4. Geotechnical Testing

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, large displacement pipeline tester 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.

In the project *Pile Pinning Effects on a Bridge Abutment in Laterally Spreading Ground During Earthquakes*, the principal investigator Prof. Ross Boulanger from the University of California, Davis, 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. 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.

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. It has the largest radius and platform area of any geotechnical centrifuge in the United States and is among the largest in the world (Fig 6).

Fig. 6 - The UC Davis centrifuge with the largest radius and platform area in the United States

A team led by UCLA Professor Scott Brandenberg 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, pore water pressure, and deformation were embedded in the levee models to characterize the response to seismic energy. The resulting data, including video, has lead 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.

A second centrifuge (Fig. 7) in the NEES portfolio of facilities was located at Rensselaer Polytechnic Institute (RPI). This laboratory is part of the Center for Earthquake Engineering Simulation, a multi-disciplinary research center. The RPI facility focuses on conducting physical model simulations of soil and soil-structure systems subjected to in-flight earthquake shaking.

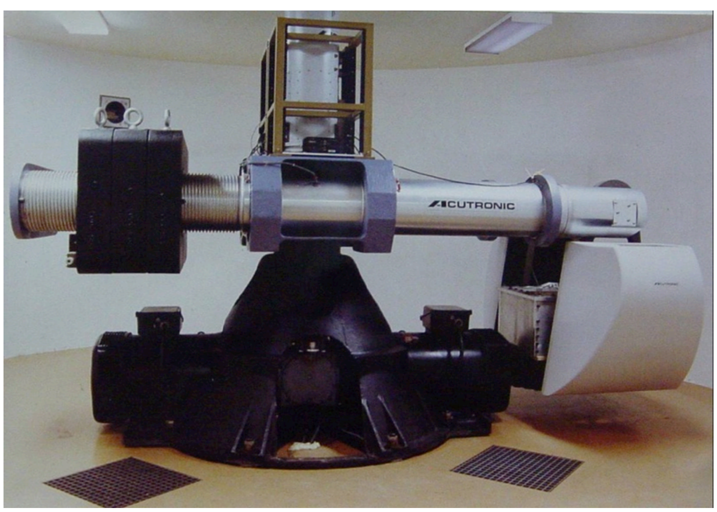

Fig. 7 - Centrifuge at RPI

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. NEES@RPI also developed the advanced NEES 3D data analyses and visualization software tools to aid near real-time processing and data mining.

5. Summary, Lessons Learned and Next Steps

The mission for NEES aligned 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. Through the work at facilities mentioned in this paper and the other outstanding facilities in NEES [1], researchers 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 non-ductile, 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. A summary of capabilities of the 14 laboratories in 2014 can be seen in Table 1. Many of these facilities remain available for shared-use.

Table 1. Key Features of Equipment Sites

Equipment Site	Key Features
University of California, Berkeley	Reconfigurable reaction wall, with accompanying servo-hydraulic actuators, 4M lb. universal test machine
University at Buffalo	Two 6-DOF reconfigurable shake tables, reaction wall, laminar box
Cornell University	Soil box for testing lifelines
University of California, Davis	Geotechnical centrifuge
University of Illinois, Urbana-Champaign	Reaction wall with 6-DOF loading boxes
Lehigh University	Near real-time testing at large scale
University of California, Los Angeles	Mobile shakers and DAQ
University of Minnesota	Reaction wall with crosshead to simulate 6-DOF loading
University of Nevada, Reno	Four 6-DOF reconfigurable shake tables
Oregon State University	Large Wave Flume and Tsunami Wave Basin
Rensselaer Polytechnic Institute	Geotechnical centrifuge
University of California, San Diego	Large uniaxial outdoor shake table
University of California, Santa Barbara	Two permanently instrumented geotechnical sites
University of Texas at Austin	Mobile shake trucks and DAQ

From a decade of shared-use experience of these outstanding facilities important lessons regarding the access and operation have been learned. The success of any shared-research facility must be evaluated mainly by the contribution of the facility towards the advancement of knowledge. In the NEES research program, individual projects were selected independently of each other with little or no coordination among them. This independence: (1) encouraged innovation by individual researchers and small teams; (2) minimized conflicts of interests; and (3) led to numerous advances in earthquake and tsunami engineering; however, the funding of numerous, relatively small projects made it more difficult to identify and communicate key research successes to the broader community. This independence also made difficult the prioritization of efforts towards reaching clear scientific goals. One of the key lessons of the NEES operations experience was ***the identification of the critical need to develop a coordinated research plan***. This plan must strive to balance the need to provide the necessary coordination to achieve ambitious goals, while still fostering individual creativity and initiative. Some specific lessons include:

(i) Clear policies are needed to ensure that key network goals are prioritized. Key areas include: (1) access to facilities; (2) facility scheduling; (3) researcher training before and after project award; (4) safety; (5) accountability; and (6) dispute resolution.

(ii) While day-to-day implementation and monitoring of scheduling at the site needs to be performed locally by the laboratories as they are familiar with the facility constraints and opportunities, an overall network coordinated and monitored site scheduling is essential to mediate possible conflicts and take advantage of network-wide opportunities and capabilities. Management, sites and researchers need to clearly communicate scheduling plans and, in particular, changes in plans. Monthly updated, publically available schedules provide a reasonable level of information to all participants.

(iii) If available, some of the funding allocated by the sponsor for laboratory operations needs to be set aside to meet network priorities. The network priorities need to be clearly communicated to all, and this pooled funding needs to be provided early during the fiscal year, so that the facilities receiving it have the time to implement and benefit from the new initiatives.

NEES provided U.S. researchers and international partners with access to 14 sites with capabilities that were not available at their home institutions. The negotiation of agreements with research facilities in Japan and China further extended the range of facilities available to U.S. researchers and the success of NEES caught the attention of other countries. At the submission of this paper, the process is ongoing to establish the NSF-supported Natural Hazards Engineering Research Infrastructure (NHERI). This will be the next generation of National Science Foundation (NSF) support for a natural hazards engineering research large facility, replacing NEES which concluded operations at the laboratories in 2014.

NHERI will be a distributed, multi-user, national facility that will provide the natural hazards engineering community with access to research infrastructure (earthquake and wind engineering experimental facilities, cyberinfrastructure, computational modeling and simulation tools, and research data), coupled with education and community outreach activities. NHERI will enable research and educational advances that can contribute knowledge and innovation for the nation's civil infrastructure and communities to prevent natural hazard events from becoming societal disasters. This infrastructure will consist of the following components, established under separate awards: a Network Coordination Office (NCO), a Computational Simulation Center (SimCenter); a post-event reconnaissance facility (RAPID) Facility; a cyberinfrastructure (CI); and features six already determined experimental facilities for earthquake engineering and wind engineering research (https://www.designsafe-ci.org/facilities/experimental/).

6. Acknowledgements

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